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# An Investigation About the Historic Global Foodborne Outbreaks of *Salmonella* spp. in Eggs: From Hatcheries to Tables

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## ABSTRACT

*Salmonella enterica* serovar Enteritidis is the main pathogen of concern in eggs and egg products, although other serotypes have been reported worldwide. Egg processing guidelines and regulations vary widely from country to country; some are ambiguous, incomplete, or obsolete. However, foodborne outbreaks linked to *Salmonella* spp. and eggs continue to be reported worldwide and are constantly increasing, with many illnesses, deaths, and significant economic impact. This review aims to conduct a comprehensive investigation in egg processing regulations and *Salmonella* foodborne outbreaks in several countries of six continents in the last 50 years. The manuscript presents and contrasts the lack of surveillance programs, regulations, adequate testing, and traceability in some countries but also the creation of new regulations to reduce the incidence of *Salmonella* in eggs. One of the newest trends in the egg industry is related to farmers markets and backyard egg producers, which might represent a food safety gap in the production chain if these are not regulated. The review also discusses some interventions and approaches to control the growth and presence of *Salmonella* in fresh eggs, such as refrigeration. Though regulations in many countries do not require eggs to be under refrigeration and some other countries do not have enough access to them, jeopardizing the food safety of the product.

## 1 | Introduction

One of the main branches of the poultry industry is fresh eggs and egg products. Some of the most common products sold in different parts of the world include in-shell eggs, liquid whole egg, liquid whites, liquid yolk, whole egg powder, spray-dried white solids, hard-boiled eggs, dried mixes, among others. However, eggs are also used as ingredients in thousands of industries and homemade products.

An affordable product with a high nutrient profile, eggs are an essential part of the diet in many countries. Asia is recognized as the continent with 60% of the global egg production (de Luna et al. 2022). In 2022, the Food and Agriculture Organization (FAO)

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(2024) reported China as one of the leading egg producers, with about 34% of the global production, followed by India, the United States, Indonesia (7% each), Brazil, Mexico (4% each), Japan, and Russia (3% each). China is recognized not only as the world's largest egg producer but also as one of the major egg consumers (Li et al. 2020). The American egg market reported by the end of 2023 an annual production of 110 billion eggs and 94.2 billion table eggs. The average number of layers in the United States in 2023 was 382 million (USDA 2024a). In India, the annual production of eggs is about 74 billion eggs (3.4 million tons), with about 260 million layers (Srivastava et al. 2024). In Australia, the annual production of eggs was reported at 397.4 million dozen a decade ago (Moyle et al. 2016). Recently, egg consumption has been reported as 244.83 per capita (McWhorter and Chousalkar 2020). In New Zealand, on average, a person consumed 225 eggs during 2024 (New Zealand Egg Production Federation 2025).

However, eggs and egg products are also related to foodborne outbreaks worldwide; the presence of different *Salmonella* species has been associated with them. It is estimated that between 200 million and 1 billion cases of *Salmonella* infections are recorded worldwide annually, with 93 million cases of gastroenteritis and 155,000 deaths. From these numbers, about 85% are foodborne related (Lamichhane et al. 2024). Salmonellosis is the infection produced by this pathogen, characterized by diarrhea, fever, abdominal cramps, and vomiting after 6–48 h of ingestion of contaminated food. The duration of the illness can be from 4 to 7 days (Adley and Ryan 2025), and about 5% of the patients can develop further side effects (Lamichhane et al. 2024). Furthermore, the economic impact on salmonellosis has been recently reported; for example, in the United States, the annual cost is about $4.1 billion (USDA 2021), in the European Union about €3 billion (Li et al. 2025), and in Australia AUS$811 million (Simpson et al. 2018).

The egg industry is very different in each country, and the regulations about handling, processing, storing, transporting, and marketing eggs are ambiguous in many nations, contradictory in others, and missing in several more. Food safety of eggs starts with hatcheries and finishes when they are properly prepared and consumed. More research is needed to fill those research gaps regarding the food safety of eggs to decrease the incidence of this pathogen in this area of the poultry industry, reducing the cases of salmonellosis and deaths worldwide.

This review presents an overview of the egg industry worldwide and the regulations during processing until they reach the consumer. Information from several countries from six continents is presented and discussed. The manuscript also compares the historic *Salmonella* outbreaks related to eggs in several countries from the 1970s to early 2025. The discussion about the lack of information identifying *Salmonella* and specific egg products and reporting these outbreaks in some nations is also discussed. A final section includes some interventions that could reduce the incidence of *Salmonella* in eggs and some research opportunities.

## 2 | Eggs

In the last decade, the egg market in the United States has come with a range of options to meet consumer demand when purchasing in-shell eggs. In Table 1, there is a list of current egg choices in the American market and some characteristics. Similar options exist in several countries, including some specific product characteristics, geographic origin, or nature of the bird. The newest term in the egg industry is "pasture-raised" eggs, which often becomes confused with pasteurized eggs, and it is very important to separate and identify each term. The term pasture-raised is related to a sustainable agriculture practice for products in which the animals are raised in the pasture, grazing and foraging and can receive a supplementary diet. The term pasteurized is related to the thermal process in which the food is kept at a specific temperature-time combination to inactivate pathogens. In the case of eggs, the pathogen of concern is *Salmonella* spp., and the conventional thermal pasteurization for in-shell eggs is 57°C for at least 57.5 min (Bermudez-Aguirre and Niemira 2023).

Eggs are classified based on their weight (individual or per dozen) but also graded according to quality characteristics. Although this information is not essential in food safety, some countries, such as Canada, use the grading program to decide which eggs will be used for pasteurization, as it will be discussed later in this manuscript. In Table 2, the information about egg weight and grades is presented for a few locations for further information of the reader. In general, eggs graded as A or AA represent the best quality and the highest freshness.

### 2.1 | Microbiology of Eggs

Eggs are surrounded by a rich microbial environment from when they are laid until they reach the consumer. It is considered that, on average, an eggshell contains $10^5$ microorganisms, and the contamination will start from the cloaca until it is used, being the source of contamination of the nest, trays, hands, dust, soil, feces, and packaging materials (Board and Tranter 2017). Most microorganisms that contaminate eggshells are Gram-positive because of their exceptional tolerance to dry conditions. A complete list of microorganisms associated with eggs is described by Board and Tranter (2017).

One of the leading public health concerns worldwide is the presence of *Salmonella* spp. in eggs and egg products (Whiley and Ross 2015). There are more than 2500 recognized serotypes for *Salmonella* worldwide (Kabeta et al. 2024; Ehuwa et al. 2021). The common pathogen associated with eggs is *Salmonella enterica* serovar Enteritidis (Gast et al. 2021; Kingsbury et al. 2019; Martelli & Davies 2012; Gantois et al. 2009); however, several serotypes have been identified in egg contents and eggshells. The three more common strains associated with infections in the United States and Canada are *S*. Enteritidis, *S*. Heidelberg, and *S*. Typhimurium (Christidis et al. 2020; Schoeni et al. 1995). Meanwhile, in Mexico, the most common serotypes are *S*. Typhimurium (20.4%), *S*. Enteritidis (18.3%), and *S*. Typhi (7.1%) (Godinez-Oviedo et al. 2020).

In a study conducted with backyard poultry (chicken and ducks) in Chile (Alegria-Moran et al. 2017), the results showed that the most prevalent *Salmonella* strain was *S*. Typhimurium (52%), followed by *S*. Infantis (16%), *S*. Enteritidis (16%), *S*. Hadar (8%),

**TABLE 1** | Main characteristics of commercial eggs sold in the United States (American Egg Board 2020a).

| Type of egg | Characteristics |
|---|---|
| Certified organic | Eggs are laid by cage-free or free-range hens. No synthetic pesticides, fungicides, herbicides, or fertilizers have been used to feed hens. All agricultural ingredients must be certified organic |
| Cage-free | Eggs are laid by hens that nest indoors in open areas with food and water. Some hens feed for food outdoors |
| Free-range | Hens lay eggs with access to outdoors under the weather, environment, and state laws. The diet is based on grains, but they can also forage for wild plants and insects |
| Vitamin enriched | Eggs are laid by hens with a controlled diet to produce higher vitamin content |
| Omega-3 enriched | Hens lay eggs with a modified and enriched diet to increase the omega-3 content per egg (from 30 up to 300 mg) |
| Pasteurized | Eggs are laid and then subjected to a thermal process, commonly a warm water bath, to inactivate pathogens inside without cooking |

**TABLE 2** | Classification of eggs based on weight and grading program in different world locations.

| Country or region | Classification based on weight | Egg grading program[a] | Reference |
|---|---|---|---|
| United States | Jumbo: 30 oz (850.4 g)[b]<br>Extra-large: 27 oz (765.4 g)<br>Large: 24 oz (680.3 g)[c]<br>Medium: 21 oz (595.3 g)<br>Small: 18 oz (510.2 g)<br>Pee wee: 15 oz (425.2 g) | • AA (freshest and highest quality)<br>• A<br>• B | American Egg Board (2020b, 2020c), USDA (2024b) |
| Canada | Jumbo: 70 g or more[d]<br>Extra-large: at least 63 g<br>Large: at least 56 g<br>Medium: at least 49 g<br>Small: at least 42 g<br>Pee wee: less than 42 g | • Canada A<br>• Canada B<br>• Canada C<br>• Canada Nest Run | CFSI (2024) |
| European Union | XL or very large: ≥73 g[d]<br>L or large: ≥63 or <73 g<br>M or medium: ≥53 or <63 g<br>S or small: <53 g | • Grade A<br>• Grade B | European Commission (2023) |
| Japan | LL: ≥70 or <76 g[d]<br>L: ≥64 or <70 g<br>M: ≥58 or <64 g<br>MS: ≥52 or 58 g<br>S: ≥46 or <52 g<br>SS: ≥40 or 46 g | • Special Grade<br>• Grade 1<br>• Grade 2 | Kashimori (2021) |

[a]Based on egg quality characteristics.
[b]Minimum weight per dozen.
[c]Most common in the USA market.
[d]Based on single product.

*S*. Tennessee (4%), and *S*. Kentucky (4%). Guerrero et al. (2022) reported a comprehensive study, including 13 countries from Latin America, showing the most common serotypes being *S*. Enteritidis and *S*. Senftenberg linked to outbreaks of eggs, mainly in Chile, Ecuador, Colombia, and Brazil.

In Europe, *S*. Enteritidis (58%) and *S*. Typhimurium (21.9%) are the most common serotypes associated with eggs. However, several serotypes have been recognized during outbreaks and surveys conducted in European countries, such as *S*. Infantis, *S*. Virchow, *S*. Newport, *S*. Livingstone, *S*. Braenderup, *S*. Derby, *S*. Isangi, *S*. Senftenberg, *S*. Altona, *S*. Ohio, and *S*. Mbandaka (Martelli and Davies 2012).

In Asia, the most common *Salmonella* serotypes were *S*. Typhi and *S*. Typhimurium from 2012 to 2022, according to Salvador et al. (2022). The most common serotype in Southeast Asia is *S*. Typhimurium (Patra et al. 2021). However, other serotypes, such as *S*. Enteritidis, are prevalent in some Central and East Asian countries, such as China, Japan, Hong Kong, South Korea, and Taiwan. In one of the most recent studies in South Korea, the most common strains in eggshells were *S*. Infantis, and, for egg contents, *S*. Enteritidis (Jung and Lee 2024).

In Australia, the most prevalent strain in eggs is *S. enterica* serovar Typhimurium; however, some studies have isolated *S*. Enteritidis as the primary pathogen of concern in egg contents and *S*. Typhimurium in eggshells because of cross-contamination (Lin et al. 2021; McWhorter and Chousalkar 2020; Simpson et al. 2019; Whiley et al. 2017). In Tasmania, the leading serotype from 2001 to 2004 was *S*. Mississippi; the second was *S*. Typhimurium (Stephens et al. 2007). The most common strain in New Zealand is *S*. Typhimurium (Kingsbury et al. 2019).

## 2.2 | Egg Contamination

The eggshell represents a barrier to the egg's contents against the outside environment, preserving their quality and safety. Eggs are one of these foods with very high porosity in the eggshell, allowing the exchange of moisture and gases with the exterior, but microorganisms can also penetrate this barrier. Each egg is unique from top to bottom, presenting random smooth surfaces and highly porous areas in the shell as shown in Figure 1a,b. The eggshell characteristics depend on several factors, such as hen breed, the diet of the flock, and egg storage conditions (Sirri et al. 2018; Jones et al. 2018). The degree of contamination is also affected by the hen age. As the hen ages, the number of microorganisms in the eggshell is higher, and the eggshell porosity allows the pass of more bacteria. The study conducted by Moyle et al. (2016) included a comprehensive analysis of about 600 eggs in 2 farms with 2 free-range flocks, finding a significant effect ($p < 0.05$) of the hen age on the microbial loads of the eggs, because of the changes in the composition and quality of the egg cuticle that is a protective layer of the egg. There is a gradual decline in the egg cuticle quality with age. Furthermore, the chemical components in the egg cuticles that have some antimicrobial activity change as the hen ages, that is, the glycosylation of the cuticle proteins. The reduction in the glycosylation decreases the mechanical properties of the cuticle, leading to the decline on the resistance of the egg cuticle to bacterial penetration (Rodriguez-Navarro et al. 2013; Kretzschmar-McCluskey et al. 2009).

