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COMPREHENSIVE REVIEWS IN FOOD SCIENCE AND FOOD SAFETY

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A systematic review and meta-analysis of the efficacy of processing stages and interventions for controlling *Campylobacter* contamination during broiler chicken processing

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Abstract

Systematic review and meta-analysis were conducted to quantify the effects of processing stages and interventions on the prevalence and concentration of *Campylobacter* on broiler carcasses. To comprehensively capture relevant evidence, six databases were searched using the keywords "*Campylobacter*" and "broiler chicken." The literature search yielded 10,450 unique citations, and after applying predetermined inclusion and exclusion criteria, 72 and 53 relevant citations were included in meta-analyses for processing stages and interventions, respectively. As the two primary outcomes, log reduction and prevalence changes were estimated for each stage or intervention using a random-effects meta-analysis approach whenever possible. The outcome-level quality assessment was conducted following the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach. The analysis revealed that scalding and chilling majorly reduces the prevalence and concentration of *Campylobacter*. Immersion chilling reduces the concentration regardless of chemical additives, but its effect on prevalence is not conclusive. The effects of carcass washing applications remain uncertain due to the inconsistency and imprecision of both outcomes. Defeathering and evisceration were identified as stages that can increase both prevalence and concentration. Both chemical and physical processing interventions provide limited efficacy in concentration and prevalence reduction. Major limitations of the review were inconsistency and imprecision at the outcome level and reporting issues and data gaps at the study level. The results are expected to inform quantitative microbial risk assessment model development and support evidence-based decision-making.

KEYWORDS

chemical decontamination, mitigation strategies, physical decontamination, poultry processing

1 | INTRODUCTION

Campylobacter is the leading cause of bacterial foodborne illness both globally and in the United States. WHO (2015) estimates that there are more than 95 million cases of campylobacteriosis annually, with an annual disease burden of more than 2 million disability-adjusted life years (DALY). In the United States, 85,000 (90% CrI: 288,500–1,637,600) cases of campylobacteriosis are estimated to occur annually, with an associated disease burden of 22,500 (90% CrI: 10,400–38,600) DALY (Scallan et al., 2015). Recent source attribution studies indicate that chicken meat is the dominant source of *Campylobacter*-related illness. Based on foodborne outbreaks in the United States, the IFSAC (2018) estimated that 47.5% (90% CrI: 32.8–64.8) of campylobacteriosis cases were attributable to chicken consumption. Moreover, Ravel et al. (2017) estimated that 65%–69% of cases in Canada were attributable to chicken meat by comparative exposure assessment and genetic fingerprinting approaches. In Europe, it was estimated that 29% of campylobacteriosis cases were attributed to consumption of chicken (Pires et al., 2010). Despite this significant impact on public health, a recent survey showed that risk factors for *Campylobacter* contamination and the importance of processing interventions are not properly recognized by broiler industry professionals (Hwang & Singer, 2020). Hence, a better understanding of the effectiveness of processing stages and interventions is crucial to reduce the incidence of foodborne campylobacteriosis as part of a comprehensive public health strategy.

Efforts to control *Campylobacter* focus on preventing infection at the preharvest stage on farms and reducing contamination during the postharvest stage in processing facilities through regular processing stages and interventions. Wagenaar et al. (2013) outlined challenges in controlling the prevalence and concentration of *Campylobacter* in these two stages, including the unpredicted effectiveness of preharvest interventions due to complex environmental factors and the lack of evidence-based interventions at the postharvest level, and advocated a "multilevel approach." According to EFSA Panel on Biological Hazards et al. (2020), preharvest interventions can achieve substantial reductions in population risks; however, high degree of uncertainty exists around the estimates. This opinion also advocates *Campylobacter* control throughout the whole production chain, rather than focusing on individual pre- or postharvest stages. Many suggested preharvest interventions to focus on maintaining biosecurity, with the aim of limiting the transmission of *Campylobacter* outside the farm. However, the mechanisms of flock colonization remain largely unclear, and preharvest interventions are unlikely to be sufficient to control *Campylobacter* in the final product. Therefore, processing stages and interventions are critical for control (Havelaar et al., 2007).

A number of quantitative microbial risk assessment (QMRA) models investigating *Campylobacter* in broiler meat were reviewed by Nauta et al. (2009) and Chapman et al. (2016). Most established QMRA models are data-driven, stochastic models that depend on quantified efficacies of processing stages or interventions. In these models, input distributions were mainly sourced from a small set of studies or experimental data. Both reviews report that the quality of QMRA studies often suffers from lack of quantitative information and undetermined amounts of uncertainty around the estimates that are used to construct input distributions for simulations. Furthermore, it is known that QMRA models must account for variability in their input parameters such as intervention efficacies or baseline contamination, because the risk estimates are mostly driven by the tail of their distributions (Duarte et al., 2016; Nauta et al., 2009). A systematic review and meta-analysis approach can provide a comprehensive list of efficacies of processing stages and interventions, combine them into composite estimates, and provide information about the overall and individual variability around those estimates.

The numerous studies of various processing stages and interventions available in the literature frequently offer conflicting evidence on the direction and magnitude of the effects of processing stages or interventions due to differences in study characteristics such as study design, sample size, or detection methods. As a result, individual studies offer relatively low strength for informing evidence-based risk management. To address the limitations of individual studies, a systematic review approach is useful, as it combines available data and takes into account variations among studies to assess the overall quality of evidence.

A systematic review and meta-analysis provides a methodical framework for collecting scientific evidence with minimum bias and maximum transparency and for identifying knowledge gaps in order to inform sound decision-making among agri-food stakeholders with the ultimate aim of public health protection (Sargeant et al., 2006). In addition to providing direct evidence for determining critical control points in food processing systems and assessing intervention efficacies, systematic reviews provide input estimates for food safety risk assessments in the most accurate and transparent manner. As a result, the systematic review methodology is increasingly popular among risk assessors and is highly recommended to strengthen the application of risk assessment findings (Aiassa et al., 2015; EFSA, 2010).

Several narrative and systematic reviews addressing the issue of *Campylobacter* contamination along the broiler supply chain are available. Recent narrative reviews such

as Thames and Theradiyil Sukumaran (2020), Klein et al. (2015), Cox and Pavic (2010), and Keener et al. (2004) have provided up-to-date contextual knowledge and can serve as starting points to define the scope of a systematic review. However, narrative reviews often lack sufficient focus on quantitative information as well as associated variability and uncertainty measurements, which are particularly useful for QMRA. The sporadic, nonstructured evidence retrieval process of nonsystematic reviews also risks missing important data. Among systematic reviews of *Campylobacter* contamination throughout the processing of broiler carcasses, Golden and Mishra (2020) focused on the prevalence of *Campylobacter* and *Salmonella* in farm and processing samples. These data may provide valuable baseline prevalence information for future risk assessment studies but are less insightful for quantifying the effects of various processing steps. Bucher et al. (2015) focused only on the effects of different chilling practices on prevalence and concentration changes. Guerin et al. (2010) provided an overview of changes in *Campylobacter* due to scalding, defeathering, evisceration, washing, and chilling but only discussed prevalence.

The objective of this study is to conduct a systematic review and meta-analysis to identify and evaluate the impact of processing stages and interventions implemented during the processing of broiler chicken on the control of *Campylobacter* contamination. This systematic review is part of a broader project comprising QMRA and cost-effectiveness analysis for prioritizing the implementation of possible pre- and postharvest interventions. Preliminary results from this study have been successfully used to develop a QMRA model and proved useful in allowing flexible model design (Dogan et al., 2019). The findings from this integrated project are expected to inform risk assessment and aid decision-making on intervention adoption that balances food safety and public health protection and associated monetary costs.

2 | METHODOLOGY

2.1 | Research question and eligibility criteria

The following research question for the systematic review was formulated based on the population–intervention–comparator–outcome (PICO) framework (Higgins & Green, 2011): "Is there evidence from the literature that processing stages and interventions (I) can reduce *Campylobacter* spp. prevalence and/or concentration (O) on processed broiler carcasses (P) compared with untreated carcasses (C)?" The research question was used as a basis for developing the overall review protocol, eligibility criteria, data collection, and quality of evidence assessment processes.

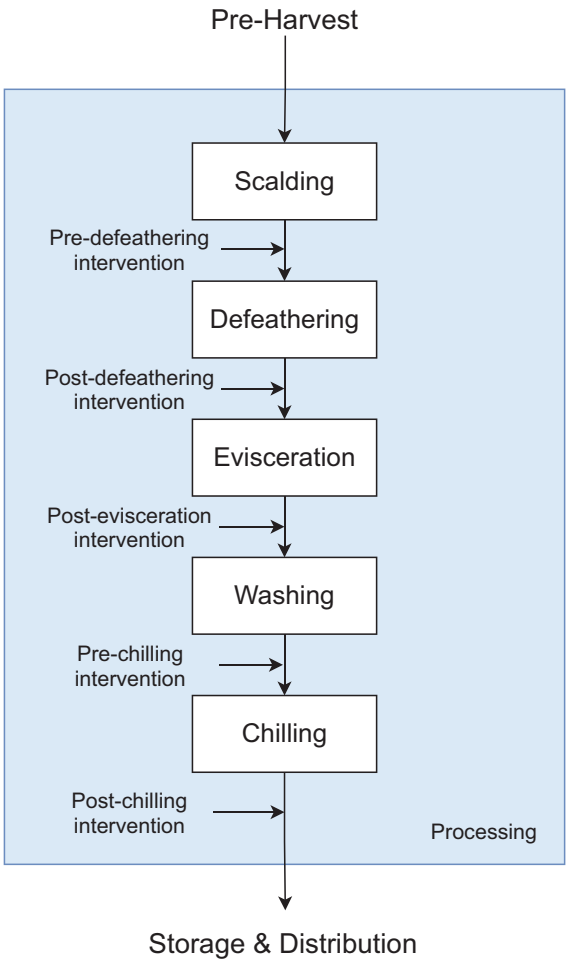

FIGURE 1 Standard stages of broiler processing after harvest and prior to storage and distribution

Studies eligible for the review were expected to be primary research studies (excluding reviews) reporting *Campylobacter* concentration or prevalence changes with appropriate statistical measures in broiler chickens subjected to processing stages or interventions. In this review, a study refers to a single published article, whereas a trial refers to a reported result from a study where a comparison was made between before and after treatment or between treated and untreated control samples. One study may provide data from multiple trials. Information on processing stages and interventions was collected based on the conventional broiler processing approach outlined in Figure 1 and is presented in order of appearance in the processing line.

2.2 | Information sources

The review team collaborated with University of Nebraska–Lincoln library experts with professional

experience in food science and veterinary medicine to identify potential databases and develop search strategies. Six digital bibliographic databases, namely, CAB Abstracts and Global Health (CABI; via Web of Science; 1910–2020), MEDLINE® (via PubMed; 1950–2020), Web of Science Core Collection (WOS; via Web of Science; 1900–2020), Food Science and Technology Abstracts (FSTA; via Web of Science; 1969–2020), Biological Abstracts (via Web of Science; 1926–2020), and BIOSIS Citation Index (via Web of Science; 1926–2020), were considered as main information sources for this review.

2.3 | Database searches

The search strategy included terms for the identified outcome "*Campylobacter*" and population "broiler chicken" and their variations and synonyms. A preliminary database search (data not shown) revealed that including specific intervention terms limited the extent of the retrieved articles. Therefore, the final search strings were not restricted by any keywords regarding processing stages or interventions. The search strings were tested in the Web of Science Core Collection and finalized for all target databases with modifications (Table A.1 in the Supporting Information). The search was conducted with no restrictions on date of publication beyond the inclusion dates of the databases. Similarly, no restrictions were placed on language in the initial search, although publications not in English were excluded during the screening process due to limited resources for translation. The initial search was performed in March 2015, and an update search was conducted in March 2020 to capture any newly available citations since the initial search.

2.4 | Study selection and relevance screening

Primary research articles captured by the database searches were combined and recorded by using the reference management software Endnote™ X7 (Clarivate, Philadelphia, PA, USA). The combined records were deduplicated prior to further selection. Articles were selected via a two-stage screening process conducted by two reviewers independently and confirmed by another reviewer in the event of disagreement. In the first screen, only the titles and abstracts of the records were reviewed, and articles were removed at this stage due to irrelevance to our research question and deviation from the eligibility criteria. Next, the full texts of the articles that passed the first screening were retrieved, and articles were removed if either the full text was unavailable or the publication language was not English. In the second screen, the full texts were reviewed, and articles were excluded if (1) no data on *Campylobacter* spp. prevalence or concentration were available; (2) no comparison between treatment and control groups was made; (3) only graphical data were presented without numerical values; (4) statistical analysis or measures of variability were not available; (5) the intervention effect was reported from an in vitro study; or (6) the study did not discuss any potential intervention or processing stage.

2.5 | Data extraction process and data items

Relevant information from the retrieved articles was manually extracted, stored in Microsoft Excel 2016 (Microsoft Corp., Redmond, WA, USA) spreadsheets, and then grouped by intervention or processing stage. Data extraction forms were developed based on criteria suggested by Sargeant and O'Connor (2014) in four categories: general information, population characteristics, intervention protocols, and details of outcome measurement and results. General information included unique study and trial identification numbers, bibliographic information, study design, type of random allocation, geography, and location information. Population characteristics comprised the type(s) of chickens sampled, treatments, and sampling units (carcass, parts, or skin). Intervention characteristics were described by time, temperature, or other processing conditions together with the dose of any antimicrobial agents if present. This information was intended to aid explanation in the event of high heterogeneity for composite effect estimates across trials and studies. Outcomes were collected from the studies in the form of prevalence or concentration changes. For prevalence changes, the numbers of *Campylobacter*-positive and *Campylobacter*-negative sampling units before and after or with and without a treatment were recorded. For concentration changes, either the log number of *Campylobacter* counts ($\log_{10}$CFU/unit) before and after or with and without a treatment or the reported log change values were recorded in the data extraction sheets. In addition, appropriate statistical measures (sample size, variance, standard deviation or error) were extracted from the included studies. Methods of sample collection and detection or enumeration of *Campylobacter* in samples were also extracted at this stage in order to assess additional variability or detection biases due to different methods of detection.

2.6 | Pooled estimates

Two main summary measures were produced in this systematic review to address changes in prevalence and concentration. For prevalence changes (dichotomous outcome), odds ratios (ORs) were calculated as the pooled estimates. For concentration changes (continuous outcome), mean $\log_{10}$ change in the number of *Campylobacter* was reported. Related confidence intervals (CIs), standard errors, and heterogeneity measures (τ^2, I^2) were also reported in order to account for variability and heterogeneity around the summary measures. When serious heterogeneity was detected, pooled effects were reported but not discussed in detail; instead, the totality of the individual studies was used as the basis for result interpretation. For quality assessment purposes, risk ratios for dichotomous outcomes and standardized mean differences were also calculated for each outcome, but the results are not reported.

2.7 | Synthesis of results

The results were synthesized by a meta-analysis approach using the "metafor" package (Viechtbauer, 2010) in R version 4.0 (R Core Team, 2020). For each outcome (i.e., OR or $\log_{10}$CFU change as a result of a specific processing step or intervention), a random-effects meta-analysis model built on trial-level data was developed using inverse-variance weighting and the restricted maximum likelihood method for variance estimation. The Haldane–Anscombe correction was applied by adding 0.5 to the elements of 2×2 matrix to estimate ORs when before or after prevalence is zero. The heterogeneity associated with the summary outcomes was quantified by calculating inconsistency (I^2) (Higgins & Thompson, 2002) and tested for statistical significance using Cochran's Q-test (Hedges & Olkin, 2014). To explore the sources of possible heterogeneity, subgroup analyses were also conducted. Meta-regression was not attempted for subgroups because it is not recommended for small meta-analyses, especially when there are fewer than 10 trials (Higgins et al., 2019).

Results of the meta-analyses were reported in terms of inverse-variance weighted means, CIs, and heterogeneity measures. CIs (95%) are calculated based on the unconditional variance in Equation (1) as suggested by Higgins and Thompson (2002).

$$\text{var}\,(y_i) = \sigma^2 + \tau^2, \tag{1}$$

where y_i is the outcome measure, σ^2 is within-study variance, and τ^2 is between-study variance as described in Equation (2):

$$\tau^2 = \frac{I^2 \cdot \sigma^2}{1 - I^2}. \tag{2}$$

Random-effects meta-analysis model assumes that the observed effects are normally distributed (Viechtbauer, 2010). Therefore, composite outcomes from this review can be implemented in risk assessments using normal distributions. However, it should be noted that for the meta-analysis of OR, natural logarithmic transformation is used. Therefore, log-normal distribution is appropriate to simulate ORs obtained from this review. When heterogeneity is high, the assumption of normal distribution may be violated; therefore, pert distribution can be used with mean, minimum, and maximum or 2.5% and 97.5% percentile can be used (Buczinski & Vandeweerd, 2016; Dogan et al., 2019).

2.8 | Risk of bias assessment

The risk of bias, also known as study limitations, was assessed for individual studies based on the Cochrane risk-of-bias (RoB 2) tool (Sterne et al., 2019). Because RoB 2 was developed mainly for healthcare interventions, slight modifications were made to the original protocol to account for the particularities of food safety studies partly based on suggestions from Sargeant and O'Connor (2014). Briefly, risk of bias judgments were made at three levels (low risk, some concerns, high risk) for the four domains of risk, that is, selection bias, reporting/attribution bias, detection bias, and other bias covering any other types of reporting or methodological issues that might affect the internal validity of the studies. Subsequently, an overall risk of bias was assigned based on the domain-level risks. Details of the risk of bias assessment are provided in Appendix A.3 in the Supporting Information. To visualize the risk of bias assessment, traffic light plots showing the risk of bias at the study level and risk of bias summary plots showing the risk of bias at the outcome level were produced by using the "robvis" package (McGuinness & Higgins, 2021) in R.

