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Perspectives in the implementation of risk-based meat safety assurance system (RB-MSAS) in broiler meat production

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ABSTRACT

We discuss the challenges associated with risk-based meat safety assurance system (RB-MSAS) focussed on chicken meat production. *Campylobacter*, *Salmonella,* and more recently, antimicrobial resistance (AMR), are the primary causes of foodborne illness attributed to poultry meat and pose the most significant challenges for food safety assurance systems. To achieve the goals of RB-MSAS, thorough data collection and risk assessment are essential for food business operators (FBOs).

The use of harmonised epidemiological indicators (HEIs) implies a set of standardized metrics that facilitate the assessment of the distribution and determinants of health-related events in animal populations. These indicators ensure consistency and comparability of data across different contexts or geographic areas and are valuable for informing risk management decisions. Current challenges encompass the limited availability of data on *Campylobacter* infection prevalence, concerns related to flock uniformity, and the burden of antibiotic resistance. The failure mode and effect analysis (FMEA) model should be applied to prevent non-conformity from leading to unacceptable risk levels. We also address the challenges associated with implementing risk-based meat inspection (RBMI) at the slaughterhouse, highlighting the crucial role of public veterinary officers (PVOs) in ensuring compliance with food laws and maintaining good management standards. Towards these goals, the paper emphasizes the necessity for evidence-based interventions to enhance meat safety. It also advocates for the application of failure mode and effect analysis to implement efficient corrective and preventive actions, specifically targeting non-compliance and contamination issues.

1. Introduction

The new risk-based meat safety assurance system (RB-MSAS) has been designed to address current and the most relevant food safety issues that cannot be controlled using traditional inspection procedures (Blagojevic et al., 2021). These traditional inspections were originally developed primarily to detect the clinical signs and macroscopic lesions of zoonotic diseases, such as echinococcosis, cysticercosis, and tuberculosis, when their incidence was high in cattle. The improved hygiene and epidemic surveillance have significantly reduced their presence (Calvo-Artavia et al., 2013; Garcia-Saenz et al., 2015; Laranjo-González, Devleesschauwer, Gabriël, Dorny, & Allepuz, 2016; Willeberg et al., 2018). Today, post-mortem inspection often only identifies pathological lesions caused by organisms insignificant to public health or lesions related to animal welfare issues and animal diseases that are endemic in intensive farming systems (Blagojevic & Antic, 2014). Based on the recommendations of their scientific advisory panels, regulatory bodies adopted new guiding principles for addressing major meat safety challenges. Minimal handling of carcasses and offal on the slaughter line and visual-only inspection is applied for animal categories with a negligible risk of tuberculosis and cysticercosis, such as pigs and veal (Ghidini et al., 2018; Laukkanen-Ninios et al., 2020). A RB-MSAS was proposed to address the most significant meat-borne hazards and protect both human and animal health and welfare (Ferri et al., 2023). The reallocation of inspection activities has been planned in the scenarios described by the advisory boards at European Food Safety Authority

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(EFSA) and U.S. Food Safety and Inspection Service (FSIS). These scenarios now emphasize interventions to reduce contamination in meat production lines (EFSA, 2012; FSIS, 2014).

In light of the food safety-related epidemic data, some competent authorities (CAs) have issued national action plans to reduce the prevalence of *Salmonella* and *Campylobacter* in poultry and swine, and livestock producers have been required to implement effective biosecurity measures (Commission Regulation, 2012; FSIS, 2022; Olsen et al., 2024). Monitoring plans have been also initiated to collect data on *Yersinia* and *Toxoplasma* in some swine and sheep farms, and strategies and action plans regarding antimicrobial resistance (AMR) have been implemented. Inspections, audits, and sampling are conducted to collect data useful for focusing interventions in areas with the highest risk and evaluating their actual implementation and effectiveness (Blagojevic et al., 2021; Bonardi et al., 2021; Cegar et al., 2022; Ferri et al., 2023; Luukkanen & Lundén, 2016). Harmonised epidemiological indicators (HEIs) have been proposed by EFSA to provide adequate information and ensure consistency and comparability of data across different contexts or geographic areas. These indicators should be used to guide risk management decisions (EFSA, 2011; EFSA, 2012; EFSA, 2013). HEIs are not legal requirements within the European Union (EU) today, and no country has formally integrated HEIs into its risk categorization system. Some HEIs are implemented as monitoring and surveillance systems (MOSS) or official control programs (Langkabel et al., 2023). The monitoring activity makes it possible to subsequently set up a surveillance plan that provides for specific control measures and is also able to evaluate their effect. In Europe, only the northern countries have implemented national *Campylobacter* surveillance plans (Olsen et al., 2024). Apart from estimating the likelihood of specific pathogen-free herds, valuable data also includes assessing biosecurity compliance on farms, control of feedstuffs and breeding stocks for *Salmonella*, and the evaluation slaughterhouses' ability to control and prevent cross-contamination (Cameron, 2012; Kloska et al., 2017; Li et al., 2021; Silva et al., 2019; Tilli et al., 2022).