In the poultry industry, two types of contamination of eggs with *Salmonella* spp. are common: vertical and horizontal. This refers to how the pathogen enters contact with the eggs. For vertical contamination, *Salmonella* cells infect the eggs inside the hen; meanwhile, horizontal contamination is related to cross-contamination during egg handling, for example, when the product is in contact with gloves, nests, processing equipment, packaging materials, hands, animals, among others (Bermudez-Aguirre and Niemira 2023).

Through cross-contamination, the bacterial cells become attached to the eggshell and usually migrate to protection sites, such as egg cracks and more prominent pores. McWhorter and Chousalkar (2020) conducted a study to demonstrate that egg washing removes bacteria from the surface but not from the pores, probably because the cuticle protects the cells. These authors infected hens with controlled doses of *S*. Typhimurium and the eggs were used for an egg washing experiment using chemicals in the eggshell surface, such as 0.5% Circhlor solution (40–45°C) for 30 s, followed by 0.4% Virogard (58°C) for 10 s. Results showed the reduction of *Salmonella* in the eggshell surface, but the presence of the pathogen in the pores. In Figure 1c,d, *S. enterica* serovar Typhimurium cells were inoculated in eggshell and attached for 4 h. Cells migrated to shell cracks and hid inside the eggshell's porosity, representing a food safety risk for standard disinfection technologies. McWhorter and Chousalkar (2020) also showed that *Salmonella* spp. was present in dust from an egg farm and survived for at least 8 weeks. Carrique-Mas and Davies (2008) reported that *Salmonella* can survive in poultry houses for about 53 weeks in dust and 26 months in litter, feces, and feed.

The egg contents can be contaminated from the outside if the microorganisms cross the different layers of the egg, starting from the surface to the cuticle, following the egg pores and eggshell membranes until they reach the internal contents of the egg (Moyle et al. 2016). An intact egg presents three layers: the cuticle, crystalline shell, and shell membranes (Figure 2). If the microorganisms pass these layers and reach the albumen, this egg component has antimicrobial properties from specific proteins that can affect the microbial cell integrity. If the action of these proteins does not damage the microbial cells and can make it to the vitelline membrane, the migration from here to the yolk is easy, and the rich medium offered by the yolk allows fast microbial growth (Gantois et al. 2009).

In the research conducted by Gast et al. (2021), two strains of *Salmonella* cells were studied, *S*. Enteritidis and *S*. Typhimurium, used to infect hens under controlled indoor conditions (cage-free housing). Examining laid eggs from the hens resulted in 3.41% positive egg contents for *S*. Enteritidis and 1.19% positive for *S*. Typhimurium. In a different study, eggshells were contaminated with feces containing *Salmonella* cells, and it was shown that the pathogen could penetrate the shells during storage and grow in the egg's contents, mainly when the temperature was not controlled. The three *Salmonella* strains studied showed that *S*. Typhimurium could cross the eggshell but not the membrane when the temperature was kept at 4°C, so the egg contents were not contaminated (Schoeni et al. 1995).

A study conducted with an emerging foodborne pathogen named *S*. Hessarek observed that this serotype could penetrate the eggshell and survive in the egg pores but was highly dependent on the temperature. When the temperature was low (refrigeration), the penetration and replication of *Salmonella* cells were reduced. Additional factors that contributed to the reduction were the shell thickness and cuticle integrity; any shell damage can trigger the safety of the egg contents (Lin et al. 2021). Besides the temperature, a critical environmental factor is the moisture

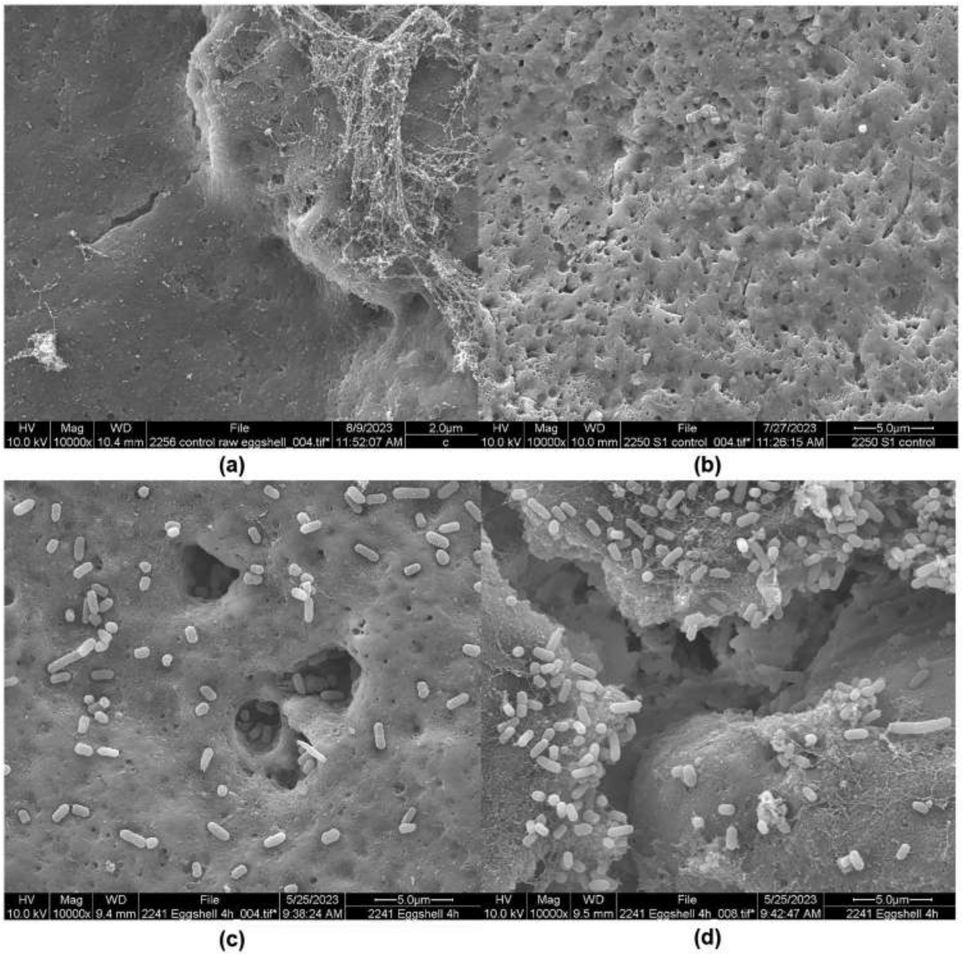


**FIGURE 1** | Microscopy images of eggshell, (a) and (b) control samples of USA commercial eggs show the variability on the surface characteristics for eggshell; (c) and (d) *Salmonella enterica* serovar Typhimurium proliferation in eggshell after 4 h of contact. Magnification 10 K. *Source*: Images: USDA ARS ERRC.

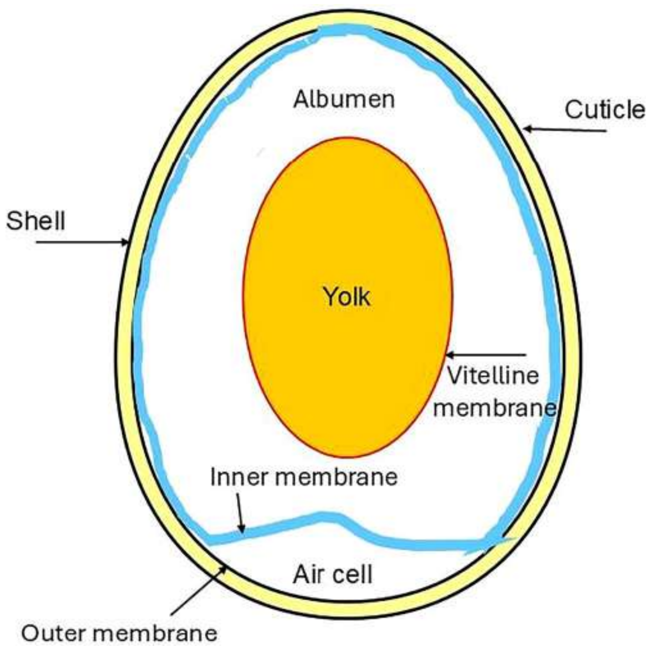


**FIGURE 2** | Main layers and components of an egg. *Source*: Adapted from Gantois et al. (2009).

surrounding the eggshell (Ramtahal et al. 2022). Queensland Health (2021) recommends to consumers in Australia basic egg safety guidelines: to never use dirty eggs, throw them away, not wash eggs, and keep them under refrigeration to prevent the growth of *Salmonella*.

Figure 3 presents a typical egg stand in a food market in the Philippines, in which eggs are sold at room temperature under tropical weather with high temperature and humidity, a couple of factors that promote the growth and penetration of *Salmonella* in eggs. The eggs shown in a box are sold in a tray, so the consumer or seller selects them by hand and places them in a tray. The presence of a dirty egg, likely contaminated with bird feces, is observed in the photo. The contamination of eggshells, probably with albumen from a broken/damaged egg, is also observed. This situation represents a high food safety risk not only for the consumer but also for the seller that can contaminate other eggs and other food or even make themselves sick.

## 3 | Egg Processing and Regulations

The egg industry has very diverse regulations regarding handling the eggs after they are laid until they reach the


**FIGURE 3** | The egg selling point in a local market in the Philippines shows some eggshells contaminated, likely with feces and albumen.

consumer's house. Basic steps such as washing are banned in some countries because of the possible contamination of egg contents with outside microorganisms (Eissa and Shehata 2024; Singh and Brar 2016; Gole et al. 2014). Refrigeration is mandatory in some countries, recommended in a few more, and not required by others. So, in this section, some unit operations and regulations for specific countries will be discussed to understand better how egg outbreaks might be triggered.

### 3.1 | North, Central, and South America

The egg processing in North America varies widely from country to country. In the United States, for example, fresh eggs need to be refrigerated during production, and the cold chain shall not be broken at any point. The refrigeration of eggs since they are laid through the production chain is a preventive measure to reduce the growth of *Salmonella* in case the microorganism is present inside or in the eggshell that can quickly multiply at room temperature. Furthermore, if the cold chain is broken and refrigerated eggs are left at ambient temperature, the condensation of moisture on the eggshell can facilitate the movement of microorganism into the egg contents (USDA Food Safety and Inspection Service [FSIS] 2024). Eggs have intensive control measurements evaluating the presence of cracks or any damage on the shell (Gantois et al. 2009) and are washed and sanitized with specific protocols before they reach the market. Egg washing is conducted with food-grade shell-egg sanitizers approved and cleared by the Food and Drug Administration (FDA) 21CFR 178.1010 and following the guidelines described by the Environmental Protection Agency (EPA). Some of the sanitizers allowed to be during the egg washing process include quaternary ammonium, chlorine, and iodine compounds diluted in water (EPA 2025). Once eggs are in retail, they are kept refrigerated to maintain quality and freshness and ensure safety (American Egg Board 2019). Egg safety and quality is a joint effort coordinated by several agencies in the United States, such as the Agricultural Marketing Service (AMS, grading), Animal and Plant Health Inspection Service (APHIS, disease control of flocks), FSIS (food safety and education), Agricultural Research Service (ARS, research on eggs), National Agricultural Statistic Service (NASS, production and economic analysis), and the FDA, together with FSIS oversees egg safety and problems related to *Salmonella* in this commodity (USDA FSIS 2024). In 2009, the FDA issued a prevention plan to reduce *Salmonella*'s incidence in eggs, known as the Egg Safety Rule (21 CFR part 118, 2009). It is intended for farms with >3000-layer flocks to implement some actions to prevent the presence of *S*. Enteritidis in the farms and eggs. As part of the guidelines in this plan, the FDA advises egg processors to purchase chicks from *Salmonella*-free breeders. Farms should follow a biosecurity plan with a rodent and pest control program. Egg layer flocks should be tested at 40–45 weeks of age. Furthermore, eggs should always be stored at a temperature of 7.2°C from when they are laid during storage, transportation, and commercialization. Moreover, the poultry houses should be cleaned and disinfected constantly (Eggs CoPfL 2013). Consumers are advised to keep eggs under refrigerated conditions at home. It is very common to see eggs in the cold aisle of supermarkets in the United States (Figure 4a). In terms of pasteurization, in the United States, no official regulation requires in-shell eggs to be pasteurized before they reach the consumer. However, a few supermarkets offer pasteurized in-shell eggs, usually marketed with a red ink "P" sign and at a higher price. Pasteurized eggs are typically processed for institutions such as hospitals, schools, and nursing homes where food safety is critical.