2.9 | Quality of evidence assessment (GRADE)

To assess the quality of the collected evidence in terms of their influence on effect size estimates of major outcomes, Grading of Recommendations Assessment, Development, and Evaluation (GRADE) guidelines (Guyatt et al., 2011) were employed with slight modifications to account for the particularities of food safety studies. Briefly, risk of

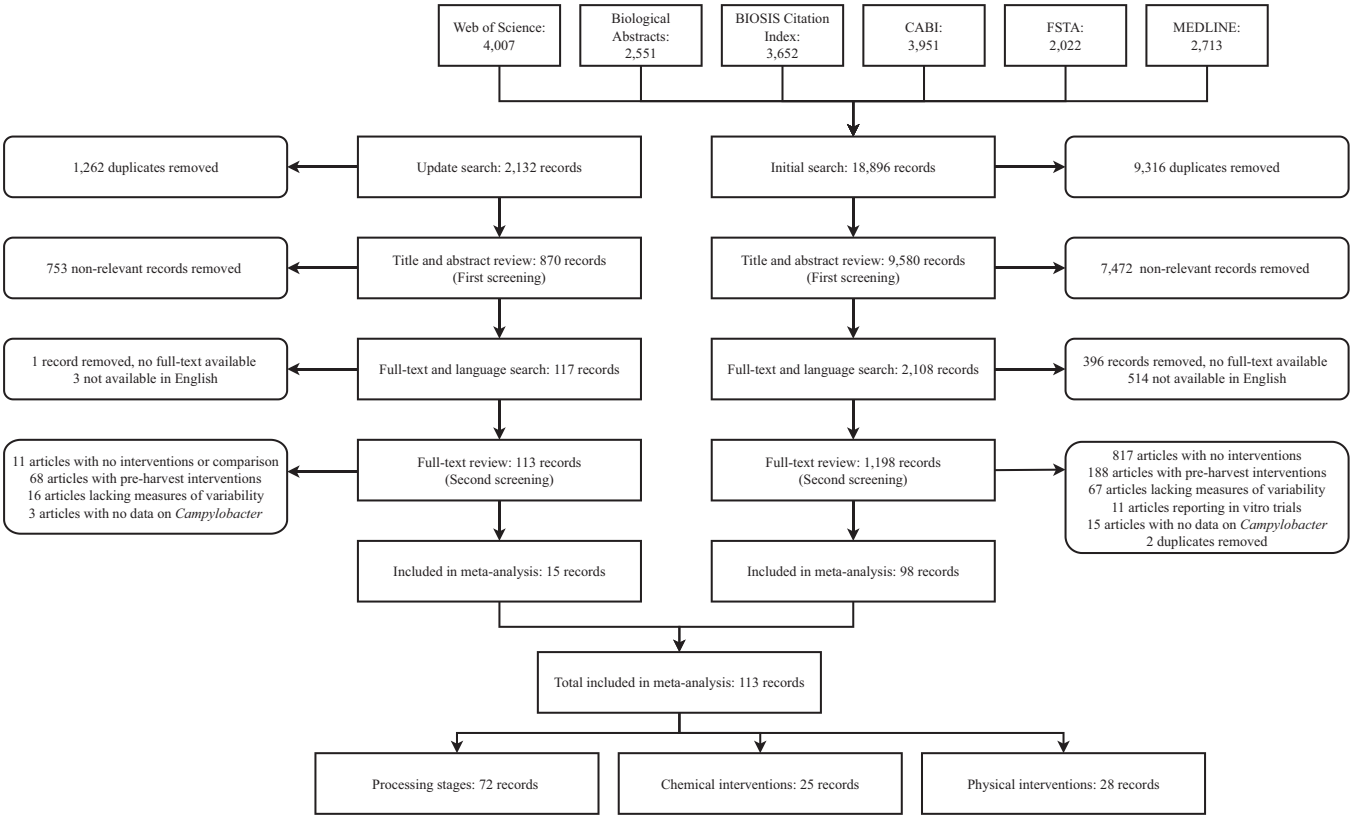

FIGURE 2 Flow chart of the systematic review process

bias, inconsistence, indirectness, and imprecision were included as upgrading factors, whereas large effect was assessed for downgrading. Details of the quality assessment procedures are given in Appendix A.3 in the Supporting Information. GRADE scores for individual outcomes are also presented in summary of findings tables and plots.

3 | RESULTS AND DISCUSSION

3.1 | Study selection and characteristics

An overview of the systematic review process, including the numbers of included and excluded records with reasons at each step, is outlined in Figure 2. A total of 9,580 unique records were identified in the initial search in 2015, and 870 new unique records were added after the update search in 2020. Through stepwise screening processes, 98 records from the initial search and 15 records from the update search were included in the meta-analysis. Among the 113 total records, 72 reported processing stages, 25 reported chemical interventions, and 28 reported physical interventions applied during broiler processing. Individual records are listed in Table 1 with detailed study characteristics. Among the 72 studies reporting processing stages, 25 reported prevalence changes only, 27 reported concentration changes only, and 20 reported both. Most of the included studies were performed in North America and Europe, and thus the results are most likely to represent broiler chicken processing practices in these regions. Specifically, the analysis included 35 studies from North America (United States only), 21 from Europe, seven from Asia, four from South America, four from the Middle East and North Africa, and one from Australia.

Results were analyzed on a trial basis rather than on a study basis because a single study may include several trials. As a result, 449 unique trials were extracted, including 289 reporting concentration changes (Total sample size, $n = 29{,}293$) and 160 reporting prevalence changes ($n = 28{,}881$). The extracted data identified 385 before–after trials and 64 challenge trials. Challenge trials can provide useful evidence about the applicability of an intervention, but the external validity of such studies is often questioned because the reported effect measure may be overestimated. In addition, challenge trials are primarily conducted in laboratory or pilot plant settings and thus may not be representative of commercial processing conditions (Bucher et al., 2012). Therefore, for this review, outcomes were mainly grouped depending on the study design, and different types of studies were only combined when there was no meaningful overestimation of the effect. The research location was also considered as a factor that might affect

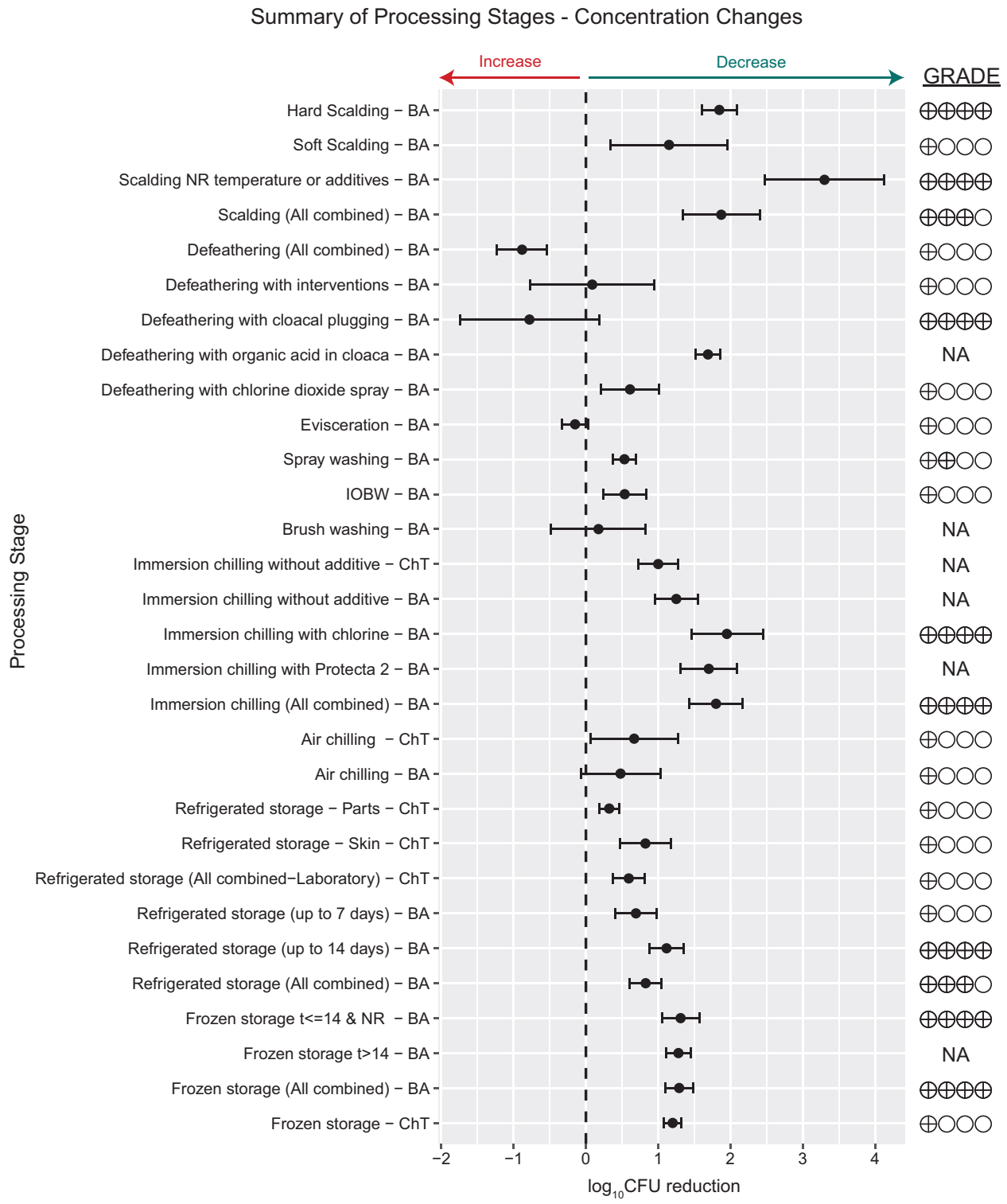

FIGURE 3 Summary of meta-analysis results for concentration changes due to processing stages
BA, before–after trials; ChT, challenge trials.

TABLE 1 List of included studies with demographic and study-specific information

Reference	Stage/intervention	Country[a]	Design	Random-ization	Location	Treatment unit	Sampling unit	Method	Enrichme-nt/dilution	Enumeration/ detection method	Outcome measure
Abu-Ruwaida et al. (1994)	Air chilling/ evisceration/ washing	KW (MENA)	BA	NR	Processing	Carcass	Neck skin	Homogenate	LB	Skirrow	C
Allen et al. (2007)	Air chilling/evisceration	UK (EU)	BA	NR	Processing	Carcass	Carcass	Rinse	BB	mCCDA	P & C
Arritt et al. (2002)	Processing aids spray	US (NA)	ChT	NR	Laboratory	Skin	Skin	Rinse	BPW		C
Baker et al. (1987)	Immersion chilling	US (NA)	BA	NR	Processing	Carcass	Skin on carcass	Swab (undefined)	BrB	BAP	P & C
Bashor et al. (2004)	Immersion chilling/washing/ processing aids spray	US (NA)	BA	NR	Processing	Carcass	Carcass	Rinse	NA	CCDA & CBFA	P
Bauermeister et al. (2008)	Immersion chilling	US (NA)	BA	NR	Processing	Carcass	Carcass	Rinse	BB	mCCDA	P
Beers et al. (2006)	Processing aids spray	US (NA)	BA	Systematic	Processing	Carcass	Carcass	Rinse	NR	NR	P & C
Berghaus et al. (2013)	Immersion chilling	US (NA)	BA	NR	Processing	Carcass	Carcass	Rinse	BB	CCA	P & C
Berndtson et al. (1996)	Immersion chilling	SE (EU)	BA	NR	Processing	Carcass	Skin on carcass	Swab (cotton)	Preston	Preston	P
Berrang and Dickens (2000)	Defeathering/ evisceration/ immersion chilling/ scalding	US (NA)	BA	Systematic	Processing	Carcass	Carcass	Rinse	PBS	CCA	P & C
Berrang et al. (2000)	Defeathering	US (NA)	BA	NR	Pilot Plant	Carcass	Carcass	Rinse	PBS	CCA	C
Berrang et al. (2001)	Defeathering/scalding	US (NA)	BA	NR	Pilot Plant	Carcass	Skin on carcass	Swab (sponge)	PBS	CCA	P & C
Berrang et al. (2003)	Scalding	US (NA)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	PBS & CEB	CCA	P & C
Berrang et al. (2006a)	Defeathering	US (NA)	BA	NR	Pilot Plant	Carcass	Skin on carcass	Swab (sponge)	PBS	CCA	C
Berrang et al. (2006b)	Defeathering	US (NA)	BA	NR	Pilot Plant	Carcass	Skin on carcass	Swab (sponge)	PBS	CCA	C
Berrang and Bailey (2009)	Washing	US (NA)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	PBS & CEB	CCA	C
Berrang, Meinersmann, et al. (2011)	Defeathering	US (NA)	BA	NR	Processing	Carcass	Carcass	Rinse	PBS	CCA	C

(Continues)

TABLE 1 (Continued)

Reference	Stage/intervention	Country[a]	Design	Random-ization	Location	Treatment unit	Sampling unit	Method	Enrichme-nt/dilution	Enumeration/ detection method	Outcome measure
Berrang, Windham, et al. (2011)	Scalding	US (NA)	BA	NR	Processing	Carcass	Carcass	Rinse	PBS	CCA	P & C
Berrang et al. (2018)	Defeathering	US (NA)	BA	NR	Pilot Plant	Carcass	Skin on carcass	Swab (sponge)	PBS	CCA	C
Bhaduri and Cottrell (2004)	Freezing/refrigeration	US (NA)	ChT	NR	Laboratory	Skin	Skin	Homogenate	BPW	mCCDA & TSAB	C
Borges et al. (2020)	Refrigeration/freezing	BR (SA)	BA	Rep. Random	Processing	Carcass	Skin on carcass	Rinse	BPW	ISO & qPCR	P
Boysen and Rosenquist (2009)	Air chilling/steam + ultrasound/crust freezing	DK (EU)	BA	NR	Processing	Carcass	Carcass	Rinse	BPW	AHBA	C
Boysen et al. (2013)	Freezing/processing aids immersion	DK (EU)	ChT	NR	Laboratory	Parts, Skin	Parts, Skin	Homogenate	MRD	AHBA	C
Buhr et al. (2003)	Defeathering	US (NA)	ChT	NR	Pilot Plant	Carcass	Skin	Homogenate	PBS	CCA	P & C
Burfoot et al. (2016)	Rapid cooling	UK (EU)	BA	NR	Processing	Carcass, Skin	Skin	Homogenate	BPW	mCCDA	P & C
Byrd et al. (2011)	Refrigeration/ freezing/MAP	US (NA)	BA	NR	Processing	Carcass	Carcass	Rinse	BB	CCA	P & C
Chaine et al. (2013)	Processing aids immersion/steam pasteurization/ steam + lactic acid	FR (EU)	ChT	NR	Laboratory	Skin	Skin	Homogenate	Preston	Karmali	C
Chantarapanont et al. (2004)	Processing aids immersion	US (NA)	ChT	Rep. Random	Laboratory	Skin	Skin	Homogenate	Tween	CCA	C
Corry et al. (2007)	Hot water immersion	UK (EU)	ChT	NR	Pilot Plant	Carcass	Skin	Homogenate	MRD	mCCDA	C
Cortez et al. (2006)	Evisceration	BR (SA)	BA	NR	Processing	Carcass	Carcass	Rinse	Water	BAP	P
Dan et al. (2012)	Processing aids immersion	RO (EU)	ChT	NR	Laboratory	Parts	Parts	Homogenate	BB	ISO	C
Demirok et al. (2013)	Air chilling/immersion chilling	US (NA)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	BB	CCA	P
Dickens et al. (2000)	Immersion chilling	US (NA)	BA	NR	Pilot Plant	Carcass	Carcass	Rinse	Saline	CCA	C
Dickens and Ingram (2001)	Immersion chilling	US (NA)	BA	NR	Pilot Plant	Carcass	Carcass	Rinse	BPW	CCA	C
Duffy et al. (2014)	Immersion chilling	AU (AU)	BA	Systematic	Processing	Carcass	Carcass	Rinse	BPW	mCCDA, Skirrow	C

(Continues)

TABLE 1 (Continued)

