Microbiological Risks in the Poultry Meat Production and Processing Chain: A Systematic Review of the Literature

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Abstract
Considering the continuous increase in global poultry meat consumption, along with a significant diversification of product ranges and increasingly sophisticated consumer demands, ensuring the microbial safety of carcasses and anatomically processed poultry cuts has become a fundamental priority in the food industry. This paper provides an integrated examination of bacterial contamination throughout the poultry meat processing chain - from poultry farms to the point of consumption - by identifying multiple sources of contamination. Consequently, the necessity of implementing advanced microbiological control strategies is highlighted, relying on rigorous standards and cutting-edge technologies that are essential for ensuring food safety, protecting public health, and optimizing economic efficiency by minimizing losses throughout the production chain.

Keywords: bacteria, chicken meat, food safety, meat chain, poultry.

1. Introduction

Animal husbandry represents a fundamental pillar of the agricultural industry, with poultry farming playing a critical role in fostering sustainable economic development, ensuring food security, and optimizing farmers' revenues. Through the continuous production of poultry meat and eggs, this sector contributes to the stability of the agri-food market and serves as a driving force for rural economic growth [1].

Poultry encompasses a diverse group of domesticated avian species that are economically exploited for the production of eggs, meat, and feathers. This category includes species such as *Gallus gallus domesticus* (chickens), *Meleagris gallopavo* (turkeys), *Numida meleagris* (guinea fowls), *Anas platyrhynchos domesticus* (ducks) and *Anser anser domesticus* (geese), alongside species traditionally associated with game, such as quails (*Coturnix coturnix*), pigeons (*Columba livia domestica*), and pheasants (*Phasianus colchicus*). Among these, chickens account for approximately 90% of the global poultry population, being recognized as the most significant avian species in terms of agri-food production and global food security [2].

Ensuring a healthy and balanced diet is a primary objective of any state's policy, as food represents a complex issue with profound cultural, social, and economic implications. Consequently, animal husbandry bears the responsibility of providing increasingly larger quantities of high-quality food products to meet the demands of a continuously growing population [3].

To meet these demands, the poultry industry has invested in large-scale, specialized processing facilities, where production line speeds are constantly increasing. Currently, a high-speed broiler processing line can handle up to 15,000 birds per hour, marking a sixfold increase compared to previously used methods [4].

It is projected that the annual global poultry production will exceed 37 billion units by 2050, amid a significant decline in agricultural labour

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availability. This trend is driving a rapid transition in the poultry industry from traditional manual management models to intelligent, automated, and high-capacity production systems designed to optimize efficiency and sustainability in the poultry sector [5].

In 2021, global poultry meat production was estimated at 137.8 million tons [6], further solidifying poultry farming as a key sector within the global agri-food industry. The highest production volumes were recorded in the United States (22.705 million tons), China (19.500 million tons), Brazil (14.076 million tons), and the European Union (13.769 million tons) [7]. Within the EU, more than two-thirds of poultry production is concentrated in five member states, with Poland leading at 19.2%, followed by Germany (13.1%), France (12.8%), Spain (10.1%) and Italy (9.9%) [7].

Poultry meat is marketed in various forms, including whole carcasses, cut portions, and processed products, which account for 25%, 44%, and 31% of total consumption, respectively.

According to data provided by the Organisation for Economic Co-operation and Development (OECD), global poultry meat consumption has shown a consistent upward trend. In 2023, the average global poultry meat consumption was estimated at 17.01 kg per capita. In the United States, this consumption was significantly higher, reaching 35.7 kg per capita, while in the European Union, it stood at 15.9 kg per capita. Overall, in OECD member states, the annual average poultry meat consumption was 21.9 kg per capita [8]. These figures confirm a rising trend in poultry meat consumption both globally and across the analysed regions, reflecting shifts in dietary preferences and the increasing accessibility of this type of meat.

Therefore, ensuring the microbiological safety of poultry meat products is a crucial aspect in the context of expanding consumption and production. The increasing demand for this type of meat necessitates stringent sanitary control measures throughout the entire production chain, from farm to consumer, to prevent the risks associated with microbial contamination and to guarantee food quality and safety.

Poultry meat is recognized as a potential vector for the transmission of foodborne pathogens, posing a significant global food safety and public health concern [9]. According to data reported by the World Health Organization (WHO), approximately 600 million cases of foodborne diseases were recorded globally in 2010, with 420,000 fatalities resulting from the consumption of food contaminated with enteric pathogens. In the European Union, data from 2018 indicate the occurrence of approximately 5,146 foodborne outbreaks, with meat and meat-derived products identified as a major source of contamination, accounting for 17.9% of all reported outbreaks. These figures underscore the critical importance of implementing stringent food safety measures throughout the entire production and distribution chain to mitigate the risk of pathogen transmission through food [10].

