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COMPREHENSIVE REVIEWS IN FOOD SCIENCE AND FOOD SAFETY

Salmonella in eggs: From shopping to consumption—A review providing an evidence-based analysis of risk factors

Maria João Cardoso[1] | **Anca Ioana Nicolau**[2] | **Daniela Borda**[2] | **Line Nielsen**[3] | **Rui Leandro Maia**[4] | **Trond Møretrø**[5] | **Vânia Ferreira**[1] | **Susanne Knøchel**[3] | **Solveig Langsrud**[5] | **Paula Teixeira**[1]

[1] Universidade Católica Portuguesa, CBQF - Centro de Biotecnologia e Química Fina – Laboratório Associado, Escola Superior de Biotecnologia, Porto, Portugal

[2] Faculty of Food Science and Engineering, Dunarea de Jos University of Galati, Galati, Romania

[3] Department of Food Science, University of Copenhagen, Copenhagen, Denmark

[4] UFP Energy, Environment and Health Research Unit (FP-ENAS), University Fernando Pessoa, Porto, Portugal

[5] Norwegian Institute of Food, Fisheries and Aquaculture Research, Ås, Norway

Correspondence
Paula Teixeira, Escola Superior de Biotecnologia, Universidade Católica Portuguesa, Rua Diogo Botelho 1327, 4169-005 Porto, Portugal.
Email: pcteixeira@porto.ucp.pt

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Abstract

Nontyphoidal salmonellae are among the most prevalent foodborne pathogens causing gastrointestinal infections worldwide. A high number of cases and outbreaks of salmonellosis are associated with the consumption of eggs and egg products, and several of these occur at the household level. The aim of the current study is to critically evaluate the current status of knowledge on *Salmonella* in eggs from a consumer's perspective, analyzing the hazard occurrence and the good practices that should be applied to reduce salmonellosis risk. Following a HACCP (Hazard Analysis and Critical Control Point) based approach, some steps along the food journey were identified as Critical Consumer Handling (CCH)—steps in which consumers, through their behavior or choice, can significantly reduce the level of *Salmonella* in eggs and egg products. From shopping/collecting to consumption, each of these steps is discussed in this review to provide an evidence-based overview of risk factors of human salmonellosis related to egg consumption. The main message to consumers is to choose *Salmonella*-free eggs (those that some official entity or producer guarantees that does not contain *Salmonella*), when available, especially for dishes that are not fully heat treated. Second, as guaranteed *Salmonella*-free eggs are only available in a few countries, refrigerated storage from the point of collection and proper cooking will significantly reduce the risk of salmonellosis. This will require a revision of the actual recommendations/regulations, as not all ensure that eggs are maintained at temperatures that prevent growth of *Salmonella* from collection until the time of purchasing.

1 | INTRODUCTION

Nontyphoidal salmonellae are estimated to be the cause of approximately 153 million cases of gastroenteritis and 57,000 deaths globally each year (Hunter & Watkins, 2017). It is apprised that diarrheal and invasive infections caused by nontyphoidal *Salmonella enterica* result in 4.07 million DALYs (Disability Adjusted Life Years), being considered the largest burden of a disease among enteric diseases (Kirk et al., 2015). The European Food Safety Authority (EFSA) and the European Centre for Disease Prevention and Control (ECDC) reported an overall

European Union (EU) notification rate of 20.1 cases per 100,000 population, corresponding to 91,857 confirmed cases in 2018. *Salmonella* was implicated in 30.7% of the reported foodborne outbreaks of 2018. Salmonellosis was the second most commonly reported zoonotic disease that caused hospitalization following campylobacteriosis, and the second cause of death following listeriosis, due to the consumption of contaminated food in Europe in 2018 (EFSA & ECDC, 2019). In the United States, it was estimated a total number of 1 million illnesses due to nontyphoidal salmonellae in 2013, accounting for 24% of the economic burden (3666 million dollars) among foodborne diseases (USDA, 2019).

Several foods have been linked to cases and outbreaks of salmonellosis (CDC, 2020b; EFSA & ECDC, 2019; Meinen et al., 2019). However, in 2018, 45.6% of the reported salmonellosis outbreaks in the EU were associated with the consumption of "eggs and egg products" (EFSA & ECDC, 2019). This pathogen–food vehicle combination also caused most of the outbreak-associated illnesses in the United States—2422 illnesses (Dewey-Mattia et al., 2018). In a meta-analysis conducted by Domingues et al. (2012), consumption of undercooked or raw eggs and poultry was found as a risk factor for sporadic cases of salmonellosis. When studying the source of provenance in 24 European countries, laying hens were proven to be the main reservoir of strains responsible for human salmonellosis, causing 42.4% of all human cases of infection—95.9% of which were reported to have *Salmonella* Enteritidis as the causative agent (de Knegt et al., 2015). *Salmonella* Enteritidis has been the main serovar associated with human salmonellosis (reviewed by Ferrari et al., 2019), including those infections linked to eggs (Threlfall et al., 2014), and has been implicated in recent outbreaks in different countries (Table 1).

There are two possible routes for *Salmonella* contamination of the contents of intact eggs. In horizontal transmission, the bacterium penetrates through the eggshell; in vertical transmission (transovarian route), the egg content is directly contaminated as a result of *Salmonella* infection of the reproductive organs, before the eggs are covered by the shell components (Gantois et al., 2009; Howard et al., 2012). It is still not clear which route is the most important one for *Salmonella* contamination of the egg content. However, for *S*. Enteritidis, the transovarian route of contamination seems to be more relevant than the penetration of the eggshell (Gantois et al., 2009).

Levels of salmonellas in the content of intact eggs are typically less than 10 CFU/egg (Humphrey et al., 1989, 1991), although eggs containing more than 10^5 CFU/g have also been found (Humphrey et al., 1991). The albumen is more frequently positive for *Salmonella* than the yolk (Humphrey et al., 1989, 1991), suggesting that the oviduct is the colonization site (reviewed by Gantois et al., 2009). The low levels of *Salmonella* found in most of the contaminated eggs, even when stored at room temperature, might be explained by this finding (Humphrey et al., 1989). Although few differences have been reported concerning the behavior of *Salmonella* in egg albumen, it is consensual that growth is restricted in this medium even at ambient temperatures (Kang et al., 2006; Schoeni et al., 1995) due to its antimicrobial constituents. In the yolk, storage at ambient temperatures may result in high numbers of *Salmonella* within a relatively short time, for example, generation times of 3.5 hr and 35 min have been reported for *Salmonella* in egg yolks incubated at 15.5 and 37 °C, respectively (Bradshaw et al., 1990). During storage at 10 °C, growth has been reported in some studies (Bradshaw et al., 1990; Schoeni et al., 1995). However, Chen et al. (2005) did not observe any increase in *Salmonella* counts during storage for 7 weeks at 10 °C. Reducing the temperature to 8 °C or below seems to inhibit the growth of *Salmonella* in egg yolks (Bradshaw et al., 1990; Lublin & Sela, 2008). Most of the previous studies have been conducted at constant temperatures. Nevertheless, this does not represent real scenarios and there is strong evidence that fluctuations in temperatures (including periods of exposure to 25 to 35 °C) will increase levels of *Salmonella* in eggs (Okamura et al., 2008).

Data for the prevalence of *Salmonella* in table eggs are scarce and variable, reflecting differences in, for example, the prevalence in food-production animals, as well as the quality and coverage of the surveillance systems (sampling schemes, sampling context, sampling strategy, sampling unit, sample size). Despite the reported variability, it is generally agreed that the prevalence of *Salmonella* in commercial table eggs is low in most developed countries (Braden, 2006; Martelli & Davies, 2012); a large number of eggs have to be analyzed to detect *Salmonella* and to obtain an accurate measurement of the egg contamination rate (Carrique-Mas & Davies, 2008). Ebel and Schlosser (2000) estimated that one in every 20,000 eggs annually produced in the United States was *Salmonella* positive (0.005%). In Europe, according to EFSA and ECDC (2019), roughly 0.37% of the tested table eggs (n = 6252) were *Salmonella* positive (n = 23). It should be highlighted that these results were reported by only 13 EU Member States and that positive eggs were only reported by Bulgaria, the Czech Republic, Italy, Poland, Portugal, Slovakia, Spain, and Romania (EFSA & ECDC, 2019). Special guarantees have been granted by the European Commission to Finland, Sweden, Norway, and Denmark as recognition of a low prevalence of *Salmonella* and of strict national control programs (European Commission, n.d.). Also, the United Kingdom reports a drastically reduced prevalence of *Salmonella* (ACMSF-Ad hoc Group on Eggs,

TABLE 1 Reported salmonellosis outbreaks related to raw eggs and egg products

Year/Country	Implicated food/place of consumption	Likely cause	No. of cases	*Salmonella* serotype	Reference
2012-2020/Multi-country outbreak	Contaminated eggs/not specific	Contaminated eggs produced in Poland—10 firms belonging to the same operator 2019	1600	*S.* Enteritidis	Whitworth, 2020a
2019/Australia	Contaminated eggs/not specific	Contaminated eggs	235	*S.* Enteritidis	Food Standards Australia New Zealand, 2019
2019/United Kingdom multi-year outbreak	Contaminated eggs/not specific	Contaminated British eggs	45	*S.* Enteritidis	Wasley et al., 2019
2019/Netherlands	Contaminated eggs/not specific	Contaminated eggs produced in Spain (part of an outbreak that started in 2018)	30	Not specified	Whitworth, 2019a
2019/United Arab Emirates	Hollandaise sauce/served at a local restaurant	Sauce prepared with raw eggs	15	Not specified	Gulf Business, 2019
2019/Belgium	Tartare sauce/served at a school	Sauce prepared with raw eggs	200	Not specified	Food Safety News, 2019a
2019/United Kingdom	Contaminated eggs/not specific	Contaminated eggs produced in Poland (part of an outbreak traced to eggs from Poland that started in 2012)	11	*S.* Enteritidis	Whitworth, 2019b
2019/Australia	Vietnamese rolls/sold in three bakeries	Handling of raw egg products	>50	Not specified	Food Safety News, 2019c
2018/Romania	Mayonnaise/fast food products served in Iasi	Not specified	134	Not specified	Ziarul de Iasi, 2018
2018/Chile	Mayonnaise/served at a local restaurant in Lota	Homemade mayonnaise prepared with raw eggs	174	Not specified	Mackin, 2018
2018/United States multi-state outbreak	Contaminated eggs/not specific	Contaminated shell eggs produced by Gravel Ridge Farms	44	*S.* Enteritidis	Centers for Disease Control and Prevention, 2018b
2018/Australia	Contaminated eggs/not specific	Contaminated shell eggs produced by Glendenning Farms	23	*S.* Enteritidis	Whitworth, 2018