Reference	Stage/intervention	Country[a]	Design	Random-ization	Location	Treatment unit	Sampling unit	Method	Enrichme-nt/dilution	Enumeration/ detection method	Outcome measure
Franchin et al. (2007)	Evisceration/freezing/ immersion chilling	BR (SA)	BA	NR	Processing	Carcass	Carcass & Parts	Rinse & Homogenate	BPW	BB	P & C
Georgsson et al. (2006)	Freezing/refrigeration	IS (EU)	BA	NR	Processing	Carcass	Carcass	Rinse	BPW	mCCDA & Preston	C
Gonzalez-Fandos et al. (2015)	Processing aids immersion	ES (EU)	ChT	Rep. Random	Laboratory	Parts	Skin	Homogenate	Peptone water	mCCDA	C
González-Fandos and Maya (2016)	Processing aids immersion	ES (EU)	ChT	Rep. Random	Laboratory	Parts	Skin	Homogenate	Peptone water	mCCDA	C
Gonzalez-Fandos et al. (2020)	Processing aids immersion/MAP/ refrigeration	ES (EU)	ChT	NR	Laboratory	Parts	Skin	Homogenate	Peptone water	mCCDA	C
Gumhalter Karolyi et al. (2003)	Immersion chilling	HR (EU)	BA	NR	Processing	Carcass	Skin on carcass	Swab (undefined)	NR	NR	P
Haughton et al. (2011)	Ultraviolet	IE (EU)	ChT	NR	Laboratory	Parts, Skin	Parts, Skin	Homogenate	MRD	mCCDA	C
Haughton et al. (2012)	Pulsed electric field	IE (EU)	ChT	NR	Laboratory	Parts	Parts	Homogenate	MRD	mCCDA	C
Hinton and Ingram (2000)	Processing aids immersion	US (NA)	CT	NR	Laboratory	Skin	Skin	Rinse	Peptone water	CBA	C
Hinton and Ingram (2003)	Processing aids immersion	US (NA)	CT	NR	Laboratory	Skin	Skin	Rinse	Peptone water	CBA	C
Hinton et al. (2004a)	Evisceration/ refrigeration	US (NA)	BA	NR	Processing	Carcass	Carcass	Rinse	Peptone water	CBA	P & C
Hinton et al. (2004b)	Evisceration/ refrigeration	US (NA)	BA	NR	Processing	Carcass	Carcass	Rinse	Peptone water	CBA	P & C
Hinton and Ingram (2006)	Processing aids immersion	US (NA)	CT	NR	Laboratory	Skin	Skin	Rinse	Peptone water	CBA	C
Hinton et al. (2009)	Processing aids spray	US (NA)	ChT	NR	Pilot Plant	Carcass	Carcass	Rinse	Peptone water	CBA	C
Huang et al. (2017)	Evisceration/freezing	CN (AS)	BA	Rep. Random	Processing	Carcass	Skin on carcass	Swab (wipes)	PBS	mCCDA	P
Huezo, Northcutt, et al. (2007)	Air chilling	US (NA)	ChT	Rep. Random	Pilot Plant	Carcass	Carcass	Rinse	Peptone water	CCA	P & C
Hulankova et al. (2018)	Refrigeration/MAP	CZ (EU)	BA	NR	Laboratory	Half carcass	Parts, skin	NR	BB	CAT & CBFA	P
Isohanni and Lyhs (2009)	Ultraviolet	FI (EU)	ChT	NR	Laboratory	Carcass, skin, cuts	Carcass, skin, cuts	Rinse, Swab	BPW, saline	mCCDA, TSAB	C

(Continues)

TABLE 1 (Continued)

Reference	Stage/intervention	Country[a]	Design	Random-ization	Location	Treatment unit	Sampling unit	Method	Enrichme-nt/dilution	Enumeration/ detection method	Outcome measure
James et al. (2007)	Air chilling/steam pasteurization/hot water immersion/ crust freezing	UK (EU)	ChT	NR	Pilot Plant	Carcass	Skin	Homogenate	MRD	mCCDA	C
Jozwiak et al. (2006)	Evisceration/washing	HU (EU)	BA	NR	Processing	Carcass	Skin on carcass	Swab (undefined)	Preston	mCCDA	P
Juven and Rogol (1986)	Immersion chilling	IL (MENA)	BA	NR	Processing	Carcass	Skin on carcass	Swab (cotton)	NA	CBA	P
Kameyama et al. (2012)	Immersion chilling	JP (AS)	BA	NR	Processing	Carcass	Skin on carcass	Swab (undefined)	Preston	CCDA	C
Kemp et al. (2001)	Washing/processing aids spray	US (NA)	BA	NR	Processing	Carcass	Carcass	Rinse	Butterfield	Line	P
Khalafalla et al. (2019)	Defeathering/ evisceration	EG (MENA)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	ISO	ISO	P
Koolman et al. (2014a)	Processing aids immersion	IE (EU)	ChT	NR	Laboratory	Parts	Parts	Rinse	MRD	mCCDA	C
Koolman et al. (2014b)	Ultrasound	IE (EU)	ChT	NR	Laboratory	Parts	Parts	Rinse	MRD	mCCDA	C
Kure et al. (2020)	Steam pasteurization	NO (EU)	ChT	NR	Pilot Plant	Carcass	Skin on carcass	Swab (FLOQswab)	MH	MH	C
Lee et al. (2017)	Air chilling/immersion chilling/washing	KR (AS)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	BPW	CCA	P
Li et al. (2017)	Processing aids immersion	US (NA)	ChT	Rep. Random	Pilot Plant	Carcass	Carcass	Rinse	BB	BAP	C
McCrea et al. (2006)	Washing	US (NA)	BA	NR	Processing	Carcass	Skin on carcass	Swab (cotton)	NR	NR	P
Meredith et al. (2013)	Refrigeration/ processing aids immersion/ processing aids spray	IE (EU)	BA, ChT	Rep. Random	Processing, Laboratory	Carcass, Skin	Skin	Swab (sponge), Rinse	MRD	mCCDA	C
Meredith et al. (2014)	MAP	IE (EU)	ChT	NR	Laboratory	Parts	Parts	Homogenate	MRD	mCCDA	C
Mild et al. (2011)	Edible film coating with antimicrobials	US (NA)	ChT	NR	Laboratory	Parts	Parts	Homogenate	PBS	CCA	C
Musavian et al. (2014)	Air chilling/steam ultrasound	DK (EU)	BA	Rep. Random	Processing	Carcass	Skin	Homogenate	MRD	mCCDA	C

(Continues)

TABLE 1 (Continued)

Reference	Stage/intervention	Country[a]	Design	Random-ization	Location	Treatment unit	Sampling unit	Method	Enrichme-nt/dilution	Enumeration/ detection method	Outcome measure
Musgrove et al. (1997)	Defeathering	US (NA)	BA	Rep. Random	Pilot Plant	Carcass	Carcass	Rinse	PBS	CCA	P & C
Northcutt et al. (2003)	immersion chilling	US (NA)	BA	NR	Pilot Plant	Carcass	Carcass	Rinse	PBS	CCA	P
Northcutt et al. (2008)	Immersion chilling	US (NA)	BA	Rep. Random	Processing	Carcass	Half, whole	Rinse	Peptone water	CBA	C
Olaimat et al. (2014)	Edible film coating/ MAP	CA (NA)	ChT	NR	Laboratory	Parts	Parts	Homogenate	BPW	Karmali	C
Oosterom et al. (1983)	Air chilling/ defeathering/ evisceration/ scalding	NL (EU)	BA	NR	Processing	Carcass	Skin	Homogenate	THAL	Skirrow	C
Osiriphun et al. (2011)	Defeathering/ immersion chilling	TH (AS)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	BPW	mCCDA	P & C
Oyarzabal et al. (2004)	Immersion chilling/washing/ processing aids immersion	US (NA)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	BB	CCA & Line & Karmali, mCCDA	P & C
Ozdemir et al. (2006)	Processing aids immersion	TR (EU)	ChT	NR	Laboratory	Skin	Skin	Homogenate	BPW	CCDA	C
Park et al. (2002)	Processing aids immersion	US (NA)	ChT	NR	Laboratory	Parts	Parts	Rinse	Peptone water	CBA	C
Perez-Arnedo and Gonzalez-Fandos (2019)	Air chilling/evisceration/ washing	ES (EU)	BA	NR	Processing	Carcass	Skin, Parts	Homogenate	BB	PCR	P
Potturi-Venkata et al. (2007)	Immersion chilling	US (NA)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	Preston	CCA & mCCDA	C
Purnell et al. (2014)	Processing aids spray	UK (EU)	BA	NR	Pilot Plant	Carcass	Skin	Homogenate	MRD	mCCDA	C
Rahimi et al. (2010)	Evisceration	IR (MENA)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	Preston	CBA	P
Reich et al. (2006)	Air chilling/ evisceration	DE (EU)	BA	NR	Processing	Carcass	NR	NR	Preston	CCDA & Karmali	P
Reich et al. (2008)	Air chilling/ evisceration	DE (EU)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	Preston	mCCDA & Karmali	C
Reiter et al. (2005)	Defeathering/ immersion chilling	BR (SA)	BA	Rep. Random	Processing	Carcass	NR	NR	Preston	VIDAS & CLA	P

(Continues)

TABLE 1 (Continued)

Reference	Stage/intervention	Country[a]	Design	Random-ization	Location	Treatment unit	Sampling unit	Method	Enrichme-nt/dilution	Enumeration/ detection method	Outcome measure
Rejab et al. (2012a)	Washing	MY (AS)	BA	NR	Processing	Carcass	Skin	Homogenate	BB	mCCDA & Karmali	P
Rejab et al. (2012b)	Immersion chilling	MY (AS)	BA	NR	Processing	Carcass	Skin	Homogenate	BB	mCCDA & Karmali	P
Riedel et al. (2009)	Processing aids immersion	DK (EU)	ChT	NR	Laboratory	Skin, Parts	Skin, Parts	Rinse	BPW	AHBA	C
Rosenquist et al. (2006)	Evisceration/freezing	DK (EU)	BA	Rep. Random	Processing	Carcass	Skin	Homogenate	BPW	AHBA	P & C
Sarjit and Dykes (2015)	Processing aids immersion	MY (AS)	ChT	NR	Laboratory	Parts	Parts	Homogenate	BPW	mCCDA	C
Seliwiorstow et al. (2015)	Evisceration	BE (EU)	BA	NR	Processing	Carcass	Skin	Homogenate	Peptone water	CFA	P & C
Seliwiorstow et al. (2016)	Defeathering/evisceration/ washing	BE (EU)	BA	NR	Processing	Carcass	Skin	Homogenate	Peptone water	CFA	C
Sexton et al. (2007)	Processing aids immersion	AU (AU)	BA	NR	Processing	Carcass	Carcass	Rinse	BPW	CBFA	P & C
Shrestha, Wagle, Upadhyay, Arsi, Donoghue, et al. (2019)	Processing aids immersion	US (NA)	ChT	Rep. Random	Laboratory	Skin	Skin	Rinse	Butterfield	Line	C
Shrestha, Wagle, Upadhyay, Arsi, Upadhyaya, et al. (2019)	Edible film coating with antimicrobials/ without antimicrobials	US (NA)	ChT	Rep. Random	Laboratory	Parts	Parts	Homogenate	Butterfield	Line	C
Slavik et al. (1994)	Processing aids immersion	US (NA)	CT	NR	Laboratory	Carcass	Carcass	Rinse	BB	CBA	P
Smith et al. (2015)	Processing aids spray	US (NA)	ChT	NR	Laboratory	Carcass	Carcass	Rinse	BPW	CCA	C
Son et al. (2007)	Immersion chilling	US (NA)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	BB	CVA	P
Stern and Robach (2003)	Immersion chilling	US (NA)	BA	Rep. Random	Processing	Carcass	Carcass	Rinse	NA	CCA	P & C
Thormar et al. (2011)	Processing aids immersion	IS (EU)	BA	NR	Laboratory	Parts	Parts	Rinse	NA	CCA	C

(Continues)

TABLE 1 (Continued)

Reference	Stage/intervention	Country[a]	Design	Random-ization	Location	Treatment unit	Sampling unit	Method	Enrichme-nt/dilution	Enumeration/ detection method	Outcome measure
Thung et al. (2020)	Refrigeration	MY (AS)	ChT	NR	Laboratory	Parts	Parts	Homogenate	MRD	mCCDA	C
Tong et al. (2003)	Refrigeration/freezing/ rapid cooling	US (NA)	ChT	Rep. Random	Laboratory	Cut	Parts	Rinse	Peptone water	CBA	C
Vashin and Stoyanchev (2004)	Defeathering/ evisceration/ scalding	BG (EU)	BA	NR	Processing	Carcass	Skin on carcass	Swab (cotton)	THAL	Skirrow	P
Wagle, Arsi, et al. (2019)	Processing aids immersion	US (NA)	ChT	Rep. Random	Laboratory	Skin	Skin	Rinse	Neutralizing Broth	Line	C
Wagle, Upadhyay, et al. (2019)	Edible film coating with antimicrobials/ without antimicrobials	US (NA)	ChT	Rep. Random	Laboratory	Parts	Parts	Rinse	Neutralizing Broth	Line	C
Wempe et al. (1983)	Immersion chilling	US (NA)	BA	NR	Processing	Carcass	Skin	Homogenate	Nutrient Broth	CBA	P
Whyte et al. (2001)	Processing aids immersion	IE (EU)	BA	NR	Processing	Carcass	Skin	Homogenate	Peptone water	Preston	C
Whyte et al. (2003)	Processing aids spray/ hot water immersion/ steam pasteurization	IE (EU)	BA, ChT	NR	Processing, Laboratory	Carcass. Parts	Skin	Homogenate	Preston	mCCDA	C
Zhang et al. (2011)	Processing aids spray	US (NA)	BA	NR	Processing	Carcass	Carcass	Rinse	BPW	CCA	P & C
Zhang et al. (2018)	Evisceration	CN (AS)	BA	NR	Processing	Carcass	Skin on carcass	Swab (cotton)	BB	mCCDA	P
Zhao and Doyle (2006)	Processing aids immersion	US (NA)	ChT	NR	Laboratory	Parts	Parts	Rinse	Peptone water	CBA	C
Zhuang et al. (2019)	Refrigeration/high voltage	US (NA)	ChT	NR	Laboratory	Parts	Parts	Rinse	PBS	CCA	C
Zweifel et al. (2015)	Air chilling/ defeathering/ evisceration/ scalding/washing	CH (EU)	BA	Rep. Random	Processing	Carcass	Skin	Homogenate	Saline	CFA	P & C

Abbreviations: AHBA, Abeyta–Hunt–Bark agar; BA, before–after trials; BAP, Brucella agar with *Campylobacter* supplement; BB, Bolton broth; BPW, buffered peptone water; BrB, Brucella broth; Butterfield, Butterfield's phosphate buffer; C, concentration; CAT, cefoperazone amphotericin teicoplanin agar; CBA, *Campylobacter* blood agar (Blaser); CBFA, *Campylobacter* blood-free agar; CCA, Campy cefex agar; CCDA, cefoperazone charcoal deoxycholate agar; CEB, *Campylobacter* enrichment broth; CFA, Campy-food agar; ChT, challenge trials; CLA, Campylosel agar; CT, controlled trials; CVA, cefoperazone, vancomycin, amphotericin B agar; ISO, ISO method 10272-1; Karmali, Karmali *Campylobacter* agar; LB, lactose broth; Line, Campy-Line agar; mCCDA, modified cefoperazone charcoal deoxycholate agar; MH, Mueller–Hinton agar; MRD, maximum recovery diluent; NA, not available; NR, not reported; P, prevalence; PBS, phosphate buffered saline; PCR, polymerase chain reaction; Preston, Preston broth; qPCR, quantitative polymerase chain reaction; Rep. random, reported random; Skirrow, Skirrow agar; Systematic, systematic sample collection; THAL, thioglycolate enrichment broth; TSAB, tryptic soy agar containing sheep's blood; Tween, Tween enrichment broth; VIDAS, mini-VIDAS automated enzyme-linked fluorescent immunoassay.

[a]The UN/LOCODE system was used to code the countries (https://unece.org/trade/cefact/unlocode-code-list-country-and-territory): AS, Asia; AU, Australia; EU, Europe; MENA, Middle East and North Africa; NA, North America; SA, South America.

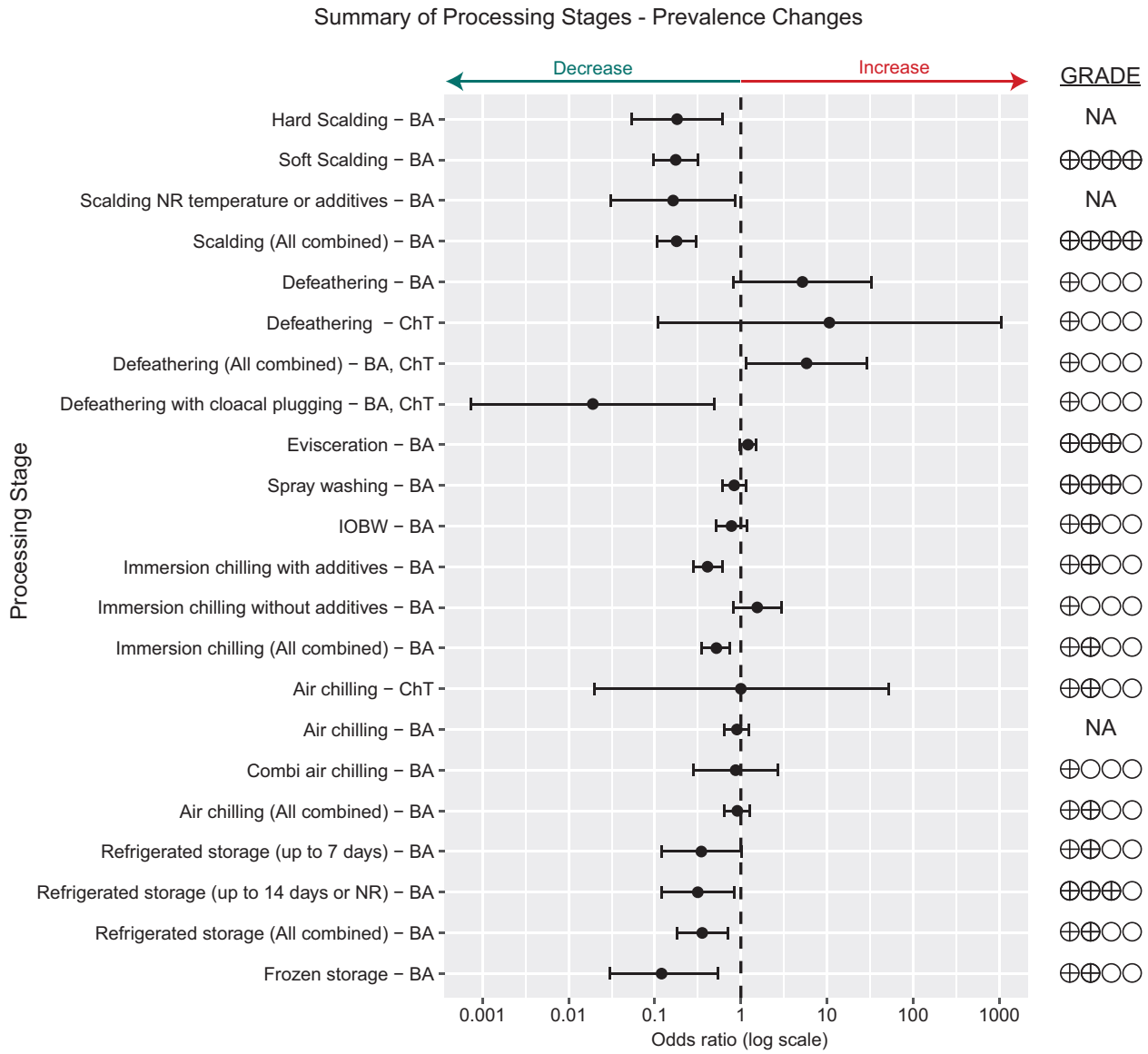

FIGURE 4 Summary of meta-analysis results for prevalence changes due to processing stages
BA, before–after trials; ChT, challenge trials.

the strength of the available evidence, and thus laboratory trials were separated from trials conducted in processing facilities and pilot plants.