Therefore, ensuring the microbiological safety of poultry meat products is a critical aspect in the context of the continuous growth in consumption and production. Their safety is influenced not only by slaughterhouse processes but also by the rearing conditions and management practices within poultry farms. Factors such as flock density, feed and water quality, farm hygiene standards, and the use of antimicrobials play a decisive role in shaping the microbiological profile of poultry before slaughter.

During and after the slaughtering process, carcasses, cut portions, and processed meat products may be exposed to bacterial contamination originating from the natural microbiota of poultry, the slaughterhouse environment, and the surfaces of equipment used in the technological process [11].

De Quadros et al. (2019) reported that over the course of one year in a poultry slaughterhouse, out of a total of 4,372,619 broiler carcasses examined, microbiological contamination was identified as the primary cause of rejection, accounting for 24.84% of all cases. This significant incidence highlights critical vulnerabilities within the poultry production chain and underscores the necessity of stringent sanitary control measures [12]. Pathogens such as *Campylobacter jejuni* [13], *Salmonella spp.* [14], and *Escherichia coli* [15] have been consistently isolated from samples collected from slaughtered broilers, demonstrating the persistence of these microorganisms in the production process and the associated public health risks. Other emerging pathogens, such as Aeromonas spp., also warrant special attention in the assessment of microbiological risks related to poultry products [16]. These opportunistic bacteria, frequently identified in poultry meat and other animal-derived products, represent a potential source of gastrointestinal infections in humans.

A study conducted by Chai et al. (2017) analysing 1,114 foodborne illness outbreaks reported in the United States between 1998 and 2012, based on strict evaluation criteria, found that 279 outbreaks (accounting for 25% of the total) were associated with poultry products. Among these, 149 were linked to confirmed pathogens, of which 43% were attributed to *Salmonella* infections, 26% to *Clostridium perfringens,* 7% to norovirus, another 7% to *Campylobacter*, 5% to *Staphylococcus aureus*, 3% to *Bacillus cereus* and 3% to *Listeria monocytogenes* [17].

The origin of these contaminations is often linked to systemic deficiencies in hygienic and sanitary management, which are not limited solely to the slaughtering stage but extend throughout the entire poultry production process, from the rearing phase in farms to final processing in slaughterhouses. Factors such as poor sanitary conditions during poultry rearing, improper handling during transportation, and contamination within the processing environment contribute to the microbial load of carcasses, thereby increasing the risk of pathogen transmission. Consequently, the adoption of advanced biosecurity strategies, the implementation of strict hygiene protocols, and the optimization of control measures across the entire production chain are imperative for reducing contamination and ensuring the microbiological safety of poultry products intended for human consumption.

The aim of this study is to investigate and synthesize the main sources of microbiological contamination in poultry meat throughout the entire production chain, highlighting the impact of technological, environmental, and biosecurity factors on the microbial load of poultry products. The study focuses on analysing pathogens of major epidemiological significance, such as *Salmonella spp.*, *Campylobacter jejuni*, and *Escherichia coli*, along with emerging pathogens like *Aeromonas spp.*, while identifying the key factors that contribute to their persistence in poultry products.

Furthermore, the study explores critical vulnerabilities within the poultry production chain and emphasizes the importance of implementing effective biosecurity and microbiological control strategies. It evaluates modern methods for preventing and reducing contamination, including good agricultural practices, intervention measures applied in slaughtering and processing facilities, as well as innovative technologies used in post-processing stages to enhance the safety of poultry products. This approach aims to contribute to the improvement of food safety standards and the promotion of sustainable solutions for mitigating microbiological risks associated with poultry meat consumption.

2. Materials and methods

For the completion of this scientific study, a rigorous and systematic review of the specialized literature and international databases was conducted, including Web of Science (WoS), Google Scholar, and Scopus.

This systematic analysis enabled the identification of the most relevant studies in the field of microbiological risk assessment associated with poultry farming systems, predictive modelling of risk factors, and the prevalence of pathogens.

Following the initial data collection process, duplicate records were removed, and the titles and abstracts of the articles underwent a critical analysis to assess their relevance. The selection was conducted without geographical restrictions, ensuring a comprehensive and globally representative approach. Studies that did not meet the predefined inclusion criteria were excluded from the analysis.