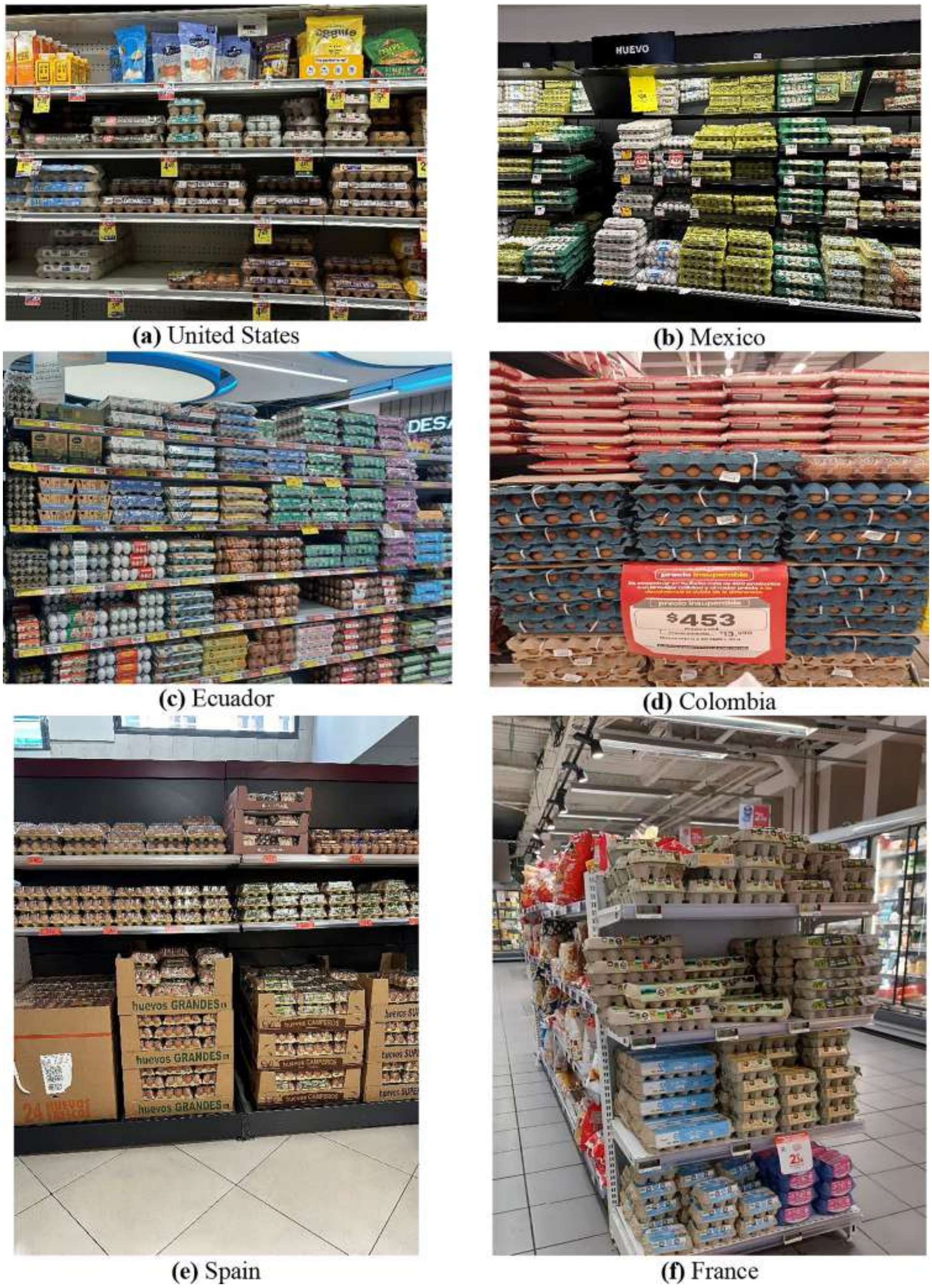


**FIGURE 4** | Comparison in the egg market in different countries worldwide, (a) United States (supermarket—refrigeration), (b) Mexico (supermarket—refrigeration), (c) Ecuador (supermarket—room temperature), (d) Colombia (supermarket—room temperature), (e) Spain (supermarket—room temperature), (f) France (supermarket—room temperature), (g) Czech Republic (supermarket—refrigeration), (h) Czech Republic (supermarket—room temperature), (i) China (supermarket—room temperature), and (j) Philippines (local market—room temperature).

In Canada, the Canadian Food Inspection Agency (CFIA) oversees the food safety of eggs. The agency mentions that pasteurized in-shell eggs are considered a novel food product. Usually, the Canadian Grade A eggs (the highest quality in Canada, Table 2) are pasteurized to minimize food safety risks. The egg processing chain from laying flocks to grading facilities follows a HACCP plan to reduce the risk of contamination with *Salmonella*. Eggs in Canada follow a pre-washing step that is basically a sorting phase in which egg are examined, and any stain, dirt, weak shells, or leakers are detected and removed from the batch. A further washing process is conducted under controlled temperature (>40°C) and pH (>10) conditions with a shell cleaning compound that could be chlorine or non-chlorine based. The final rinse removes the detergent and washes water from the eggshell and has a warming effect to prepare the product for air blowing and drying. Afterward, eggs are stored at refrigerated conditions, and the temperature depends on the grading score: 10°C for Canada A, Canada B, and Canada C, and 13°C for Canada Nest run (Table 2); relative humidity during storage should be kept at about 85% (CFIA 2024). Pasteurization of in-shell eggs in Canada is not

(g) Czech Republic

(h) Czech Republic

(i) China

(j) Philippines

**FIGURE 4** | (Continued)

mandatory, although it is considered a novel process. In Canada, eggs are usually found in the cold products area of supermarkets and small convenience stores.

Finally, there have been significant changes in regulations and sanitary specifications during the last decade in Mexico. As of today, the specifications for handling eggs are written in the Mexican Official Norm NOM-159-SSA1-2016 (2018) for eggs and egg products, published in 2018 (Table 3). The document establishes that the egg processing chain should follow a comprehensive HACCP program. However, it mentions that in-shell eggs should not be washed, and any egg with visible cracks should be discarded. Dirty eggs should be washed with water and approved detergents from a previous washing step for further use only as an ingredient. However, the norm also mentions that clean eggs should not be washed before commercialization. The document also shows the pasteurization conditions for liquid whole egg, white, and yolk in Mexico, as shown in Table 3. The Mexican legislation establishes zero tolerance for *Salmonella* in foods (Godinez-Oviedo et al. 2020).

Regarding refrigeration, the specification mentions that if the egg has been kept under refrigerated conditions, it should continue in the same situation until it reaches the consumer. However, refrigeration is not mandatory. Eggs in big supermarkets can be found in refrigerators but also at room temperature, as shown in Figures 4b and 5a,b; images belong to the same supermarket. In some small local markets in Mexico, it is common to find eggs sold in the standard egg carton stored at room temperature but also in contact with other food products (Figure 5c).

Each country in Central and South America also has specific egg handling and processing regulations. For example, through

**TABLE 3** | North, Central, and South America processing conditions for fresh eggs and egg products.

| Country | Product | Processing conditions | Regulatory agency | Reference |
|---|---|---|---|---|
| **North America** | | | | |
| Canada | Fresh eggs | Pre-wash, wash, sanitize, dry, and stored at refrigerated conditions (10 or 13°C, 85% RH) | Canadian Food Safety Inspection (CFSI) | CFSI (2024) |
| | Egg white (albumen) without chemicals | 54°C, 3.5 min[a] | | |
| | Whole egg with less than 24% egg solids | 60°C, 3.5 min[a] | | |
| | Yolk | 61°C, 3.5 min[a] | | |
| | Spray-dried egg white (albumen) | 54°C, 7 days[a] | | |
| United States | Fresh eggs | Wash, sanitize, dry, and keep under refrigeration conditions at farm, during storage, transportation, and marketing (7.2°C) | Food Safety and Inspection Service (FSIS) | FDA (2009) |
| | Liquid whole egg | 60°C, 3.5 min | Food Safety and Inspection Service (FSIS) | CFR 590.570 2025 |
| | Fortified liquid whole egg and blends (24%–38% egg solids, 2%–12% added non-egg ingredients) | 62.2°C, 3.5 min<br>61.1°C, 6.2 min | | |
| | Plain yolk | 61.1°C, 3.5 min<br>60°C, 6.2 min | | |
| | Spray-dried albumen | 54.4°C, 7 days | | |
| Mexico | Fresh eggs | Optional washing<br>Optional refrigeration | National Service of Agro-Alimentary Health, Safety and Quality (SENASICA) | NOM-159-SSA1-2016 (2018) |
| | Liquid whole egg | 60°C, 3.5 minb | National Service of Agro-Alimentary Health, Safety and Quality (SENASICA) | NOM-159-SSA1-2016 (2018) |
| | Liquid whites | 57°C, 3.5 min[b] | | |
| | Liquid yolk | 61°C, 3.5 min[b] | | |
| **Central and South America** | | | | |
| Ecuador | Fresh eggs | HACCP plan | National Agency for Food Regulation, Control, and Surveillance (ARCSA) | Agrocalidad (2017) |
| Argentina | Pasteurized egg products | Kept under 4°C | National Food Safety and Quality Service (SENASA) | SENASA (2024) |
| | Frozen egg products | Kept under −12°C | | |
| Colombia | Fresh eggs | Discard broken, damaged, dirty eggs<br>If egg processor starts cold chain, keep it until eggs are consumed<br>Refrigeration is not mandatory | National Institute of Surveillance for Drugs and Food (INVIMA) | INVIMA (2020) |

(Continues)

**TABLE 3** | (Continued)

| Country | Product | Processing conditions | Regulatory agency | Reference |
|---|---|---|---|---|
| Chile | Fresh eggs | None processing (max shelf life 8 days) | Ministry of Health | Chilean Ministry of Health (2023) |
| | Preserved eggs | Refrigerated or cold storage (max shelf life 30 days) | | |
| | Refrigerated eggs | Eggs kept under refrigerated conditions from laying to table (2°C, 80%–90% HR) | | |
| Brazil | Fresh eggs | Mandatory spray washing (35–45°C) followed by drying | Ministry of Agriculture (MAPA) | Fernandes (2025), MAPA (2024) |

[a]These products have specific cooling requirements within 2 h after processing.
[b]These products must be cooled down to 4°C after processing.


**FIGURE 5** | Comparison among three egg selling points in Mexico, (a) supermarket—room temperature, (b) supermarket—refrigerated conditions, and (c) local market—room temperature.

AGROCALIDAD (Ecuadorian Quality and Assurance Agency) and the National Agency for Food Regulation, Control, and Surveillance (ARCSA), Ecuador oversees egg production. However, the document about egg regulation, "*Good Poultry Practices*" (2017), highlights the importance of preventing and controlling risks from farm facilities, workers, hens, and eggs. This document has no information regarding pasteurization or refrigeration. In Figure 4c, eggs are shown in a supermarket in Ecuador, all at room temperature inside egg cartons. In Argentina, eggs are overseen by the National Food Safety and Quality Service (SENASA 2024), which mentions that egg standards and quality should match those of all the countries in the Mercosur (Southern Common Market). The main state parties of Mercosur are Argentina, Brazil, Paraguay, Uruguay, and Venezuela. Other South American countries, such as Chile and Colombia, are named associated states. SENASA highlights the need for appropriate labeling of eggs, which should be specified as liquid whole egg, liquid whites, or liquid yolk, as well as the dehydrated products from eggs. The classification is made based on physical characteristics. In terms of food safety, SENASA (2024) establishes that pasteurized egg products should be kept under refrigerated conditions (<4°C), and frozen egg products should be kept under −12°C. However, the document does not mention pasteurization or refrigeration for in-shell eggs. The image in Figure 4d belongs to the eggs sold in a supermarket in Colombia. Again, room temperature seems to be the product's standard marketing; in this case, the egg carton only protects the bottom of the eggs. Additional regulations for eggs in South America, such as Chile and Brazil, are presented in Table 3.