3.2 | Effectiveness of processing stages

Conventionally, broiler chickens are processed in five standard stages to ensure the safety and quality of the end product as shown in Figure 1. To loosen the skin follicles that hold the feathers in place, scalding is applied by immersing whole carcasses in warm water. During scalding, reduction in contamination can be expected due to microbial inactivation at high temperatures and removal by water; however, contaminated scalding water can induce cross-contamination between carcasses and fecal leakage can also cause contamination from feces (Osiriphun et al., 2012). After scalding, defeathering (also known as picking or plucking) is performed by passing the carcasses through vibrating rubber fingers. This process may place pressure on the carcass, causing fecal material to leak and contaminate the carcass skin and rubber fingers can cause cross-contamination from *Campylobacter*-positive carcasses to negative ones (Dickens & Whittemore, 1997). Evisceration refers to the removal of internal organs from inside the carcass. Although evisceration methods may vary based on the scale and modernity of the processing facility, automated systems are frequently used. These systems increase

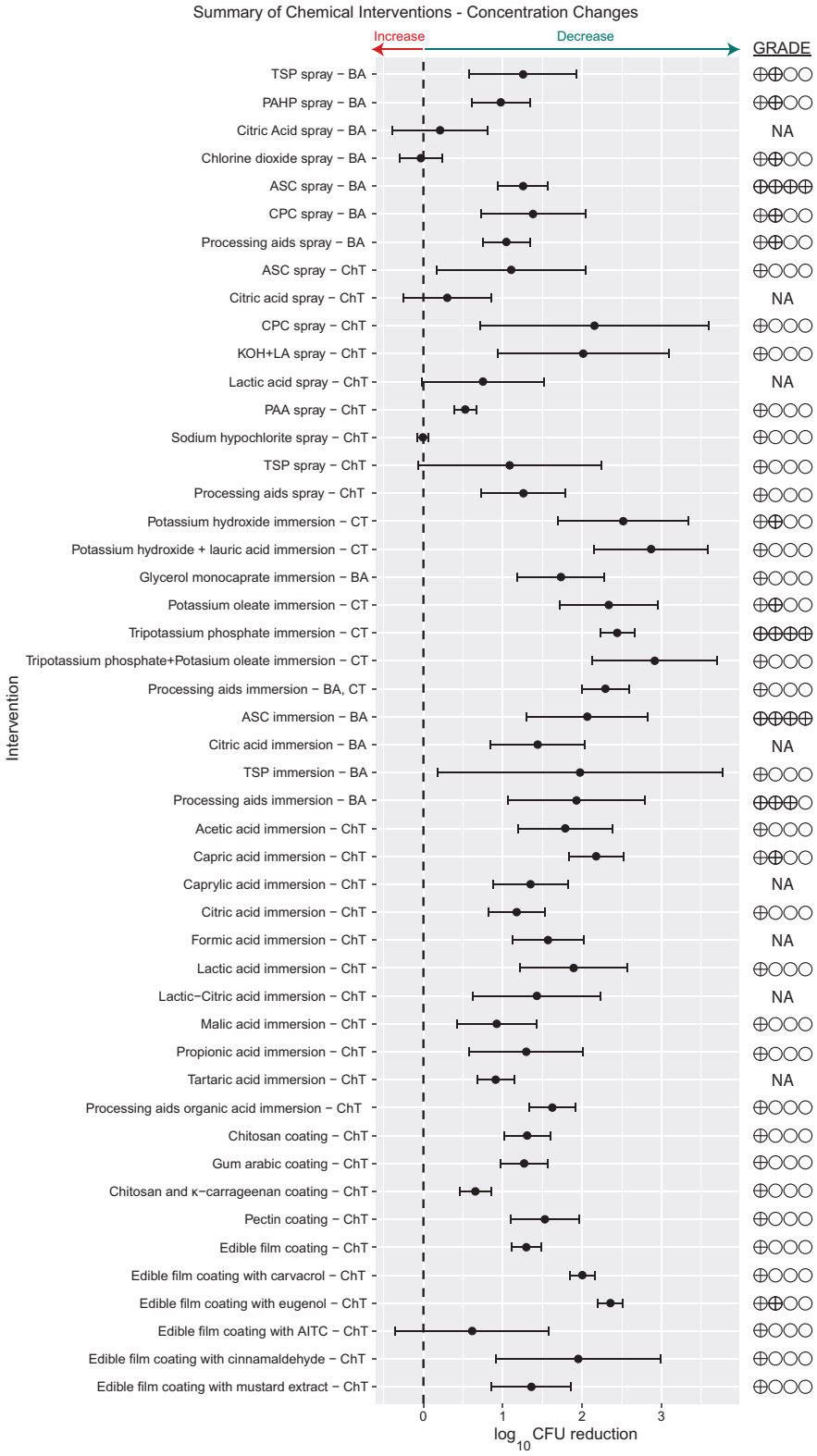

FIGURE 5 Summary of meta-analysis results for concentration changes due to chemical interventions
BA, before–after trials; ChT, challenge trials; CT, controlled trials.

production capacity but may rupture the intestine and cause leakage of fecal material to contaminate carcass exterior and cross-contamination via the equipment, increasing prevalence and concentration (Hue et al., 2010). Consequently, carcasses are washed immediately after evisceration and prior to chilling. Washing can reduce concentration by physical removal and inactivation of *Campylobacter* if additives are used (Bashor et al., 2004). Chilling ensures that the carcass is cooled quickly, which reduces the possibility of microorganism growth and thus is an

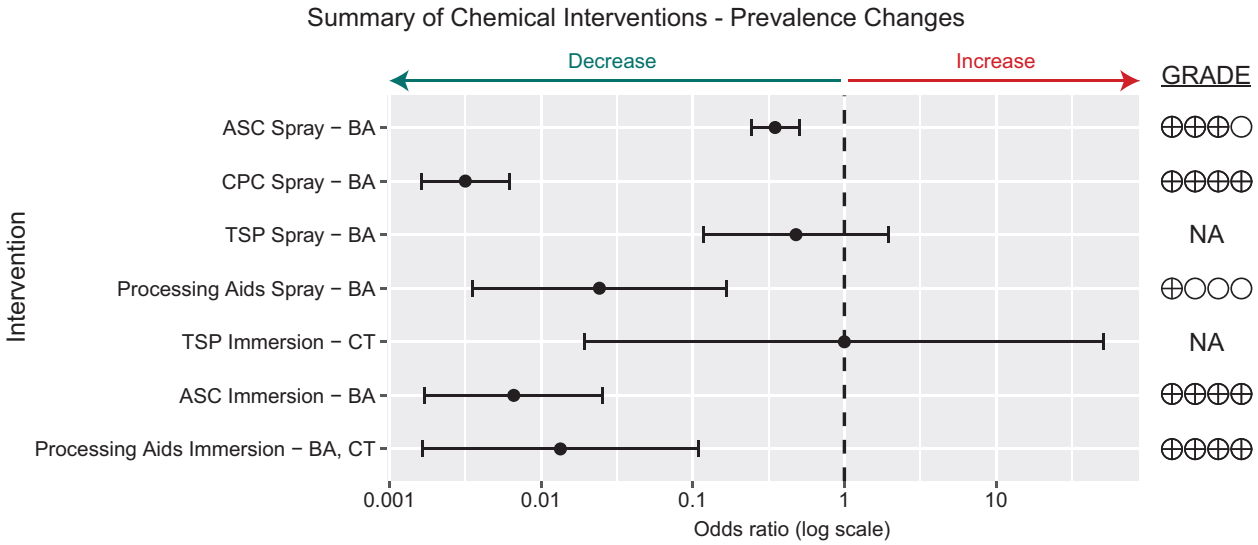

FIGURE 6 Summary of meta-analysis results for prevalence changes due to chemical interventions
BA, before–after trials; CT, controlled trials.

TABLE 2 Summary of the effects of broiler processing stages on concentration and prevalence changes of *Campylobacter*

Stage[a]	Log_{10}CFU reduction [mean (95% CI)]	Range[b]	Odds ratio [mean (95% CI)]	Range[b]
Scalding	1.87 (1.34, 2.41)	−0.29, 4.10	0.18 (0.11, 0.30)	0.03, 0.38
Defeathering	−0.88 (−1.23, −0.54)	−2.02, 0.22	5.80 (1.15, 29.42)	0.69, 108.41
Evisceration	−0.15 (−0.33, 0.03)	−2.75, 2.06	1.21 (0.98, 1.49)	0.14, 7.22
Washing	0.52(0.38, 0.67)	−0.18, 1.56	0.82 (0.65, 1.05)	0.04, 3.21
Immersion chilling	1.84 (1.43, 2.17)	0.70, 4.12	0.52 (0.35, 0.75)	0.10, 5.06
Air chilling	0.48 (−0.07, 1.03)	−1.49, 2.62	0.91 (0.65, 1.28)	0.48, 14.54
Refrigeration	0.83 (0.60, 1.05)	−0.08, 1.67	0.36 (0.18, 0.70)	0.01, 4.03
Freezing	1.29 (1.10, 1.48)	−0.24, 2.87	0.12 (0.0.3, 0.54)	0.002, 4.38

[a]Only before–after studies are summarized.
[b]Minimum and maximum effect sizes across trials included for a specific outcome.

important step in controlling product safety. During chilling, inactivation and removal of cells can occur, reducing the concentration on the product. However, depending on the type (air or immersion cooling), chilling fluid can induce cross-contamination between carcasses, which may result in an increase in the prevalence (Yang et al., 2002). In the following subsections, the effectiveness of each processing stage in reducing prevalence and/or concentration is presented in order of their appearance in a conventional broiler processing line. For each outcome, the synthesis of the results with pooled effects and forest plots, quality of evidence assessment, summary of current evidence, and possible limitations are discussed. A summary of processing stages is provided in Table 2. Summary of outcome-level meta-analysis results regarding the effects of processing stages on *Campylobacter* concentration and prevalence can be found in Figure 3 and 4, and Table 3 and 4. For the sake of brevity, limited results are presented in this review; for other results including forest plots, risk of bias summaries, traffic light plots, and other related information, readers are advised to refer to the appendices in the Supporting Information.

3.2.1 | Scalding

Scalding refers to the immersion of broiler carcasses in warm water prior to feather removal in order to enlarge the follicles that hold the feathers. This stage is commonly applied under two different conditions. Soft scalding (51.4–53.1°C, 120–229 s) uses milder temperatures and longer time to retain some visible and sensory quality aspects,

TABLE 3 Summary of findings for concentration changes due to processing stages

Processing stage	Setting	Treatment unit	Study design	No. of studies	No. of trials	Sample size	I^2 (%)	*Q*-test *p*-value	LR	95% CI		Include null	GRADE
										Lower	Upper		
Air chilling	Pilot	Carcass	ChT	2	3	112	86.47	.0006	0.67	0.06	1.28	No	⊕◯◯◯
Air chilling	Pilot	Carcass	BA	7	13	574	94.40	<.0001	0.48	−0.07	1.03	Yes	⊕◯◯
Air chilling (All combined)	Pilot	Carcass	BA, ChT	9	16	686	94.08	<.0001	0.52	0.02	1.02	No	⊕◯◯◯
Defeathering with interventions	Pilot, processing	Carcass	BA	7	13	876	99.23	<.0001	0.09	−0.77	0.95	Yes	⊕◯◯◯
Defeathering with cloacal plugging	Pilot, processing	Carcass	BA	4	8	576	99.19	<.0001	−0.78	−1.74	0.18	Yes	⊕◯◯◯
Defeathering with organic acid in cloaca	Pilot, processing	Carcass	BA	2	4	240	0	.6671	1.69	1.51	1.86	No	⊕⊕⊕⊕
Defeathering with chlorine dioxide spray	Processing	Carcass	BA	1	1	60	NA	NA	0.61	0.21	1.01	No	NA
Defeathering (All combined)	Pilot & processing	Carcass	BA	7	16	453	94.63	<.001	−0.88	−1.23	−0.54	No	⊕◯◯◯
Evisceration	Processing	Carcass	BA	12	61	1376	93.07	<.001	−0.15	−0.33	0.03	Yes	⊕◯◯◯
Frozen storage $t \leq 14$ & NR	Processing	Carcass	BA	4	8	441	0.00	.7414	1.31	1.05	1.57	No	⊕⊕⊕⊕
Frozen storage $t > 14$	Processing	Carcass	BA	1	20	235	75.63	<.0001	1.28	1.11	1.45	No	NA
Frozen storage (All combined)	Processing	Carcass	BA	4	28	676	69.45	<.001	1.29	1.10	1.48	No	⊕⊕⊕⊕
Frozen storage	Laboratory	Parts, skin	ChT	3	32	180	97.59	<.001	1.20	1.08	1.32	No	⊕◯◯◯
Immersion chilling without additive	Pilot	Carcass	ChT	1	1	64	NA	NA	1.00	0.72	1.28	No	NA
Immersion chilling without additive	Pilot	Carcass	BA	1	2	144	87.82	.0042	1.25	0.96	1.55	No	NA
Immersion chilling with chlorine	Processing	Carcass	BA	10	17	2167	97.81	<.0001	1.95	1.46	2.45	No	⊕⊕⊕⊕
Immersion chilling with Protecta2	Pilot	Carcass	BA	1	3	252	92.59	<.0001	1.70	1.31	2.09	No	NA
Immersion chilling (All combined)	Pilot, processing	Carcass	BA	13	23	2645	98.13	<.001	1.80	1.43	2.17	No	⊕⊕⊕⊕
Hard scalding	Processing	Carcass	BA	2	7	104	0	.9427	1.85	1.60	2.09	No	⊕⊕⊕⊕
Soft scalding	Processing	Carcass	BA	3	7	173	83.11	<.0001	1.15	0.34	1.96	No	⊕◯◯◯
Scalding NR temperature or additives	Processing	Carcass	BA	3	3	145	85.44	.0005	3.30	2.48	4.12	No	⊕⊕⊕⊕
Scalding (All combined)	Processing	Carcass	BA	6	17	422	89.31	<.0001	1.87	1.34	2.41	No	⊕⊕⊕◯
Refrigerated storage	Laboratory	Parts	ChT	3	11	78	82.70	<.0001	0.32	0.19	0.46	No	⊕◯◯◯
Refrigerated storage	Laboratory	Skin	ChT	3	14	144	97.16	<.0001	0.82	0.47	1.18	No	⊕◯◯◯
Refrigerated storage	Laboratory	Skin, parts	ChT	6	25	222	97.28	<.0001	0.59	0.37	0.82	No	⊕◯◯◯
Refrigerated storage (up to 7 days)	Processing	Carcass	BA	2	13	168	82.71	<.0001	0.69	0.41	0.98	No	⊕◯◯◯
Refrigerated storage (up to 14 days)	Processing	Carcass	BA	2	6	110	45.68	.0795	1.12	0.88	1.35	No	⊕⊕⊕⊕
Refrigerated storage (All combined)	Processing	Carcass	BA	3	19	278	81.10	<.0001	0.83	0.60	1.05	No	⊕⊕⊕◯
Spray washing	Processing	Carcass	BA	4	33	709	92.84	<.0001	0.53	0.38	0.69	No	⊕⊕◯◯
IOBW	Processing	Carcass	BA	2	3	210	75.12	.0141	0.54	0.24	0.84	No	⊕◯◯◯
Brush washing	Processing	Carcass	BA	1	2	100	0	.5890	0.17	−0.48	0.83	Yes	NA
Washing (All combined)	Processing	Carcass	BA	7	38	1019	91.76	<.0001	0.52	0.38	0.67	No	⊕◯◯◯