Keywords used in the search:

- Poultry species typology: poultry, chicken, broiler, hens;
- Contamination and pathogen-related aspects: microbiological contamination, bacterial contamination, pathogens, *Salmonella*, *Campylobacter*, *Escherichia coli*, *Aeromonas spp.*;
- Food safety and decontamination strategies: food safety, decontamination methods, control measures, reduction of microbiological risks;
- Agri-food chain and risk management: farm-to-fork, risk assessment, exposure, QMRA (Quantitative Microbial Risk Assessment), good agricultural practices, good hygiene practices.

This methodological approach enables a detailed and relevant assessment of microbiological risks in the poultry sector, contributing to the strengthening of food safety measures and the optimization of contamination prevention strategies.

3. Results and discussion

Food Security and Quality in the Poultry Production Chain: From Farm to Consumer

Studies have demonstrated that pathogenic bacteria can be detected throughout the entire production chain, from the originating farm to the consumer. This includes primary production stages, live bird transportation, slaughtering processes, slaughterhouse environmental conditions, and the storage of the final product until the moment of consumption [18].

Figure 1 provides a detailed schematic representation of the critical points in the poultry meat supply chain where the risk of contamination is significant. This food chain consists of a series of fundamental stages, each playing a crucial role in maintaining the safety and quality standards of poultry products.

From primary production in farms, where environmental factors, feed quality, and veterinary management can influence the initial microbial load, to industrial processing, distribution, and ultimately final consumption, each stage of this chain represents a potential source of microbiological contamination. Exposure of the product to pathogens at any point in the supply chain can not only compromise the quality of poultry meat but also have significant public health implications by contributing to the transmission of foodborne diseases.

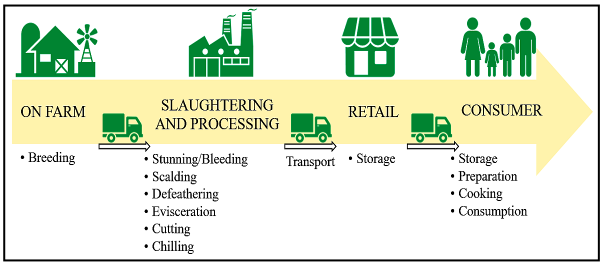

Figure 1. The poultry meat supply chain, from farm to fork, as conceptualized in quantitative microbial risk assessments. Processed by: [10]

Given that poultry serves as a significant reservoir for pathogens, it is imperative for processors in the poultry industry to be aware of contamination risks and to implement appropriate measures to mitigate these risks [14].

In this context, a comprehensive understanding of the key stages in the poultry slaughtering process is essential for optimizing microbiological control strategies and ensuring food safety standards. Therefore, the following sections will provide a detailed presentation and analysis of the critical stages of the slaughtering process, highlighting the critical contamination points and specific preventive measures necessary to maintain the microbiological integrity of poultry products.

Contamination and poultry safety at the farm level

The poultry farm represents the first essential link in the poultry meat production chain, exerting a decisive impact on the microbiological quality of the final product. In slaughterhouses, the surrounding environment plays a crucial role in poultry meat contamination (Figure 2) [11].

One of the most common sources of contamination is the bedding used in poultry housing, particularly if it is not replaced regularly. Old bedding can become a reservoir for pathogens, sustaining viable bacteria over extended periods and facilitating the continuous exposure of birds to contaminants [19].

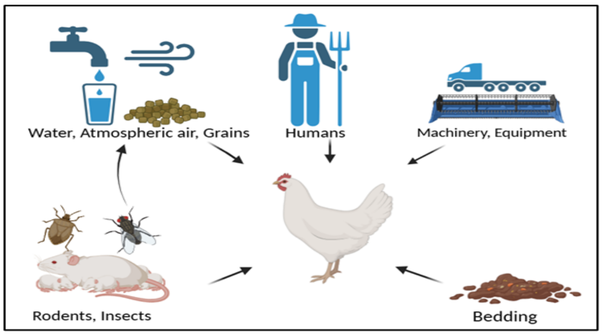

Figure 2. Schematic representation of poultry contamination sources in the farm. Created with Biorender.com (Accessed on February 2, 2025).

As the bedding accumulates organic matter such as faeces, wasted feed, and feathers, it transforms into poultry litter, a complex environment with a significant microbial load [20].

Poultry litter hosts an extensive and diverse microbial population, with concentrations reaching up to 10^{10} CFU/g. The majority of microorganisms identified in the litter are Gram-positive bacteria, including *Actinomycetes*, *Clostridia/Eubacteria*, and *Bacillus/Lactobacillus*, which collectively account for approximately 90% of the microbial diversity [21]. *Escherichia coli* is ubiquitous in poultry litter, with a prevalence rate of up to 100%. However, the pathogenic serotype *E. coli O157:H7* has not been detected in poultry litter or compost samples [22].