Through the collection and analysis of these data, risks can be assessed and prioritized, allowing for the development of targeted risk mitigation measures. These measures include scheduled slaughter and specific measures to prevent alimentary tract content leakages during evisceration, as well as the washing of the carcasses with hot water or approved sanitizers. In this context, the role of public veterinary officers (PVOs) is to ensure that food business operators (FBOs) effectively comply with the food laws and good management standards (Blagojevic et al., 2021). The goals of RB-MSAS are not easy to achieve because they require the careful evaluation of risk assessment and management procedures. For instance, FBOs should be cautious when the prevalence of pathogens in farms is not known or not negligible. In the framework of RB-MSAS, it is the responsibility of managers to identify the root causes of problems, implement actions to stop the problem from recurring, and track the effectiveness of their actions. All actions should be supported by evidence-based proof of efficacy. An analysis of scientific studies and technical literature must assist the risk manager and CAs in developing appropriate corrective and preventive interventions. PVOs should verify compliance and ensure prompt actions are taken to address significant instances of non-compliance (Commission Implementing Regulation, 2019, Article 46). If contamination is detected on external surfaces of a carcass or its cavities, and the FBO does not take appropriate action to rectify the situation, a reduction in the speed of slaughter can be required. The CAs shall increase the intensity of inspection until they are satisfied that the FBO has regained control of the process. Withdrawal and decontamination or destruction of carcasses/edible tissues contaminated by pathogens with levels exceeding those tolerated by food laws are aimed at correcting or solving non-conformance. In addition, interventions to prevent recurrence and improve management systems should be planned, logistic slaughter should be used to reduce cross-contamination, and pre-harvest control should be implemented. This perspective paper aims to provide insights for the implementation of broiler risk-based meat inspection (RBMI) in the framework of RB-MSAS. It will explore challenges related to food hygiene and safety management. A qualitative risk assessment identified *Campylobacter* spp., *Salmonella* spp., ESBL/AmpC gene-carrying *Enterobacteriaceae*, and generic *Escherichia coli* as the most relevant biological hazards in the context of meat inspection for poultry, given that none of these are detected by traditional visual meat inspection methods (EFSA Panel on Biological Hazards EFSA Panel on Contaminants in the Food Chain and EFSA Panel on Animal Health and Welfare, 2012; Langkabel et al., 2023). In this study, failure mode and effect analysis (FMEA) was employed to assess the criticality of the broiler mechanical evisceration technology. The analysis involved evaluating the severity of potential failures, assessing the likelihood of their occurrence, and discussing the effectiveness of preventive and corrective actions aimed at reducing risks.

2. Risk-based meat inspection (RBMI) of broilers. Process failure mode and effect analysis (FMEA)

Current challenges in RB-MSAS encompass the risk posed by the high-speed mechanical evisceration process combined with the manual selection of birds in the hanging line; limited availability of data on the prevalence of *Campylobacter* infection, with some flocks showing high prevalence, and evidence indicating that current biosecurity procedures are inadequate in ensuring *Campylobacter* - negative flocks. Notably, there is not a rare lack of compliance with process hygiene criteria on carcasses, revealing ineffective management of faecal contamination along the slaughter line.

To address these challenges, FBOs should monitor the frequency of identified potential failures and analyse their severity, especially when accepting batches of chickens from *Campylobacter*- and *Salmonella*-positive farms. If risks are significant and frequent, they should consider implementing effective corrective actions in their processes.

2.1. Mechanical evisceration of chickens with poor size uniformity

Mechanical evisceration is a significant production technology in the chicken industry for improving production efficiency. However, heterogeneity in carcass weight within a batch can pose a risk for the contamination of chicken carcasses (Malher et al., 2011; Pacholewicz, Barus, et al., 2016). When the vent opener and draw hand are misaligned, carcasses can easily become contaminated with faecal material. Some batches shipped to the slaughterhouses can be problematic, particularly when flocks of birds being shipped have varying sizes due to health problems. The manual selection of birds in the hanging line might be inefficient due to time constraints, and there are no alternative options for handling high numbers of live birds that fall outside the tolerance of the slaughter line (Brizio et al., 2015; Libera et al., 2023). Even when FBOs ensure that equipment is properly calibrated and maintained, it is impossible to adjust slaughter equipment for each carcass individually. Broilers not fitting the size tolerance of the evisceration machine can contribute to the faecal contamination of carcasses (Libera et al., 2023). Manual work is most often used to remove the residual part of intestines remaining in the carcasses, and automatic cleaning sprays are used for rinsing the carcasses and the contact surfaces. The consequences of these events, in the presence of *Salmonella* and/or *Campylobacter*-positive flocks, might not be entirely under control even with the use of chlorinated water and chilling the poultry carcasses to 4 °C or below within a few hours after the evisceration (Boubendir et al., 2021; Buess et al., 2019; Rivera-Pérez et al., 2014). The severity and probability of hazards vehiculated by faecal contamination depends on the epidemic status of the supplying farms.