(Continues)

TABLE 1 (Continued)

Year/Country	Implicated food/place of consumption	Likely cause	No. of cases	*Salmonella* serotype	Reference
2017-2018/United States	Shell eggs/not specific	Contaminated shell eggs produced by Rose Acre Farms	45	*S.* Braenderup	Centers for Disease Control and Prevention, 2018a
2014/Multi-country outbreak	Contaminated eggs	Contaminated eggs produced in Germany In France reported in homemade chocolate cream made with raw eggs	350	*S.* Enteritidis	European Commission, 2015; Whitworth, 2014
2013/Great Britain	Mayonnaise/two social events in Jersey	Homemade mayonnaise No cooking or "kill" step	21	*S.* Typhimurium DT 8	Ashton et al., 2015
2011/French Polynesia	Tuna dish/restaurant	Prepared with raw eggs	6	*S.* Enteritidis	Le Hello et al., 2015
2011/Poland	Angel cake/served at a family event In Warsaw	Home-produced eggs used Storage at room temperature (warm autumn day)	34	*S.* Enteritidis	Zielicka-Hardy et al., 2012
2010/Austria	Potato salad/student residence	Cross-contamination as a result of preparing in parallel egg-containing breaded cutlets	14	*S.* Enteritidis phage type 14b	Hrivniakova et al., 2011
2009/Australia	Russian salad with raw egg mayonnaise/community barbeque in Sydney	No cooking or "kill" step	71	*S.* Typhimurium phage-type 108/170	Jardine et al., 2011
2009/Australia	Tiramisu dessert with raw egg/served at a restaurant in Canberra	Broken shells used to separate the egg yolk No cooking or "kill" step	20	*S.* Typhimurium phage type 170	Reynolds et al., 2010
2009/South Korea	Pan-fried foods/served at a wedding in Gyeongju	Insufficient cooking	31	Not specified	Yoo et al., 2014
2009/Australia	Garlic aioli/served at a wedding reception	Raw egg yolk No cooking or "kill" step	30	*S.* Typhimurium phage type 44	Denehy et al., 2011

(Continues)

TABLE 1 (Continued)

Year/Country	Implicated food/place of consumption	Likely cause	No. of cases	*Salmonella* serotype	Reference
2008/Mauritius	Marlin mousse/available in supermarkets	Prepared with raw eggs	53	*S.* Typhimurium	Issack et al., 2009
2008/Australia	Chocolate mousse containing raw eggs/served at an aged care facility in New South Wales	Eggs used were "seconds," with evidence of some being cracked and dirty, and there was no procedure for rejecting cracked or dirty eggs at time of receipt. No cooking or "kill" step	45	*S.* Typhimurium phage type 44	Roberts-Witteveen et al., 2009
2002/Spain	Glazed biscuit/served at two banquet halls in Valencia	Use of raw egg No cooking or "kill" step Production of large quantities ahead of time	250	*S.* Enteritidis	Carbó Malonda et al., 2005
2001/Brazil	Potato salad made with homemade mayonnaise/served at a restaurant in Aracaju	Use of raw egg No cooking or "kill" step Mayonnaise left at ambient temperature, which was around 30 °C	114	*S.* Enteritidis	Carneiro et al., 2015
2000/United Kingdom	Egg mayonnaise sandwiches/served at Morriston Hospital, Swansea	Pasteurization failure of the egg roll used in the sandwiches Extended time out of temperature control	17	*S.* Indiana	Mason et al., 2001
2000/Australia	Mock ice cream/dessert served at a local community dinner in Perth	Use of raw eggs purchased directly from a local egg farm that used inappropriate shell cleaning methods Cross-contamination during preparation Insufficient heat treatment	53	*S.* Typhimurium PT135	Sarna et al., 2002

2016). More than 90% of the eggs in the United Kingdom are produced under the British Lion Code of Practice. The risk is thought to be very low for consumptions of eggs obtained in farms adopting this scheme of production. Unfortunately, in the last years, several cases of salmonellosis were traced back to contaminated British Lion eggs (Food Safety News, 2019b, 2019d; Whitworth, 2020b).

In addition to the frequent use of pooled eggs to produce and enrich many types of dishes such as dressings, pasta, meat/fish pies, custard, and desserts, some of which are not thoroughly heat treated or properly stored (EFSA & ECDC, 2010; Howard et al., 2012; Mumma et al., 2004), many other factors could contribute to outbreaks of salmonellosis associated with eggs and egg products (Brown et al., 2017; Jones et al., 2017). As shown in Table 1, undercooking, storing at temperatures that allow growth, and cross-contamination incidents are the most common factors. Several of the reported outbreaks were linked to contaminated eggs and dishes with raw eggs served at restaurants and private and official events, and, in some of these, the strain of the outbreak was not identified.

In the EU, 40.5% of the reported foodborne outbreaks in 2018 were home based and salmonellosis was more frequently reported in such settings when compared to others (EFSA & ECDC, 2019). In the United States, from 2009 to 2015, 12% of the reported foodborne outbreaks were attributed to foods prepared in the domestic environment (Dewey-Mattia et al., 2018). Cases of salmonellosis acquired in the domestic setting may be underestimated as they may not be reported as a part of an outbreak.

Parry et al. (2002) conducted a case–control study of sporadic salmonellosis cases in South East Wales to identify risk factors in the domestic kitchen. The authors concluded that consumption of raw eggs was the most significant risk factor. However, this only explained 20% of the cases. As the authors stated, some risk factors may not have been detected as they only asked about factors that are generally believed to be the main drivers of risk. Concerning home-based foodborne diseases, a broader approach is needed. Consumers' behaviors at every step of a food journey, from the time of shopping until serving, may affect the risk for salmonellosis linked to the consumption of eggs and egg products. Previous risk assessments, although differing in some assumptions and in the attributed risk, have agreed that the probability of getting salmonellosis from eggs results from a combination of factors including, for example, the source of the eggs, the type of food, and the storage time and temperature (Mokhtari et al., 2006; Thomas et al., 2006; World Health Organization & Food and Agriculture Organization of the United Nations, 2002). Nevertheless, all documents report relevant sources of uncertainty.

A prerequisite for the safe handling of eggs by consumers is to be aware of the risk and how to reduce it. Educational resources informing consumers that they need to protect themselves against *Salmonella* infections have been made available worldwide by governments, public health authorities, health professionals, scientists, consumer groups, and the food industry (examples in Table S1). It is important to highlight that information given are sometimes contradictory (e.g., whether to apply cold storage or not after harvest), not always correct (e.g., the need to cook until both the yolk and white are firm to eliminate salmonellae), or science based (e.g., proposing an egg floating test to check eggs before use). Moreover, in a digital world, food safety messages are crossing borders and it is questionable whether consumers from countries where the prevalence of salmonellae in eggs is very low (e.g., Norway) should take into consideration those messages that are delivered in countries where the prevalence is high.

2 | CONSUMER FOOD JOURNEY: WHERE AND HOW RISK MAY OCCUR

Figure 1 illustrates each step, from purchase/collection to the consumption of egg and egg products in a domestic setting.

The flowsheet was developed by a team of sociologists and food safety experts from six European countries (France, Hungary, Norway, Portugal, Romania, and the United Kingdom) (http://safeconsume.eu/about/timeline). Similar flowsheets are also used in professional food production in connection with the implementation of HACCP (Hazard Analysis and Critical Control Points), an internationally recognized methodology to ensure safe food (World Health Organization & Food and Agriculture Organization of the United Nations, 2009). The flowsheet was designed to include common recipes, in which either whole eggs or just the yolk or the albumen are used, prepared just with eggs or by mixing eggs with other ingredients, and being served cooked or raw, because eggs may be used for preparing a variety of dishes in the domestic setting. Some steps are marked as CCH (Critical Consumer Handling), indicating that in these particular steps, consumers, through their behavior or choice, can avoid, eliminate, or significantly reduce the level of *Salmonella*, thus obtaining levels below the infective dose if ingested. CCH1 is placed at the point of collection/purchase (step 1) where consumers can reduce the probability of contracting salmonellosis by purchasing eggs that are guaranteed *Salmonella* free, as opposed to those in which there is no such guarantee (discussed in Section 2.2). At the handling steps before storage and preparation (steps 3 and 5, respectively), consumers may reduce potential transmission by