## 3.2 | Europe

The European Commission recently replaced EC Regulation No. 589/2008 with the new EC Regulation 2023/2465 (European Commission 2023), establishing several aspects of egg

**TABLE 4** | European processing conditions for fresh eggs and egg products.

| Country | Product | Processing conditions | Regulatory agency | Reference |
|---|---|---|---|---|
| **Europe** | | | | |
| European Union members (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden | Fresh eggs | No washing<br>No refrigeration | European Food Safety Authority (EFSA) | European Commission (2023) |
| Finland[a] | Fresh eggs | Surveillance program for flocks<br>Refrigeration (2–5°C)<br>Cooling (10–14°C) | Finnish Food Safety Authority | Lievonen et al. (2004) |
| United Kingdom | Fresh eggs | British Lion Code of Practice, including *Salmonella* testing in eggs and flocks, no washing, controlled temperature in farms, refrigeration (5–20°C) | Food Standards Agency | British Lion Quality (2024), Chousalkar et al. (2018) |
| Russia | Fresh eggs | For short storage (7–25 days), keep them between 0°C and 20°C (85%–88% RH); for longer storage (90 days), keep them between −2°C and 0°C | Rosselhoznadzor | Fikiin et al. (2020) |

[a]Some members of the European Union have specific food safety programs to enhance guidelines.

preservation, handling, and marketing standards. Besides the information regarding marketing, grading, and commercialization, this new regulation specifies that "*eggs should not be washed or cleaned because such practices can cause damage to the eggshell….*" The updated regulation mentions that eggs should not be kept under refrigerated conditions. Fikiin et al. (2020) critically reviewed EC Regulation No. 598/2008, mentioning incongruities and incompleteness in the information related to egg handling. According to these authors, the information in this regulation is missing specific values of control temperature and humidity to process, transport, and store eggs, confusing European food operators and consumers. This research team highlights that the regulation prohibits refrigeration for eggs, downgrades the eggs that have been chilled, and misses information about the storage temperature and upper limit. Fikiin et al. (2020) contrast the information from EC Regulation No. 589/2008 with all the available scientific literature showing that a continuous cold chain and proper humidity control can improve egg safety. The agency that oversees egg safety in the European Union is the EFSA. It is common to find fresh eggs in European supermarkets at room temperature, as shown in Figure 5e,f, corresponding to supermarkets in Spain and France. In the Czech Republic, eggs can be found in the refrigerated aisle of the supermarket but also at room temperature, as shown in Figure 5g,h, a similar situation to Mexico. All eggs sold in this supermarket in the Czech Republic are fully packaged in egg cartons with a lid or egg cartons covered with a plastic film.

Although most European Union members in Table 4 follow the EC Regulation 2023/2465, some countries have specific food safety programs. Three countries of the European Union, Finland, Sweden, and Norway, have low incidence of *Salmonella* spp. in eggs because of the strict control programs (European Commission n.d.). The Finnish *Salmonella* control program started in 1995, aiming to keep *Salmonella* below 1% in animal food products. The egg control is carefully monitored, and this pathogen is controlled in shell eggs with strict control of the layer flocks that deliver the eggs in an egg packaging center, and 96% of these eggs are graded. There are preventive actions to maintain *Salmonella*-free eggs. Eggs that are not graded are sold from farms, local markets, or door-to-door. The National Food Agency in Finland recommends keeping the eggs under refrigerated conditions (2–5°C) or coolers (10–14°C). In addition, consumers have information about egg-handling practices such as washing hands, consuming eggs before the expiration day, and storing them under refrigerated conditions (93% of consumers do that); other practices include eating well-cooked eggs (Lievonen et al. 2004).

Furthermore, in Finland, there is a national legislative requirement for food handlers, known as a Finnish hygiene passport, which is required for those working with food. To obtain this passport, the person must pass several tests, including essential microbiology, food contamination and poisoning, and personal hygiene. By 2016, almost one in five citizens had a hygiene passport (Vaarala et al. 2021). Contrasting this is egg handling and purchasing in Portugal, where consumers usually purchase eggs from uncontrolled sources; some of them eat raw or uncooked eggs, only 1.1% look for pasteurized eggs, and many consumers have never heard about pasteurized eggs, although almost half of the egg consumers keep them under refrigerated conditions (Junqueira et al. 2022).

The European Union also operates with the EU Rapid Alert System for Food and Feed (EU RASFF), a system to alert consumers and legal entities about risky food and feed. From 2000 to 2022, this system alerted about egg and egg products 434 times. The highest numbers of notifications were related to pathogenic microorganisms (40.78%). A total of 158 notifications were sent only for *Salmonella* spp., which represents 36.41% of the total. Some of the countries that received the most notifications were Italy, Germany, France, and Poland. These notifications can end in withdraws, recalls, or destruction (Eissa and Shehata 2024).

In the United Kingdom, the British Lion Code of Practice was established in 1989, and it is a mandatory program that 90% of egg processors follow (Eggs CoPfL 2013). With the implementation of this code, the number of cases of salmonellosis was reduced in the United Kingdom. As part of the guidelines in this code, the egg processors should be conducting regular testing for *Salmonella* in eggs and flocks. The farms need to control the temperature, but egg washing is strictly prohibited in the United Kingdom. Eggs should have a printed code to identify the production system. Lion eggs should be kept between 5°C and 20°C, and the British Lion Code of Practice advises the consumer to keep the eggs below 20°C at home (British Lion Quality 2024). However, in the British supermarkets and convenience stores, they are usually sold at room temperature.

Finally, in Russia, the Russian Standard GOST 31654–2012 requires keeping the eggs between 0°C and 20°C and relative humidity between 85% and 88% if the product will be stored for a short time (7–25 days). For more extended storage (90 days), eggs should be kept between −2°C and 0°C (Fikiin et al. 2020).

### 3.3 | Asia

In Asia, regulations about egg processing also vary widely because each country has specific rules about egg handling, storing, washing, transporting, and selling (Table 3). However, almost all the Asian egg production is conducted in caged environments. More than 90% of eggs in China, 80% in India, and 100% in Malaysia belong to caged egg production (de Luna et al. 2022). There is currently a constant debate about whether caged versus free-range hens could reduce the incidence of *Salmonella* in eggs.

In the case of Singapore, the Singapore Food Agency oversees food safety and animal health standards. In this country, eggs are processed locally and come from overseas farms. To meet the country's food safety standards, eggs must come from approved sources in accredited countries or farms with regular inspection and testing. Farms must be free of *S.* Enteritidis and follow good management practices. If the eggs result in a positive for *Salmonella*, the farm is suspended until it is again *Salmonella*-free. The Singapore Food Agency also advises the consumer to follow good practices at home and refrigerate dishes containing eggs (Teo 2023). However, the refrigeration of fresh eggs is not mentioned as part of the regulations in this country.

In China, several regulations and institutions have been created in the last two decades to oversee the country's food safety. For example, in 2000, the National Food Contamination Monitoring System was established, and the China Food Safety Law was created in 2009 and revised in 2015 (He and Shi 2021). Zhang et al. (2016) discussed in detail the previous Chinese standards that regulate eggs and egg products and mentioned the existence of 11 recommended and 6 compulsory standards for egg and egg products. The authors discussed the inconsistency between the standards and the need to improve the communication between the Chinese agencies. The standards related to eggs deal with microorganisms, contaminants, additives, pesticides, and residues of veterinary drugs. Previously, the Chinese standards related to egg and egg products were GB2748-2003 (Hygiene Standard for Fresh Eggs) and GB 2749-2003 (Hygiene Standard for Egg Products), both issued by the Ministry of Health and the Standardization Administration of the Agencies of the People's Republic of China. However, *Salmonella* limits were also part of the Standard NY/T 754 (Green Food—Egg and Egg Products) issued by the Ministry of Agriculture. *Salmonella* Enteritidis, *Shigella*, and *Staphylococcus aureus* should not be detected in all these standards. A few years later, the Chinese National Standard GB 2749-2015, implemented in 2016, applies to poultry in-shell eggs using storage methods to ensure the quality of fresh eggs such as refrigeration, immersion, coating, disinfecting, controlled atmosphere, and dry storage (Fikiin et al. 2020; USDA FAS 2016). The same standard established the microbial limits for eggshells' total plate count and coliforms. However, the limits for pathogenic microorganisms in eggs and egg products are included in the standard GB29921-2021 published by the National Standards of the People's Republic of China published in September 2021 and implemented in November 2021, in which all ready-to-egg products that include processed eggs and other egg products should be *Salmonella* spp. free in five samples (25 g or mL each). In Figure 4i, eggs sold at a local Chinese supermarket are shown at room temperature. The label only mentions "fresh eggs," and no additional information related to further processing is mentioned.

In the Philippines, the Bureau of Product Standards, through the Philippine National Standard PNS/BAFPS 35:2005 (2005), mentions the terms related to eggs and the different classes of eggs according to weight (seven classes). The processing of eggs is not mentioned; it only specifies that eggs should be clean, but the presence of specks, cage marks, or stains is allowed if they are present in less than 10% of the egg surface. No refrigeration requirements are mentioned in this standard. In Figures 3 and 4j, eggs are sold in the Philippines market. In the first case, eggs are sold wholesale, and the consumer picks the eggs from boxes at different prices. In the second case, eggs are sold at room temperature in an egg carton without upper protection.

In South Korea, the Ministry of Food and Drug Safety established to keep eggs at temperatures between 0°C and 15°C and advises consumers to keep them inside the refrigerator at home. Eggs are sold mainly in stores and supermarkets under refrigerated conditions (Koppel et al. 2014). In the same country, a new food safety program started in 2020 related to eggs and the presence of *Salmonella*. This new program establishes that all eggs from layer farms >10,000 units must be washed in an egg grading and packaging plant (GP). Although this program aims to reduce the incidence of the pathogen in eggs, a study conducted by Jung and Lee (2024) analyzed 16,800 eggs in 60 egg GP plants, showing that 18.3% of the eggshells were positive for *Salmonella* spp. and 20% of the egg contents contained the microorganism. The study showed that the prevalence of *Salmonella* spp. occurred in eggs from hens that are older than 80 weeks.

In India and Thailand, eggs are sold at room temperature, and consumers usually keep them at the same temperature at home. In India, a small portion of eggs can be sold at small or large grocery stores, but because of insufficient cold storage facilities, eggs remain at room temperature. It is estimated that 99% of the food in India is sold in traditional retailers such as street vendors and wet market stands, selling most of the products at room temperature (Koppel et al. 2014). *Salmonella* spp. was reported to be as high as 2–4-log in samples of drinking water and hand washing in street food poultry vendors in the locality of Hyderabad, India, promoting likely cross-contamination of other foods such as eggs (Sudershan et al. 2012). The Food Safety and Standards Authority of India (Food Safety and Standards Authority of India [FSSAI] 2025) has a list of regulations about eggs and egg products; however, refrigeration is not mandatory, and the recommendation is to use eggs that are kept at room temperature (30°C ± 5°C) in the next 2 weeks after laying. There is no information regarding how the consumer can track the egg shelf life to verify these 2 weeks. In contrast, if the eggs were kept under refrigerated conditions (2–8°C), eggs could be consumed after 5 weeks of laying.

### 3.4 | Oceania

The Department of Health and Primary Industries oversees egg regulations in Australia and New Zealand. However, each territory has specific specifications regarding egg processing. For example, Queensland follows the Food Production (Safety) Act 2000, Food Act 2006, and the Egg Scheme 2002; the main points are about egg washing and pasteurization of liquid eggs. In Tasmania, the regulations are mentioned in the Food Act (2003) and the Egg Industry Act (2002). In Victoria, the Food Act 1984 is followed.

Meanwhile, in New South Wales (Food Act 2003), Northern Territory (Food Act 2004), South Australia (Food Act 2001), and Western Australia (Food Bill 2005), there are no specific requirements for eggs (Food Standards Australia New Zealand 2009a). In another document, egg washing is recommended for all territories (Food Standards Australia New Zealand 2009b). So, in Australia, a voluntary egg quality program oversees the food safety of eggs. Egg washing is commonly practiced in Australia using different sanitizers, like the egg washing programs in the United States and Japan. Chlorinated or food-grade detergents with neutral or alkaline pH are used during egg washing in Australia (NSW Government 2015). However, as previously mentioned, the government of Queensland (2021) recommends not washing eggs. Regular *Salmonella* testing is not mandatory in Australia (Lee 2015). In the case of New Zealand, the egg producers are members of the Egg Producers Federation, and some guidelines must be followed, such as selling clean eggs, minimizing condensation on eggshells, and specific temperature conditions for washing and storing. If an egg test is conducted, *Salmonella* spp. must not be detected in 5–25 g samples (Food Standards Australia New Zealand 2009a). Consumer information is fully available in Australia to provide guidance to prevent food spoilage and contamination with pathogens. In a survey conducted in Australia, 91% of the respondents mentioned keeping eggs under refrigerated conditions at home, and 84% did not consume raw eggs; however, 86% had consumer batter made with raw eggs (Whiley et al. 2017).