Within this framework, the utilization of FMEA is recommended to enhance production quality. Taking a proactive approach, corrective measures are employed to reduce the severity and occurrence of failures. This involves identifying potential failures and assessing their likelihood and severity. The goal is to implement strategies that prevent or mitigate their impact (Nikpay et al., 2014; Scipioni et al., 2002; Trafialek et al., 2014). When applying FMEA to the production cycle, FBOs need to monitor the frequency of identified potential failures and analyse their severity, particularly when accepting batches of chickens from *Campylobacter*- and *Salmonella*-positive farms. It is crucial to determine if the prevalence of these contaminants is negligible, considering the enterprise's safety management procedures (Fig. 1). The burden of antibiotic resistance is also matter of concern when faeces contain, for example, strains of *E. coli* carrying genes for ESBL-/AmpC beta lactamase. Consequently, slaughterhouse management should collect relevant data. The greatest risks are connected to functioning of Hazard Analysis and Critical Control Point (HACCP) system in areas of verification, record keeping and corrective actions.

In slaughterhouses, the PVOs analyse livestock documentation, observe whether different slaughter operations are carried out under hygienic conditions, and can detect evidence of below-standard welfare and endemic diseases that may lead to poor flock uniformity, malfunctioning in evisceration lines and visually contaminated carcasses (Libera et al., 2023; Törmä et al., 2022).

2.2. Analysis of surveillance and monitoring data, and the harmonised epidemiological indicators (HEIs)

The successful integration of surveillance data gathered along the food chain is essential for validating the effectiveness of preventive and control measures aimed at ensuring food safety and preventing potential health risks.

2.2.1. Foodborne illness source attribution and poultry meat

In the United States, 16.8% and 64.7% of foodborne *Salmonella* and *Campylobacter* illnesses, respectively, that occurred in 2019 were attributed to poultry products (IFSAC, 2021). The EU One Health 2021 Zoonoses Report (ECDC & EFSA, 2022b) reported an annual notification rate equal to 15.7 cases per 100,000 for salmonellosis. The report highlighted that a large proportion of *Salmonella*-positive samples were from mechanically separated meat (13.3%), meat products made from poultry meat intended to be eaten cooked (10%), minced meat and meat preparations made from poultry meat intended to be eaten cooked (5.2%), and fresh poultry meat (3.1%) that were sampled at the manufacturing level.

2.2.2. Farms - biosecurity

Surveys indicate that the farms with a higher number of broilers and more staff involved in the daily care of the animals may find it harder to maintain a satisfactory level of 'internal biosecurity' and pathogens can be spread among poultry houses (Van Limbergen et al., 2018). They also indicate that the disposal of dead birds and used litter, and the control of animal vectors with adequate infrastructures were strongly correlated with the biosecurity benchmarks (Tilli et al., 2022; Van Limbergen et al., 2018; Wang et al., 2023). Furthermore, although prevalence can be substantially reduced at farm level with improvements to biosecurity, cleaning, and disinfection, *Salmonella* may be difficult to eradicate and some hatcheries are still severely affected by *Salmonella* infection in chicks (Oastler et al., 2022).

In the regions where the endemic infection of *Salmonella* is well controlled, contaminated feeds can be a major source of *Salmonella*