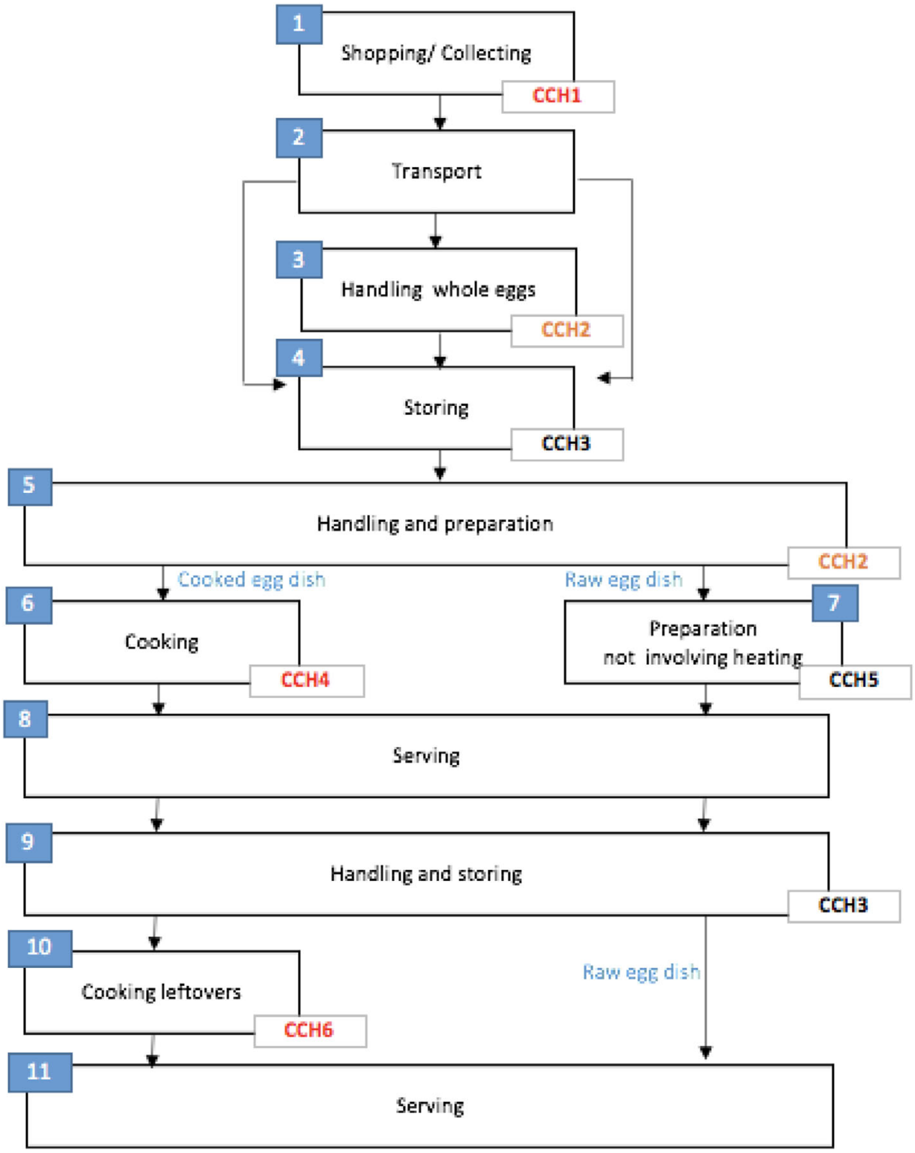

FIGURE 1 Generic flowsheet for Critical Consumer Handling (CCH) of eggs/egg products (CCH—steps in the flow diagram where the consumer through actions or choices can significantly reduce, eliminate, or prevent the hazard; a flowchart developed in the frame of the SafeConsume project). CCHs that will eliminate the hazard in subsequent steps are in red; CCHs related to cross-contamination leading to increased probability of ingestion via hands/other foods are in orange

hygienic handling or washing of dirty eggs (CCH2, discussed in Section 2.3.1). CCH3 refers to storage (steps 4 and 9), where consumers can prevent the growth of *Salmonella* by storing eggs/egg-containing foods in the refrigerator (discussed in Section 2.3.2). Consumers can thermally kill *Salmonella* at steps 6 and 10 (CCH4 and CCH6, respectively, or chemically inhibit the pathogen at step 7 [CCH5]; these are discussed in Sections 2.4.3 and 2.5). An important difference must be noted from a hazard analysis perspective between professional/commercial kitchen setting and home setting, taking into account that *Salmonella* from eggs may not only be ingested at the time of consumption of the ready meal, but also at earlier steps, either intentionally (e.g., tasting raw dough) or unintentionally (e.g., touching the mouth with fingers contaminated during handling contaminated raw eggs). Each of these steps in the consumer journey is discussed in more detail in the following sections.

2.1 | Risk factors before purchase

Food choice is the first step in the consumer journey where consumers can reduce the risk of foodborne diseases. Origin, production mode, place of purchase, storage conditions, visual appearance, size, price, or social concerns are factors that influence consumers in their egg purchasing decisions (Adriano & Ulrich, 2019;

Ayim-Akonor & Akonor, 2014; Sass et al., 2018; Rondoni et al., 2020; Torquati et al., 2019), some of which could have an important impact on safety.

However, consumers generally cannot control risk factors that occur during production until the time of purchase, especially for industrially produced eggs. Factors such as the biosecurity measures implemented, the breeder genotype, nutrition and age, handling, storage until and transportation to the retail store, and storage at retail will affect *Salmonella* contamination and/or growth in eggs. Although these factors are outside the primary scope of this review, we will present some examples in this section.

The eggshell is the first barrier against the penetration of *Salmonella* that may occur by horizontal contamination. The eggshell quality—resistance to breakage, plasticity, and permeability (Wolc et al., 2020)—is dependent on the feeding regime, the genotype of the laying hen, the egg storage conditions, and the hen age (Jones et al., 2018; Sirri et al., 2018). However, with the exception of the feeding regime, which is occasionally used for marketing purposes, the consumer will not have access to this information and consequently, these factors would hardly influence the consumers' buying decisions.

Storage temperature after egg collection will affect the growth of *Salmonella*, but it is difficult to assess if the temperature at which eggs are kept in stores influences consumers' choices, both with regard to purchase and storage conditions at home. There are differences in the legislation in force in different countries regarding egg storage (Fikiin et al., 2020). For example, in Spain and Italy, in more than 85% of the cases, consumers bought eggs placed at room temperature in the store, whereas in Russia and Estonia only 54% and 23%, respectively, bought eggs stored at room temperature (Koppel et al., 2015). Although in the United States, eggs must be hold and transported at or below 7.2 °C (45 °F) beginning 36 hr after time of lay, in the EU, according to Regulation (EC) No. 853/2004, "eggs should be stored and transported preferably at a constant temperature, and should in general not be refrigerated before sale to the final consumer" as "cold eggs left out, at room temperature, may become covered in condensation, facilitating the growth of bacteria on the shell and probably their ingression into the egg." Fikiin et al. (2020) suggested revising this regulation with the inclusion of well-defined requirements of temperature and humidity conditions before purchasing by consumers. For those eggs contaminated with *Salmonella* through the horizontal route, hazardous levels of *Salmonella* may be reached at the time of purchase, even if initially it is present in very low numbers, because *Salmonella* grows rapidly in the egg yolk stored at room temperature (Lublin & Sela, 2008). This is corroborated with the exposure assessment model for the Australian egg industry conducted by Thomas et al. (2006). According to this model, there is a significant potential for the growth of *Salmonella* in contaminated eggs, depending on the temperature and storage period at wholesale and retail levels.

Many European countries such as Spain, Belgium, the Netherlands, and France do not have defined specific legislative requirements for time/temperature conditions associated with eggs storage at retail level. Several countries established a maximum temperature of 18 °C either throughout the whole egg chain or in certain stages, whereas other European countries (e.g., Germany) impose more strict conditions, such as storage between 5 and 8 °C from the 18th day onward after laying, until they reach the final consumer or a constant temperature of 12 °C (e.g., Denmark) throughout the whole egg chain (EFSA Panel on Biological Hazards, 2014).

In cases where the sell-by date for household consumption is extended from 21 to 28 days, EFSA's experts consider eggs' refrigeration as the only way to reduce the increased risk of infections. However, in the worst-case scenario, where the sell-by date is 42 days and the best before date is 70 days, the risk increases even with refrigeration in shops (EFSA Panel on Biological Hazards, 2014). According to Thomas et al. (2006), growth of *Salmonella* may occur at the retail level in 18 days if eggs are stored at 16 °C, 10 days if stored at 22 °C, and 4.6 days if stored at 30 °C.

Depending on the countries, eggs may be stamped with a "best before" date. This indicates the date until the food retains its expected quality. In the EU, eggs are an exception. Eggs must be sold 7 days before the "best before" date expires (28 days after the eggs are laid) (European Commission, 2008). This is based on the recognition that the risk of salmonellosis increases when eggs are consumed after their "best before" date (Food Standards Australia New Zealand, 2009) and is not necessarily applicable where eggs are stored refrigerated. On the other hand, the use of a "best before" date is not a Federal regulation in the United States. When applied, consumers can check the expiration dates on industrial eggs but not on farm eggs.

Summing up, although time and temperature are recognized as factors that control the growth of *Salmonella*, these cannot be controlled by the consumers before retail and often consumers are not informed about the time and temperature regime earlier in the chain. Storing eggs at temperatures allowing the growth of *Salmonella* (>7 °C) from laying to purchase is common, and the consequence is that eggs with high numbers of *Salmonella* can be introduced along the processing chain up to consumers.