TABLE 4 Summary of findings for prevalence changes due to processing stages

Processing stage	Setting	Treatment unit	Study design	No. studies	No. trials	Sample size	I^2 (%)	*Q*-test *p*-value	OR	95% CI		Include null	GRADE
										Lower	Upper		
Air chilling	Pilot	Carcass	ChT	1	1	64	NA	NA	1.00	0.02	51.93	Yes	NA
Air chilling	processing	Carcass	BA	4	7	272	0.00	.7411	0.90	0.65	1.25	Yes	⊕⊕◯◯
Combi air chilling	Processing	Carcass	BA	2	2	332	86.78	.006	0.87	0.28	2.67	Yes	⊕◯◯◯
Air chilling (All combined)	Processing & pilot	Carcass	BA, ChT	7	10	686	28.38	.2673	0.91	0.65	1.28	Yes	⊕⊕◯◯
Defeathering	Processing	Carcass	BA	7	10	1268	96.20	<.0001	5.19	0.82	32.66	Yes	⊕◯◯◯
Defeathering	Processing	Carcass	ChT	2	2	273	92.50	.0003	10.67	0.11	1052.89	Yes	⊕◯◯◯
Defeathering (All combined)	Processing	Carcass	BA, ChT	9	12	1541	95.47	<.0001	5.80	1.15	29.42	No	⊕◯◯◯
Defeathering with cloacal plugging	Processing	Carcass	BA, ChT	3	3	398	88.43	.0017	0.02	0.00	0.50	No	⊕◯◯◯
Evisceration	Processing	Carcass	BA	17	44	2649	0.00	.9960	1.21	0.98	1.49	Yes	⊕⊕⊕◯
Frozen storage	Processing	Carcass	BA	5	11	1011	84.56	<.0001	0.12	0.03	0.54	No	⊕⊕◯◯
Immersion chilling with additives	Processing & pilot	Carcass	BA	18	26	4257	69.71	<.0001	0.41	0.28	0.61	No	⊕⊕◯◯
Immersion chilling without additives	Processing	Carcass	BA	2	5	378	0.00	.6509	1.55	0.81	2.96	Yes	⊕◯◯◯
Immersion chilling (All combined)	Processing & pilot	Carcass	BA	20	31	4635	71.20	<.0001	0.52	0.35	0.75	No	⊕⊕◯◯
Hard scalding	Processing	Carcass	BA	1	1	50	NA	1.0000	0.18	0.05	0.62	No	NA
Soft scalding	Processing	Carcass	BA	2	4	149	0.00	.7001	0.18	0.10	0.32	No	⊕⊕⊕⊕
Scalding NR temperature or additives	Processing	Carcass	BA	1	3	145	80.07	.0096	0.16	0.03	0.87	No	NA
Scalding (All combined)	Processing	Carcass	BA	5	8	344	29.71	.1504	0.18	0.11	0.30	No	⊕⊕⊕⊕
Refrigerated storage (up to 7 days)	Processing	Carcass	BA	2	11	806	63.66	.0156	0.35	0.12	1.01	Yes	⊕⊕◯◯
Refrigerated storage (up to 14 days or NR)	Processing	Carcass	BA	5	10	732	22.97	.2958	0.32	0.12	0.83	No	⊕⊕⊕◯
Refrigerated storage (All combined)	Processing	Carcass	BA	5	21	1538	42.40	.0341	0.36	0.18	0.70	No	⊕⊕◯◯
Spray washing	Processing	Carcass	BA	4	10	1185	0	.6519	0.84	0.62	1.14	Yes	⊕⊕⊕◯
IOBW	Processing	Carcass	BA	5	10	1160	20.38	.3270	0.78	0.51	1.18	Yes	⊕⊕◯◯
Washing (All combined)	Processing	Carcass	BA	9	20	2345	7.77	.5792	0.82	0.65	1.05	Yes	⊕⊕◯◯

TABLE 5 Summary of findings for concentration changes due to application of chemical interventions

Intervention	Setting	Population	Study design	No. studies	No. trials	Sample size	I^2 (%)	*Q*-test *p*-value	LR	95 % CI		Include null	GRADE
										Lower	Upper		
TSP spray	Pilot, processing	Carcass	BA	2	5	106	91.09	<.0001	1.26	0.58	1.93	Yes	⊕⊕◯◯
PAHP spray	Pilot	Carcass	BA	1	4	80	0	.9429	0.98	0.61	1.35	Yes	⊕⊕◯◯
Citric acid spray	Processing	Carcass	BA	1	1	6	0	1.0000	0.21	−0.40	0.81	No	NA
Chlorine dioxide spray	Pilot	Carcass	BA	1	2	60	22.36	.2564	−0.03	−0.30	0.24	No	⊕⊕◯◯
ASC spray	Processing	Carcass	BA	1	4	1265	50.48	.1145	1.26	0.94	1.57	Yes	⊕⊕⊕⊕
CPC spray	Pilot, processing	Carcass	BA	2	4	140	99.43	<.0001	1.38	0.72	2.04	Yes	⊕⊕◯◯
Processing aids spray	Pilot, processing	Carcass	BA	4	20	1657	97.31	<.0001	1.05	0.75	1.34	Yes	⊕⊕◯◯
ASC spray	Laboratory	Skin	ChT	2	2	30	82.12	.0180	1.11	0.17	2.05	Yes	⊕◯◯◯
Citric acid spray	Laboratory	Skin	ChT	1	1	18	0	1.0000	0.3	−0.26	0.86	No	NA
CPC spray	Laboratory	Skin	ChT	1	2	24	98.99	<.0001	2.16	0.72	3.60	Yes	⊕◯◯◯
KOH + LA spray	Pilot	Carcass	ChT	1	7	140	99.74	0	2.01	0.93	3.10	Yes	⊕◯◯◯
Lactic acid spray	Laboratory	Skin	ChT	1	1	18	0	1.0000	0.75	−0.02	1.52	Yes	NA
PAA spray	Laboratory	Carcass, Skin	ChT	1	3	54	69.37	.0458	0.53	0.39	0.67	No	⊕◯◯◯
Sodium hypochlorite spray	Laboratory	Carcass	ChT	1	2	36	0	.5987	−0.01	−0.08	0.07	No	⊕◯◯◯
TSP spray	Laboratory	Skin	ChT	2	2	30	90.33	.0013	1.09	−0.07	2.24	Yes	⊕◯◯◯
Processing aids spray	Pilot, laboratory	Carcass, Skin	ChT	4	20	350	99.59	0	1.26	0.73	1.79	Yes	⊕◯◯◯
Potassium hydroxide immersion	Laboratory	Skin	CT	1	4	48	92.84	<.0001	2.52	1.70	3.34	No	⊕⊕◯◯
Potassium hydroxide + lauric acid immersion	Laboratory	Skin	CT	1	4	48	90.53	<.0001	2.87	2.15	3.59	No	⊕◯◯◯
Glycerol monocaprate immersion	Laboratory	Cuts	BA	1	12	72	91.81	<.0001	1.73	1.18	2.28	No	⊕◯◯◯
Potassium oleate immersion	Laboratory	Skin	CT	2	12	144	89.91	<.0001	2.34	1.72	2.95	No	⊕⊕◯◯
Tripotassium phosphate immersion	Laboratory	Skin	CT	1	4	48	0	.7153	2.44	2.23	2.66	No	⊕⊕⊕⊕
Tripotassium phosphate + potassium oleate immersion	Laboratory	Skin	CT	1	3	36	90.44	.0104	2.92	2.13	3.70	No	⊕◯◯◯
Processing aids immersion	Laboratory	Skin, Cuts	BA, CT	4	39	396	94.80	<.0001	2.29	1.99	2.59	No	⊕◯◯◯
ASC immersion	Processing	Carcass	BA	2	3	197	87.84	.0041	2.07	1.30	2.83	No	⊕⊕⊕⊕
Citric acid immersion	Processing	Carcass	BA	1	1	6	0	1.0000	1.44	0.85	2.03	Yes	NA
TSP immersion	Processing	Carcass	BA	2	2	66	99.42	<.0001	1.97	0.18	3.77	Yes	⊕◯◯◯
Processing aids immersion	Processing	Carcass	BA	4	6	269	98.33	<.0001	1.93	1.07	2.79	No	⊕⊕⊕◯

(Continues)

TABLE 5 (Continued)

Intervention	Setting	Population	Study design	No. studies	No. trials	Sample size	I^2 (%)	Q-test p-value	LR	95 % CI		Include null	GRADE
										Lower	Upper		
Acetic acid immersion	Laboratory	Skin, Cuts	ChT	2	5	32	94.38	<.0001	1.79	1.19	2.37	No	⊕◯◯◯
Capric acid immersion	Laboratory	Skin, Cuts	ChT	2	3	72	35.87	.2065	2.18	1.84	2.52	No	⊕⊕◯◯
Caprylic acid immersion	Laboratory	Skin, Cuts	ChT	1	1	36	0	1.0000	1.35	0.88	1.82	Yes	NA
Citric acid immersion	Laboratory	Skin, Cuts	ChT	2	4	72	57.53	<.0001	1.18	0.82	1.53	Yes	⊕◯◯◯
Formic acid immersion	Laboratory	Skin, Cuts	ChT	1	1	40	0	1.0000	1.57	1.12	2.02	No	NA
Lactic acid immersion	Laboratory	Skin, Cuts	ChT	6	10	152	97.15	<.0001	1.89	1.21	2.57	No	⊕◯◯◯
Lactic–citric acid immersion	Laboratory	Skin, Cuts	ChT	1	1	12	0	1.0000	1.43	0.63	2.23	Yes	NA
Malic acid immersion	Laboratory	Skin, Cuts	ChT	1	2	24	95.85	<.0001	0.92	0.42	1.42	Yes	⊕◯◯◯
Propionic acid immersion	Laboratory	Skin, Cuts	ChT	1	2	24	82.03	.0183	1.30	0.58	2.01	Yes	⊕◯◯◯
Tartaric acid immersion	Laboratory	Skin, Cuts	ChT	1	1	34	0	1.0000	0.91	0.68	1.15	Yes	NA
Processing aids organic acid Immersion	Laboratory	Skin, Cuts	ChT	10	30	498	96.33	0	1.62	1.33	1.91	No	⊕◯◯◯
Chitosan coating	Laboratory	Cuts	ChT	2	20	200	97.82	<.0001	1.31	1.01	1.60	No	⊕◯◯◯
Gum arabic coating	Laboratory	Cuts	ChT	1	10	100	97.91	<.0001	1.27	0.97	1.57	Yes	⊕◯◯◯
Chitosan and k-carrageenan coating	Laboratory	Cuts	ChT	1	4	48	0	.5097	0.65	0.46	0.85	No	⊕◯◯◯
Pectin coating	Laboratory	Cuts	ChT	2	10	100	94.33	<.0001	1.53	1.10	1.96	No	⊕◯◯◯
Edible film coating	Laboratory	Cuts	ChT	3	44	448	97.74	<.0001	1.30	1.11	1.48	No	⊕◯◯◯
Edible film coating with carvacrol	Laboratory	Cuts	ChT	2	69	654	96.71	<.0001	2.00	1.85	2.16	No	⊕◯◯◯
Edible film coating with eugenol	Laboratory	Cuts	ChT	1	60	600	87.91	<.0001	2.36	2.20	2.52	No	⊕⊕◯◯
Edible film coating with AITC	Laboratory	Cuts	ChT	1	9	54	95.71	<.0001	0.61	−0.35	1.58	Yes	⊕◯◯◯
Edible film coating with cinnamaldehyde	Laboratory	Cuts	ChT	1	8	96	97.20	<.0001	1.95	0.92	2.98	Yes	⊕◯◯◯
Edible film coating with mustard extract	Laboratory	Cuts	ChT	1	12	144	95.68	<.0001	1.36	0.86	1.86	Yes	⊕◯◯◯

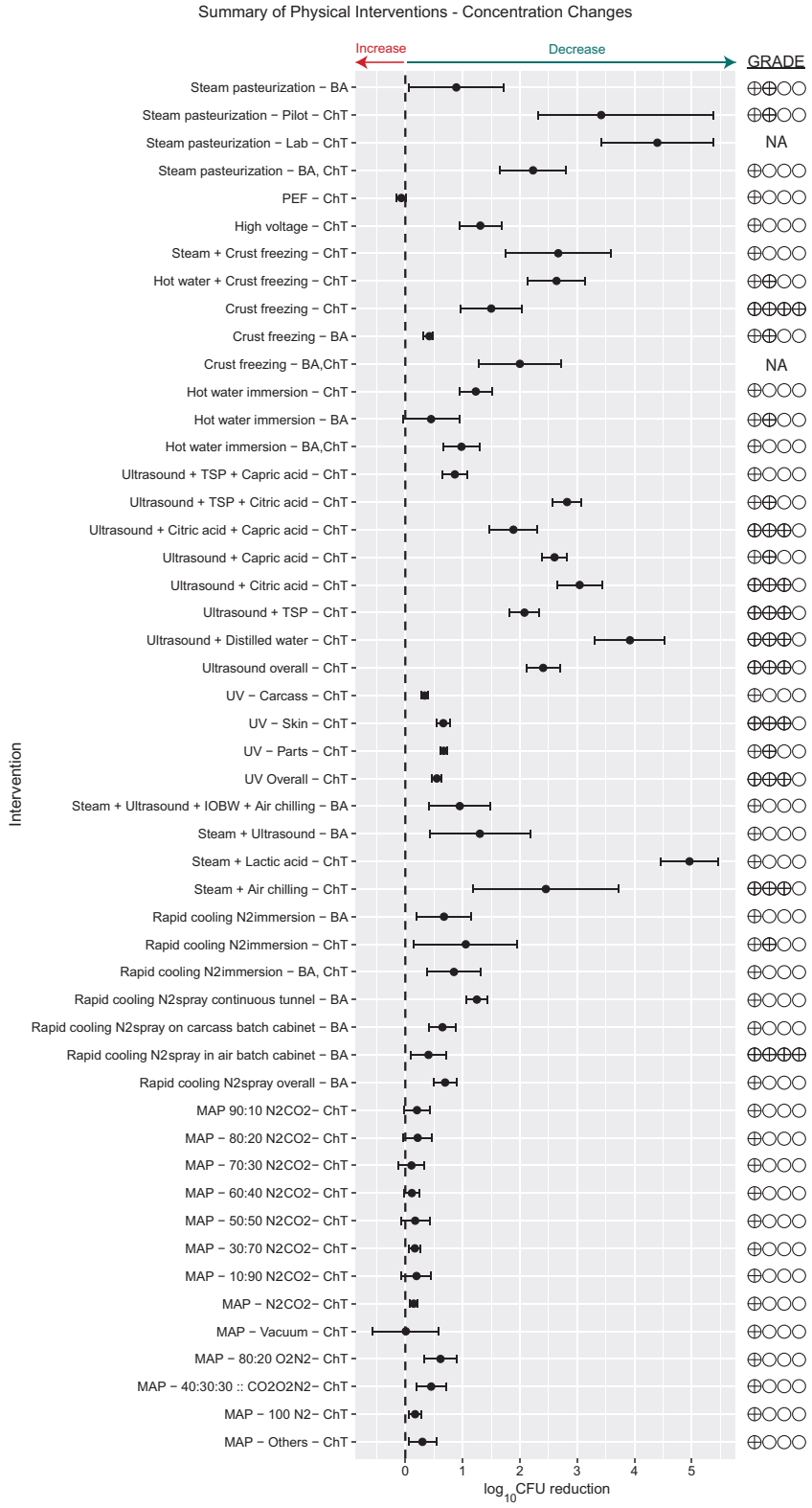

FIGURE 7 Summary of meta-analysis results for concentration changes due to physical interventions
BA, before–after trials; ChT, challenge trials.

whereas hard scalding (55–58°C, 80–150 s) increases the defeathering efficacy and reduces the processing time by applying higher temperatures. Soft scalding is used for chicken to be sold fresh or air chilled, whereas hard scalding is generally applied to frozen products (James et al., 2006; Thomas, 1977). The scalding stage can affect microbial contamination by washing excess dirt from feathers and/or providing mild thermal inactivation. However, the contaminated fecal content will remain the same inside the carcass leaving the process without changes

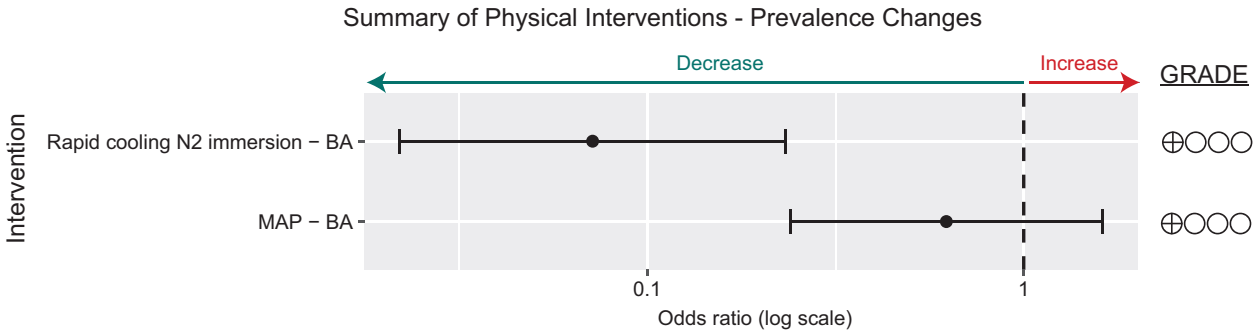

FIGURE 8 Summary of meta-analysis results for prevalence changes due to physical interventions
BA, before–after trials.

in fecal contamination; therefore, exterior concentration can increase further down the processing chain if fecal leakage contaminates the skin and feathers. Scalding is evaluated under the two main subgroups of hard and soft scalding, in addition to trials where temperature is not reported.

Concentration changes due to scalding were reported by 17 trials reported in six studies, and prevalence changes were reported by eight trials in five studies, as summarized in the forest plots in Figure B.1 in the Supporting Information. The meta-analysis indicated an overall mean reduction of 1.87 $\log_{10}$CFU (95% CI: 1.34–2.42) due to all types of scalding. However, significant heterogeneity was detected among the trials (I^2 = 89%, $p < .001$), indicating very serious inconsistency within the dataset. Hard scalding showed a combined mean effect of 1.85 $\log_{10}$ CFU (95% CI: 1.60–2.09) with 0% heterogeneity, whereas very serious heterogeneity was detected for soft scalding and scalding with additives or unreported temperatures. Due to the significant heterogeneity across trials, the pooled mean effects are not discussed in detail. Scalding with additives or unreported temperatures seemed to cause a mean log reduction of 3.30 $\log_{10}$ CFU; however, due to the lack of information about processing conditions, no definitive conclusions can be made about the effectiveness of scalding with various additives. All trials for soft scalding except two showed consistent reductions. However, the conditions for soft scalding should be properly optimized, as elevated concentrations were detected in some studies that tested procedures at low scalding temperatures (Oosterom et al., 1983; Zweifel et al., 2015).

Five studies with eight trials reporting prevalence changes during scalding were identified in the review and are summarized in Figure B.12 in the Supporting Information. The scalding stage was estimated to have a combined OR of 0.18 (95% CI: 0.11–0.30), indicating a reduction of prevalence after scalding. Heterogeneity of the dataset was relatively low (I^2 = 30%) and not statistically significant (p = .1504). The results for the analysis of prevalence suggested a consistent decrease in the number of contaminated carcasses after scalding.