### 3.5 | Africa

Africa is one of the continents with low egg production, with only 4.6% of the global output in 2022, according to the FAO (2024). Although in recent years, the production and consumption of eggs have increased in some countries of this continent, the number of eggs per capita is still very low (Diriba 2018). In Africa, 73 kcal per capita is provided from dairy and eggs daily; meanwhile, in America, the daily per capita is 325 kcal from the same foods (FAO 2024). The low egg production in Africa is because of an inefficient management system, according to Tukur (2011). Although there are countries with high egg production, such as Nigeria, South Africa, Egypt, and Morocco, representing about 15% of the continent production, there are also countries with medium production (33%), but most of the African countries belong to the low production nations, representing 48% of the continent.

Although many African countries are missing specific regulations for eggs, South Africa is one nation with very detailed standards for eggs. The Department of Agriculture, Forestry, and Fisheries published 2020 Act 119 of 1990 (Agricultural Products Standard Act) related to eggs. The document mentions those restrictions on the sale of eggs and clearly defines the size and grade of eggs (Grades 1, 2, and 3) according to the weight, that eggs must comply with previously established standards, and must be packaged in a container that is marked with particular characteristics such as "antibiotic-free," "cage-free," "grass-fed," "organic," and "pasteurized." This act mentions pasteurization to achieve a 5-log reduction of *Salmonella* spp. in shell eggs and names the controlled treatment such as irradiation, microwave, hot water, or hot air. *D*- and *z*-values are also mentioned. Besides these requirements, the act establishes the responsibilities of egg producers besides the egg sorting program, such as constant microbial testing as part of the quality management system, conducting Good Manufacturing Practices (GMP) in the farms, conducting a regular *Salmonella* screening of the flocks, having a traceability program of eggs, and maintaining a record system.

In Ethiopia, the consumption of eggs has increased, and it is reported the processing steps for eggs and egg products that include washing the shells, keeping the eggs under refrigerated temperature (13°C), and pasteurizing the liquid egg for further storage at <4°C. Most of the eggs in Ethiopia (95%) come from indigenous chickens raised under village management systems

(Diriba 2018). Other regulations for African countries, such as Egypt and Morocco, are presented in Table 5.

### 3.6 | Farmers Markets and Backyard Eggs

The presence of farmers markets and egg sellers, known as backyard eggs, is becoming more common. The increase in the number of farmers markets in the United States has been considerable in the last 20 years; from 1994 to 2019, the number went from 1755 to 8771, being stable in the last few years (USDA ERS 2024; Sirsat et al. 2015). In addition, the USDA conducted a survey and found that some persons have backyard flocks as a hobby, family tradition, lifestyle, or for food reasons (Pollock et al. 2012). Farmers markets are known to offer fresh products from farm to table without any or minimal processing and selling local, high-quality products. However, some farmers markets and backyard egg sellers also lack basic food safety precautions. For example, in research conducted in Canada in 2018, 60 farmers markets were evaluated in the province of Ontario, and results showed that 79% of the sellers handled the food without gloves; furthermore, only 66% of the products that required refrigerated conditions were following this storage condition (Young et al. 2020). Sirsat et al. (2015) mentioned that 42% of the managers in the US farmers markets do not follow food safety practices. In the farmers markets, it is common to hear egg sellers say the eggs were washed and sanitized or some affirmed eggs did not receive any treatment.

In the United States, the FDA established a new regulation in 2009 called the Egg Safety Rule. This regulation specifies that farms with >3000-layer hens must have an *S. enterica* serotype Enteritidis plan (SE plan) in place. The regulatory protocol focuses on decreasing this pathogen in eggs during production, storage, and transport (Stilz et al. 2022).

However, some studies have already been published about the incidence of pathogens in eggs sold at farmers markets and eggs from backyards. For example, Kilonzo-Nthenge et al. (2016) tested eggs from small poultry farms and farmers markets in the United States and were able to identify several species of Enterobacteriaceae, such as *Salmonella*, in eggshells and egg contents. From the 504 eggs, 3.6% were positive for *Salmonella* spp. only in the eggshell. Furthermore, the microbial species isolated from these eggs showed antimicrobial resistance. Something important to highlight here is that of the 15 farms and farmers markets, 11 were keeping the eggs under refrigerated conditions. Stilz et al. (2022) presented a comprehensive study showing a food safety risk related to *Salmonella* and eggs from small farms or backyards. Four outbreaks were linked to *S*. Enteritidis and eggs in Tennessee from 2012 to 2020, reporting 93 positive cases of salmonellosis and 10% of hospitalizations. The outbreak in 2012 was linked to raw eggs and eggs without proper temperature control during cooking. Eggs came from a small farm (<3000-layer farms), so the Egg Safety Rule did not apply. The next outbreak, in 2016, was reported from a restaurant using raw eggs for a sauce; eggs came from multiple hens' houses with <3000-layer hens from Tennessee. The 2018 outbreak was due to undercooked eggs served in a restaurant with eggs from Alabama that has >3000-layer hens but was not registered for the SE plan. This farm initiated a food recall that ended with 44 positive cases of salmonellosis in 11 states. Finally, the fourth outbreak in 2020 included eggs from Kentucky used in a restaurant sold as eggs and ingredient for mayonnaise, but the farm was <3000-layer hens, so the SE plan did not apply either. So, it is very clear that the number of layer hens represents a food safety gap in the egg production chain.

In a different study and country, three categories of eggs were tested: backyard, organic, and conventional processing eggs from markets in Spain. From all the samples, *Salmonella* cells were found in one egg, in the eggshell, and inside egg contents coming from the conventional processing eggs batch (Fenollar et al. 2019). In a survey conducted in South Wales with 50 farmers market sellers, the results showed that 84% of the sellers disagreed that their products could cause food poisoning; meanwhile, 86% of the consumers had few or no concerns about the food safety of the products (Worsfold et al. 2004). In Europe, a high percentage of the population purchases backyard eggs from neighbors, friends, or relatives; for example, 49% in Romania, 39% in Portugal, 29% in Greece, 18% in Spain, 17% in Hungary, and 16% in France are consumers of backyard eggs. The study conducted in Portugal and Romania showed that 96% of the backyard eggs sold in Portugal were dirty and stored at room temperature, and 3% were positive for *Salmonella* spp. The pathogen was found in the eggshell and egg contents. The egg samples from Romania were *Salmonella*-free (Ferreira et al. 2020). The problem with backyard eggs is related to the presence of pathogens and the raising conditions for the hens, in which many owners feed the flocks with specific diets and provide medications, such as antibiotics (Cornejo et al. 2020).

In the Philippines, eggs are sold in four different arenas: public markets, supermarkets, directly from farms, and *sari–sari* stores. Public markets are equivalent to farmers markets, where eggs are sold at lower prices, in bulk or small quantities, and are kept at room temperature. *Sari–sari* stores are neighborhood convenience stores in urban and rural areas (Mula 2024). All eggs in the Philippines (regardless of the retail point) are sold at room temperature according to the Philippine National Standard PNS/BAFPS 35:2005 (2005) (BAFPS 2005).

A study in South Africa tested small and large layer farms to identify the presence of *Salmonella* spp. in table eggs sold in informal chicken markets; a total of 39 farms participated in the study. The evaluation was conducted mainly with battery cage systems and a few farms using free-range and deep litter systems. The results showed that *Salmonella* was present in 3 farms out of 39 (7.7%), and the prevalence of this pathogen in eggshells was about 2% (4 out of 196 tested eggs). No presence of *Salmonella* was found in egg contents (Adesiyun et al. 2020). In a similar study in three Caribbean countries (Trinidad and Tobago, Grenada, and St. Lucia), eggs were positive for *Salmonella* spp. when they were produced in large farms (77.8%); the incidence decreased as the farm size was smaller, 33.3% for medium; and 26.1% for small facilities. It is worth mentioning that among the *Salmonella* serotypes found in this study, only 2.9% belong to *S*. Enteritidis, which is the most common; other serotypes identified were *S*. Anatum, *S*. group C, and *S*. Kentucky (Adesiyun et al. 2014).

Farmers markets and backyard egg sellers can be a safe option for the consumer when proper training is provided to the sellers.

**TABLE 5** | Asia, Oceania, and Africa processing conditions for fresh eggs and egg products.

| Country | Product | Processing conditions | Regulatory agency | Reference |
|---|---|---|---|---|
| **Asia** | | | | |
| Singapore | Fresh eggs | Eggs from *Salmonella*-free farms<br>Follow GMP[a]<br>Refrigerated dishes with eggs | Singapore Food Agency | Teo (2023) |
| China | Fresh eggs | Any technology to keep quality: refrigeration, immersion, coating, disinfection, controlled atmosphere, dry storage | Ministry of Agriculture | Fikiin et al. (2020) |
| Philippines | Fresh eggs | No refrigeration<br>Eggshells with stains are accepted for commercialization if they represent less than 10% of surface | Bureau of Agricultural and Fisheries Standards | Philippine National Standards PNS/BAFPS 35:2005 (2025) |
| South Korea | Fresh eggs | Wash in a GP[b], store at refrigerated conditions (0–15°C) | Ministry of Food and Drug Safety | Jung and Lee (2024), Koppel et al. (2014) |
| India | Fresh eggs | Clean, check shell for cracks, leaks, and fecal contamination<br>If stored at room temperature (30°C ± 5°C) consume after 2 weeks of laid, if stored under refrigerated conditions (2–8°C) consumer after 5 weeks | Food Safety and Standards Authority of India (FSSAI) | FSSAI (2025) |
| | Frozen egg products | Strain, homogenize, desugarize, pasteurize (61–63°C, 5 min), freeze (−23.3°C to −40°C) | | |
| | Liquid egg products | Pasteurize and preserve with $\beta$-hydroxybutyric acid, lactic acid, and succinic acid. Store up to 7 days at 4°C | | |
| **Oceania** | | | | |
| Depends on the territory | Fresh eggs | Voluntary washing and refrigeration | Department of Health and Primary Industries | Food Standards Australia New Zealand (2009a, 2009b) |
| **Africa** | | | | |
| South Africa | Fresh eggs | Any processing to achieve 5-log reduction of *Salmonella* | Food Safety Agency | Department of Agriculture, Forestry, and Fisheries (2020) |
| Ethiopia | Fresh eggs | Washing and refrigeration (13°C) | Ethiopian Food and Drug Authority | Diriba (2018) |
| Egypt | Fresh eggs | No mandatory washing or refrigeration | National Food Safety Authority | USDA FAS (2019) |
| | Liquid whole eggs, liquid white, liquid yolk, salted whole eggs, liquid white with additives | Thermal pasteurization, storage at <4°C (3 months), −18°C (1 year) | | Epec (2025) |
| Morocco | Fresh eggs | No mandatory washing or refrigeration | Moroccan National Office for Food Safety (ONSSA) | ONSSA (2025) |

[a]GMP: Good Manufacturing Practices.
[b]GP: Egg grading and packaging plan.

For example, gloves, tongs, or barriers to touching the product, constant and efficient handwashing, and antimicrobial hand sanitizers can reduce cross-contamination between products. Furthermore, protecting the products based on their characteristics (i.e., cold chain) and keeping them away from contamination sources such as the ground, animals, or environmental conditions (rain, direct sunlight) can reduce the number of foodborne outbreaks related to small markets (Sirsat et al. 2015). Some of the risk factors associated with contamination with pathogens from small egg processors include the lack of knowledge about food animal farming and the potential contamination with microorganisms, but also the lack of veterinary care (Stilz et al. 2022).

## 4 | *Salmonella* Foodborne Outbreaks and Egg Recalls in Six Continents

Historical data about *Salmonella* spp. linked to foodborne outbreaks are available for a few countries. The historical survey conducted from 1934 to 1975 identified 1.5 million cases of human and nonhuman salmonellosis in 109 countries with the following serovars: *S*. Typhimurium, *S*. Enteritidis, *S*. Infantis, *S*. Heidelberg, *S*. Newport, and *S*. Dublin. However, eggs were not reported as part of the vehicles (D'Aoust 1994). Early reports about the presence of *Salmonella* spp. in different foods in the 1970s showed the concern of a fast increase of this pathogen in the food production chain (Bryan 1981). Afterward, the presence of *Salmonella* spp. in egg and egg products has been constantly reported in several countries since the 1980s (Humphrey 1994), and it is often associated together (Gantois et al. 2009). Many countries have statistics about each *Salmonella* outbreak hospitalizations, deaths, and costs. According to Davis et al. (2022), there are about 92 million cases of salmonellosis every year worldwide and 50,000 related deaths. The fatality rate is higher in children, elderly, and immunecompromised people (Stanaway et al. 2019). Unfortunately, in some developing countries, there are no statistics about cases of salmonellosis, because of the lack of medical services, accurate lab testing, or some patients do not seek medical assistance.