2.2 | Egg choice at the time of purchase

Eggs can be purchased from various places, such as stores, markets, and from backyard hens (Table 2). In many

TABLE 2 Place of purchase of eggs in different countries

	Farms/home production (%)	Markets (e.g., farmers' market) (%)	Stores (%)	Reference
India ($n = 115$)	2.6	21.7	75.7	Koppel et al., 2014
Korea ($n = 101$)	6.9	8.9	74.2	
Thailand ($n = 100$)	5.0	32.0	63.0	
Argentina	20.0	48.0	32.0	Koppel et al., 2016
Colombia	17.3	2.0	80.6	
Estonia ($n = 113$)	11.5	3.5	85.0	
Italy ($n = 94$)	25.5	1.1	73.4	
Russia ($n = 100$)	–	11.0	93.0	
Spain ($n = 102$)	21.5	4.9	73.6	
United States	5.7	6.2	88.1	
Finland[a]	–	–	91.0	Lievonen et al., 2004;
Australia ($n = 282$)	10.7	–	–	Whiley et al., 2017
Denmark ($n = 943$)	26.2	6.8	79.9	**
France ($n = 917$)	30.9	21.8	75.0	**
Germany ($n = 939$)	29.6	23.7	71.7	**
Greece ($n = 852$)	36.9	31.8	67	**
Hungary ($n = 976$)	29.5	40.3	61.5	**
Norway ($n = 959$)	18.1	4.3	87.4	**
Portugal ($n = 915$)	43.3	15.8	78.1	**
Romania ($n = 970$)	55.4	33.7	73.9	**
Spain ($n = 990$)	23.6	38.9	64.6	**
United Kingdom ($n = 934$)	13.4	13.7	85.3	**

Note: Respondents were asked: "Where do you typically get the whole, raw eggs you eat at home?" Possible answers were: "Shop," "Market," "Farm," "Backyard eggs," "Other," or "None of the above." Respondents were allowed to select more than one answer.
[a]A total of 4.5% reported buying eggs from direct sale.
**Results of a household online survey conducted between December 2018 and April 2019 in 10 countries: Denmark, France, Germany, Greece, Hungary, Norway, Portugal, Romania, Spain, and the United Kingdom (Langsrud et al., 2020; Møretrø et al., 2020).

countries, eggs sold in stores and supermarkets are under more strict control, both with regard to production processes and storage conditions, than those produced in backyards or from small-scale producers. Therefore, the place of purchase will affect the risk of *Salmonella* infection later in the chain.

The percentage of consumers buying eggs in markets varies, ranging from 1.1% in Italy to 48% in Argentina (Koppel et al., 2016). According to Parker (2013), local farmers' markets are becoming more attractive to consumers. However, several publications raise concerns about the hygiene and microbiological quality of environment and foods available in some farmer markets (reviewed by Young et al., 2017; Oliveros et al., 2019). Bellemare and Nguyen (2018) reported a positive relationship between the number of farmers' markets and the number of outbreaks or cases of foodborne diseases, although the authors stated that "…our results do not allow studying the precise mechanisms through which farmers markets may increase the number of cases and outbreaks of foodborne illness…"

Urban farming is growing in both developed and developing countries (Pilloni, n.d.) and backyard production is an extension of this practice. Driven by different motivations—for example, reducing food waste by feeding chicken with leftovers from household kitchens production, ready source of fresh meat and eggs, and learning opportunity for children—raising backyard chickens for meat or eggs production is becoming more popular, although the real number of backyard flocks is unknown, because registration is not mandatory (Elkhoraibi et al., 2014; Karabozhilova et al., 2012). As shown in Table 2, the number of consumers purchasing eggs from home production should not be underestimated. The preference for backyard eggs leads consumers to buy eggs from what specialists consider to be noncontrolled sources, for example, eggs that are sold in front of a countryside household after staying for hours at the ambient temperature, in gray markets (markets organized for fruits and vegetables where peasants bring eggs unofficially) or in front of a food shop where peasants may meet backyard eggs lovers (Picture S1).

There is limited information available on the prevalence of *Salmonella* in backyard eggs. However, from the available data it appears that there is an increased risk of *Salmonella* infections linked to the consumption of home-produced eggs: outbreaks of *Salmonella* infections have been linked to backyard poultry (CDC, 2020a); home-produced eggs have been linked to outbreaks of salmonellosis (Zielicka-Hardy et al., 2012); Manning et al. (2015) reported that four backyard flocks out of 30 tested positive for *Salmonella* spp., overall *Salmonella* isolation rate was 10.4% (12 isolates from 115 samples); Ferreira et al. (2020) detected *Salmonella*-positive eggs in six out of 56 backyards (10.7%) investigated in Portugal; and some flock owners revealed a lack of awareness about biosecurity, disease prevention, and flock well-being (Elkhoraibi et al., 2014).

Definite conclusions about the role of the source of purchase are difficult to draw given the scarce scientific information available. Therefore, there is a need for further studies to evaluate the actual contribution of consumption of eggs from backyard chickens and small, local suppliers as a vehicle of salmonellosis. Nevertheless, higher occurrence of *Salmonella* in these eggs than in commercial eggs may be anticipated considering the absence of preventive measures in the domestic situation that are applied in commercial laying chicken houses (e.g., biosecurity programs, lack of surveillance of poultry flocks for *Salmonella*, vaccination, hygiene practices of the laying houses).

Table eggs are often marketed as being "organic" or "free-range," but the relevance of the type of production system itself on the risk of salmonellosis is not clear. Mainly due to concerns about the ethics of the poultry industry and animal welfare, consumers in different countries have shown a marked preference for eggs produced in uncaged systems. Cage-free eggs are often perceived as being of better quality, more nutritious, and safer than caged eggs (reviewed by Rondoni et al., 2020).

Eggs from different production systems may pose a different risk of salmonellosis, but so far, this is not clear, because different results have been found in different studies (reviewed by Whiley & Ross, 2015). Several works showed a higher prevalence of *Salmonella* and/or other microbiological indicators in eggs from free-range systems than conventional systems (Huneau-Salaün et al., 2010; Moyle et al., 2016; Parisi et al., 2015); however, others have found the contrary (Huneau-Salaün et al., 2009; van Hoorebeke et al., 2010) or no significant differences (Wales et al., 2007). It is important to point out that "free-range" may refer to going free outside or being inside, but not in a cage. This may be one of the reasons for the different results obtained in different studies. Chickens grown free range in closed systems will not, for example, have contact with wild birds or animals recognized as a source of *Salmonella* for infection of chicken (Chousalkar et al., 2016).

Regarding eggshell color, this seems to be a parameter that influences consumer egg choice but preferences for shell color vary worldwide (Rondoni et al., 2020). Color per se cannot be directly linked to safety. However, several attempts have been made to correlate eggshell color with eggshell quality (reviewed by Samiullah et al., 2015). Being a barrier to the entrance of surface contaminants, eggshell quality, mainly good-quality cuticle, is related to egg safety (Chen et al., 2019; Rodríguez-Navarro et al., 2013). Previous studies reported that brown eggs have higher quality shells (Rayan et al., 2010), lower shell permeability (Dominguez-Gasca et al., 2017), and lower penetration ratio of bacteria (Chen et al., 2019) than white eggs. According to Messens et al. (2007), although brown eggs presented higher shell thickness and cuticle score, white eggs resisted better to *Salmonella* penetration. The authors observed differences in the capacity of eggshells to resist penetration and concluded that these differences cannot be attributed to the genetic strain of the laying hen or housing system. Leleu et al. (2011) found a large variation in cuticle coverage and quality within groups of white and brown eggs from old hens. Ishikawa et al. (2010) demonstrated that brown eggshells and their pigments were active against Gram-positive bacteria but not against Gram-negative bacteria including *S.* Enteritidis. However, these results were not corroborated with the ones reported by Dearborn et al. (2017).

As the brown color of eggs can be lost with stress, malnutrition, illness, and older age (reviewed by Samiullah et al., 2015), a dark color of brown eggs may indicate high quality of the egg production in general and therefore also safer eggs.

Several studies indicate consumers' preference for large eggs (Ayim-Akonor & Akonor, 2014; Żakowska-Biemans & Tekień, 2017). As previously mentioned, the size of the eggs depends on several factors including the age of the hens. Older hens lay larger eggs that due to the increase in the egg weight, volume, and eggshell surface area associated with age-related factors will have a decrease in the shell quality (Crosara et al., 2019; Sirri et al., 2018). According to Dunn (2013), larger eggs are more prone to shell damage during handling than smaller eggs. Moreover, due to the decrease in the membrane thickness, the egg structure is also altered. Older hens produce longer eggs (Crosara et al., 2019; Sirri et al., 2018) and this may result in cracking and breaking during transportation as they do not fit well in the cartons (Sarica & Erensayin, 2009 cited by Crosara et al., 2019). Although at first sight, there is no reason to point to the consumption of large eggs as a factor with food safety implications, in the light of the present scientific knowledge, the associated risk needs to be further investigated.

In general, consumers are advised to inspect the eggs at the time of purchase (Table S1), as cracks and dirt are regarded as risk factors for contamination of the content. The relevance of dirty and cracked eggs as sources of *Salmonella* infection is highlighted by *Salmonella* food poisoning outbreaks in Queensland (Australia), where it was revealed that the use of dirty and cracked eggs in restaurants was the major source of bacteria in these outbreaks (Slinko et al., 2009).

Cleanliness seems to be a factor that may determine egg purchasing. In an online survey conducted in the United States, 86% of the respondents indicated that they checked if eggs are clean and not cracked before acquiring them (Kosa, Cates, Bradley, Godwin, et al., 2015). Consumers in Ghana considered cleanliness as one of the most important parameters preceded by size and price (Ayim-Akonor & Akonor, 2014).

According to EC Regulation No. 589/2008 (European Commission, 2008), in Europe, producers are not allowed to wash eggs, although UV treatment is allowed. UV-C treatment alone or in combination with ozone or hydrogen peroxide (H_2O_2) was demonstrated to be effective for the inactivation of *Salmonella* spp. present on eggshells (Turtoi & Borda, 2014). Some member states are excepted, being authorized to implement egg-washing systems under carefully controlled conditions. According to the same regulation, fresh eggs for human consumption sold to consumers at retail level (class A) shall have clean and undamaged shells. However, this may not always be the case as shown in Picture S2. Dirty eggs are more common among those provided directly from farmers in local markets (Pictures S3 and S4). When biosecurity, husbandry, and hygiene practices are poor compared to commercial producers (Karabozhilova et al., 2012; Kauber et al., 2017; Manning et al., 2015), it is expected to find not only more eggs with dirty shells but also more contaminated eggshells. However, as previously stated, studies comparing *Salmonella* prevalence in backyard versus commercial eggs are lacking. Although consumers report to check if eggs are clean before acquiring them, this probably refers to commercial eggs. In a survey applied to urban backyard poultry owners residing in Seattle, Washington, and the surrounding metropolitan area, 42% of the participants responded that they eat dirty eggs from their chickens (Kauber et al., 2017).