Pathogens present in poultry bedding can be transmitted to humans through two main routes: directly, via contact with contaminated litter, and indirectly, through the consumption of contaminated poultry products. Direct exposure can occur on farms during litter handling or when it is used as organic fertilizer. Individuals involved in such activities may inhale contaminated aerosols or transfer pathogens onto equipment and clothing [23].

Similarly, untreated drinking water represents a major risk factor, as it can serve as an efficient vector for microorganism transmission, particularly when water sources are not adequately monitored [24]. Contamination can occur either through leaks from poultry farming systems or through the excessive application of poultry waste on agricultural land, which may lead to the infiltration of bacteria such as *Salmonella*, *Campylobacter*, and *Escherichia coli* into surface and groundwater.

The interaction of poultry with other domestic or wild animals represents another potential source of contamination. Studies have shown that poultry can acquire pathogens from other farm animals or even from domestic animals present near poultry housing facilities [25]. Additionally, insects and rodents act as biological vectors, capable of transporting pathogenic microorganisms from contaminated environments to feed, water, or contact surfaces within farms [26].

An important example of the role of vectors in the epidemiology of avian diseases is the transmission of the avian influenza virus (AIV). The main vectors involved include synanthropic animals, such as rodents and terrestrial wild birds, which live in close proximity to farms and can introduce the virus into poultry housing. Additionally, insects, particularly flies, can facilitate the spread of highly pathogenic avian influenza virus (HPAIV) to domestic birds by carrying viral particles on their body surfaces or through contact with contaminated excreta [27].

The transport and movement of equipment also play a crucial role in the spread of pathogens within poultry farms. Vehicles used for transporting feed, poultry, or agricultural equipment can introduce microorganisms from external sources, and inadequate sanitation of these vehicles can facilitate the dissemination of pathogens into poultry houses. Moreover, farm tools and equipment, including personnel clothing and footwear, can contribute to the mechanical transfer of bacteria [28].

Biosecurity conditions and veterinary management are essential for preventing contamination at the farm level. Implementing strict hygiene protocols—such as periodic disinfection of poultry houses, personnel access control, the use of protective equipment, and continuous health monitoring of flocks—can significantly reduce the incidence of pathogens. Additionally, vaccination against bacterial infections and the controlled use of antibiotics in poultry farming are fundamental measures to limit the spread of infections and to prevent antimicrobial resistance.

In conclusion, the microbiological safety of poultry meat is directly dependent on the measures implemented during the primary production stage. By optimizing farm management, strictly controlling contamination sources, and applying an effective biosecurity system, the risk of pathogen contamination in poultry can be significantly reduced, thereby minimizing its transmission in subsequent stages of the production and consumption chain.

The implementation of such strategies plays a crucial role in reducing contamination risks and ensuring a safe and sustainable production chain in the poultry industry.

Contamination and poultry safety during transport

Transport is one of the most critical stages in the poultry supply chain, significantly impacting both animal welfare and meat quality [29].

Throughout their lifecycle, poultry undergo essential transportation processes within the supply chain, each exerting a significant impact on both animal welfare and meat quality. These journeys can range from short distances of less than 15 km to extended trips exceeding 90 km, lasting several hours [30].

Broiler transportation is often perceived as a major source of physiological and metabolic stress; however, it remains an indispensable link in the complex dynamics of the poultry industry. The efficiency and success of this stage are highly dependent on the rigor of sanitary measures implemented at the farm level, which play a crucial role in maintaining the microbiological integrity of flocks and preventing contamination throughout the supply chain.

A particularly important aspect is the capture and handling of birds before loading, a critical stage in preventing contamination. Studies have shown that the hands of personnel involved in poultry handling can become active vectors for pathogens, facilitating the transfer of microorganisms through direct contact. In the absence of strict hygiene protocols—such as proper handwashing, disinfection, or the use of protective gloves—the risk of pathogen transmission to birds increases significantly, potentially compromising the entire transported flock. Therefore, optimizing handling procedures, implementing strict hygiene measures, and frequently decontaminating transport vehicles are essential for reducing microbiological risks in the poultry supply chain [31].

According to the study conducted by Dianin (2016), the hands of personnel involved in poultry handling can serve as a significant source of microbiological contamination, acting as an efficient vector for pathogen transfer. Microbiological analysis revealed that, on average, the hands of poultry industry professionals may contain 2.25 ± 0.46 CFU/cm^2 of mesophilic aerobic bacteria, 0.10 ± 0.47 CFU/cm^2 of *Enterobacteriaceae*, 1.70 CFU/cm^2 of total coliforms, and a similar concentration of *Escherichia coli* [32].