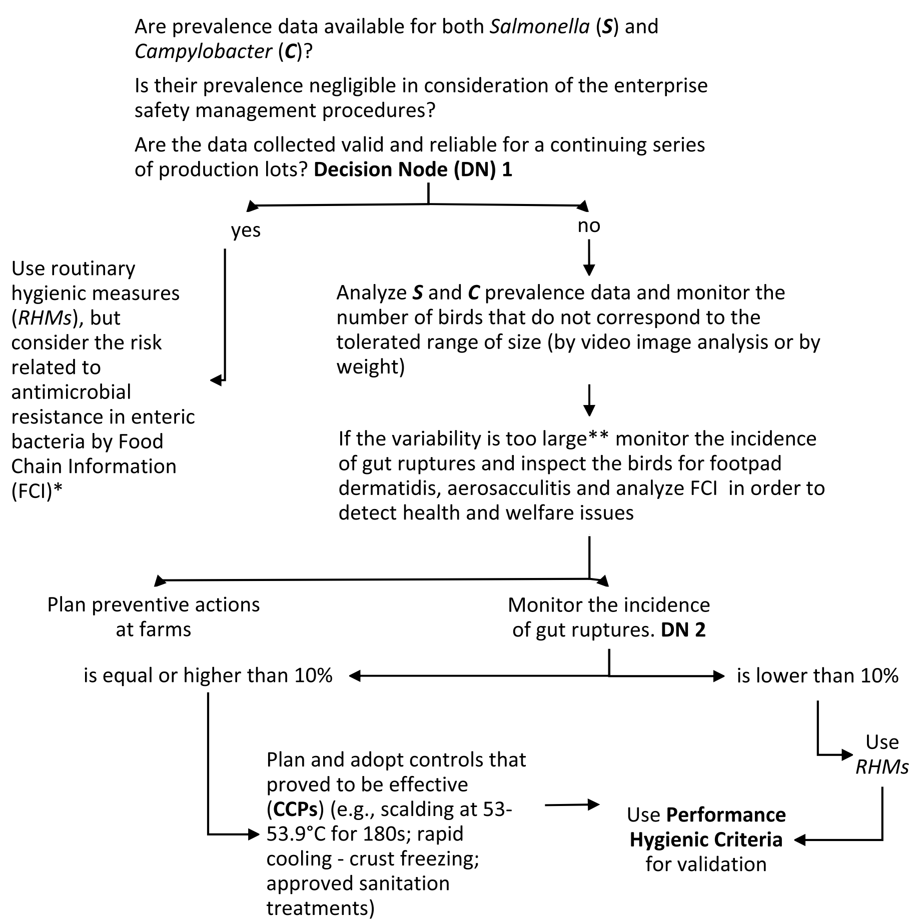

Fig. 1. Steps to plan and implement corrective actions.
* Collect data on the use of Antimicrobials and their persistence in the environment. ** Decision on the variability within each batch should be taken in consideration of adaptations of the slaughter line and selection of chicken that are hanged.

(EFSA, 2019). Despite the fact that heat treatment is recognized as effective for decontamination of feedstuffs, in some circumstances (e.g., pelleted feed for layers) this may not be appropriate (EFSA Panel on Biological Hazards, 2008) and the carryover of *Salmonella* in dust, vermin, and wild birds via the intake pits to the premises and the condensation of moisture in the feed mills was found to affect discontinuous production systems (Davies & Wray, 1997; EFSA, 2019; Gosling et al., 2022). These facts underscore the crucial importance of monitoring activities and highlight that only an integrated approach to food safety controls across the stages of primary production can diminish uncertainty regarding the status of broiler flocks for *Salmonella*.

Target hygiene actions for farm-staff and drinking water, and restricting access by other farm and wild animals were identified as successful interventions to control *Campylobacter* in poultry on farms (Pessoa et al., 2021). A combination of varied dietary approaches, modulation of the gut microbiota and immune system by probiotics, prebiotics and post-biotics has been extensively researched, but remains controversial with results showing great variability (Kim et al., 2019; Pessoa et al., 2021; Smialek et al., 2018). The high prevalence of *Campylobacter* positive flocks and human cases of campylobacteriosis suggest that current biosecurity procedures are inadequate in ensuring *Campylobacter* negative flocks (Sibanda et al., 2018). Whilst on-farm biosecurity is essential to maintain a healthy flock and reduce disease transmission, even the most stringent biosecurity measures may not have sufficient, consistent, and predictable effects in controlling *Campylobacter* (Lu et al., 2021).

2.2.3. Slaughterhouses – use of harmonised epidemic indicators (HEIs)

No country has formally integrated HEIs into its risk categorization system. Only a few countries use microbiological testing results as a basis for risk categorization of slaughterhouses, and the effectiveness of the implemented risk categorization systems has been assessed in just five countries (36%). However, these assessments often lack clarity in methodology and assessment criteria (Salines et al., 2023). The related monitoring tasks are an integral part of the risk management systems and are primarily a responsibility of FBOs, although some tasks are carried out by certification bodies and accredited laboratories. In this context, risk-based score systems can be applied to assess the on-farm application of management practices that reduce the opportunities for infectious agents to gain access to or spread within production units (Dewulf & Van Immerseel, 2018; Maes et al., 2021).

The practical application of logistic slaughter to control *Campylobacter* is less straightforward than for *Salmonella*, because *Campylobacter* colonisation frequently appears at the end of the rearing period and a logistic slaughter based on recently determined *Campylobacter* status would require last-minute changes to the slaughter schedule, which may result in excessively long fasting periods (Rasschaert et al., 2020). The relative uncertainty in the application of information on primary production suggests that attention to contamination control in meat production remains crucial, and this is paramount for RB-MSAS.