The age of the hens (Mallet et al., 2006), airborne dust concentration (De Reu et al., 2005), manual packing of the eggs, and packing in plastic rather than in recycled-pulp egg-flats (Huneau-Salaün et al., 2010) have been reported as influencing factors on eggshell contamination. The salmonellosis risk due to consumption of dirty eggs will be discussed in Section 2.4.

In summary, consumers can eliminate the possibility of ingesting *Salmonella* from purchased eggs if they choose eggs that are guaranteed *Salmonella* free, that is, those that some official entity or producer guarantees that do not contain *Salmonella*, or pasteurized eggs. Therefore, the point of purchase is a critical point (CCH), and could in principle be the only control point and exclude all other downstream CCHs (Figure 1). However, in most countries, eggs available to consumers are not certified as *Salmonella* free. The likelihood of contamination of such eggs varies with a number of factors. Small, brown, clean eggs from a caged hen may have a lower likelihood of being contaminated than large, white, dirty eggs from a free-range hen. Still, the differences are small, and safety will primarily be dependent on how the eggs are handled in later steps.

2.3 | Eggs storage

2.3.1 | Storage in domestic kitchens: Hygiene

It has been demonstrated that egg washing can reduce the microbial contamination on the eggshell (Hutchison et al., 2004; Messens et al., 2011), decreasing the probability of *Salmonella* penetration into the egg content. Nevertheless, the benefits of egg washing are still a matter of discussion among the scientific community. For example, Gole et al. (2014) demonstrated that washed eggs had more damaged cuticles when compared to unwashed eggs and that *S*. Typhimurium penetrated washed eggs at a higher rate than unwashed eggs. On the other hand, Kulshreshtha et al. (2018) showed that although the commercial washing process removed surface cuticle from the egg, cuticle pore plugs formed within the eggshell pore remained, firmly protecting the egg against invading pathogens. Different legislation exists in different countries related to this practice at industrial settings.

Although consumers can buy dirty eggs, they are advised not to wash eggs before storage at home (Table S1). Consumers' practices regarding cleaning eggs before storing them are still not widely investigated, but this maybe a common practice especially regarding those eggs that are soiled with feces, blood, or feathers as shown in Pictures S3 and S4. In a survey conducted in the United Kingdom by Karabozhilova et al. (2012), washing the eggs was a practice reported by 93% of backyard chicken flock-keepers that answered to the questionnaire ($n = 30$).

Regarding cleaning eggs before using them, different tips are given by different entities. Nevertheless, washing only dirty eggs and immediately before preparation is widely accepted and even recommended (Table S1). In

TABLE 3 Do you clean the eggs before using them?

	Denmark ($n = 943$)	France ($n = 917$)	Germany ($n = 939$)	Greece ($n = 852$)	Hungary ($n = 976$)	Norway ($n = 954$)	Portugal ($n = 915$)	Romania ($n = 970$)	Spain ($n = 990$)	United Kingdom ($n = 934$)
Every time (%)	9.1	11.5	8.6	30.2	45.2	8.4	34.3	36.4	20.8	14
If they look dirty (%)	28	22.6	31.5	35.8	31.4	17.7	37.3	34.2	28.1	25.8
Depending on where I got them (%)	13.7	9.7	8.3	8.6	9.5	11.1	4.7	11	10.9	8.7
I don't clean eggs (%)	48.1	56.1	50.7	25.2	13.5	62.2	23.2	18.2	39.7	51.1
Other (%)	1.1	0.2	0.9	0.2	0.4	0.6	0.5	0.1	0.5	0.4
Total	100	100	100	100	100	100	100	100	100	100

Note: Results of a household online survey on food safety conducted between December 2018 and April 2019 in 10 European countries: Denmark, France, Germany, Greece, Hungary, Norway, Portugal, Romania, Spain, and the United Kingdom (Langsrud et al., 2020; Møretrø et al., 2020).

the survey conducted by Stratev et al. (2017), 45.6% of the inquired veterinary medicine students (Trakia University, Bulgaria) considered that eggs should be properly washed before cooking or frying. When European consumers were asked if they clean eggs before using them, different behaviors were reported in different countries (Table 3; SafeConsume results to be published). However, with the exception of France, households from countries where approximately 50% or more reported not cleaning eggs were also those reporting getting less eggs from farms (home production included) or in open markets (Table 2). Cleaning dirty eggs varied between 17.7% in Norway and 37.3% in Portugal, but these values were probably influenced by the frequency these respondents observe in home-produced dirty eggs in their countries.

The occurrence of dirty eggs is a reality and it is difficult to convince consumers to store these eggs in the refrigerator close to other food items. Meantime, it is neither wise nor indeed reasonable to encourage consumers to waste dirty eggs. Eggs become dirty if the hens and their living space are not clean. So, a first step may rely on the education of egg producers regarding hygiene management. Even when good production practices are implemented, eggs that seem clean may have residues of dust on the surface as the contact between eggshell and feces is difficult to avoid (McWhorter & Chousalkar, 2020). In our opinion, instead of being advised against washing dirty eggs, consumers should be informed about the safest procedures for washing home-produced eggs. In fact, recommendations given to industrial producers can also be implemented at households: washing eggs in running water at least 10 °C warmer than the egg temperature as soon as they are collected and drying after washing (Department of Primary Industries [NSW Food Authority], 2015). There are also commercial products specifically designed for egg cleaning that are claimed to be "a safe and effective alternative to using soap and water" (My Pet Chicken, n.d.). Nevertheless, it is important to highlight that washing reduces the level of *Salmonella* on the eggshell but not in the shell pores (McWhorter & Chousalkar, 2020). On the other hand, CDC advises for carefully cleaning eggs with dirt and debris with fine sandpaper, a brush, or a cloth (CDC, 2020a), a practice that may generate aerosols containing salmonellae.

In summary, consumers should inspect eggs at the time of purchasing in supermarkets or stores and reject dirty eggs. Washing commercial table eggs is not a recommended practice. A different message, however, needs to be transmitted to backyard eggs' consumers. Little information exists on the levels of *Salmonella* on the shell of a dirty egg and on the effect of egg washing in reducing contamination of the pathogen. In the absence of such information, it is difficult to ascertain if washing dirty eggs is a CCH (steps 4 and 5 in Figure 1). However, in our opinion, consumers should be informed on the best washing practices of home-produced dirty eggs; advice not to wash dirty eggs will hardly be followed. Nevertheless, consumers have the opportunity to effectively eliminate *Salmonella* by proper heat treatment of the eggs before consumption (CCH4 in Figure 1).

2.3.2 | Storage in domestic kitchens: Time and temperature

Salmonellae grow at temperatures between 7 and 48 °C, but growth below 10 °C is slow or not always observed (Chen et al., 2005; International Commission on Microbiological Specifications for Foods, 1996). As for other foods, the length of time and the temperature at which contaminated eggs are kept have the greatest impact on the level of *Salmonella*. The growth of salmonellae in the albumen is low but, when they reach the yolk, growth rate increases. The higher the storage temperature, the faster the growth of the pathogen. The vitelline membrane of fresh eggs limits the passage of *Salmonella* from the albumen to the yolk.

The integrity of this membrane is lost during storage and loss of integrity increases as temperature rises. When vertical transmission occurs, as the principal site of contamination remains to be established, it should be assumed that contamination of any part of the egg, including the yolk, is possible (reviewed by Gantois et al., 2009).

According to the "Risk Assessments for *Salmonella* Enteritidis in Shell Eggs and *Salmonella* spp. in Egg Products" conducted by the Food Safety and Inspection Service (FSIS), quick refrigeration of shell eggs has a significant effect on reducing salmonellosis. According to this study, the estimated number of human illnesses would drop from 130,000 to 89,000, if eggs were stored and maintained at 7.2 °C within 36 hr of lay (Food Safety & Inspection Service, 2005). According to information made available by EFSA, "keeping eggs refrigerated is the only way to reduce the increased risk of infections due to extended storage" (EFSA Panel on Biological Hazards, 2014).

Up to now, many surveys have been carried out on consumer perception and attitudes toward eggs (Ergönül, 2013; Hansstein, 2011; Nesbitt et al., 2014; Odeyemi et al., 2019); however, studies associated with consumers' behavior focusing the storage of raw eggs at their homes are few.

The temperature for storing eggs varies between consumer groups, along factors such as consumer nationality, age, living area, vulnerability, and so on. Koppel et al. (2015) studied the consumers' purchase, storage, handling, and preparation of eggs in four different European countries (Russia, Estonia, Italy, and Spain). Almost all the consumers involved in the study in Estonia (99%), Russia (95%), and Spain (92%) stored eggs in the refrigerator, whereas 20% of Italians did not keep eggs refrigerated.

The Nordic countries have a low prevalence of *Salmonella* in eggs, as a result of a *Salmonella* control program developed several years ago (Lievonen et al., 2004). Despite this low prevalence, in a survey conducted in Finland (Lievonen et al., 2004), it was revealed that most of the respondents stored eggs under refrigeration and only 7% indicated storage at room temperature. This seems to indicate a lack of correlation between the risk in the particular country and the consumer practices; in other countries (e.g., Italy) with a higher prevalence of *Salmonella* in eggs, a high number of consumers store eggs at room temperature.

When storing eggs in the fridge, consumers adopt different storage practices that depend on the source of acquisition, eggs package, and so on. In many countries, consumers are informed how they should store eggs (Table S1). For example, The British Egg Industry instruct consumers to store eggs in their boxes to avoid eggs adsorbing through its porous shell any odors from surrounding foods with strong flavors or odors. Moreover, in the absence of the carton or plastic box, eggs lose moisture and gas faster, resulting in a decrease in egg's functional properties (Bradley & King, 2004).

On the other hand, there is a correlation between the "how" and "where" consumers store eggs in the fridge. Balzan et al. (2014) reported that 58.4% of the Italian consumers involved in their study keep eggs in the fridge door either packed or unpacked. Ovca and Jevšnik (2009) observed that Slovenian consumers that stored eggs in the original package kept them on where there was available space; safety considerations were not taken into account. The same authors showed that about 50% of the Slovenian consumers involved in the survey place eggs on the top shelf of the fridge.