It has been reported that the highest number of salmonellosis cases in Mexico occur in June. This matches the information available in some European countries and the United States, where summer months represent a good opportunity for *Salmonella* to grow (Godinez-Oviedo et al. 2020). Sher et al. (2021) also showed with the epidemiological data from the United States from 1990 to 2015 that the *Salmonella* outbreaks happened 38% in summer and only 14% in winter. Sun et al. (2021) reported a four-time increase in the cases of salmonellosis in China during the summer months, with a peak increase in August. In another Asian country, Japan, based on historical data on *Salmonella* outbreaks, the estimates show a rise between 7.2% and 12% risk of outbreaks per 1°C higher (Mori et al. 1999). A comprehensive study in Australia also showed the relationship between the increase in cases of salmonellosis and high temperatures, which show a peak during the summer months. According to Davis et al. (2022), there is an increase of 3.2% in salmonellosis per 1°C of increase in temperature in Australia. A similar correlation was found in New Zealand based on the reported data from 1997 to 2007, as reported by Lal et al. (2012, 2016); the increase in temperature during summer augmented the infection risk of *Salmonella* in cities such as Auckland and Christchurch.

### 4.1 | North, Central, and South America

Bryan (1981) reported 31,000 confirmed cases of salmonellosis in 1979 in the United States and a 60% increase in the cases in Canada by 1977, with more than 8000 illnesses. The main sources of *Salmonella* contamination were beef, pork, and turkey; ice cream manufactured with raw eggs; and desserts made from eggs were also listed as sources. The most common *Salmonella* serotype between 1969 and 1977 was *S*. Typhimurium. From 1983 to 1987, 68 outbreaks in the United States were linked to *Salmonella* spp. Meanwhile, in Canada, only in 1 year (1985–1986), there were about 50 *Salmonella* outbreaks (D' Aoust 1994). From 1976 to 1986, the number of cases of salmonellosis in the Northeast of the United States increased because of the presence of *S*. Enteritidis. Only in 2 years (1985–1987) were there 65 *Salmonella* outbreaks, with 2119 confirmed cases and 11 deaths. Of these cases, 77% were because of the consumption of eggs and egg products. The product list presented by St. Louis et al. (1988) included scrambled eggs, Hollandaise sauce, stuffed pasta with eggs and cheese, homemade pasta, rice balls/meatballs with eggs, eggnog, potato-egg salad, cake fillings, and Cesar's salad dressing. In 1988, *S*. Enteritidis was directly linked to raw or undercooked egg products as the primary source of a *Salmonella* outbreak (Hope et al. 2002). Since then, this pathogen is usually related to egg and egg products during outbreaks. From 1985 to 1999, 80% of the outbreaks associated with *S*. Enteritidis were again linked to egg and egg products (Gantois et al. 2009; Hogue et al. 1997). Braden (2006) discussed the *Salmonella* outbreaks in the United States from the early 1970s. He showed the main peak of salmonellosis cases, mainly in the late 1980s and early 1990s, calling this public health issue a national epidemic. This author also presented the control systems adopted to reduce the incidence of *Salmonella* in eggs during these years, highlighting that after these new regulations, the number of contaminated eggs with *S*. Enteritidis was 2.2 million per year in the mid-1990s. Ricke et al. (2015) mentioned a decrease in *Salmonella* outbreaks in the United States during the mid-1990s. The report presented by Sher et al. (2021) about the foodborne outbreaks in the United States from 1990 to 2015 shows the presence of *Salmonella* spp. in egg-based dishes as the primary vehicle of this pathogen, counting for more than 24% of the cases. The states with the most outbreaks during this time were California, New York, and Pennsylvania. Besides, 56% of the cases occurred in restaurant facilities. The new actions taken to reduce the incidence of *S*. Enteritidis in the United States during the 1990s were to include shell eggs as a potentially hazardous food, as the FDA Food Code was amended. By 1996, the USDA FSIS, together with the FDA, developed a risk assessment of *S*. Enteritidis in eggs called "farm to table," which was the basis of the Egg Safety Action Plan, including actions that must be taken in the farm and egg processing facilities, continued refrigeration from farm to home, and provided the consumer with education (Braden 2006).

The incidence of *S*. Enteritidis infections in the United States has not significantly reduced in the last decade (Gast et al. 2021). The numbers of *Salmonella* spp. foodborne outbreaks from 2013 to 2023 were 31,209, with about 807,396 illnesses, 18,191 hospitalizations, and 1180 deaths, according to the CDC (2025). Only in 2024, 99 new foodborne *Salmonella* spp. outbreaks were added, May, the month with the highest incidence (CDC 2025). In September 2024, an egg recall was issued in the United States involving organic eggs from two brands processed in Wisconsin and sold for retail and food service; the cause was the possibility of *Salmonella* contamination (Food Safety News 2024a). The most recent food recall for eggs happened in November 2024, when 10,800 pasture-raised organic eggs were recalled because of *Salmonella*. According to the press release, the recall was caused by the fact that the eggs sold at the warehouse were not meant for retail use. No illnesses have been reported linked to this food recall (Food Safety News 2024b). The problem related to *Salmonella* in eggs is still presenting in the United States for many reasons, such as the high processing volumes, the more considerable distances that eggs need to be transported, the antibiotic resistance of some pathogens, like *Salmonella*, and increase on temperature (Ricke et al. 2015).

In 2000, a *Salmonella* outbreak was reported in Canada in the province of British Columbia, where 62 persons became sick. Investigations found that a local bakery used eggs contaminated with *S*. Enteritidis, and the oven temperature was not working correctly (Government of Canada 2005). However, several outbreaks dealing with *Salmonella* spp. have been reported in Canada, and from 2008 to 2014, the main sources of the pathogen were eggs and pork (Christidis et al. 2020). Thomas et al. (2015) presented the results of an investigation for the first decade of 2000 in Canada about the number of foodborne outbreaks in the country. In 10 years, it was estimated that 4000 hospitalizations and 105 deaths occurred because of foodborne pathogens, including *Salmonella* spp. Jain et al. (2019) presented an estimate of the annual cost of salmonellosis in Canada, showing approximately CAD$287.78 M with an estimated incidence of 47,082 cases. In February 2024, a food recall was conducted in Canada because eggs were contaminated with *Salmonella* and were distributed in the province of Saskatchewan (Government of Canada 2024). In January 2025, a new egg recall was initiated in Canada because of the contamination of eggs with *Salmonella* distributed for retail, hotels, restaurants, and other institutions in British Columbia, Manitoba, Ontario, and likely other provinces and territories (Government of Canada 2025).

It is reported that there are about 7 million cases of salmonellosis every year in Latin America and the Caribbean Region. From 2014 to 2017, the numbers of cases related to *Salmonella* spp. infections were higher than 500,000 in Mexico (Godinez-Oviedo et al. 2019). In this country, a comprehensive study published by Godinez-Oviedo et al. (2020) about the incidence of *Salmonella* from 2000 to 2017 presented *S*. Typhimurium as the most frequent serotype found in food. During this time frame, seven studies were compared for the presence of the pathogen in egg and egg products (albumen, yolk, and liquid egg), and the incidence was low; only 0.25%–3% of about 1760 analyzed samples from different Mexican states were positive for *Salmonella*. The highest incidence of *Salmonella* (3%) was for eggshells. However, there were some limitations in the study. Unfortunately, the samples were only from supermarkets and retail shops and did not include small shops, farms, or local markets. No information was provided regarding the time of the year the sampling occurred, and only a few Mexican states were included in the studies. However, these values are low compared to other developing countries such as Uruguay and India (5.5%–9.4%).

In Central and South American countries, there is still a lack of specific data regarding the relationship between *Salmonella* and the origin of the microorganism. Adell et al. (2018) presented an investigation in several countries in South America from 1980 to 2017, and only Brazil and Argentina showed references to *Salmonella* and eggs. However, salmonellosis is still a cause of morbidity and mortality among the population in Central and South America (Rosso et al. 2023). A recent publication by Diaz et al. (2022) reported a comprehensive analysis of salmonellosis, including 157 studies from 15 countries in America, including Canada, the United States, and Mexico. The studies were published from 1980 to 2020, and 81% were about salmonellosis in the United States, Brazil, and Canada. The study presented the incidence of *Salmonella* in chicken subproducts, such as eggs and chicken meat. The results showed the highest incidence in Canada, the United States, and Mexico, with *S*. Enteritidis and *S*. Typhimurium. However, these three countries might have the highest incidence of salmonellosis because of trustable lab tests for detection of the pathogen, surveillance and control systems, and specific agencies reporting the cases of salmonellosis.

Finger et al. (2019) presented a detailed analysis of foodborne outbreaks in Brazil from 2000 to 2018, showing 13,163 foodborne outbreaks, with 247,570 illnesses and 195 deaths. However, the authors mention the lack of information about foodborne outbreaks and wonder if these numbers might be higher. Outbreaks in Brazil started to be reported and recorded in 2000 through the National Epidemiological Surveillance System for Foodborne Diseases. The information presented by these authors exhibited that the south of Brazil is the area with the most cases and that *Salmonella* spp. is the main frequent pathogen. On the basis of the available data, 17,075 infections were produced by eggs and egg products, representing 6.9% of the identified foodborne outbreaks. Main points of infection in Brazil include homes, schools, and daycare centers, followed by restaurants.

### 4.2 | Europe

Salmonellosis is the second-most common gastrointestinal illness in Europe (Ehuwa et al. 2021). Early data from 1982 to 1987 show an essential increase in the number of cases of salmonellosis in the United Kingdom because of the presence of *S*. Enteritidis, going from 1101 to 6858. The data reported from 1986 to 1988 indicate the presence of this pathogen in eggs, egg products, and foods containing eggs (Sharp 1988). Additional historical data show that from 1986 to 1988, there were about 438 *Salmonella* outbreaks in only 2 years in the United Kingdom (D'Aoust 1994).

From 1992 to 2008, 2500 foodborne outbreaks were reported in the United Kingdom, and 47% (about 1175 cases) were related to *Salmonella* that represents an estimate of 73 cases per year (Gormley et al. 2011). The decrease in the number of outbreaks in United Kingdom is clearly affected by the introduction of the British Lion Code of Practice in 1998, reducing the cases from thousand per year (as reported in the 80's) to less than a hundred per year.

In other European countries, the cases of *Salmonella* outbreaks were fewer during the previous mentioned periods. For example, from 1981 to 1982, the Netherlands reported only 15 *Salmonella* outbreaks, and Spain had 213 in only 1 year (1985), and in 1991 France reported 477 outbreaks (D' Aoust 1994). According to EFSA (2007), in 2006, there were 5710 foodborne outbreaks reported by the member states and 97 outbreaks from non-member states (Norway, Romania, and Switzerland), with *Salmonella* being the main pathogen in about 53.9% of the cases. The number of cases of human salmonellosis in 2006 reported in several countries of the European Union was higher than 165,000; of these cases, 62.5% belonged to *S*. Enteritidis (103,125 cases), and 12.9% were attributed to *S*. Typhimurium (21,285 cases) (Gantois et al. 2009).

As part of an investigation in 34 European countries, from 2015 to 2019, eggs were the most important source (33%) of the outbreaks related to *Salmonella* (Chaname Pinedo et al. 2022). Outbreaks were reported in Belgium, Croatia, Czech Republic, Denmark, Finland, France, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Romania, Slovenia, Sweden, and the United Kingdom because of eggs from Poland (Whitworth 2020). By 2016, 94,530 cases of salmonellosis were confirmed in countries of the European Union, with *S*. Enteritidis responsible for about 55,772 (59%) of them (Ehuwa et al. 2021), showing a slight decline compared to the cases reported in 2006. In 2018, the number of foodborne outbreaks was 5146, and 30.7% of them were related to *Salmonella* spp., and from these, 45.6% were associated with eggs and egg products (EFSA and European Centre for Disease Prevention and Control [ECDC] 2019). The ECDC reported 91,857 persons infected with the pathogen only in 2018 (Ehuwa et al. 2021). The statistics from 2015 to 2019 show an increase of 5% in *Salmonella* outbreaks every year (Chaname Pinedo et al. 2022). Recently, Fikiin et al. (2020) mentioned that 44%–68% of the salmonellosis in the EU is directly linked to eggs and egg products.

In recent years, during the last months of 2021 and the first month of 2022, a multi-country outbreak of *S*. Enteritidis sequence type (ST)11 was linked to the consumption of eggs and egg products. Five countries in the European Union (Denmark, France, the Netherlands, Norway, and Spain) and the United Kingdom reported 272 positive cases of salmonellosis, with 25 hospitalizations and 2 deaths (EFSA/ECDC 2022). In the last months of 2022 and the first month of 2023, a new outbreak was reported in Sweden. Twenty persons from 7 to 90 years old spread across 11 regions were confirmed with *Salmonella* and reported to eat eggs and egg products. One of the main Swedish egg processors initiated a recall because of the contamination of its facilities with *S*. Enteritidis (Food Safety News 2023).