The quality of evidence assessment for scalding indicated that the combined effect measure provided moderate quality of evidence for concentration changes but high quality of evidence for prevalence changes. The quality of evidence for concentration was downgraded for very serious inconsistency and serious imprecision but upgraded for very large effect size. Although the formal analysis pointed to high and moderate quality of evidence, caution is still needed when using the subgroups because of the bias that might be induced by the limited number of trials. Furthermore, the most current practice in the industry is to expose carcasses to multiple steps of continuous, countercurrent flow scalding tanks with variable temperatures and exposure times to achieve optimum efficiency and quality, whereas batch processing was used in the past. A precise analysis of the scalding process would therefore require the inclusion of critical factors such as the number of stages and processing conditions such as temperature, time, and additives. However, few studies included in this review comprehensively described these critical parameters, which limits the generalizability of the results. Future studies should report critical process parameters more explicitly.

3.2.2 | Defeathering

Defeathering (also known as picking or plucking) takes place after scalding, generally by passing carcasses through vibrating rubber fingers. Seven before–after studies covering 16 trials were identified for concentration changes on the exterior of carcasses during defeathering and are summarized in Figure B.2 in the Supporting Information. The pooled effect was estimated as −0.88 $\log_{10}$CFU (95% CI: −1.23 to −0.54), which corresponds to an increase

TABLE 6 Summary of findings for prevalence changes due to application of chemical interventions

Intervention	Setting	Population	Study design	No. studies	No. trials	Sample size	I^2 (%)	Q-test *p*-value	OR	95% CI		Include null	GRADE
										Lower	Upper		
ASC spray	Processing	Carcass	BA	2	2	353	0.00	.7484	0.35	0.24	0.50	No	⊕⊕⊕◯
CPC spray	Processing	Carcass	BA	2	4	1265	18.93	.3252	0.00	0.00	0.01	No	⊕⊕⊕⊕
TSP spray	Processing	Carcass	BA	1	1	60	0.00	1.0000	0.48	0.12	1.96	Yes	NA
Processing aids spray	Processing	Carcass	BA	4	7	1678	96.25	.0000	0.02	0.00	0.17	No	⊕◯◯◯
TSP immersion	Laboratory	Carcass	CT	1	1	100	0.00	1.0000	1.00	0.02	51.38	Yes	NA
ASC immersion	Processing	Carcass	BA	2	3	197	0.00	.5835	0.01	0.00	0.03	No	⊕⊕⊕⊕
Processing aids immersion	Processing, laboratory	Carcass	BA, CT	3	4	297	56.32	.0837	0.01	0.00	0.11	No	⊕⊕⊕⊕

in concentration due to defeathering. For this outcome, significant heterogeneity was detected ($I^2 = 94\%, p < .001$), indicating very serious inconsistency. Although the method of defeathering does not vary much in industrial applications, a subgroup analysis based on geographical location revealed a noticeable difference in the increase in concentration during defeathering. The data from each country may not be adequate to explain differences in practices between countries, since each subgroup was composed of multiple trials from a single study. These differences may also be explained by other factors such as initial fecal contamination prevalence and concentration but exploring the relationships between fecal and surface contamination are outside the scope of this review. Greater increases were estimated for processing and pilot plant applications in the United States (−1.94 $\log_{10}$ CFU; 95% CI: −2.10 to −1.79), which may be explained by differences in initial fecal contamination among different studies due to the effect of industrial intensity and different regulations on controlling contamination in the preharvest stages.

For prevalence changes, seven before–after studies and two challenge studies conducted at processing plants were identified (Figure B.13 in the Supporting Information). A mean OR of 5.19 (95% CI: 0.82–32.66) was estimated for before–after trials, indicating a major increase in prevalence. However, the CIs for the pooled estimates and for most of the trials indicated that the direction of the effect is imprecise. Challenge trials also resulted in estimates of increased prevalence (10.67; 95% CI: 0.15 to 1052.89). When the two subgroups were combined, the OR was estimated as 5.80 (95% CI: 1.15–29.42), although the analysis of the two subgroups both separately and together yielded significant heterogeneity.

It is possible that defeathering increases the concentration and prevalence of *Campylobacter* on the carcass surface due to the pressure applied by the fingers and consequent leakage of contaminated fecal contents. However, data collected via this systematic review only consider the exterior contamination before and after each processing stage; therefore, the actual effect of fecal contamination during defeathering is challenging to be differentiated and may contribute greatly to the overall heterogeneity. Two main approaches have been suggested to prevent contamination due to fecal leakage (Berrang et al., 2018). The first approach is to eliminate contamination in the gut using antimicrobial agents, and the second is cloacal plugging to retain the fecal contents in the gut during defeathering. Two studies and four before–after trials reported concentration changes during defeathering with different organic acids (Figure B.3 in the Supporting Information). The combined log reduction estimate indicated that organic acid injection into the cloaca results in a 1.69 $\log_{10}$ CFU (95% CI: 1.51–1.86, $I^2 = 0\%$) reduction on the exterior of defeath-

TABLE 7 Summary of findings for concentration changes due to physical decontamination and treatment combinations

Intervention	Setting	Population	Study design	No. studies	No. trials	Sample size	I^2 (%)	*Q*-test *p*-value	LR	95 % CI		Include null	GRADE
										Lower	Upper		
Steam pasteurization	Processing	Carcass	BA	1	2	40	48.08	.0245	0.89	0.06	1.71	No	NA
Steam pasteurization	Pilot	Carcass, cuts	ChT	2	15	180	87.26	.0051	3.42	2.32	5.38	No	⊕⊕◯◯
Steam pasteurization	Laboratory	Skin	ChT	1	1	20	NA	NA	4.40	3.42	5.38	No	NA
Steam pasteurization	Laboratory	Carcass, cuts, skin	BA, ChT	4	18	240	83.42	<.001	2.23	1.65	2.80	No	⊕◯◯◯
PEF	Laboratory	Cuts	ChT	1	10	60	22.00	.3256	−0.07	−0.16	0.02	Yes	NA
High voltage	Laboratory	Cuts	ChT	1	3	18	0.00	.5544	1.31	0.94	1.69	No	NA
Steam + crust freezing	Pilot	Carcass	ChT	1	2	96	91.66	.0005	2.67	1.75	3.59	No	NA
Hot water + crust freezing	Pilot	Carcass	ChT	1	2	96	69.30	.0711	2.64	2.14	3.14	No	NA
Crust freezing	Pilot	Carcass	ChT	1	2	96	88.33	.0034	1.50	0.96	2.04	No	NA
Crust freezing	Processing	Cuts	BA	1	1	147	NA	NA	0.42	0.36	0.48	No	NA
Crust freezing	Processing, pilot	Cuts, carcass	BA, ChT	2	7	435	98.59	<.001	2.00	1.29	2.72	No	⊕◯◯◯
Hot water immersion	Laboratory	Cuts, carcass	ChT	2	7	148	58.37	.0277	1.23	0.94	1.52	No	⊕⊕◯◯
Hot water immersion	Laboratory	Cuts	BA	1	4	40	41.21	.1681	0.45	−0.04	0.95	Yes	NA
Hot water immersion	Laboratory	Cuts, carcass	BA, ChT	2	11	188	71.83	<.001	0.98	0.66	1.30	No	⊕◯◯◯
Ultrasound + TSP + capric acid	Laboratory	Cuts	ChT	1	6	36	0.00	.9556	0.86	0.64	1.09	No	NA
Ultrasound + TSP + citric acid	Laboratory	Cuts	ChT	1	6	36	7.47	.3581	2.82	2.57	3.08	No	NA
Ultrasound + citric acid + Capric acid	Laboratory	Cuts	ChT	1	6	36	69.07	.0037	1.89	1.47	2.31	No	NA
Ultrasound + capric acid	Laboratory	Cuts	ChT	1	6	36	2.09	.4199	2.61	2.38	2.83	No	NA
Ultrasound + citric acid	Laboratory	Cuts	ChT	1	6	36	33.91	.1473	3.04	2.65	3.44	No	NA
Ultrasound + TSP	Laboratory	Cuts	ChT	1	6	36	0.00	.8289	2.08	1.82	2.34	No	NA
Ultrasound + distilled water	Laboratory	Cuts	ChT	1	6	36	45.05	.1087	3.92	3.31	4.53	No	NA
Ultrasound overall	Laboratory	Cuts	ChT	1	42	252	88.83	<.0001	2.41	2.11	2.70	No	NA
UV	Laboratory	Carcass	ChT	1	6	168	0.00	.7801	0.34	0.28	0.40	No	NA
UV	Laboratory	Skin	ChT	2	6	168	70.49	.0016	0.66	0.55	0.77	No	⊕⊕◯◯
UV	Laboratory	Cuts	ChT	2	6	54	0.00	.7241	0.67	0.61	0.73	No	⊕⊕⊕◯
UV overall	Laboratory	Carcass, skin, cuts	ChT	2	18	372	84.79	<.0001	0.55	0.46	0.64	No	⊕◯◯◯

(Continues)

TABLE 7 (Continued)

Intervention	Setting	Population	Study design	No. studies	No. trials	Sample size	I^2 (%)	Q-test p-value	LR	95 % CI			GRADE
										Lower	Upper	Include null	
Steam + ultrasound + IOBW + air chilling	Processing	Carcass	BA	1	2	44	75.50	.0433	0.95	0.41	1.49	No	NA
Steam + ultrasound	Pilot, processing	Carcass	BA	2	3	163	86.04	.0283	1.30	0.43	2.18	No	⊕○○○
Steam + lactic acid	Laboratory	Skin	ChT	1	2	40	0.00	.8488	4.96	4.46	5.46	No	NA
Steam + air chilling	Pilot	Carcass	ChT	1	2	96	93.22	.0001	2.45	1.18	3.73	No	NA
Steam + crust freezing	Pilot	Carcass	ChT	1	2	96	91.66	.0005	2.67	1.75	3.59	No	NA
Rapid cooling N_2 immersion	Laboratory	Skin	BA	1	5	200	96.45	<.0001	0.68	0.20	1.15	No	NA
Rapid cooling N_2 immersion	Laboratory	Cuts	ChT	1	4	48	98.67	<.0001	1.06	0.15	1.96	No	NA
Rapid cooling N_2 immersion	Laboratory	Skin, cuts	BA, ChT	2	9	248	98.72	<.0001	0.85	0.38	1.32	No	⊕○○○
Rapid cooling N_2 spray continuous tunnel	Pilot	Carcass	BA	1	6	220	33.98	.1969	1.25	1.06	1.44	No	NA
Rapid cooling N_2 spray on carcass batch cabinet	Pilot	Carcass	BA	1	11	277	77.52	<.0001	0.65	0.41	0.89	No	NA
Rapid cooling N_2 spray in air batch cabinet	Pilot	Carcass	BA	1	11	238	81.74	<.0001	0.40	0.09	0.72	No	NA
Rapid cooling N_2 spray overall	Pilot	Carcass	BA	1	28	735	85.65	<.0001	0.69	0.50	0.89	No	NA
MAP, 90:10 N_2:CO_2	Laboratory	Cuts	ChT	1	10	40	0.00	.9850	0.20	−0.03	0.44	Yes	NA
MAP, 80:20 N_2:CO_2	Laboratory	Cuts	ChT	1	6	36	0.00	.7812	0.22	−0.03	0.46	Yes	NA
MAP, 70:30 N_2:CO_2	Laboratory	Cuts	ChT	1	10	40	0.00	.9994	0.11	−0.12	0.34	Yes	NA
MAP, 60:40 N_2:CO_2	Laboratory	Cuts	ChT	1	7	42	60.49	.0213	0.11	−0.02	0.25	Yes	NA
MAP, 50:50 N_2:CO_2	Laboratory	Cuts	ChT	1	10	40	0.00	.9931	0.17	−0.08	0.42	Yes	NA
MAP, 30:70 N_2:CO_2	Laboratory	Cuts	ChT	1	10	40	0.00	.5497	0.17	0.07	0.27	No	NA
MAP, 10:90 N_2:CO_2	Laboratory	Cuts	ChT	1	10	40	0.00	.9963	0.20	−0.06	0.45	Yes	NA
MAP, N_2:CO_2	Laboratory	Cuts	ChT	2	63	278	7.90	.9990	0.15	0.09	0.21	No	⊕○○○
MAP, Vacuum	Laboratory	Cuts	ChT	2	14	132	96.93	<.0001	0.01	−0.57	0.59	Yes	⊕○○○
MAP, 80:20 O_2:N_2	Laboratory	Cuts	ChT	1	10	40	11.99	.3332	0.61	0.34	0.89	No	NA
MAP, 40:30:30 :: CO_2:O_2:N_2	Laboratory	Cuts	ChT	1	10	40	9.51	.3398	0.45	0.19	0.71	No	NA
MAP, 100 N_2	Laboratory	Cuts	ChT	1	4	24	0.00	.5412	0.17	0.07	0.27	No	NA
MAP, others	Laboratory	Cuts	ChT	3	38	236	91.22	<.0001	0.30	0.06	0.54	No	⊕○○○

TABLE 8 Summary of findings for prevalence changes due to physical decontamination and treatment combinations

Intervention	Setting	Population	Study design	No. studies	No. trials	Sample size	I^2 (%)	*Q*-test *p*-value	95% CI OR	95% CI Lower	95% CI Upper	Include null	GRADE
Rapid cooling N_2 immersion	Laboratory	Skin	BA	1	5	200	26.27	.1986	0.07	0.02	0.23	No	NA
MAP	Laboratory	Carcass	BA	2	11	858	74.19	<.0001	0.62	0.24	1.62	Yes	⊕◯◯◯

ered carcasses with an associated GRADE score of high. By contrast, the meta-analysis of cloacal plugging suggested a slight increase in concentration (−0.78 $\log_{10}$CFU; 95% CI: −1.74 to 0.18); however, the direction of effect is imprecise because the majority of the trials observed an increase in concentration, whereas two trials observed a decrease. The quality of evidence for cloacal plugging is very low, mainly due to very serious inconsistency and serious imprecision. Prevalence changes during cloacal plugging were reported by two before–after studies and one challenge study (Figure B.14 in the Supporting Information). In all three studies, major reductions in prevalence were observed with a combined OR of 0.02 (95% CI: 0.00–0.50); however, the GRADE score was very low due to some concerns of risk of bias, very serious inconsistency, and serious indirectness.

The results imply that defeathering is a critical point in broiler processing that can severely affect the microbial safety of the product. Consequently, it is advisable to closely monitor defeathering and apply appropriate interventions. A risk assessment study by Nauta et al. (2007) predicted that the exterior concentration would increase during defeathering and that fecal leakage is the major source of contamination in the end product. Organic acid injection into the cloaca seems to be a promising approach, but not enough information is available to implement this application on a broader scale. Cloacal plugging, on the other hand, is unpredictable and has limited effectiveness based on available data. Moreover, no commercial equipment is available for either application, and they may not be feasible for industry adoption.

3.2.3 | Evisceration

During evisceration, the internal organs of broilers are removed either manually or by automated systems found in most industrial settings. Due to differences in bird size and equipment properties, visceral rupture is a common issue that might allow intestinal contents to leak out and contaminate the exterior (Rosenquist et al., 2006). For this reason, the evisceration step has been studied extensively, and a large number of trials were identified in the literature.

For concentration changes, 61 trials from 12 before–after studies were included in the meta-analysis, resulting in a combined mean difference of −0.15 $\log_{10}$ CFU (95% CI: −0.33 to 0.03). However, significant heterogeneity was detected (I^2 = 85%, $p < .001$) (Figure B.4 in the Supporting Information). The pooled effect size and the CI around it indicate that evisceration has a minimal effect on concentration; however, the individual trials reported log reductions as high as 2.06 $\log_{10}$CFU and increases as high as 2.75 $\log_{10}$CFU, and thus the true effect of evisceration is inconclusive. The GRADE score for concentration change due to evisceration was low due to very serious inconsistency and serious imprecision. The reasons for these conflicting results on the effect of evisceration on concentration are unclear because the included studies did not provide details about the evisceration process or the contamination status of the previously processed batch. Similar to defeathering, exterior contamination after evisceration is also dependent on cecal prevalence and concentration of *Campylobacter*. Although the exterior contamination was reported significantly associated to fecal contamination (Seliwiorstow, Baré, Berkvens, et al., 2016), variations in fecal contamination in collected studies might contribute significantly to observed heterogeneity in this review. Seliwiorstow, Baré, Van Damme, et al. (2016) evaluated the effect of an up-line, contaminated batch by processing *Campylobacter*-positive and *Campylobacter*-negative batches through an evisceration line in tandem and concluded that up-line contamination contributes to extensive cross-contamination. Hinton et al. (2004a) reported decreased concentrations in most trials but concluded that the observed reduction rates were not significant; they attributed this variation to the effect of seasonal changes in processed flocks. Moreover, Rosenquist et al. (2006) collected samples in two different processing plants and concluded that the effectiveness of evisceration may depend on the properties of the machinery, which vary by plant. Similarly, Allen et al. (2007) collected samples during different seasons in different processing plants and associated the changes in contamination with the processing plant and the contamination status of the preceding flocks.

For prevalence changes due to evisceration, 44 trials from 17 studies were identified (Figure B.15 in the Sup-

porting Information). The pooled OR was estimated as 1.21 (95% CI: 0.98–1.49), indicating an increase; however, the individual trials reported opposing effect directions, and many studies reported no effect. Most of these trials started with all positive carcasses as the before samples and were not able to detect any increase in prevalence, resulting in very large uncertainty around their estimates. No heterogeneity was detected within the prevalence dataset, and the GRADE score was moderate due to serious imprecision. However, zero heterogeneity might be misleading because very large CIs were estimated for trials reporting no or little change. Caution is therefore needed when using the pooled estimate even though the heterogeneity and quality of evidence are seemingly acceptable.