The operating temperatures of household refrigerators were reviewed by James et al. (2017) and recently monitored in 15 households from five countries (Norway, France, Portugal, the United Kingdom, and Romania) by Dumitrașcu et al. (2020). A high number of refrigerators with temperatures higher than 7 °C were found and the door was the position in the refrigerator with the highest temperature. In addition, frequent door opening increased temperature. Fluctuation in temperatures may result in condensation on the eggshells, a condition known to promote *Salmonella* penetration. Despite the strong reasons and recommendations to not store eggs in the door, many refrigerators are still supplied with egg trays, often without a lid, on the door shelves.

As previously mentioned in Section 2.1, the risk of salmonellosis increases when eggs are consumed after their "best-before" date, assuming that they may not have always been properly stored. Although consumers are frequently advised to "Check the best-before date," alternative and sometimes contradictory information is also given, for example, "eggs that are floating in water can be used but not totally fresh" or "Use eggs within 4 to 5 weeks from the day they are placed in the refrigerator" (Table S1). In fact, messages suggesting that eggs after the best-before date can be consumed with confidence are widely disseminated on the Internet. For example, "If you keep your eggs in the fridge, you can eat them up to three weeks after the use by date," "A lot of people rely on the date on the package to tell them when food has gone bad, even with eggs, but the sell-by dates are often somewhat arbitrary and are not expiration dates," or "Eggs can be safely eaten 2 to 3 weeks beyond the expiration date." Consumers seem to follow these tips. In a survey conducted in the United States, 44% of the respondents reported that they always finished their egg cartoon regardless the age of the eggs, and of those that might discard eggs, 17% rely on smell or appearance and 9% on other methods (Maughan et al., 2016). In a study conducted in Finland, although most consumers (65%) reported that they use eggs no more than 1 week after the best-before date, 1.2% reported the use

TABLE 4 How long after you get whole eggs do you typically still eat them?

	Denmark (*n* = 943)	France (*n* = 917)	Germany (*n* = 939)	Greece (*n* = 852)	Hungary (*n* = 976)	Norway (*n* = 954)	Portugal (*n* = 915)	Romania (*n* = 970)	Spain (*n* = 990)	United Kingdom (*n* = 934)
Within the best before date (%)	26.4	31.4	26.6	32.9	23.3	19.7	43.9	30.3	30.7	38.5
Within one day (%)	2.1	3.3	2.7	0.9	1	2.8	1.6	3	2.2	4
Within 3 days (%)	6.5	7.3	7.1	5.6	5.3	4.7	4.7	10.1	8.2	8.9
Within one week (%)	23.3	13.8	27.8	32.5	25.6	15.5	25.2	31.8	31.9	22.8
Within two weeks (%)	22.8	20.4	24.4	18.2	26.4	19.5	16.1	18.4	17.2	14.7
Within 3 weeks (%)	8.9	13.2	4.3	7.5	9.6	16.1	3.9	4.3	4.8	5.1
More than 3 weeks (%)	5.9	7.4	3.4	1.6	5.3	15.8	1	1	2.4	3.1
I don't know (%)	4	3.2	3.7	0.7	3.4	5.8	3.5	1.1	2.5	2.9
Total	100	100	100	100	100	100	100	100	100	100

Note: Results of a household online survey on food safety conducted between December 2018 and April 2019 in 10 European countries: Denmark, France, Germany, Greece, Hungary, Norway, Portugal, Romania, Spain, and the United Kingdom (Langsrud et al., 2020; Møretrø et al., 2020).

of eggs up to 2 months after this period (Lievonen et al., 2004). In the survey conducted within the scope of SafeConsume, most respondents declared they eat eggs within the best-before date or within 2 weeks after getting the eggs (Table 4). Consumption after this period varied between countries, in the range of 1% (Portugal and Romania) to 15.8% in Norway.

Cutting down on food waste is a key element for reducing greenhouse gases and free farmland. Also, food waste represents an economic loss for the society, including for the consumer. To our knowledge, the contribution to food waste of throwing eggs away after the best-before date has not been estimated. Nevertheless, as there is no way consumers can detect contaminated eggs, and as recommended for other foods, consumers should be motivated to plan their meals in order to avoid buying eggs that will be not consumed during their shelf life. Exceptionally, when this is unavoidable (e.g., overproduction of backyard eggs), older eggs should only be consumed if hard-boiled or used in dishes that will be fully cooked. As the prevalence of *Salmonella* in commercial table eggs is low and the best-before date of eggs is related to quality and not to safety attributes (EFSA Panel on Biological Hazards, 2014), the majority of eggs after this date are *Salmonella* free. However, the possibility of a few eggs having a relevant contamination at this stage should not be neglected.

In summary, the storing step 4 (Figure 1) is a CCH, as keeping eggs at refrigerator temperature stops the growth of *Salmonella*. Cold storage (from collecting to use) will keep the level of *Salmonella* below infective doses. Unfortunately, eggs may have been subjected to temperatures allowing the growth of salmonellae before purchase, and in those cases refrigeration at the consumer stage may not reduce the risk. Regarding backyard eggs, refrigeration as soon as possible after laying and cook thoroughly if not fresh are important messages to pass to consumers.

2.4 | Egg preparation and consumption

Handling of dirty and contaminated eggs is a risk factor for cross-contamination of surfaces and other foods and for ingestion of *Salmonella* by food handlers via the hand to mouth route (El-Tras et al., 2010; Food Standards Australia New Zealand, 2009; Luber, 2009; Middleton et al., 2014).

The likelihood of *Salmonella* contamination on dirty eggs will depend on the nature of the dirt, with fecal contamination largely responsible for such contamination. Fecal contamination may be a source of *Salmonella* and reports also show that the presence of fecal soil increases their survival and growth (Gantois et al., 2009; Schoeni et al., 1995). *Salmonella* on the outside of eggs may be transferred to the inside content of the egg by penetration through the eggshell, and the transfer is likely higher for eggs with cracks (Gantois et al., 2009). Cracked eggs were more likely to test positive for *Salmonella* than those with intact shells, even if the shells of the intact eggs were dirty with feces (Humphrey et al., 1989). *Salmonella* may also be transferred from the eggshell to the egg content when cracking the egg when preparing a meal (Braun et al., 2002). The numbers of *Salmonella* transferred is likely to be correlated with the contamination level on the outside eggshell (Braun et al., 2002; Mokhtari et al., 2006). The prevalence of *Salmonella* is higher on eggshells (positive in eight of eight studies) than the interior (positive in four of eight studies), but there is missing information about levels of *Salmonella* (Luber, 2009). Thus, the risk associated with dirty eggs is difficult to estimate. The only quantitative data we are aware of are from Mokhtari et al. (2006) who, as an input parameter in their risk assessment, used a uniform distribution between 0 and 20 cells of *Salmonella* as an expert judgment for the transfer from an eggshell when cracking eggs during food preparation. If the numbers are so low, it is likely that dirty eggs are only a food safety risk if conditions will allow growth of *Salmonella* after the transfer, thus this risk will be affected by conditions such as egg storage temperature and the type and storage conditions of egg-based prepared dishes. If *Salmonella* is present on the outside surface of an egg, there is also a risk of infection caused by transfer to hands and mouth from handling the eggs (El-Tras et al., 2010).

In a Canadian case–control study, not washing hands after handling raw eggs almost tripled the rate of *S*. Enteritidis infection. No or borderline statistically significant risk was associated with preparing raw eggs or egg dishes containing raw eggs (Middleton et al., 2014). It has been reported that consumers do not always wash hands or clean surfaces and utensils when handling eggs. Surprisingly, most investigations on food safety and domestic practices do not mention eggs in connection with hygiene (Byrd-Bredbenner et al., 2013; Jevšnik et al., 2008; Langiano et al., 2012; Lazou et al., 2012; Moreb et al., 2017; Osaili et al., 2013; Ruby et al., 2019; Tomaszewska et al., 2018). Thus, it appears that consumer knowledge and practices about hygiene and eggs are perceived as of less importance in parts of the scientific community.

A "consumer-phase" *S*. Enteritidis risk assessment for egg-containing foods was conducted by Mokhtari et al. (2006). Foods were classified into six categories based on the use of pooled eggs (e.g., omelets), the use of eggs as a dish (e.g., fried eggs) or as an ingredient (e.g., ice cream), and the degree of cooking. Foods containing pooled raw eggs used as an ingredient (e.g., ice cream, eggnog, salad dressings, raw cookie dough) were identified as presenting the greatest risk of salmonellosis to consumers. A similar conclusion was reported in a risk assessment conducted in Australia: egg-related outbreaks of salmonellosis were associated with the consumption of foods containing raw or undercooked eggs, foods exposed to temperature abuse, and cross-contamination during preparation, storage and handling (Thomas et al., 2006). Although these studies were conducted more than 10 years ago, the conclusions would probably be similar now, although the total risk may be lower as the *Salmonella* frequency in eggs is lower.

2.4.1 | Hand washing

The practice varies between consumer groups and cultures, but in general, 30% to 50% of consumers claim that they wash hands after breaking eggs. In a survey conducted in Finland (internet), 34% answered "always" to the question "Do you wash your hands after breaking shell eggs" (women in higher number than men) (Lievonen et al., 2004). In an online survey conducted in Australia, 38.7% of the respondents answered "always" to the question "How often would you wash your hands after handling eggs during food preparation" (Whiley et al., 2017). Environmental Health Officers and food handlers reported significantly safer behaviors and no significant gender differences were identified (Whiley et al., 2017), indicating that food safety knowledge and training can eliminate gender differences.

In a survey on the preparation of homemade mayonnaise salad in Brazil, 94% of the respondents claimed that they washed hands before, during, and after preparation; the number of respondents that washed their hands immediately after touching raw eggs is uncertain because the salad contained a number of ingredients.