These microbiological indicators underscore the high risk of cross-contamination between poultry and contact surfaces, particularly during handling stages preceding transport and slaughter. Given that Escherichia coli and Enterobacteriaceae serve as key indicators of faecal contamination, their presence on the hands of personnel indicates shortcomings in the enforcement of personal hygiene measures or decontamination protocols within poultry farming and transportation facilities.

To mitigate the risk of microbiological contamination in poultry facilities, the implementation of strict personal hygiene measures is recommended for all personnel who come into contact with birds, particularly in the period preceding transport. One of the most effective strategies for preventing the introduction and spread of pathogens is thorough handwashing and, ideally, taking a shower before entering poultry farms. This practice not only removes pathogenic microorganisms from the skin and clothing but also helps reduce the risk of cross-contamination between poultry batches.

Transport crates are a crucial component of poultry logistics; however, when reused, they become critical vectors of microbiological contamination, accumulating pathogens from non-sterile environments. Poultry excreta, the primary source of contamination, can accumulate in significant quantities on crate surfaces, facilitating the persistence and transmission of pathogenic *Salmonella spp.* strains and other hazardous microorganisms [33]. To prevent cross-contamination and maintain biosecurity standards, thorough washing and disinfection of transport crates after each use are recommended. This process should involve the use of effective antimicrobial agents and mechanized cleaning methods to ensure the removal of organic residues and persistent pathogens.

Trucks are the primary means of transporting broilers to slaughter facilities; however, this process involves confining the birds in a limited space, which can promote physiological stress and microbiological contamination. In the absence of strict biosecurity measures and proper management of transport conditions, this confined environment can become a significant risk factor.

The risk of microbial contamination during broiler transport is determined by a set of interdependent factors, including the stocking density of transported flocks, human handling, truck type (open or enclosed), air quality inside and outside the vehicle, climatic conditions during transport, and the effectiveness of decontamination measures applied to trucks. In the absence of strict biosecurity measures, these variables can promote the persistence and spread of pathogens, increasing the risk of bacterial and viral infections among poultry flocks.

Thus, the transport process becomes a significant vector for pathogenic microorganisms, facilitating the transmission of infectious diseases among poultry and, consequently, compromising the safety of poultry products. The most frequently involved pathogens in such processes include *Salmonella spp., Campylobacter spp.*, and *Escherichia coli* - bacteria that can persist on vehicle surfaces and equipment, as well as be transmitted through aerosols or contaminated excreta.

The study conducted by Huneau-Salaün et al. (2022) highlights the importance of implementing rigorous decontamination measures for trucks used in broiler transport, given the significant risk of microbiological contamination. An effective strategy for preventing and mitigating excessive contamination involves the complete removal of organic matter from all vehicle surfaces, from tires to the roof, followed by the application of a detergent solution, high-pressure water washing, and disinfection using glutaraldehyde- and quaternary ammonium-based disinfectants [34].

Additionally, studies have demonstrated that, in complement to pre-washing and rinsing, applying a 1% quaternary ammonium solution for 10 minutes is an effective measure for reducing bacterial load in broiler transport trucks [35]. Implementing this strict sanitation protocol significantly limits pathogen transmission, reduces the risk of cross-contamination between poultry batches, and enhances the microbiological safety of the poultry supply chain.

Contamination and Poultry Meat Safety During Slaughtering

Slaughtering processes in poultry abattoirs represent a critical factor in the transmission of foodborne pathogens. Research has shown that the risk of microbial contamination is significant throughout the slaughtering stages [36], with defeathering, evisceration, and chilling being the most critical steps, as they have a major impact on the microbiological safety of the final product [37].

Work surfaces, air (via aerosols), and liquids used during the slaughtering and processing stages are significant sources of bacteria, contributing substantially to the contamination of carcasses and meat cuts after animal slaughter [11].

Modern poultry slaughterhouses have impressive processing capacities, handling up to 14,000 birds per hour per line, with some facilities utilizing multiple parallel lines to enhance efficiency. Each slaughterhouse is unique, and the equipment used, particularly in the evisceration area, may vary. The process begins with the transfer of birds from containers or conveyors, where they are automatically placed, followed by their suspension by the legs in the shackles of the processing line while still conscious. The method used for unloading the birds is a critical factor in determining the degree of carcass contamination. According to the study conducted by Seliwiorstow et al. (2016), birds unloaded using an automated system, which involves direct falling onto the conveyor belt, exhibited a significantly higher *Campylobacter* bacterial load compared to those handled manually. This difference can be attributed to the high level of stress induced by automated unloading, which promotes spontaneous defecation, thereby leading to external contamination of the birds' body surfaces and, consequently, the processing equipment. Subsequently, the birds are stunned either electrically or through exposure to CO_2 [38].