Indeed, 2023 was a year with an increase in the number of foodborne illnesses in Europe but a decrease in the number of outbreaks, as Whitworth (2024) reported. The number of foodborne outbreaks in 27 European Union and Northern Ireland countries was 5691, with 52,127 cases, 2894 hospitalizations, and 65 deaths. *Salmonella* spp. was responsible for more than 1100 outbreaks and 16 deaths; the leading serotype during 2023 was *S*. Enteritidis. The number of outbreaks involving *Salmonella* and eggs was 83.

Although strict controls exist in many European countries to keep the eggs from the pathogen, there is still an incidence during regular testing. Recently, in the European Union, about 0.37% of the table eggs were positive for *Salmonella* spp., coming from Bulgaria, Czech Republic, Italy, Poland, Portugal, Slovakia, Spain, and Romania (EFSA and ECDC 2019). On the basis of these data are not possible to identify a "hot spot" of *Salmonella* outbreaks in Europe, because most European countries continue reporting yearly foodborne episodes.

## 4.3 | Asia

The cases of salmonellosis in Asia have increased in the last few years at an alarming rate (Iyer et al. 2018). In China, it is estimated that *Salmonella* spp. is responsible for 30 million cases annually, representing 75% of the foodborne outbreaks in the country. Shell eggs are listed as one of the vehicles of this pathogen, with a prevalence of 4.2% (Miao et al. 2022). Sun et al. (2021) presented an investigation into the incidence of *Salmonella* spp. in foodborne outbreaks during a decade (2010–2019) in a Chinese province. The results showed 78 outbreaks dealing with *Salmonella*, 1450 cases of salmonellosis, and 353 hospitalizations in 11 cities. Only 5 were linked directly to eggs from these outbreaks, but 17 were associated with sandwiches containing eggs. The main reasons for the epidemics during this decade were cross-contamination (88%), inappropriate storage temperature (61%), and improper cooking procedures (6.8%). Li et al. (2020) conducted a study in China to identify the presence of *Salmonella* spp. in about 33,288 eggs coming from supermarkets, farmers markets, grocery stores, online stores, wholesale markets, roadside sellers, and farms. The results showed the presence of *S*. Enteritidis in about 0.5% of the samples. Additional serovars identified were *S*. Typhimurium and *S*. Stanley. The authors also showed that 14.74% of the samples exhibited surface debris such as mud, soil, feathers, and feces. In 2021, a new outbreak of *S*. Enteritidis was reported in China related to egg-fried rice that sickened 70% of 324 persons eating in a canteen with severe gastroenteritis symptoms. The investigation showed that the shell eggs were not cleaned before using them, the cooking of the egg fried rice was too short (1 min 50 s), and the finished product was placed in a container with some raw materials debris, promoting likely cross-contamination (Zhang et al. 2021). China has reported *Salmonella* spp. as the second common source of foodborne outbreaks (Sun et al. 2021).

In Japan, early reports present a high number of outbreaks related to *Salmonella*, with a peak in 1999, which added more than 800 outbreaks and more than 12,000 illnesses. However, by 2003, the number of outbreaks related to *Salmonella* had decreased to 300, and the number of diseases had been reduced by half. Eggs, egg products, and foods containing eggs are part of the products related to Japanese outbreaks. From 1998 to 2002, there were 15 outbreaks in Japan in which eggs were the main vehicle for *Salmonella*, and the investigation showed that pasteurized liquid egg was responsible for at least 2 outbreaks. In the study conducted by Hara-Kudo and Takatori (2009), testing more than 1327 samples of commercial liquid egg, 8.1% were positive for *Salmonella* spp. in the Japanese markets. Furthermore, the samples of pasteurized liquid eggs showed the presence of this pathogen in 1.7% of the samples. This information indicates that *Salmonella* spp. can be present in eggshells, contaminating liquid eggs. Still, the pasteurization process is not being conducted at the right temperature, or cross-contamination occurs after the process.

In South Korea, 76.9% of the salmonellosis outbreaks between 2017 and 2021 were linked to eggs and egg products (Jung and Lee 2024; Eun et al. 2024), and 61.8% of these events originated in restaurants. A recent *Salmonella* outbreak in this country reported 110 persons with salmonellosis eating at 2 different restaurants. The investigation concluded that eggs supplied from the same farm were the reason for the outbreak, besides the undercooking conditions of the product (Eun et al. 2024).

Thailand is also a challenging food safety country mainly because of the high temperatures. Foodborne outbreaks have also increased recently, and many are dealing with chicken and eggs because this country is a leader in poultry production. The study reported by Vindigni et al. (2007) showed the prevalence of *Salmonella* spp. in eggs sold at the fresh market (19%) compared to supermarkets (9%). Authors mention that it is common to observe the exposure of eggs to rodents, insects, and meat sold at room temperature in Thailand, and often, eggs exhibit visual fecal contamination.

In the Philippines, a National Food Safety Program started in 2013, and a new Food Safety Act was signed in the same year to strengthen the food regulatory system and enhance food safety in the country. Azanza et al. (2019) presented a study of foodborne outbreaks in the Philippines from 2005 to 2018, showing *Salmonella* spp. as one of the primary pathogens found during epidemics. However, eggs are not listed as the primary vehicle for this microorganism; some bakery items containing eggs are reported. In the inventory list, reported as "other type of foods," corresponding to 6.7% of the total reported foods, salted eggs are reported in Northern Luzon as the primary vehicle for *Salmonella* spp.

Patra et al. (2021) presented a comprehensive review of the cases of salmonellosis in Southeast Asia, including 11 countries: Malaysia, Thailand, Lao's Republic, Vietnam, Indonesia, Singapore, Philippines, Cambodia, Brunei, Timor-Leste, and Myanmar. However, in the review, the probable food sources of *Salmonella* are limited to chicken meat or poultry industry, and no information regarding eggs and *Salmonella* is presented. But these authors highlighted the economic and health burden of this pathogen in these countries, citing Vietnam as the top country for salmonellosis cases. They also mentioned the lack of information about the frequency or incidence of this pathogen in countries such as Brunei and Timor Leste.

Azanza et al. (2019) mention some reasons for foodborne outbreaks in developing Asian countries, such as poor personal hygiene, lack of clean facilities, and inadequate food storage at appropriate temperatures. In Malaysia, 50% of the outbreaks are linked to poor hygiene in food handlers; in South Vietnam, time-temperature abuse has been mentioned as one of the reasons for foodborne outbreaks. In addition, Iyer et al. (2018) noted the increase in salmonellosis cases in Asia because of poor public hygiene and sanitation standards and the lack of surveillance and control systems.

### 4.4 | Oceania

The number of cases of salmonellosis has also increased in Australia in the last few years. From 2001 to 2016, 79% of the *Salmonella* outbreaks were related to food products, with eggs and egg products the most common vehicle for this pathogen (Ford et al. 2018). From 2001 to 2011, there were 3200 cases of salmonellosis, 650 hospitalizations, and at least 4 deaths (Moffatt et al. 2016). In the same decade, 166 *Salmonella* outbreaks were linked to eggs, 159 associated with commercial eggs, and 7 to backyard eggs. The prevalence of this pathogen in layer environments is well known; however, the evidence was not enough to differentiate the influence between cage and free-range housing systems for the presence of the microorganism (Moffatt et al. 2017). From 2005 to 2015, cases ranged from 40.9 to 71.5 per 100,000 habitants. Only in 2011, 45% of the foodborne outbreaks reported in the country were related to eggs and egg products (Whiley et al. 2017). In 2014, the number of cases was higher in Australia compared to the United States and United Kingdom (Simpson et al. 2019); there were 48 *Salmonella*-egg outbreaks in Australia, and only 4 in the United States and 5 in the United Kingdom (Chousalkar et al. 2018). Recently, McWhorter and Chousalkar (2020) also mentioned the increase in egg-related cases of salmonellosis in Australia compared to other countries. Restaurants, bakeries, and commercial eating facilities are the primary sources of contamination, followed by home kitchens (Ford et al. 2018).

In the period mentioned above (2001–2016), 778 outbreaks were confirmed related to *Salmonella*, with 14,078 confirmed illnesses, 2191 hospitalizations, and 48 deaths (Ford et al. 2018). On the basis of the epidemiological data, Ford et al. (2018) estimated the cost of salmonellosis in Australia in 2015 at approximately AUD 124.4 million, including not only the hospitalization costs but also the treatment of sequelae from salmonellosis like irritable bowel syndrome and reactive arthritis. From June to December 2005, 5 egg outbreaks were reported in Tasmania dealing with *S*. Typhimurium phage type 135, sickening 125 people. (Stephens et al. 2007). The most recent food recall of eggs was reported in Australia for eggs with a date of February 2023. The eggs were from pasture-raised, free-range eggs sold in supermarkets in Queensland because of the potential contamination with *Salmonella* (Food Standards 2024).

In New Zealand, there is a lack of robust data reporting the link between *Salmonella* spp. and eggs. Historical data from 2002 to 2014 show sporadic foodborne outbreaks linked to *Salmonella* and eggs, as one or two per year (Chousalkar et al. 2018). A few reports show the incidence of this pathogen in 161 foodborne outbreaks between 2010 and 2017, but only 2 outbreaks were associated with eggs. Different studies have been conducted in the country, and in 2001, *Salmonella* was found in 13 out of 93 samples in the eggshell. Later in 2007, eggshells and egg contents were tested in several retails in Auckland and Christchurch, and 1.8% of eggshells were *Salmonella* positive. Kingsbury et al. (2019) conducted a study in 28 farms evaluating the presence of *Salmonella* on different surfaces and flocks. They confirmed *Salmonella* presence in four farms, which was more common in dust; furthermore, the presence of this pathogen was more frequent in caged flocks. The main serotypes isolated from these farms were *S.* Infantis, *S.* Thompson, *S.* Typhimurium, *S.* Anatum, and *S.* Mbandaka.

### 4.5 | Africa

Although information about foodborne outbreaks in African countries is not often in the international news headlines, outbreaks are a public health problem that happens more often than in developed countries, and very often, these facts are not well documented. Smith et al. (2016) mention the lack of health facilities in African countries to test for *Salmonella* and other diseases; meanwhile, Paudyal et al. (2017) discuss the lack of surveillance, documentation, and reporting in Africa. Kabeta et al. (2024) presented a study on the incidence of salmonellosis in Africa from 1984 to 2021 and analyzed the published references dealing with the poultry industry. The authors analyzed data from 23 African countries and found the presence of several *Salmonella* serovars, the most common of which are *S.* Enteritidis and *S.* Typhimurium. Nigeria was the country with the highest incidence of *Salmonella* in eggs. Paudyal et al. (2017) presented the incidence in seven African countries, Benin, Botswana, Ghana, Kenya, Nigeria, Sudan, and Uganda, from 2000 to 2015, showing *Salmonella* spp. as the third major pathogen after *E. coli* and *S. aureus*. In a separate study published by Ramtahal et al. (2022), a comprehensive survey on the number of cases of salmonellosis in Africa from 2010 to 2020 presents the lack of information from a handful of countries such as Mali, Chad, Libya, Congo, and Tanzania. This study shows the presence of more than 226 serotypes of *Salmonella* in Africa and the antimicrobial resistance from the bacteria. The presence of foodborne pathogens is one of the leading causes of morbidity and mortality in developing countries (Smith et al. 2016). In Algeria, 4.4% of the eggs from markets were positive for *Salmonella;* contrasting in Egypt, the cases of salmonellosis were coming from egg-based products. In Ethiopia, egg contents and eggshells from markets, farms, and retail stores were positive for *Salmonella*. Egg contents from markets in Kenya were also contaminated; meanwhile, 6.8% of the eggs sold from retail stores in South Africa were positive for *Salmonella*. In Sudan, salmonellosis was linked to cooked eggs and regular eggs; meanwhile, in Zambia, the incidence was reported in eggshells. Most of the reported cases of salmonellosis in these African countries were linked to poor hygiene practices and environmental conditions. This information agrees with the report by Damena et al. (2022) that eggs from a farm and small vendors in Ethiopia were positive for *Salmonella* spp. from all the sources, 10% positive for eggshells and 15% for egg contents.

The Egyptian Organization for Standardization and Quality Control creates standards for foods related to food safety and quality in the country. According to the Egyptian Standard Fresh Poultry eggs, "table eggs" (3169/2023) must be *Salmonella* spp. and *Staphylococcus* spp. free. El-Kholy et al. (2020, 2022) tested table eggs from poultry farms, markets, supermarkets, and grocery shops in this African country, and the results showed the presence of *Staphylococcus* spp., but not *Salmonella* cells. *Staphylococcus* spp. was found in the eggshell but also in the egg contents. In a different study conducted in Alexandria, hen and duck eggs were tested for pathogens, and *Salmonella* spp. was found in both egg contents (Awny et al. 2018).