In studies from the United States, 48.1% of the participants self-reported washing their hands with soap and water after cracking a raw egg (Kosa, Cates, Bradley, Chambers IV, et al., 2015; Kosa, Cates, Bradley, Godwin, et al., 2015), whereas 15% and 17% demonstrated "a proper hand washing" (Maughan et al., 2016) after handling raw eggs for fried eggs and for scrambled eggs, respectively. In the self-reporting study, women and individuals with a high school education or less were more prone to washing their hands after touching eggs than other groups. A reason for the lower numbers in the observation study compared with the other study could be that the criteria used for compliance when washing hands was relatively strict: >20 s with soap and warm water. Also, it is well documented that self-reporting may overestimate safe food handling practices.

In a survey conducted in European countries, more than 50% of the respondents stated that they wash hands with soap after handling raw eggs, meat, poultry, or seafood (Koppel et al., 2015). Based on the results gathered in this study, it is difficult to estimate the frequency for handwashing after handling eggs, as the practice varies between foods. For example, the number of consumers who wash their hands after handling chicken is double the number of consumers who wash their hands after handling eggs in U.S. studies (Kosa, Cates, Bradley, Chambers IV, et al., 2015; Kosa, Cates, Bradley, Godwin, et al., 2015; Maughan et al., 2016). We are not aware of studies on the effect of handwashing on *Salmonella*, but washing hands for only 5 s with no soap can reduce *Enterobacter aerogenes* (a surrogate for *Salmonella*) on the hands by approximately 1 log (Jensen et al., 2015) and proper handwashing can reduce the number of transient bacteria on hands by 0.5 to 1.5 log (Fischler et al., 2007; Ojajarvi, 1980). In most situations, the levels of *Salmonella* on hands after handling eggs will likely be so low that proper handwash will reduce the risk of infections to very low levels.

2.4.2 | Hygiene of surfaces/equipment

Salmonella may survive for weeks on surfaces that are not cleaned (Margas et al., 2014; Møretrø et al., 2020). Outbreaks of *Salmonella* in restaurants due to cross-contamination events associated with eggs have been reported (Slinko et al., 2009). There are few reports on consumer hygiene practices applied for surfaces after preparing eggs. In a survey conducted in Finland (Internet and social media posts), 87% of the consumers reported to wash utensils after preparing an egg dish, either with hot water and detergent or in the dishwasher (Lievonen et al., 2004). In an Australian study, 34% reported to wipe down the counter top after handling raw eggs (Whiley et al., 2017).

The numbers of *Salmonella* in/on the eggs will highly influence the degree of risk of salmonellosis due to cross-contamination. Only a fraction of the *Salmonella* cells is transferred upon contact between foods and surfaces. Most *Salmonella*-positive eggs will contain <10 *Salmonella* per egg (Humphrey et al., 1989, 1991), and for such eggs the risk of sickness due to cross-contamination from eggs to other foods is minimal. However, if the contaminated, prepared food dish is subsequently stored at a temperature enabling growth of *Salmonella*, the risk of infection due to cross-contamination can still be significant. For eggs with high levels of *Salmonella* (up to 10^5/g has been reported; Humphrey et al., 1991), a minimum infectious dose may be transferred to other foods though cross-contamination. Luber (2009) concluded that cross-contamination when handling eggs seems to lead to greater risk of salmonellosis than undercooking eggs. The conclusion was based on a higher prevalence of *Salmonella* on the eggshell than in the content of eggs. In our opinion, the conclusion is somewhat uncertain, because it is based on the prevalence and not on levels of *Salmonella* on the surface and inside the eggs. Relying the risk assessment on the number of *Salmonella* (instead of prevalence) would lead to better estimates of the risk of salmonellosis, but such data are lacking.

In summary, handwashing and cleaning of surfaces is a CCH (steps 3 and 5 in Figure 1), as proper handwashing and cleaning can significantly reduce the likelihood of ingestion of *Salmonella* and thus the risk of developing salmonellosis.

2.4.3 | Inactivation practices

Food writers have been considered “well placed to educate the public and to develop alternatives for recipes that require inadequately cooked eggs” (Lighton & Greenwood, 1994). However, recipes of products containing raw eggs (e.g., steak tartare, salad dressings, mayonnaise, chocolate or caramel mousse, tiramisu) are available in cookbooks, blogs, magazines, YouTube, and on the packaging or containers of some ingredients. In addition, some of these recipes are part of regional cultural heritage (e.g., tiramisu, Italy; açorda, Portugal; home-prepared mayonnaise in Romania), and can be found in different parts of the world.

Acidification

In some of the raw egg recipes such as ice cream, chocolate mousse, or tiramisu, no major inactivation is expected and using *Salmonella*-free or pasteurized eggs is the only way to reduce the risk of contracting salmonellosis. Other preparations may have potentially inhibitory amounts of acids added, such as mayonnaise or other egg-based dressings or desserts such as lemon mousse. After several larger outbreaks with mayonnaise, not least a Danish outbreak in 1955 with 10,000 reported cases, the production of commercial mayonnaise has been regulated with regard to mandatory use of pasteurized eggs and specifications regarding acidity (although maximum pH values vary between countries) (Kelly-Harris et al., 2011; Michels & Koning, 2000). Homemade mayonnaise, however, continues to be a problem in small-scale catering and at family events, where outbreaks are more easily discovered than in individual households. A range of earlier outbreaks is described in reviews such as Radford and Board (1993). More recent salmonellosis outbreaks involving homemade mayonnaise are presented in Table 1.

In the case of mayonnaise, the acid is usually from vinegar, lemon juice, or a combination of the two, whereas in, for example, hollandaise sauce and lemon mousse only lemon juice is used as the acidulant. It has been proven that the bactericidal effect is higher for acetic acid compared to citric acid, both when the same volumes are compared resulting in different pH values (Lock & Board, 1995; Nielsen & Knøchel, 2020) or if the pH of the mayonnaise is kept the same, resulting in different volumes being added (Nielsen & Knøchel, 2020; Perales & Garcia, 1990).

Besides the difference in the effect of the acidulant, the amounts suggested in recipes may vary markedly and they are normally given due to taste preferences or tradition rather than safety considerations. How much acid to add to a homemade mayonnaise from a food safety point of view has been suggested by several studies. The consensus is to use vinegar to reach a pH of 4.1 to 4.2 and a storage time of 24 to 72 hr at room temperature to ensure the right time and temperature conditions for inactivation of *Salmonella* (Keerthirathne et al., 2019; Lock & Board, 1995; Radford & Board, 1993; Smittle, 1977; Xiong et al., 2000). A recent study by Nielsen and Knøchel (2020) focused on finding the right ratio of acid to egg yolk before oil or other ingredients are added to make mayonnaise, lemon mousse, or other acidified egg recipes. Using volumes or weight may be a more consumer-friendly approach as consumers do not have easy access to pH measurements and the ratio will account for varying egg sizes. Nielsen and Knøchel (2020) found that with a ratio of 0.82 of vinegar to egg yolk (giving a pH of 3.9) a >4-log inactivation of *Salmonella* occurred within 2 hr at room temperature in the egg and acid mixture, whereas with a ratio of 0.4 of vinegar to egg yolk (giving a pH of 4.2) and storage at room temperature, the time needed for a similar inactivation was 24 hr. It was also found that a >4-log reduction of *Salmonella* cannot be reached when mayonnaise was prepared with lemon juice instead of vinegar. However, for recipes such as lemon mousse, where the lemon juice content is very high (above 20 to 25 mL per egg), lemon juice can be used as the sole acidulant for inactivating *Salmonella* (Nielsen & Knøchel, 2020; Xiong et al., 1999).

Lastly, the temperature is also a major factor to consider. Although chilling will inhibit growth in low-acid products, which would otherwise permit growth, in contrast, low temperatures will slow down inactivation in products with pH and acid combinations otherwise lethal to *Salmonella* (Lock & Board, 1995; Nielsen & Knøchel, 2020; Xiong et al., 2000; Zhu et al., 2012). Zhu et al. (2012) found an average difference of 1.27 log CFU/mL in the survival of *S*. Enteritidis exposed to increasing amounts of vinegar when stored at 4 °C compared to 25 °C. The higher survival rate at decreasing temperatures can be a result of the cellular changes that occur at cold temperatures including decreased membrane fluidity, expression of protective proteins, and synthesis of trehalose (Ricke et al., 2018).

Safe consumption of homemade raw egg mayonnaise mainly depends on the *Salmonella* status of the eggs. If a consumer uses eggs from potentially unsafe sources, for example, backyard eggs, it is still possible to decrease the numbers of the pathogen, if present (CCH5 in Figure 1), by using adequate amounts of acid, preferably vinegar, and storing the final product at room temperature for at least 24 hr before moving it to refrigeration temperatures. However, this message needs to be transmitted to the consumers, who might find it counterintuitive to leave a product outside the refrigerator. "Homemade mayonnaise should be stored in the fridge" is a common advice given to consumers.

Heat treatment and monitoring doneness

For safety concerns, it is recommended to cook eggs/egg-containing products to a minimum internal temperature of 71.1 °C (160 °F) (Table S1). Ten seconds at this temperature will kill approximately 8 log of *Salmonella* cells (Doyle & Mazzotta, 2000). The egg white and yolk coagulate at different temperatures. The egg white will be thoroughly coagulated at 65 to 70 °C, whereas the egg yolk starts to coagulate at 62 to 72 °C (Brown, 2011). Due to these egg properties, consumers are advised to cook the eggs until both the white and yolk are firm (Table S1), which is a guarantee that safe temperatures have been achieved. However, for sensorial reasons, when creamy sauces are desired "the key to cooking eggs is to keep the temperature low and/or the cooking time short" (Brown, 2011). Although there is a general lack of scientific information on the safety of these recipes, Lopes and Tondo (2020) demonstrated that the traditional method for the preparation of *spaghetti alla carbonara* does not ensure the inactivation of *Salmonella* if highly contaminated eggs are used. In some recipes, for example, Béarnaise sauce, the temperature should be maintained at 60 to 65 °C and the use of a thermometer is recommended. However, it is not known how/if temperature is monitored in domestic cooking.