Stunning animals before slaughter is a widely adopted practice globally. The requirement for stunning-inducing unconsciousness before slaughter (neck cutting) - is based on two fundamental principles: (a) the recognition that animals are sentient beings and (b) the prevention of pain and suffering caused by neck cutting, which can be avoided through prior stunning. Consequently, most guidelines and regulations on animal welfare during slaughter include a list of recognized stunning methods applicable to different species, as well as minimum standards for each method, aimed at ensuring the immediate induction of unconsciousness and its maintenance until the animal's death through bleeding [39].

Subsequently, the birds undergo manual or automatic neck cutting, ensuring a precise incision in the major blood vessels to allow for rapid and complete bleeding. This process is essential for preventing additional suffering in the birds and for improving meat quality by avoiding blood retention in tissues, which could promote the proliferation of pathogenic microorganisms. A critical aspect of this procedure is maintaining strict hygienic and sanitary conditions.

After bleeding, carcasses undergo a scalding process in hot water baths. The slaughtering process for poultry exhibits distinct characteristics compared to that of mammals due to the biological differences and smaller size of these species. A defining aspect is the use of water baths, either hot or chilled, at various stages of processing. The scalding bath (50–60°C) is essential for loosening feathers, facilitating their mechanical removal; however, it can also lead to follicle dilation and the transfer of bacteria from feathers to the skin. Scalding at high temperatures facilitates feather removal but may cause epidermal damage.

Although hot water temporarily reduces the microbial load, it can also promote cross-contamination, especially when reused for multiple carcasses. Some studies have identified the scalding stage as a critical point for *Campylobacter* cross-contamination. Research has detected the presence of this pathogen in the scalding tank water even before the arrival of the first birds, suggesting the persistence of contamination despite the cleaning measures applied [40], [37].

Microbiological analyses have also indicated an average concentration of *Campylobacter jejuni* of 2.90 CFU/mL in scalding water [41], highlighting that despite rigorous sanitation of the tank, certain bacterial populations can survive and contribute to carcass contamination at this stage of the slaughtering process. After scalding, feathers are mechanically removed using plucking machines equipped with rotating discs fitted with rubber fingers. At this stage, the head and feet are usually removed, and the carcasses are automatically transferred to the evisceration line.

According to the study conducted by Rasschaert et al. (2007), the feather plucking machine was identified as the equipment with the highest *Salmonella* contamination rate, with values ranging between 6.7% and 40%, depending on the slaughterhouse, and an overall average of 17.3% [42]. Firstly, the direct contact of carcasses with the rubber fingers of the plucking machine plays a crucial role in contamination. During plucking, the rubber fingers come into contact with the birds' skin, transferring microorganisms from one carcass to another. Studies have shown that bacteria can persist in cracks and irregularities caused by wear on the rubber fingers, making them difficult to clean and disinfect effectively [43]. As the rubber fingers lose their original texture, they become more porous, promoting bacterial adhesion and protecting microorganisms from cleaning agents.

Secondly, the organic matter accumulated during the plucking process significantly contributes to *Salmonella* contamination. Feathers, skin residues, and faecal matter left on the equipment can create a favourable environment for bacterial survival. Additionally, the pressure exerted on the birds' abdomen during plucking can lead to the release of intestinal contents, further increasing the risk of *Salmonella* contamination [44].

This phenomenon facilitates the spread of the pathogen onto the surface of carcasses and equipment, creating a critical contamination point within the slaughterhouse.

The evisceration process involves the removal of viscera from the carcass, representing a critical stage in slaughtering with a high risk of cross-contamination and subsequent microbial proliferation [45]. Thus, the crop, neck, and lungs are removed using scoops or clamps, followed by the complete extraction of the internal organs. The removal of the crop during evisceration is essential for maintaining food safety and hygiene standards. The crop, a muscular sac located at the beginning of the oesophagus, serves as a temporary storage site for food before digestion. If not properly removed, it can retain food residues and pathogenic bacteria such as *Salmonella* and *Campylobacter*, which may contaminate the carcass during processing. Furthermore, the presence of undigested food in the crop can lead to unpleasant odours and negatively impact meat freshness, accelerating spoilage. Proper removal prevents accidental leakage of food contents and ensures the correct separation of internal organs, thereby optimizing the entire evisceration process. Evisceration involves the removal of the bird's internal organs. If the equipment used is not properly calibrated to the size of the carcasses or if the integrity of the gastrointestinal tract is compromised, there is a high risk of intestinal content leakage, which can contaminate both the carcass surface and processing equipment [45]. These are inspected by veterinary personnel, and certain organs, such as the liver, may be selected for further use. Throughout the slaughter line, both equipment and carcasses are frequently sprayed with potable water; however, the most crucial washing stage occurs in the inside-outside washing machine, where carcasses are thoroughly rinsed to remove residual matter.