2.3. Control programmes and sampling plans: manage the uncertainty

EU Member States (MSs) and other countries have introduced *Salmonella* control programs for poultry populations and well-defined plans have been implemented to achieve reduction targets. Trade restrictions have been introduced in the event that these populations are infected with *S.* Enteritidis or *S.* Typhimurium. In recent years, the on-farm prevalence of some poultry-related *Salmonella* serovars such as *S.* Kentucky, *S.* Heidelberg, *S.* Livingstone and *S.* Mbandaka has increased significantly (Guillén et al., 2020). *S.* Heidelberg and *S.* Thompson are also considered emerging serovars (EFSA Panel on Biological Hazards, 2019). Epidemiological surveillance in primary production has a key role in the possible implementation of risk mitigation strategies and progress has been made in this regard. Despite the fact that reduction trends for the monitored *Salmonella* serovars have been observed in different contexts and regions, the numbers have remained constant in recent years. Furthermore, the number of reported cases of campylobacteriosis remains high, increasing in 2021 to 127,840 compared to 120,946 in 2020 and chicken' and turkeys' meat was the most common source (EFSA & ECDC, 2022b). Resources should be prioritized to survey and control *Campylobacter* spp. Targeted control of high-risk farms could significantly reduce the risk of campylobacteriosis for consumers (Foddai et al., 2022). In terms of process hygiene criteria (PHC) in slaughterhouses, it is disheartening to note that official audits have called into question the reliability of FBO data. Indeed, discrepancies have been observed between data relating to the monitoring plans of individual FBOs and the survey data of some national authorities for *Salmonella*. The overall proportion of *Salmonella*-positive neck skin samples collected to verify compliance with PHC on carcasses at the slaughterhouse was higher among those collected by the CAs than by own check of producers (14 versus 3.2%) (EFSA & ECDC, 2022b). Nowadays, the epidemic status of chicken farms for pathogenic *Campylobacter* infections is even more uncertain or even critical, with 42.1% *Campylobacter*-positive samples and 18.4% exceeding the limit of 1000 CFU/g. Again, the number of samples exceeding the limit was significantly higher in official samples (19.4%) than in own checks (7.3%) in eleven MSs who analysed these data (EFSA & ECDC, 2022b). These observations rise concerns around companies' own data used in the RB-MSAS framework.

2.4. Prevention of carcass contamination and tolerances relative to chicken body size

Given the uncertainty of the data, it is crucial to prioritize the prevention of carcass contamination during slaughter operations. With this aim, FBOs should specify reasonable tolerances for chicken body size and best manufacturing practices within their specifications. Poultry batches with a previous history of compromised health and welfare or the rearing of broilers of mixed sex may present serious challenges for slaughter hygiene management. Poor environmental conditions can compromise the health and welfare of chickens, diminishing their immune function (Abo-Al-Ela et al., 2021; Wu et al., 2023). Proactively managing animal health and welfare not only positively impacts animal hygiene but also reduces the reliance on drugs for disease control.

Research results suggest that there are several factors that may affect broilers' general health status and poor weight uniformity, though there is still lack of research on the factors affecting uniformity in broiler flocks of similar slaughter age. Flock uniformity varied from 11% to 18% between flocks within the same hybrid, with similar management standards and similar slaughter age (Vasdal et al., 2019). Poor weight uniformity has been associated with first-week mortality, increased total mortality and feed conversion rate, and reduced growth rate. Variation in the weight of broilers was also correlated with changes in the temperature profile at bird level and poor air quality, variations in the nutrient content of the feed, and in the initial (day-old) body weight (Gous, 2018; Van Limbergen et al., 2018). High stock density and the presence of severe footpad dermatitis (FPD) in broilers were associated with poor uniformity of flocks and a higher risk of *Campylobacter* infection (Alpigiani et al., 2017). Broilers infected with *C. jejuni* produce more liquid stools, so the litter is wetter and the foot lesions more frequent. Although symptomatic enteritis due to *Campylobacter* is not evident, foot lesions can be observed at slaughter (Humphrey et al., 2014). In some flocks with many birds underweight because of aerosacculitis, faecal spillage, digestive tract rupture, or bile overflow has been observed in 5.5%–25.2% of broilers (Russell, 2003). Data concerning total mortality, low feed conversion rate, reduced growth rate, and increased rejection rate at slaughter are element of the food chain information that should carefully be evaluated when the birds are delivered to slaughterhouses and in the framework of RB-MSAS.

Other than poor flock uniformity, inappropriate feed withdrawal time is a factor related to carcass contamination (Northcutt et al., 1997;

Xue et al., 2021). When the bird's intestine is full, it can be torn during evisceration. Ruptures were also observed because of excessive feed withdrawal time because the lining epithelium become too week (Thompson & Applegate, 2006; Wickramasuriya et al., 2022). Some carcasses may even be contaminated through the aspiration of contaminated water when the birds' head is in the electrical stunner (Gregory, 2005). The contamination of the thoracic cavity occurs when the lung's tissues are lacerated by the vacuum lung removal system. The spillage of the crop content onto the carcasses may occur during crop removal and this can lead to contamination with *Campylobacter* (Rasschaert et al., 2020). Evisceration is not the only step of the mechanical slaughtering process that can lead to faecal contamination. De-feathering operations can exert pressure on the abdominal area, leading to faecal leakage. A looser setting for de-feathering machines can reduce this pressure, but it also reduces the effectiveness of the removal of feathers, and the different impacts of de-feathering on carcasses were correlated to differences in bacterial concentrations of *E. coli* and *Campylobacter* spp. on the exterior and in the excreta of carcasses (Pacholewicz et al., 2016b). Notably, *Campylobacter* was detected in transport crates, both after bird unloading and after the cleaning and disinfection process. The bacterial counts observed ranged from 3.60 to 3.90 log CFU/cm2 after unloading, and from 1.30 to 3.48 log CFU/cm2 after cleaning and disinfection (Perez-Arnedo & Gonzalez-Fandos, 2019). Company quality management system should monitor and document all these facts and events, and their consequences assessed in the framework of an RB-MSAS.