3.2.4 | Washing

Carcasses are generally washed after evisceration to eliminate any excess dirt on the exterior, but in some cases, a pre-scald brush wash step is also added. Postevisceration washers can be in the form of regular spray (cabinet) washers in which only the exterior is washed, inside–outside bird washers (IOBW), and brush washers. Common critical parameters for the washing stage are water temperature, flow rate, and pressure; nozzle type and arrangement; line speed; and the addition of chemical processing aids (Keener et al., 2004).

Four studies with 33 before–after trials reporting concentration changes due to spray washing were identified in the literature (Figure B.5 in the Supporting Information). The meta-analysis results suggested that spray washing can reduce the concentration by 0.53 $\log_{10}$CFU (95% CI: 0.38–0.69); however, significant heterogeneity was detected (I^2 = 93%, $p < .001$). Although the point and interval estimates indicated a precise direction of effect (decrease), several trials reported an increase in concentration during spray washing. The GRADE score for spray washing was also low due to very serious inconsistency.

For prevalence changes during spray washing, 10 before–after trials from four studies were included in the meta-analysis (Figure B.16 in the Supporting Information). The model outputs indicated a slight decrease in prevalence, but the CI covered both increased and decreased prevalence (OR = 0.84, 95% CI: 0.62–1.14), and the trials reported conflicting information about the direction of the effect. The GRADE score for prevalence changes during spray washing was moderate due to serious imprecision. In summary, the meta-analyses of spray washing were unconclusive in terms of the direction of the effect.

Information on IOBW systems was scarcer, as only three before–after trials from two studies were identified for concentration changes. The overall log reduction was estimated as 0.54 $\log_{10}$CFU (95% CI: 0.24–0.84), suggesting small changes in concentration before and after an IOBW step with a quality of evidence score of very low due to very serious inconsistency and serious imprecision. For prevalence changes, 10 before–after trials were extracted from five studies. The overall OR estimate was 0.78 (95% CI: 0.51–1.18), indicating a decrease in prevalence, but the direction of the effect was imprecise because the trials reported conflicting information; in addition, the GRADE score was low due to serious imprecision.

For brush washing, only two trials from a single study were identified for concentration changes, and no information on prevalence changes could be collected. One of the trials quantified changes during a pre-scald brush washing; in the other trial, brush washing was applied after IOBW, and combining the two types of wash did not seem to provide an additional protective effect. When used prior to scalding, brush washing was responsible for a reduction of 0.06 $\log_{10}$CFU (95% CI: −0.71 to 0.83), suggesting no effect on concentration in the given study settings. When used after IOBW, the point estimate (0.46 $\log_{10}$CFU) suggested a greater reduction of concentration compared with pre-scald brush washing, but the wide CI (−0.77 to 1.69) showed that the direction of the effect may vary by setting.

Overall, the effectiveness of carcass washing on prevalence and concentration remains unclear, and the lack of reporting of process characteristics in the included studies contributes to the variability and uncertainty in the meta-analysis estimates. Although washing is considered an important step in controlling *Campylobacter*, different applications and varying process conditions makes it harder to compare and summarize (Zweifel et al., 2015).

3.2.5 | Immersion chilling

Chilling is an important step in poultry processing that aims to cool processed carcasses as rapidly as possible to ensure minimal microbial growth during storage. Two approaches of carcass chilling are adopted worldwide: immersion chilling, in which carcasses are dipped in cold water, often amended with antimicrobials, and air chilling, in which cold air is blown onto the carcasses. Immersion chilling is the dominant method in the United States, whereas air chilling is the preferred method of carcass chilling in Europe, Canada, and Brazil and is gaining popularity in the United States (Carroll & Alvarado, 2008; James et al., 2006).

Immersion chilling is well-documented in the literature as a highly effective processing stage in terms of microbial safety and is often compared to air chilling. In this review, 23 before–after trials from 18 studies reporting concentration changes due to immersion chilling were

identified (Figure B.6 in the Supporting Information). All included trials consistently reported log reductions within a range of 0.70–4.12 $\log_{10}$CFU, with a combined effect of 1.80 $\log_{10}$CFU (95% CI: 1.43–2.17). The GRADE score was very high and was downgraded due to inconsistency but upgraded for very large effect size.

Heterogeneity for this dataset was significant ($I^2 = 93\%$, $p < .001$) due to possible differences in processing parameters that were unreported. Three subgroups based on the use of additives were identified within the immersion chilling group for concentration changes. Most trials reported immersion chilling with chlorine; only two trials reported immersion chilling without any additives, and another three focused on a commercial antimicrobial herbal extract named "Protecta2," the contents of which were not disclosed and which was used as a processing aid during immersion chilling. When immersion chilling was performed without any additives, a significant log reduction of 1.25 $\log_{10}$CFU (95% CI: 0.96–1.55) was estimated. Compared with Protecta2, chilling with chlorine resulted in a higher mean log reduction estimate (1.95 $\log_{10}$CFU; 95% CI: 1.46–2.45), indicating that the addition of chlorine might control the concentration on carcasses more efficiently. However, significant heterogeneity ($I^2 = 93\%$, $p > .001$) was detected among the trials, with a GRADE score of very high that was downgraded for very serious inconsistency but upgraded for very large effect. Despite the inconsistent results, immersion chilling can clearly reduce the concentration on broiler carcasses and may be potentiated by the addition of chlorine, reiterating the importance of this processing stage in the processing chain.

Similarly, studies reporting prevalence changes due to immersion chilling with chlorine were more abundant than those without additives (Figure B.17 in the Supporting Information). Overall, a pooled OR of 0.52 (95% CI: 0.35–0.75) was estimated when combining trials reporting immersion chilling with and without additives. The GRADE score for this outcome was low due to some concerns of risk of bias and serious inconsistency. In particular, the pooled OR for immersion chilling with additives was estimated as 0.71 (95% CI: 0.28–0.61). Although most of the trials reported a reduction in prevalence, a few trials indicated increased prevalence even when the chilling water was amended with chlorine. The results of the meta-analysis also suggest that immersion chilling without any additives may increase prevalence, as a combined OR of 1.55 (95% CI: 0.81–2.96) was estimated for this outcome. No heterogeneity was detected for this outcome, but both increased and decreased prevalences were reported in the trials, so the direction of the effect was imprecise. The GRADE score was very low for this outcome due to the high overall risk of bias and serious imprecision. Increased prevalence can be explained by cross-contamination of carcasses due to the washing effect of the chilling water, and the results suggest that chlorinating the chilling water can control the spread of *Campylobacter* during the immersion chilling process.

3.2.6 | Air chilling

Air chilling is commonly used as an alternative to immersion chilling and may offer some practical advantages and product quality improvements. Air chilling can be advantageous in terms of reducing water use and wastewater discharge, minimizing chilling water absorption by the carcass, extending shelf life, and improving the retention of quality parameters such as color and texture (Carroll & Alvarado, 2008; Huezo, Smith, et al., 2007). Air chilling is also reported to reduce cross-contamination compared with immersion chilling, but cross-contamination can still be an issue, especially when water mist sprays are utilized to increase chilling efficacy (Mead et al., 2000).

Three challenge trials from two studies and 13 before–after trials from seven studies for concentration changes due to air chilling of carcasses were identified and are summarized in Figure B.7 in the Supporting Information. In general, air chilling was responsible for a slight decrease in *Campylobacter* concentration. In particular, the combination of before–after trials suggested that a 0.48 $\log_{10}$CFU (95% CI: −0.07 to 1.03) reduction can be expected, although the direction of the effect is imprecise. The individual trials reported slight decreases in concentration, except for one trial where a notable increase in concentration was observed. The authors did not explain this observation but hinted at the possibility of cross-contamination due to chilled air being pulled from the processing area (Oosterom et al., 1983). Heterogeneity was significant for this outcome ($I^2 = 94\%$, $p < .0001$), and the GRADE score indicated very low quality of evidence due to some concerns of risk of bias, very serious inconsistency, and serious imprecision. Three challenge trials yielded similar estimates of a slight decrease (0.67 $\log_{10}$CFU; 95% CI: 0.06–1.28) with a very low GRADE score due to some concerns of risk of bias, very serious inconsistency, serious indirectness, and serious imprecision.

With regard to prevalence changes, one challenge trial from a pilot plant and 10 before–after trials from seven studies in processing plants were included in the meta-analysis (Figure B.18 in the Supporting Information). The before–after trials were further grouped by regular air chilling and combi-inline air chilling, which combines immersion and air chilling. The analysis of the regular air chilling trials resulted in an average OR of 0.90 (95% CI: 0.65–1.25), indicating a small decrease in prevalence; however, the direction of the effect was imprecise. No significant het-

erogeneity was detected for this outcome, and the GRADE score was estimated as low due to some concerns about risk of bias and serious imprecision. The two trials on combi-inline air chilling yielded a similar pooled OR of 0.87 (95% CI: 0.28–2.68) with significant heterogeneity (I^2 = 87%, p = .006) and a GRADE score of very low due to very serious inconsistency and very serious imprecision. The single challenge trial showed no effect. The main limitation of the collected evidence is the lack of reporting on some critical parameters, such as temperature and air flow rate, that might explain the heterogeneity within the compiled dataset.

The meta-analysis results suggest that, in terms of log reduction, immersion chilling is more effective than air chilling, regardless of the use of chlorine in immersion water. Regarding prevalence, the meta-analyses imply that air chilling can produce a slight decrease that is superior to that obtained with immersion chilling without additives; however, immersion chilling with added chlorine seems to be a safer option in terms of microbial safety because it provides a greater reduction in prevalence.

3.2.7 | Refrigeration

Refrigerated storage is crucial for ensuring broiler safety and quality and is the dominant storage method in broiler chicken supply chains (USDA, 2020). The effect of refrigeration on *Campylobacter* concentration was reported by 19 before–after trials from three studies and 25 challenge trials from six studies (Figures B.8 and B.9 in the Supporting Information). Separate meta-analyses were conducted for the before–after trials and challenge trials because the challenge tests were conducted under laboratory settings with artificial contamination on chicken parts or skin, possibly contributing to indirectness of the outcomes. The meta-analysis of before–after studies yielded a mean log reduction of 0.83 $\log_{10}$CFU (95% CI: 0.60–1.05), pointing to a decrease in concentration during refrigeration. However, there was significant heterogeneity for this outcome (I^2 = 81%, p < .001), and the GRADE score was very low due to some concerns about risk of bias and serious inconsistency. To explore the sources of the heterogeneity, the trials were split into two subgroups depending on storage time. Refrigeration for up to 7 days was estimated to cause a reduction of 0.69 $\log_{10}$CFU (95% CI: 0.41–0.98), but heterogeneity for this subgroup was still significant (I^2 = 83%, p < .0001). The mean difference was estimated as 1.12 $\log_{10}$CFU (95% CI: 0.88–1.35) for refrigeration for up to 14 days, and heterogeneity was moderate but marginally significant (I^2 = 0.46, p = .0796). The challenge trials were also split into two subgroups based on the treatment unit. The combined mean difference was estimated as 0.32 $\log_{10}$CFU (95% CI: 0.19–0.46) for challenge trials on chicken parts and 0.82 $\log_{10}$CFU (95% CI: 0.47–1.18) for challenge trials on chicken skin. Because these studies were not conducted in a processing environment with natural contamination, direct application of these results in industrial settings needs to be made with caution. However, trials on chicken parts may be a starting point for evaluating the safety of packaged chicken products sold in pieces. Although the heterogeneity and indirectness issues might hamper the interpretation of the estimates, longer storage times seem to be more effective in reducing *Campylobacter* concentrations on broiler carcasses. Nevertheless, it should be noted that this review only covers *Campylobacter*, and extended storage might increase the risk of growth of other pathogenic or spoilage microorganisms.

Regarding prevalence changes due to refrigeration, 21 before–after trials from five studies were included in the meta-analysis (Figure B.19 in the Supporting Information). The trials were again split into subgroups by refrigeration times of up to 7 days or up to 14 days or unreported time. When the two subgroups were combined, a mean OR of 0.36 (95% CI: 0.18–0.7) was estimated, and subgroup analysis yielded very similar results. Heterogeneity for this outcome was moderate but statistically significant (I^2 = 42%, p = .0341), with a low GRADE score due to some concerns with risk of bias and serious inconsistency. Overall, a reduction in prevalence is likely to occur during refrigerated storage, and storage time does not have a meaningful effect on this reduction.

3.2.8 | Freezing

Freezing of broiler parts and carcasses is offered as an alternative to refrigeration in order to ensure food safety and quality for prolonged periods. For the meta-analysis of changes in concentration, 28 before–after trials on whole carcasses from four studies were included (Figure B.10 in the Supporting Information). The mean log reduction due to freezing was estimated as 1.29 $\log_{10}$CFU (95% CI: 1.10–1.48) with high heterogeneity (I^2 = 69%, p < .001). Storage time and temperature are the two main parameters in freezing applications, and most of the studies were conducted at −20°C but variable times. For this reason, the trials were grouped according to storage times for storage periods of up to 14 days and from 1 to 7 months. However, grouping did not explain the overall heterogeneity, and there was no meaningful difference between the subgroups, indicating that extending the storage time does not have a positive effect on log reduction.

The effect of freezing was also studied in challenge trials under laboratory conditions on different chicken parts such as wings, breast meat, or skin. Thirty-two challenge

trials from three studies were identified in the literature and included in the meta-analysis (Figure B.11 in the Supporting Information). These trials resulted in a combined log reduction estimate of 1.20 $\log_{10}$CFU (95% CI: 1.08–1.32) with very high heterogeneity ($I^2 = 98\%$, $p < .001$). Challenge tests conducted in the laboratory with treatment units other than carcasses are considered indirect evidence within the scope of this review. However, the estimates from both before–after and challenge trials indicate that challenge tests on freezing may be able to capture accurate information.

Eleven before–after trials from five studies providing information about prevalence changes due to freezing of carcasses were identified (Figure B.20 in the Supporting Information). The mean OR estimate from these trials was 0.12 (95% CI: 0.03–0.54), with significant heterogeneity ($I^2 = 83\%$, $p < .0001$). The GRADE score was low due to very serious inconsistency. Although a few trials indicated an increase in prevalence and the quality of evidence was low, an overall trend toward a reduction in prevalence was detected.

3.3 | Chemical interventions

The addition of antimicrobial chemicals during broiler chicken processing has been suggested to enhance the efficacy of microbial contamination control. Chemical interventions are most commonly applied by immersing the carcasses in solutions of chemical processing aids or spraying solutions directly onto carcasses. Another application is to coat broiler products, most commonly parts to be sold, using edible films that may be fortified with commercial antimicrobials. Chemical interventions mostly inactivate the cells, but the application can also remove the cells from the carcass surface, leading to a reduction in the concentration. Depending on the type of application, cross-contamination between the carcasses can also occur, especially when immersed into processing aid solutions. Chemicals for food industry use are required to be approved by local regulatory agencies and some of the chemicals identified in this review are still at proof-of-concept stage without approval for use. Hence, the results presented here include preliminary experiments for the evaluation and screening of novel chemicals. Summary of outcome-level meta-analysis results regarding the effects of chemical interventions on *Campylobacter* concentration and prevalence can be found in Figure 5 and 6, and Table 5 and 6. Other results including forest plots, risk of bias summaries, traffic light plots, and other related information, readers are advised to refer to the appendices in the Supporting Information.

3.3.1 | Chemical processing aids

Carcass decontamination by chemical processing aids (also known as sanitizers, disinfectants, sterilants, antiseptics, biocides, antimicrobials, or decontaminating agents; EFSA, 2008) is commonly used by the broiler industry to eliminate fecal contaminants from carcasses. The use of processing aids is widely allowed in the United States and is regulated by the Food and Drug Administration (FDA) and U.S. Department of Agriculture (USDA). In the European Union, the use of processing aids is still debated; however, a number of processing aids have been shown by the EFSA (2005, 2008, 2014) to be safe in terms of toxicity, environmental concerns, and potential to induce antimicrobial resistance. Processing aids are either applied as spray or immersion treatments with solutions of chemicals such as chlorine dioxide, acidified sodium chlorite (ASC), trisodium phosphate (TSP), and peracetic acid (PAA). The effectiveness of the treatment may depend on several factors such as concentration, order of application in the processing line, method of application (spray vs. immersion), and organic matter in dipping solutions. In this review, different applications were grouped according to spray or immersion treatments. The evaluated spray treatments were applied either after evisceration or during final washing, whereas immersion treatments were evaluated at points after defeathering, after evisceration, or after chilling.

Evidence for the effectiveness of spray applications in reducing concentration was collected from before–after and challenge studies conducted in pilot or processing plants and laboratories. Four studies with 20 before–after trials conducted in pilot or processing plants reported the effects of various chemicals. When combined, an average log reduction of 1.05 $\log_{10}$CFU (95% CI: 0.75–1.37) was estimated with very high heterogeneity ($I^2 = 99.5\%$, $p < .001$), as shown in Figure C.1 in the Supporting Information. The GRADE score for this outcome was low due to some concerns of overall risk of bias and very serious inconsistency. Among the different chemicals, CPC, ASC, and TSP produced the highest possible log reduction estimates, with values of 1.38 $\log_{10}$CFU (95% CI: 0.72–2.04), 1.26 $\log_{10}$CFU (95% CI: 0.94–1.57), and 1.26 $\log_{10}$CFU (95% CI: 0.58–1.93), respectively. For ASP and TSP, the GRADE scores were low, and heterogeneities were significant. For ASC, moderate but insignificant heterogeneity was observed, and the GRADE score was very high. An additional 20 challenge trials from four studies studying the effects of spray treatments in laboratory or pilot plant settings were retrieved (Figure C.2 in the Supporting Information). The estimated composite effects showed that spray treatments might cause an average log reduction of

1.26 $\log_{10}$CFU (95% CI: 0.73–1.79). However, heterogeneity was very high ($I^2 = 99\%$, $p < .001$), and the GRADE score was low due to some concerns of risk of bias and very serious inconsistency and indirectness. Among the different treatments, CPC and a mixture of potassium hydroxide and lauric acid offered the highest log reduction estimates of 2.16 $\log_{10}$CFU (95% CI: 0.72–3.60) and 2.01 $\log_{10}$CFU (95% CI: 0.93–3.09), respectively.