Additionally, the generation of aerosols during this process can facilitate the airborne dissemination of pathogens to other carcasses. After evisceration, the cooling process follows, which can be carried out either by immersion in water baths at temperatures of 0-2 °C or by air chilling at 0-4°C for several hours. The water chilling method is faster but carries a higher risk of cross-contamination, whereas air chilling is considered microbiologically safer. After cooling, carcasses are sorted by weight and either packaged whole or transferred to the cutting section for further processing.

Modern poultry processing involves numerous critical points where microbiological contamination can occur, particularly with pathogens such as *Salmonella spp., Campylobacter*, and *Escherichia coli*. Therefore, strict adherence to biosecurity and hygiene measures is essential to prevent contamination and ensure the safety of products intended for human consumption [44].

Although *Campylobacter* lacks the ability to multiply outside the intestinal tract of its hosts and exhibits pronounced sensitivity to environmental factors, multiple studies have demonstrated its persistence on slaughter lines even after the implementation of cleaning and disinfection procedures. According to the investigation conducted by Peyrat et al. (2008), *Campylobacter* was isolated from the surfaces of cleaned and disinfected processing equipment in three out of the four slaughterhouses analysed, recording an alarming positivity rate of 18% [46]. The most affected areas were found to be the rubber fingers of defeathering machines, as well as the equipment used for evisceration-critical points in terms of contamination risk. In the same vein, the study conducted by Kudirkienė et al. (2011) revealed that, despite rigorous sanitation procedures, 67% of the samples collected from the post-disinfection environment remained positive for *Campylobacter*. These findings highlighted the persistent presence of the bacterium not only on equipment used in the technological process but also on auxiliary elements of the production flow, such as conveyor belts, floors, and scalding water [47].

Contamination of poultry meat in the retail sector

After the processing stage is completed, whole carcasses and poultry meat cuts are transported to retail outlets, where they are stored at temperatures below 4°C to prevent the proliferation of pathogenic microorganisms and spoilage bacteria. At this stage, meat contamination can arise from multiple sources, including improper handling, cross-contamination between products, and exposure to adverse environmental factors.

One of the main sources of contamination is the improper handling of products by retail sector personnel. If strict hygiene measures, such as frequent handwashing and the use of appropriate protective equipment, are not followed, pathogenic microorganisms such as *Salmonella*, *Campylobacter* or *Listeria monocytogenes* may be transferred from work surfaces or equipment to the meat, increasing the risk of contamination.

Another critical factor is inadequate temperature control during transportation and storage. If the cold chain is disrupted and the temperature exceeds 4°C, bacterial growth accelerates, promoting the proliferation of pathogenic agents. Exposure to temperature fluctuations may also lead to condensation forming on the surface of packaged products, creating a favourable environment for microbial development.

Contamination can also occur due to damaged packaging or the use of inadequate packaging materials. Modified atmosphere packaging (MAP) and antimicrobial films are effective methods for extending shelf life; however, if the packaging integrity is compromised, the meat may come into contact with environmental contaminants. Studies have shown that accidental tearing or perforation of the packaging significantly increases the risk of bacterial contamination by exposing the product directly to microorganisms present in the storage environment.

In addition, contamination can occur through direct contact between carcasses or meat cuts, especially when stored in bulk or placed on common surfaces. If one product is already contaminated, bacteria can easily be transferred to other products through direct contact, particularly under conditions of high humidity. This phenomenon is commonly encountered in retail units where meat is repackaged or portioned before being sold.

To minimize the risk of contamination at this stage of the process, it is essential to implement strict food safety measures, such as maintaining the cold chain, using appropriate packaging materials, ensuring the hygiene of equipment, and providing proper training for staff in retail units. Only through effective management of these aspects can poultry meat safety be maintained, and the risk of pathogen transmission to consumers be reduced.

Contamination and safety of poultry meat at the consumer stage

With the increasing demand for poultry meat, a growing number of consumers are paying closer attention to product quality, guiding their purchasing decisions based on criteria such as food safety, environmental impact, and animal welfare [48].

The consumer stage of poultry meat includes four essential processes: storage, preparation, cooking, and consumption. Numerous studies have highlighted that most foodborne outbreaks are associated with improper storage of products, cross-contamination during handling, and inadequate thermal treatment during cooking. Given the significant impact of these factors on food safety, the following sections provide a detailed analysis of these three critical aspects [10]. The study conducted by Collineau et al. (2020) highlighted the essential role of storage temperature in reducing the risk of contamination with *Salmonella spp.* and in preventing the occurrence of salmonellosis cases [49].