2.5. Consequences of faecal contamination

Many studies have already analysed the possible consequences of faecal contamination of chicken carcasses and these data could be factored into decisions on the effectiveness of control options. Libera et al. (2023) observed that *E. coli* counts increase more than three-fold (17.9%) in the case of carcasses contaminated with faeces. Collineau et al. (2020) conducted a literature review and meta-analysis, estimating a laceration probability of 18% (95% CI: 14–23) during evisceration and a *Salmonella* load increase of 1.02 log CFU (95% CI: 0.72–1.33). The probability of cross-contamination during evisceration in positive flocks was 0.07 (95% CI: 0.03–0.15), while the load reduction factors during post-evisceration wash and inside-outside bird wash were −1.17 (95% CI: −1.28 to −1.06) and −0.92 (95% CI: −1.29 to −0.55), respectively (i.e., 'number of bacteria on bird exterior'). Visible faecal contamination results in a higher prevalence of *Campylobacter*-positive carcasses (Giombelli & Gloria, 2014), and in the flocks positive for *Campylobacter*, average contamination levels of 8.05 log CFU/g of ceca and 2.39 CFU/g of carcasses were reported (Hue et al., 2011). A correlation was found between numbers in the caeca and on carcasses (Pacholewicz, Barus, et al., 2016; Rosenquist et al., 2006; Rouger et al., 2017).

The increase in proportion of ruptured gastrointestinal packages and damaged cloaca was associated with higher *Campylobacter* counts on broiler carcasses collected after chilling (Bashor et al., 2004; Seliwiorstow et al., 2016). An action threshold of 10% for the percentage of ruptured gastrointestinal packages is suggested. When the proportion was either higher or lower than 10%, the mean *Campylobacter* counts on carcasses from *Campylobacter*-positive batches were 3.2 log CFU/g and 2.8 log CFU/g, respectively. A proportion of registered damaged cloaca above 5% after the vent cutter was also correlated with higher mean *Campylobacter* count (3.3 vs 3.0 log CFU/g) (Seliwiorstow et al., 2016). In this study, the stunning method was also found to be a risk factor for *Campylobacter* carcass contamination. Mean counts of 3.2 and 2.7 log CFU/g were observed on the bird breast skin after the post-evisceration washing in the electrical stunned and gas stunned groups, respectively (Seliwiorstow et al., 2016).

2.6. Antibiotic resistance burden

The presence of ESBL-/AmpC producing bacteria in commercialized chicken meat has been documented repeatedly (Li et al., 2022; EFSA & ECDC, 2022a; Musa et al., 2020; Ribeiro et al., 2023) and some studies highlight the potential of industrial meat as a reservoir of high-priority *E. coli* lineages in the community (Overdevest et al., 2011; Paumier et al., 2022; Soncini et al., 2022). The poultry industry is witnessing a growing trend in antibiotic-free farming in alignment with evolving EU regulations and shifting consumer preferences. As a result, chicken meat is increasingly marketed under labels like "Raised Without Antibiotics" (RWA). Nevertheless, some studies have observed that the production category (conventional, RWA, and organic) had a negligible effect on resistance prevalence among *E. coli* isolates. This effect did vary significantly among distinct brands within each production category (Davis et al., 2018; Kim et al., 2020; Pesciaroli et al., 2020), although higher *E. coli* loads were observed in RWA compared to organic flocks (Pesciaroli et al., 2020). De Cesare et al. (2022) found that while antibiotic-free production significantly reduced AMR load in the caeca compared to conventional production, there was no distinction when it came to carcasses from the two types of farms, where the AMR load was also found to be notably higher than in the caeca. These authors emphasized the importance of microbial contamination and AMR not only at the farm level but also in subsequent stages of meat production. Other studies highlighted the importance of cross-contamination through transport trucks and cages (Althaus et al., 2017; Buess et al., 2019; Rasschaert et al., 2020). The previously reported estimates for cross-contamination events with *Salmonella* and *Campylobacter* may also apply to ESBL-/AmpC-gene carrying enterobacteria.