Finally, the study presented by El Ftouny et al. (2022) analyzed the egg safety of eggs sold in formal and informal venues in Morocco. The results showed the presence of *S.* Enteritidis in 2% of eggshells from formal refrigerated markets and 2% of egg contents from informal markets. The authors mentioned that the contamination of eggs could result from the lack of a refrigerated chain from farms to stores.

## 5 | Interventions to Reduce the Incidence of *Salmonella* spp. in Eggs

The food safety of eggs is the responsibility of several persons, from the egg farms to the table consumer. To a different degree, each processing step, selling point, and consumer practice can enhance the food safety of the product and reduce the incidence of foodborne outbreaks. Unfortunately, the ambiguous or inexistent legislation in several countries allows egg processors to commercialize products that can be potentially contaminated. Actions can also be taken at the retail level, such as providing refrigeration conditions to sell eggs. A separate point relates to these remote locations in some countries where refrigeration is not an option because of the lack of infrastructure or economic resources. Adequate packaging is also essential to protect eggshells and minimize the risk of cross-contamination. Furthermore, several novel technologies can be used in eggs and egg products to inactivate pathogenic microorganisms. Finally, the consumer can also enhance food safety practices at home when handling eggs, including refrigeration, hand washing, food separation, and consuming fully cooked products.

### 5.1 | *Salmonella* Vaccines in Hens and Pest Control

The protection of the layer flocks from *Salmonella* is a complex process. Although vaccines are available, many factors influence the reduction and elimination of *Salmonella* from hatcheries, for example, the flock size, the flock age, the stress, the feed, the type of available vaccines, and the cleaning routines (Whiley and Ross 2015). Omwandho and Kubota (2010) listed several available vaccines for hens, including details about the methodology and observations. However, Carrique-Mas and Davies (2008) mentioned the limited protection of vaccines in flocks, making hens still susceptible to *Salmonella* infection. Martelli and Davies (2012) noted that introducing vaccines in layer flocks in the United Kingdom by 1998 reduced the number of salmonellosis cases. However, these layer farms were subscribed to the British Egg Industry Council (BEIC), which provides a code of practice related to farm hygiene (British Lion Code). The available vaccines for British flocks are against *S.* Enteritidis and *S.* Typhimurium (Inns et al. 2015). In Australia, live attenuated vaccines are used for poultry, and that action has reduced *Salmonella* shedding in broilers (Groves et al. 2015; Bachtiar et al. 2003). In New Zealand, starting in 2004, the Animal Products Act requires egg processors to have a risk management program, and vaccines are recommended but not mandatory (Kingsbury et al. 2019).

Many references in this manuscript mention the importance of a pest control program to reduce the incidence of *Salmonella* in eggs (Gast et al. 2024; Martelli et al. 2017; Davies and Wales 2015). A decrease in the number of cases of *S.* Enteritidis in flocks was observed when rodents were eliminated from the hatcheries (Carrique-Mas and Davies 2008). Besides rodents, insects also play a crucial role in cross-contamination of pathogens. During a study conducted in 2006 at different farms in the European Union, *Salmonella* cells were found in more than 30% of dust and fecal samples (Gantois et al. 2009). Environmental conditions, such as climate and region, are also involved in controlling *Salmonella* in hatcheries (Whiley and Ross 2015). Strict control of sanitation and hygiene in hatcheries must be included as part of the actions to reduce the incidence of this pathogen.

### 5.2 | Refrigeration

Although refrigeration is an option for many developed countries to protect food quality and ensure food safety, it is not mandatory for eggs storage in some countries. For example, the European Union does not require to refrigerate eggs, according to the EC Regulation 2023/2465 (European Commission 2023). In contrast, some developing countries do not have access to refrigerators, or the cost is excessive, representing a barrier to preserving the quality of the food and controlling food safety risks. In India, for example, 80% of the consumers store their food at room temperature because only 19% own a refrigerator (Koppel et al. 2014).

The FAO Guide for producing and selling eggs mentions the requirement to keep the product below 13°C and the relative humidity between 75% and 80% (Fikiin et al. 2020). Several references have shown that the growth of pathogenic microorganisms is delayed or inhibited when eggshells are maintained under refrigerated conditions. Kilonzo-Nthenge et al. (2016) mentioned that eggshells kept at 7°C reduce the risk of salmonellosis. The effect of temperature on *Salmonella* spp. growth in egg and egg contents has been widely studied and reported (Schoeni et al. 1995; Kilonzo-Nthenge et al. 2016). Schoeni et al. (1995) examined the effect of temperature on the growth of *Salmonella* in yolk and albumen, and the results showed that room temperature (25°C) allowed the growth of 3-log in a day, and 10°C also allowed some cell growth in a lower rate compared to 25°C. Finally, 4°C showed a sporadic growth of the pathogen. Some authors (Lublin and Sela 2008; Bradshaw et al. 1990) reported the inhibition of *Salmonella* spp. growth on eggs when temperature is below 8°C, but other authors also confirm the temperature fluctuation in eggs when exposed to ambient conditions (25–25°C) that will allow the growth of *Salmonella* cells (Okamura et al. 2008). Fikiin et al. (2020) mentioned that 4°C has the most substantial inhibiting effect on *S.* Enteritidis.

Consumers are also responsible for the food safety of the products at home. In Australia, 91% of the respondents to a survey mentioned keeping the eggs at home under refrigerated conditions (Whiley et al. 2017). Koppel et al. (2015) reported that 85% of consumers purchased eggs in Spain and Italy that were sold at ambient temperature. Many European countries, such as Spain, Belgium, France, and the Netherlands, do not have specific requirements to keep the eggs during retail. Other countries, such as Germany and Denmark, have different requirements, such as refrigerated temperature, but the required value in Denmark is 12°C (EFSA Panel on Biological Hazards 2014). Eggs in the United States must be kept at or below 7.2°C after 36 h after the hens are laying them (FSIS 2005). It has been reported that home refrigerators do not have a constant temperature in countries such as the United Kingdom, Sweden, the Netherlands, Portugal, and Mexico; besides, several homeowners often do not clean their refrigerators between each batch of food (Godinez-Oviedo et al. 2019).

Finally, the use of risk assessment in food safety helps to evaluate and manage the foodborne microbial risks, including four steps: hazard identification, hazard characterization, exposure assessment, and risk characterization. This process estimates the magnitude for health risks when exposure to a pathogen and provides the scientific base for decision-making (Lammerding 1997). In 1998, the USDA FSIS, together with the FDA, completed a risk assessment "from farm to table" focused on *Salmonella* and eggs with the goal to reduce the incidence of this pathogen. As new data became available and more complex modeling techniques were developed, Schroeder et al. (2006) presented a new approach to evaluate the risk assessment to reduce *S.* Enteritidis in eggs based on the previous model launched in 1998. With new data back in 2005 regarding egg production, the mathematical model showed that if eggs are pasteurized to achieve a 3-log reduction of *Salmonella*, the number of annual illnesses could be reduced from 130,000 to 40,000. If the eggs are kept at 7.2°C the following 12 h after laying, the cases will be reduced to 28,000. Meanwhile, if pasteurization achieves a 5-log reduction, the cases will be reduced from 130,000 to only 19,000 yearly. The main interventions proposed in this risk assessment approach are rapid cooling (refrigeration) and a complete pasteurization process.

### 5.3 | Packaging

Packaging is a single step in the food production chain, and using the adequate materials for eggs can prevent contamination with *Salmonella*. For example, in early times, eggs were sold only in single egg cartons, as shown in Figures 4d,j and 5c. Eggs are usually grouped in groups of 30, placed in the carton, and sent for commercialization. However, in this kind of packaging, the upper side of the eggs is exposed to all environmental factors; microorganisms (not only *Salmonella* spp.) coming from hands, insects, rodents, dust, and other surfaces can easily be attached to the eggshell and start the proliferation. Some egg companies use the classic egg carton with a plastic film or a plastic mesh covering the eggs. However, in some small markets, eggs in cartons are kept close to other raw foods or placed on the floor, representing a food safety risk.

Furthermore, in some farmers markets, the egg carton is reused several times without any previous sanitation. In some local markets, sellers ask the consumer to bring back the egg carton to reuse it. It is an environmentally friendly way to reduce waste, but it also creates a food safety gap in the informal market of eggs.

### 5.4 | Food Safety Interventions

In the United States, the conventional technology for in-shell egg pasteurization is thermal pasteurization, which consists of submerging eggs in water for about 57.5 min at 57°C until the center of the yolk reaches this temperature to ensure a complete *Salmonella* inactivation (Bermudez-Aguirre and Niemira 2023). Albumen quality and functionality can be affected by the treatment. Furthermore, this process is lengthy, costly, and non-mandatory in the United States.

In the last three decades, much research has been conducted to study novel interventions to inactivate pathogens in different food commodities and minimize the undesirable changes of conventional thermal processing. Eggs and egg products have been one of the target foods not only for egg contents pasteurization but also for shell decontamination. Several references are available about the use of novel technologies aimed at inactivating *Salmonella* spp. in liquid egg products and preserving the quality, such as ohmic heating (Wang et al. 2021, 2024; Almeida Rosa et al. 2023; Alamprese et al. 2019), high-pressure carbon dioxide (Sheng et al. 2021; Garcia-Gonzalez et al. 2009), and pulsed electric fields (Jin and Zhang 2020; Baba et al. 2018; Monfort et al. 2010). For the pasteurization of in-shell eggs, some technologies, such as radio frequency (Bermudez-Aguirre et al. 2024; Yan and Geveke 2020; Geveke et al. 2017) and irradiation (Alvarez et al. 2013; Mészáros et al. 2006), showed positive results. For eggshell decontamination, there are several novel technologies with effective outcomes, such as ultraviolet (Turtoi and Borda 2014; Wells et al. 2010; De Reu et al. 2006), cold plasma (Movasaghi et al. 2025; Narasimhan et al. 2023; Illera et al. 2022), ozone (Wlazlo et al. 2020; Braun et al. 2011), and other nonthermal approaches such as natural antimicrobials (Agregan et al. 2023; Bermudez-Aguirre and Niemira 2023).

### 5.5 | Consumer Information

One of the main gaps in the food production chain is the lack of information from the consumer about how to handle and store food from supermarkets to table. Information about the risk of *Salmonella* in eggs, salmonellosis, cross-contamination, refrigeration, cooking guidelines, risk of raw eggs, and other food safety topics is widely distributed worldwide. Godinez-Oviedo et al. (2019) presented a study about consumer behavior toward *Salmonella* exposure in Mexico and surveyed several persons about the incidence of this pathogen. However, no eggs or egg-related products are mentioned in the survey or reported by the authors. This is a critical point to consider when eggs and egg products are the main vehicle of *Salmonella* spp. transmission. Smith et al. (2016) mentioned the need to improve health education in the consumer and sanitation practices in the egg industry, mainly in developing countries. In other developing countries, eggs are sold at room temperature in supermarkets and markets, sometimes close to raw chicken or meat or stored close to different foods.

## 6 | Conclusions

Regulations about egg processing and the control of *Salmonella* spp. have been improved in several countries in the last decade. Some countries are still in the way of developing robust surveillance, monitoring, and recording systems to have statistical data about the medical and economic burden of foodborne outbreaks. However, the presence of *Salmonella* spp. in eggs and egg products is a global concern regardless of the country; the numbers of foodborne outbreaks continue to grow, and cases of illnesses, hospitalizations, deaths, and egg recalls are becoming common.

The poultry industry needs to take urgent action to reduce the incidence of *Salmonella*, mainly in fresh eggs. Several of the actions some countries took to minimize the presence of the pathogen have had a positive outcome. However, there are still vulnerable areas, and those food safety gaps in the egg production chain need to be narrowed. Several interventions are available that can help to mitigate the presence of *Salmonella* in the egg contents and the eggshells. The egg industry needs to start looking for alternatives, find the best combination of interventions, and invest to ensure the food safety of eggs and protect the consumer.

#### Author Contributions

**Daniela Bermudez-Aguirre**: conceptualization, investigation, writing – original draft, formal analysis, data curation. **Joshua Carter**: investigation, writing – review and editing. **Brendan A. Niemira**: supervision, project administration, writing – review and editing.


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#### Conflicts of Interest

The authors declare no conflicts of interest.

#### Data Availability Statement

The mention of trade names or commercial products in this article is solely for the purpose of providing specific information. It does not imply a recommendation or endorsement by the US Department of Agriculture. USDA is an equal opportunity provider and employer.

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