Studies have demonstrated that the risk of human campylobacteriosis is significantly influenced by the method of poultry meat storage. According to the research, the probability of infection is 4.10 times lower when chicken carcasses are stored in a frozen state, compared to storage at refrigeration temperatures [50]. This considerable reduction in risk is attributed to the fact that *Campylobacter spp.* is a thermolabile bacterium that loses its viability under prolonged freezing conditions. These findings underscore the importance of maintaining an optimal cold chain throughout the entire distribution process and implementing rigorous freezing practices in processing and retail units as an effective strategy for mitigating the microbiological risks associated with poultry consumption. The preparation stage of poultry meat represents a critical point in the food safety chain, as the risk of cross-contamination is high before cooking. Studies have shown that improper handling of raw meat can lead to the transfer of pathogens, such as *Salmonella spp.* and *Campylobacter spp.,* onto other ready-to-eat foods or kitchen work surfaces [51].

Another critical factor in preventing microbial contamination is inadequate handwashing, which has been identified as one of the main causes of pathogen spread during food handling. According to studies, 74% of reported cases of campylobacteriosis in Germany were associated with improper hygiene practices during poultry meat handling. Of these, 39% of infections were attributed to indirect contamination via dirty hands, while 35% resulted from the lack of proper sanitation of utensils after contact with raw meat [52].

After the preparation stage, where cross-contamination poses a major risk, adequate thermal treatment becomes an essential measure for eliminating pathogens present on the surface and inside poultry meat. Studies have demonstrated that harmful bacteria such as *Salmonella spp.* and *Campylobacter spp.* are completely destroyed only when the product reaches an internal temperature of at least 70°C. This thermal threshold ensures the denaturation of bacterial proteins and the destruction of the cellular structure of pathogenic microorganisms, thereby reducing the risk of foodborne infections.

Insufficient cooking of poultry meat, especially in the case of thick cuts or cooking methods that do not ensure even heat distribution, can allow bacteria to survive inside the product. For instance, rapid cooking methods, such as shallow frying or frying at insufficient temperatures, can create an environment where the outer layer of the meat appears cooked, while the interior remains inadequately exposed to temperatures lethal to microorganisms. In this context, the use of a food thermometer becomes a recommended practice for checking the internal temperature of the meat, ensuring it has undergone sufficient thermal treatment to eliminate bacteria. Moreover, it is essential that cooking methods be selected based on the type and thickness of the product, ensuring even heat distribution. For example, methods such as high-temperature baking, boiling, and deep frying ensure effective heat penetration, eliminating the risk of pathogenic microorganism persistence.

In conclusion, proper cooking is the final and most important step in preventing the microbiological risk associated with poultry consumption. Combined with rigorous hygiene measures and the prevention of cross-contamination during handling, ensuring adequate thermal treatment is essential for protecting consumer health.

4. Conclusions

This study conducted a thorough analysis of the critical vulnerabilities within the poultry meat production chain, highlighting the major risk points that can compromise food safety. The evaluation of the "farm-to-fork" process significantly contributes to understanding the mechanisms through which pathogens such as *Salmonella spp., Campylobacter spp.,* and

Escherichia coli can contaminate poultry products at various stages of production, from the rearing and handling of poultry on farms to the processing, packaging, and distribution of the finished products.

The results of the study emphasize that contamination sources can be multiple and varied, including both endogenous factors, such as the microbiota of the poultry, and exogenous factors, such as equipment surfaces, processing personnel, and environmental conditions within production facilities. Within slaughterhouses, identified critical points include stunning, slaughtering, evisceration, and chilling operations, where direct contact with equipment, contaminated air, or liquid leaks can promote the proliferation of pathogenic bacteria. Furthermore, subsequent stages, such as cutting, packaging, and storage of products, present additional risks in the absence of strict hygiene and microbiological control measures.

The study demonstrated that maintaining an optimal level of microbiological safety requires the implementation of rigorous hygiene protocols at every stage of the production process. The effectiveness of equipment decontamination measures, the use of safe antimicrobial substances, constant monitoring of bacterial load, and adherence to good manufacturing practices are critical factors in preventing cross-contamination and maintaining the quality of poultry products. Deficiencies in these processes can not only facilitate contamination of products but can also lead to significant economic losses and major health risks for consumers.

Thus, the present study provides a detailed perspective on the risks present in the poultry industry, highlighting the need for strict and integrated contamination control throughout the entire production chain, from the sanitary management of farms to ensuring safe and compliant products on the consumer market.

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