2.7. Control options to decrease the contamination along the slaughtering process

A Canadian study found that *Salmonella* contamination significantly decreased during the slaughtering process when the carcasses were dry-air chilling, with a *Salmonella* prevalence of 2.5% compared to over 89% at the bleeding stage. The authors hypothesised that while some *Salmonella* may enter the slaughterhouse on incoming birds, they either exist in lower numbers or have a reduced ability to survive the slaughter process, thereby not contaminating the final meat product. Sanitation treatments, likely involving cetylpyridinium chloride—a quaternary ammonium compound used during dry-air chilling—might have contributed to the reduction in the number of viable *Salmonella*. These bacteria may remain undetected through conventional culture-based methods. Contamination risk associated with carcasses are not only linked to the prevalence and numbers of *Salmonella*, *Campylobacter*, and antibiotic-resistant bacteria in the gut content and on the skin of chicken flocks; they are also affected by flocks from other farms slaughtered earlier on the same sampling day (Boubendir et al., 2020). Effective sanitation practices in slaughterhouses and processing plants are crucial for managing these hygiene risks. Furthermore, survival mechanisms, such as biofilm formation and viable but nonculturable state enable *Campylobacter* to persist during food processing (Soro et al., 2020). Carcasses are washed by water spraying from nozzles on both sides of the washer. Care must be taken to minimize water droplets, as they can potentially spread contamination. This washing process generally reduce *Campylobacter* and *Salmonella* levels by approximately 0.5 log CFU/g on breast skin and 1.17 log CFU/mL in carcass rinsate (Collineau et al., 2020; Seliwiorstow et al., 2015). Seliwiorstow et al. (2015) observed *Campylobacter* counts exceeding a limit of 1000 CFU/g on 11–78% of carcasses in four slaughterhouses in Belgium. While washers effectively remove visible faeces, they may not significantly reduce enteric pathogens contamination. However, washer systems using 2.2–9.1 L of water per carcass, along with trisodium phosphate or acidified sodium chlorite can further reduce the *Campylobacter* count by an additional log 1.03 to log 1.26, respectively (Bashor et al., 2004).

While equipment cleaning, disinfection between batches, and thorough inspections to detect any signs of contamination are valuable, they may not completely eliminate faecal pathogens from dirty carcasses. In one German slaughterhouse, an increase in the scalding water temperature from 53.0 °C to 53.9 °C (both for 180 s) during the processing of *Campylobacter*-colonised flocks led to a significant reduction in *Campylobacter* contamination. The contamination levels dropped from 4.5 log CFU/ml per carcass rinsate to less than 3.4 log CFU/ml (the detection limit) after scalding and plucking (Lehner et al., 2014). Similar results were observed in another study, which reported a reduction of 0.52 log CFU/g on breast skin for every one-degree increase in temperature within the range 50.5 and 55 °C (Seliwiorstow et al., 2016).

Variations in concentration resulting from scalding were documented in 17 trials. Hard scalding associated with sanitizers exhibited a combined mean effect of 1.85 log CFU (95% CI: 1.60–2.09) with no observed heterogeneity. In contrast, considerable heterogeneity was observed in the case of soft scalding and scalding with additives or unreported temperatures (Dogan et al., 2022). Nevertheless, scalding at 53.9 °C can cause skin lesions, resulting in a brownish appearance of the skin after air cooling. Various interventions - including rapid cooling with liquid nitrogen (crust freezing) or a combination of steam (84–88 °C) and ultrasound treatment (30–40 KHz) for 1.5 s (Sono Steam) before inside/outside carcass washing - have been found to reduce *Campylobacter* counts by approximately 1 log CFU/g on the neck skin of chicken carcass (Burfoot et al., 2016; Moazzami et al., 2021; Musavian et al., 2014). However, it is important to note that the viable but not-culturable state of these bacteria can influence the quantification results (Lázaro et al., 1999; Lv et al., 2020). Immersing carcasses in water at 80 °C for 6 s resulted in a significant decrease of 1.1 log CFU/ml in the *E. coli* count recovered from whole-carcass rinsates, without evident skin damage. Immersion in a 5% lactic acid solution led to a substantial reduction of 3.9 log CFU/ml in *E. coli* levels, but a white coating developed on carcasses after drying (Hauge et al., 2023). A systematic review and meta-analysis revealed that the mean log reduction of *Campylobacter* by freezing was 1.29 log CFU (95% CI: 1.10–1.48). However, it is worth noting that there was a significant level of heterogeneity observed in these findings (Dogan et al., 2022).

Campylobacter can survive for several weeks on moist skin at low temperature (4 °C), whereas freezing at – 22 °C for 24 h can reduce their number by about 1 log CFU (Bhaduri & Cottrell, 2004; Sampers et al., 2010; Stella et al., 2021). Treatment with chlorous acid water at 400 ppm or sodium hypochlorite at 200 ppm for 15 s can reduce the counts of *C. jejuni* by 1.26–2.60 log MPN/cm2 (Vetchapitak et al., 2021). The effectiveness of these 'mild' interventions - which have been used in the United States but have not been approved in the EU - require careful assessment.

A systematic review and meta-analysis examining the impact of decontamination interventions during the primary processing of broiler chickens revealed a pooled reduction in the odds of *Campylobacter* spp. concentration by 0.57 log 10 CFU/carcass, accompanied by a 57.2% decrease in the relative risk of *Campylobacter* spp. prevalence on broiler carcasses. The meta-analysis further suggests that, in comparison to physical decontamination methods, chemical treatments are more effective at reducing concentration but less effective at reducing prevalence (Gichure et al., 2022).