The use of a thermometer is the most common recommendation to monitor the doneness of foods. According to the FSIS "Using a food thermometer is the only reliable way to ensure safety and to determine desired "doneness" of meat, poultry, and egg products" (USDA, 2015). Nevertheless, when it comes to eggs this advice is hardly followed and other methods (if any) are used. Barriers to the use of thermometers during cooking were reviewed by Feng and Bruhn (2019).

Maughan et al. (2016) reported that none of the consumers observed during cooking poultry and eggs in domestic settings (Manhattan, Kansas City, and Nashville) used thermometers to monitor doneness of fried or scrambled eggs. The use of multiple techniques to determine if the eggs were cooked was registered (43% and 42% for fried and scrambled eggs, respectively); mostly the observed and reported methods were appearance (43% and 44% for fried and scrambled eggs, respectively), color (25% and 11% for fried and scrambled eggs, respectively) yolk consistency for fried eggs (31%), amount of liquid (20% and 51% for fried and scrambled eggs, respectively), texture (19% and 27% for fried and scrambled eggs, respectively), opaque white for fried eggs (17%), and puffiness or fluffiness for scrambled eggs (17%). Observers found that 23% of the scrambled eggs and 51% of fried eggs prepared did not reach a safe temperature (71 °C), although this was due to personal preferences for the majority of the participants.

In a survey conducted by Kosa, Cates, Bradley, Godwin, et al. (2015), only 5.2% of food thermometer owners (62%) used them during the preparation of baked egg dishes as recommended by the USDA and FDA. Instead, most of the respondents relied on cooking time (56.5%) or their senses, inserted a knife, toothpick, or other utensils that came out clean (45.3%), shook it, and it was firm (did not wiggle) (21.5%), touched it with finger, and it was firm (12.9%), and tasted it (7.4%). Major reasons for not using the thermometer were as follows: "I never thought to use one" (50.9%), "I used another method to determine whether the dish was done and ready to eat" (35.3%), "I didn't know I was supposed to use one for egg dishes" (24.0%), and "It is not practical to use" (9.8%).

Her et al. (2020) reported that of the 67% U.S. consumers (n = 4169) that owned a thermometer, 58% never used it when cooking eggs dishes. According to this study, using thermometers is positively influenced by consumers' microbial awareness and risk perceptions and food safety practices.

Considering that consumers are not adhering to the recommendations regarding the use of thermometers and that behaviors are difficult to change, the reliability of the alternative methods being used should be investigated. Moreover, we are not aware of studies that have evaluated the performance of thermometers to monitor egg doneness. When such studies were conducted for meat products, it was concluded that some thermometers were not accurate and presented a slow response time (Langsrud et al., 2020; Liu et al., 2009). Moreover, Langsrud et al. (2020) also demonstrated that when frying chicken, the recommended use of food thermometers to measure the core temperature may not be as safe as believed, as bacteria may still survive on the surface when the core reaches "safe" temperatures.

In summary, given the versatility of eggs in the kitchen, used as ingredients or served as a dish, and the endless number of methods of preparation, it is not possible to make general recommendations to guarantee safety (monitor doneness; CCH4 in Figure 1). The visual observation of solid whites and yolks ensures that an egg reached temperatures high enough to destroy *Salmonella*. This method can be used, for example, for hard-boiled eggs but not for soft-boiled eggs. In this and other situations where liquid yolks and whites are required or preferred, information on safe time and temperature combinations and on monitoring methods other than food thermometers is still needed.

2.5 | Consumption of eggs and egg products

Despite the alerts on the risks of eating raw eggs or foods containing raw eggs (Table S1), consumers continue to frequently engage in consumption that might be considered high risk and outbreaks continue to occur (Table 1). Varying degrees of awareness of the risk associated with eating raw or undercooked eggs have been reported. In a study conducted in Canada, only about half of the respondents (n = 2474) reported being aware of the risk associated with eating undercooked eggs or salad dressing that contained raw eggs (Murray et al., 2017). On the other hand, Kauber et al. (2017) reported that 100% and 98% (n = 50) of the respondents to a survey conducted in Seattle (USA) associated transmission of *Salmonella* with "Eating undercooked/raw eggs" and "Eating a dish made with raw eggs." Nevertheless, 51% of participants answered that they eat raw or undercooked eggs.

Fein et al. (2011) analyzed trends in the U.S. consumption of "risky" foods from 1988 to 2010, and the most commonly reported "risky" food consumption was eating raw eggs; following a significant decrease from 1993 (53.6%) to 1998 (39.1%), a slight increase was found thereafter (41.3% in 2010). In a later survey, more than 90% of the respondents reported they had not eaten raw eggs or foods made with raw or undercooked eggs (in the 12 months before the survey). However, eating raw homemade cookie dough or cake batter—which represents a risk for salmonellosis, because shell eggs are one of the main ingredients (Wu et al., 2017)—was reported by 25.5% of the respondents (Kosa, Cates, Bradley, Godwin, et al., 2015). A similar situation was reported by Whiley et al. (2017) for Australian consumers. Although 84% of the participants in a survey reported that they did not consume products with raw eggs at home, 86% reported that they had licked utensils used to prepare mixtures containing raw eggs. In another study conducted in the United States, half of the participants (Mexican born individuals) reported the consumption of not fully cooked eggs (e.g., eggs with runny yolks and soft scrambled eggs) or products made with raw eggs (e.g., handmade frosting), even though 90% of these participants were aware of the risk of salmonellosis due to eating raw eggs (Parra et al., 2014).

In a study conducted in Finland (Lievonen et al., 2004) among 918 individuals, more than 80% reported the consumption of well-cooked eggs/dishes containing eggs (e.g., hard-boiled eggs, fried eggs, homemade bakery products). However, the consumption of risky products was also reported by a high number of respondents, for example, (tasting) homemade batters (57%), soft boiled eggs (44.3%), eggs fried sunny side up (27.9%), cold desserts with eggs (23.7%), raw eggs (12.3%), runny omelets (9%), and homemade mayonnaise (5.8%).

In the United Kingdom, advice regarding the consumption of raw or undercooked eggs has changed in recent years (Table S1): "those vulnerable to infection could now safely eat raw or lightly cooked eggs—provided they were produced under the British Lion code of practice—without risking their health." However, the question now is whether this message is understandable by all consumers or if some will generalize this advice for all eggs including those from home production.

Due to preference for certain egg/egg dishes or lack of awareness of the risk, it is evident that a high number of consumers eat uncooked or cooked foods containing raw egg/egg products. According to Thomas et al. (2006), this is considered a significant contributing factor in egg-related outbreaks.

3 | CONCLUSION

Several studies focusing on consumers' food safety perception, knowledge, and practices in the domestic environment have been conducted, but research specifically toward eggs is scarce, particularly in Europe as most studies were conducted in the United States. Knowledge on egg-related handling behaviors and on the barriers for changing from a hazardous to a safe behavior should be a priority in order to define the main intervention opportunities (tools, information, education, policy models) where it is possible to obtain a significant reduction in the number of cases and outbreaks of foodborne salmonellosis.

As this literature review shows, the master key to reduce the likelihood of getting ill from *Salmonella* in eggs from the point of the consumer is to buy *Salmonella*-free eggs. So far, and despite the improved situation in several countries, Finland, Sweden, Norway, and Denmark are still the only countries where special guarantees have been granted. Eggs produced under the British Lion code of practice are also considered *Salmonella* free.

The large majority of consumers do not have access to eggs with this guaranteed *Salmonella*-free status. When purchasing/collecting and using these eggs in cooked dishes, three practices will together reduce *Salmonella* to acceptable numbers: (1) washing hands after touching dirty eggs or egg contents to avoid ingestion of spilled raw eggs, (2) assuring a proper control of cooking time and temperature, monitored by reliable methods, and (3) cleaning of surface that has been in contact with dirty eggshells or egg containments.

If contaminated eggs are used in dishes that are not fully cooked, the hazard can be reduced but not eliminated. The occurrence of *Salmonella* can be reduced by the purchase of eggs with low initial contamination (e.g., industrial produced eggs, clean eggs stored refrigerated in the shop or collected soon after laying), washing of dirty eggs, storing eggs at refrigerated temperature, performing good personal hygiene, and storing leftovers at cool temperatures. Another option could be inactivating *Salmonella* in eggs used for raw dishes by home heat pasteurization or by organic acids (only relevant for some dishes, e.g., mayonnaise). However, these measures do not exclude the need for proper hygiene and may be regarded as inconvenient. From this, it can be concluded that the main message to consumers is to choose *Salmonella*-free eggs when these are available, especially for dishes that are not fully heat treated. Second, refrigerated storage and proper heating will reduce risk significantly. Nonetheless, refrigeration at the consumer stage will only be effective if the eggs from the collection until the time of purchasing are kept at temperatures that prevent the growth of *Salmonella*. However, there are discrepancies in recommendations and legislation regarding temperatures early and later in the chain and lack of scientific data supporting these advice and regulation.

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All the authors contributed to the literature search and drafting and editing of the manuscript. P. Teixeira contributed with the initial concept and design of the manuscript. S. Langsrud critically reviewed the original draft. M. J. Cardoso, V. Ferreira, A. I. Nicolau, D. Borda, L. Nielsen, S. Knøchel, and P. Teixeira prepared the original draft. R. L. Maia contributed with formal analysis. M. J. Cardoso, A. I. Nicolau, D. Borda, S. Knøchel, Trond Møretrø, S. Langsrud, and P. Teixeira reviewed and edited the manuscript. All authors read and approved the final manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

ORCID

Anca Ioana Nicolau https://orcid.org/0000-0001-8018-1478
Trond Møretrø https://orcid.org/0000-0001-5176-1158
Paula Teixeira https://orcid.org/0000-0002-6296-5137

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SUPPORTING INFORMATION

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