Novel technologies and strategies - such as cold plasma, ultraviolet light, high-intensity light pulses, pulsed electric fields, antimicrobials, and modified atmosphere packaging - have been evaluated for reducing *Campylobacter* contamination (Lu et al., 2019; Taha-Abdelaziz et al., 2023). While these measures have shown promise, many have not been integrated into processing operations due to a lack of knowledge or a reluctance to make changes to existing processing systems. However, a combination of existing and novel strategies may be the only solution to reduce the prevalence of this pathogen in poultry meat and enhance food safety. Further research will be essential to assess the effectiveness of all these strategies (Soro et al., 2020).

2.8. Corrective and preventive actions and risk-based meat inspection – the role of competent authorities (CAs)

Meat producers often lack precise estimates of the number of batches testing positive for *Campylobacter*, and while *Salmonella* contamination may be controlled in some lots through surveillance at the farm level, logistic slaughter procedures and effective sanitation, within-batch prevalence remain high in batches originating from the farms that are not '*Salmonella*-free' (Collineau et al., 2020).

The food safety acceptance criteria of supplier companies may be questionable, as is the effectiveness of risk categorization systems lacking adequate validation criteria. For instance, ensuring the reliability of such systems requires accurate estimation of the prevalence of *Campylobacter* and *Salmonella* carriers on poultry farms. Official reports reveal 42.1% of samples tested positive for *Campylobacter*, with 18.4% exceeding the limit of 1000 CFU/g, even though the overall proportion of positive units in broilers was 10.5% in 2021. In the same period, sampling by CAs to verify compliance with process hygiene criteria at the slaughterhouse found 14% of samples to be positive for *Salmonella* in broilers whilst only 3.8% of the flocks tested positive (EFSA & ECDC, 2022b).

Despite the fact that the data used by CAs in their reports are composite and originate from various production systems, they should serve as a catalyst for reprogramming hygiene management in many enterprises and improving the monitoring of critical operational parameters. These parameters include the number of birds outside the tolerated size range and the associated number of carcasses contaminated due to ruptures of the gastrointestinal tract and leakage of its content during evisceration and scalding, which can lead to a high carcass microbial load (Collineau et al., 2020; Libera et al., 2023; Seliwiorstow et al., 2016). Where information on the epidemiological status of the farms is limited, monitoring activities and effective process controls are essential to determine possible corrective actions to be applied (Fig. 1). Process hygiene criteria (i.e., for *Salmonella* and *Campylobacter*) are indicative of contamination values above which corrective actions should be applied to the processing operations in order to comply with the hygiene standards according to the food law (Regulation EU No 2073/2005 and Regulation EU 2017/1495). In the case of an excessive number of gut ruptures and fecal contamination, EU regulation (EU 2017/625, Article 138) specify that if serious problems impacting human or animal health are identified during ante/post-mortem inspections, all birds must undergo supplementary examinations. Implying that only bird batches with a confirmed positive status for *Campylobacter* and *Salmonella* 'need to be inspected' seems impractical. PVOs can also demand that FBOs implement immediate corrective measures, such as reducing the speed of the slaughter line, if excessive contamination is detected on carcasses and where the PVOs believe that good hygiene practices (GHPs) are compromised. FBOs can determine autonomously the preventive and corrective actions to be applied, but they must outline and implement an action plan, which is supervised by the PVOs (Regulation EU 2019/627, Articles 35 and 36). The European Commission initially set the hygiene criterion for *Campylobacter* in broilers, intending to progressively tighten regulations by 2020 and 2025. However, ensuring that FBOs effectively meet the progressively stringent EU *Campylobacter* process hygiene criteria will require a time-driven effort in many countries (Zwietering et al., 2023).

Preventive actions that can be used to reduce the incidence of gut ruptures include the utilization of advanced, computerized slaughter lines. The application of image processing techniques guiding a 'multi-fingered robot hand' for the evisceration of poultry of various sizes has the potential to enhance hygiene (Chen & Wang, 2018; Chen et al., 2021a,b;Chen et al., 2023). While various studies describe the development of Computer Vision Systems (CVSs), not all have been validated; only three articles reported results from real-time evaluations of CVS performance in slaughterhouses compared to the performance of an expert meat inspector (Sandberg et al., 2023).

3. Conclusions

Ante and post-mortem inspection can still serve a valuable purpose by addressing health and welfare conditions that impact flock uniformity. Implementing corrective actions is crucial for ensuring compliance with product quality standards.

A realistic risk-based meat safety assurance approach should not rely solely on categorizing the risk of supplying farms based on their biosecurity standards. A critical control point to mitigate contamination by *Campylobacter* and ESBL-/AmpC producing bacteria must be integrated in the HACCP plans, unless their prevalence in the supplied flocks is negligible. Process improvement, aligned with Commission Implementing Regulation (EU) 2019/627, which ensures official controls, aims to evaluate the reliability of self-checks made by FBOs.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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