Prevalence changes due to spray applications of processing aids were reported by seven trials in four studies for ASC, CPC, and TSP as shown in Figure C.12 in the Supporting Information. The composite OR for the three treatments was estimated as 0.2 (95% CI: 0.004–0.17) with considerable heterogeneity ($I^2 = 96\%$, $p < .0001$) and a low GRADE score due to very serious inconsistency and some risk of bias concerns. Spray application of CPC was the most promising in terms of prevalence reduction, with a summary OR of 0.0032 (95% CI: 0.0016–0.0062). Despite some concerns of risk of bias, the quality of evidence was high due to very large effect size estimations. Furthermore, the heterogeneity among the trials was not significant ($I^2 = 19\%$, $p = .3252$), indicating that the included trials were consistent. For CPC, two trials resulted in a combined OR of 0.35 (95% CI: 0.24–0.50) with zero heterogeneity and a moderate GRADE score due to some concerns of risk of bias. Only one trial reported TSP spray application, with an OR of 0.48 (95% CI: 0.12–1.96), indicating a decrease in prevalence; however, the CI included the null value (OR = 1), so the direction of the effect is imprecise.

Processing aids applied by immersing carcasses were reported by before–after, controlled, and challenge trials in processing plants and research laboratories. Six before–after trials from four studies conducted at processing plants reported log reductions due to immersion treatment in ASC, citric acid, and TSP (Figure C.3 in the Supporting Information). The pooled OR of all three groups was estimated as 1.93 $\log_{10}$CFU (95% CI: 1.07–2.79), indicating that the intervention would be effective for reducing *Campylobacter*; however, significant heterogeneity ($I^2 = 95\%$, $p < .001$) was detected. The GRADE score for this outcome was moderate and was downgraded for very serious inconsistency and serious imprecision but upgraded for very large effect size. Although subgrouping into chemical agents did not explain the heterogeneity in the dataset, the stratified analysis suggested that immersion treatment with ASC was the most effective processing aid for immersion, with an average log reduction estimate of 2.07 (95% CI: 1.30–2.83), followed by TSP (1.97 $\log_{10}$CFU; 95% CI: 0.18–3.77). In addition to before–after trials conducted in processing plant settings, the majority of information was collected from challenge studies conducted under laboratory conditions using broiler skin or cuts as the sampling units rather than carcasses, which contributed to a higher level of indirectness of the collected evidence. The results of 12 before–after and 27 controlled trials from four laboratory studies are summarized in Figure C.4 in the Supporting Information and yielded an overall log reduction of 2.29 $\log_{10}$CFU (95% CI: 1.99–2.59). The GRADE score for this outcome was very low due to some concerns with risk of bias and very serious inconsistency and indirectness. Among the different treatments, TSP and a mixture of potassium hydroxide with lauric acid produced the highest log reduction estimates, with values of 2.92 $\log_{10}$CFU (95% CI: 2.13–3.70) and 2.87 $\log_{10}$CFU (95% CI: 2.15–3.59), respectively.

Three before–after studies in processing plants reported prevalence changes due to immersion in ASC (Figure C.13 in the Supporting Information). All trials reported decreases in prevalence with a pooled OR of 0.01 (95% CI: 0.00–0.03; $I^2 = 0\%$, $p = .58$). One laboratory trial reported no effect of TSP immersion on prevalence (Slavik et al., 1994), as all 50 units were positive before and after the treatment.

Challenge tests of a variety of chemical treatments and their combinations were identified in the literature search. The analysis was separated into three groups: organic acids, other chemicals, and combination treatments. Immersion applications of organic acids were reported by 30 challenge trials from eight studies as summarized in Figure C.5 in the Supporting Information. On average, organic acid immersions were reported to be responsible for reductions of 1.62 $\log_{10}$CFU (95% CI: 1.33–1.91) on skin or cut samples of chicken. The GRADE score for this outcome was very low due to risk of bias and very serious inconsistency and indirectness. Among the different treatments, capric acid offered the highest effectiveness, with a 2.18 $\log_{10}$CFU (95% CI: 1.84–2.52) reduction. With respect to processing aids other than organic acids, 12 different chemicals were identified in 11 studies with 67 challenge trials. The overall log reduction for this group was 1.47 $\log_{10}$CFU (95% CI: 1.24–1.70), and heterogeneity was significant ($I^2 = 91\%$, $p < .001$), as shown in Figure C.6 in the Supporting Information.

Because challenge tests conducted in the laboratory are quicker and more cost-effective than before–after trials in processing plants, a variety of treatments were evaluated in these settings, including unconventional treatments such as electrolyzed water, benzalkonium chloride, and grapefruit extracts. For processing aids included in before–after trials, such as ASC, CPC, and TSP, the effectiveness estimates reported by challenge tests were similar, implying that challenge studies can provide results that remain accurate under actual processing conditions.

A few studies also reported challenge tests of the effectiveness of combinations of processing aids (Figure C.7

in the Supporting Information). Thirteen challenge trials from three studies were identified in the literature search. On average, the log reduction was estimated as 2.81 $\log_{10}$CFU (95% CI: 2.09–3.53) with significant heterogeneity (I^2 = 98%, $p < .001$), possibly due to the use of different types of chemicals in combination. A very extreme combination of acidic calcium sulfate, lactic acid, ethanol, sodium dodecyl sulfate, and propylene glycol resulted in the highest log reduction estimate (4.91 $\log_{10}$CFU; 95% CI: 4.61–5.21). When combined, some processing aids included in previously mentioned groups did not offer a cumulative increase in log reduction compared with the use of a single processing aid. For example, the combined effect of ASC and TSP was estimated as 1.88 $\log_{10}$CFU reduction, whereas the mean log reduction values for ASC and TSP applied individually were estimated as 1.25 and 1.23 $\log_{10}$CFU, respectively. These findings indicate that combinations of processing aids may not always yield cumulative increases in effectiveness.

In summary, chemical processing aids can reduce levels of contamination on broiler carcasses. However, their effectiveness depends on many factors, such as initial contamination, amount of organic matter in the immersion system, and other processing parameters. Overall, the effects of these aids on *Campylobacter* are limited to approximately 1–2 $\log_{10}$CFU reductions, although a 2 log reduction in the final product is estimated to decrease the incident of campylobacteriosis by 30 times (Rosenquist et al., 2003); the effectiveness of processing aids can be lower depending on the order of application within the processing chain (e.g., postchilling or prechilling) (Dogan et al., 2019). Therefore, processing aids might not always be sufficient to reduce the risk of foodborne disease, especially when pretreatment contamination levels are very high. Processing aids can be effective but it should also be noted that processing aids should be the part of an integral food safety system and should not be regarded as alternatives to good hygiene practices (EFSA, 2005; Loretz et al., 2010). Furthermore, the increased use of antimicrobial chemicals as processing aids has raised concerns about the development of antimicrobial resistance (EFSA, 2008; Mavri & Smole Možina, 2013). Although the emergence of antimicrobial resistance due to interventions is outside the scope of this review, it is advisable to monitor the possibility of resistance before implementing interventions involving antimicrobial aids on a large scale in production facilities.

3.3.2 | Edible film coatings

Although processing aids are widely used in broiler production, consumers often have negative perceptions of chemical use due to health concerns. Therefore, naturally extracted, plant-based edible coatings containing natural antimicrobials are gaining popularity as novel methods to improve shelf life and product quality (Shrestha, Wagle, Upadhyay, Arsi, Donoghue, et al., 2019). Applications of polysaccharide-based edible coatings such as chitosan or pectin have been reported, and their antimicrobial activity can be further enhanced by fortification with additional antimicrobial compounds. For this reason, edible films were analyzed in two groups: films only and films containing antimicrobials. Due to the availability of a large number of trials, films containing carvacrol and eugenol were also grouped separately. All trials reported for these outcomes were laboratory challenge trials, as these interventions are still in the developmental stage. Applications of natural polysaccharides, chitosan, gum arabic, κ-carrageenan, and pectin coatings followed by refrigeration were evaluated in 44 challenge trials in three studies in the laboratory using chicken parts as shown in Figure C.8 in the Supporting Information. On average, edible coatings without added antimicrobials were estimated to reduce *Campylobacter* contamination by 1.30 $\log_{10}$CFU (95% CI: 1.11–1.48); however, heterogeneity was very high (I^2 = 98%, $p < .001$), and the GRADE score was very low due to risk of bias and very serious inconsistency and indirectness. Point estimates of efficacy for chitosan, gum arabic, and pectin were similar, with values of 1.31, 1.27, and 1.53 $\log_{10}$CFU, respectively, and the lowest efficacy was reported for combined coating with chitosan and κ-carrageenan (0.65 $\log_{10}$CFU). Subgroup analysis failed to reduce heterogeneity, indicating that the use of different agents in the coatings is not the major source of the great disparity among studies.

Edible film coatings with added antimicrobials to enhance antimicrobial activity have also been reported in the literature. The effect of pectin and chitosan coatings fortified with eugenol was reported in 60 trials from a single study (Figure C.9 in the Supporting Information). The overall change in concentration was estimated as 2.36 $\log_{10}$CFU (95% CI: 2.20–2.52), and the heterogeneity was significant (I^2 = 88%, $p < .001$). Chitosan and gum arabic films containing carvacrol were evaluated in 69 challenge trials from two studies (Figure C.10 in the Supporting Information). The pooled effect was estimated as 2.00 $\log_{10}$CFU (95% CI: 1.85–2.16) with significant heterogeneity (I^2 = 97%, $p < .001$). Other reported challenge trials include addition of cinnamaldehyde, allyl isothiocyanate, and mustard extract in 29 trials from two studies, as shown in Figure C.11 in the Supporting Information. These three subgroups were estimated to provide a 1.28 $\log_{10}$CFU (95% CI: 0.81–1.77) reduction on chicken parts after various times of refrigeration. Within this group, allyl isothiocyanate offered the highest log reduction (1.95 $\log_{10}$CFU;

95% CI: 0.92–2.98), and cinnamaldehyde offered the lowest (0.61 $\log_{10}$CFU; −0.35 to 1.58); a few trials reported the possibility of increased levels of contamination with the addition of cinnamaldehyde.

Edible film coatings seem to have potential as natural alternatives to industrial chemical disinfectants, as logarithmic reductions similar to those obtained using chemical processing aids were observed. However, the calculated efficacy of film coatings should be interpreted with caution. All edible film coating trials included in this review included refrigeration for certain periods. As previously mentioned in Section 3.2.7, refrigeration alone can decrease contamination in the product by an average of 0.83 $\log_{10}$CFU. Therefore, a major portion of the decontamination effect due to edible film coatings may actually be attributable to refrigeration. Edible film coatings have been suggested as a novel method to preserve the quality and safety of a range of food products, but the actual efficacy of large-scale implementations remains uncertain due to a lack of knowledge in the currently available literature.

3.4 | Physical decontamination treatments and treatment combinations

Physical decontamination methods refer to interventions that aim to reduce contamination on broiler carcasses or meat products by means of temperature changes or electrochemical, electromagnetic, or mechanical disruptions of pathogenic cells. Most physical interventions are currently in the development phase, with only limited applications in industry. Accordingly, most of the trials in this group were conducted under laboratory conditions, used broiler parts or skin sections as treatment units, and were performed in challenge trial settings. Consequently, data on concentration changes are abundant, but only limited information could be collected on prevalence changes. Summary of outcome-level meta-analysis results regarding the effects of physical interventions on *Campylobacter* concentration and prevalence can be found in Figure 7 and 8, and Table 7 and 8. Other results including forest plots, risk of bias summaries, traffic light plots, and other related information, readers are advised to refer to the appendices in the Supporting Information.

3.4.1 | Steam pasteurization and its combinations

Steam pasteurization has been suggested as a novel method of surface decontamination of broiler carcasses and parts that involves applying saturated steam for short periods of time. Two before–after and 16 challenge trials from four studies are summarized in Figure D.1 in the Supporting Information. The pooled concentration change for all trials was estimated as 2.23 $\log_{10}$CFU (95% CI: 1.65–2.80), and the heterogeneity was very high (I^2 = 96%, $p < .001$). Subgrouping based on study type did not improve the heterogeneity. The GRADE score for this outcome was very low due to some concerns of risk of bias and very serious inconsistency and indirectness. The log reduction estimates from challenge trials were noticeably higher than those from before–after trials, possibly due to more controllable experimental conditions and higher initial inoculum concentrations in the former; however, some of the trials did not report the initial contamination levels. Although steam pasteurization offers rapid and effective decontamination of broiler samples, careful process optimization is advised because overheating may cause partial or complete cooking or underheating may compromise the expected log reduction (James et al., 2000, 2007; Kure et al., 2020).

Steam pasteurization is often studied in combination with other interventions and processing stages to increase the decontamination efficacy. Combined effects were reported in five before–after and six challenge trials in four studies as shown in Figure D.2 in the Supporting Information. Although a forest plot was produced to include all different combinations, a pooled estimate was not calculated because the treatments were too different to combine. Among these combinations, steam and lactic acid treatment on chicken skin showed the highest efficacy (4.96 $\log_{10}$CFU; 95% CI: 4.46–5.46) with zero heterogeneity. Compared with previous estimates for steam pasteurization or lactic acid application alone, the observed values reflected a cumulative effect of the two treatments. Although this combination appeared to be highly effective, the number of trials and the sample size were too small to be conclusive. Other combinations were not noticeably different from the estimates for steam or the coupled treatment when applied alone.

3.4.2 | Pulsed electric field

The literature search identified only one study reporting the effect of pulsed electric field (PEF) treatment on concentration in 10 challenge trials on skinless breast meat under laboratory conditions (Figure D.3 in the Supporting Information). The pooled effect of these trials showed that PEF treatment had no effect on *Campylobacter* concentration on skinless breast meat samples, with a pooled log reduction −0.07 $\log_{10}$CFU (95% CI: −0.16 to 0.02, I^2 = 22%, p = .3256). The GRADE score for this outcome was very low due to risk of bias and very serious indirectness.

3.4.3 | High-voltage treatment and its combinations

High-voltage treatment was studied by Zhuang et al. (2019) in three challenge trials with different doses of treatment on skinless chicken breasts (Figure D.3 in the Supporting Information). The pooled log reduction estimate was 1.31 $\log_{10}$CFU (95% CI: 0.94–1.69), and the heterogeneity was very low ($I^2 = 0\%$, $p = .55$). The GRADE score for this outcome was very low because of some concerns of risk of bias and very serious indirectness and imprecision due to limited sample size.

3.4.4 | Crust freezing

Crust freezing refers to the process of freezing the skin of a carcass quickly without freezing the meat under the skin. Only one before–after trial in a processing plant (Boysen & Rosenquist, 2009) was identified and reported a log reduction of 0.42 $\log_{10}$CFU (95% CI: 0.36–0.48). The remaining six trials from the single study in this dataset reported challenge trials in pilot plant settings with solo crust freezing or crust freezing combined with steam or hot water immersion, with two trials in each group (Figure D.4 in the Supporting Information). The overall pooled estimate for log reduction was estimated as 2.00 $\log_{10}$CFU (95% CI: 1.29–2.72), and the GRADE score was very low. The effectiveness was noticeably lower in the single before–after trial than in the challenge trials, suggesting that although crust freezing seems effective under highly controlled conditions, the feasibility of large-scale implementation is still in question.

3.4.5 | Hot water immersion

Hot water immersion for short time (up to 40 s) at 70–80°C was reported by seven challenge trials and four before–after trials in the laboratory by two studies as summarized in Figure D.5 in the Supporting Information. The pooled log reduction estimate for the challenge trials was 1.23 $\log_{10}$CFU (95% CI: 0.94–1.52) with significant heterogeneity ($I^2 = 58\%$, $p = .028$). By comparison, the before–after trials reported lower efficacy (0.45 $\log_{10}$CFU; 95% CI: −0.04 to 0.95) with moderate heterogeneity ($I^2 = 41\%$, $p = .17$). Therefore, even if hot water immersion seems to be moderately effective when challenging samples with high inoculation levels, its effectiveness might be limited under natural contamination conditions at processing plants.

3.4.6 | Ultrasound with various processing aids

All trials regarding log reduction by ultrasound treatment coupled with chemical processing aids were reported by Koolman et al. (2014b) in 42 challenge trials in laboratory settings. The data were divided into seven groups according to the chemical processing aid used: TSP with capric acid, TSP with citric acid, citric acid with capric acid, capric acid, citric acid, TSP, and distilled water as a control, as shown in Figure D.6 in the Supporting Information. Overall, the effect of ultrasound with various processing aids was estimated as a 2.41 $\log_{10}$CFU (95% CI: 2.11–2.70) reduction with significant heterogeneity ($I^2 = 89\%$, $p < .001$). The highest reduction was observed for the TSP and capric acid combination, 3.92 $\log_{10}$CFU (95% CI: 3.31–4.53, $I^2 = 45\%$, $p = .1087$), whereas the lowest reduction was observed for distilled water, 0.86 $\log_{10}$CFU (95% CI: 0.64–1.09). Therefore, in this study, the change in concentration was primarily attributable to the chemicals used rather than the ultrasound treatment itself.

3.4.7 | Ultraviolet

Ultraviolet (UV) treatment trials were grouped into three categories according to the treated sample unit as shown in Figure D.7 in the Supporting Information: whole carcass, skin, and skinless breasts. A total of 18 challenge trials from two laboratory studies were included in the meta-analysis. The pooled effect for the UV treatment was estimated as 0.55 $\log_{10}$CFU (95% CI: 0.46–0.64) with significant heterogeneity ($I^2 = 85\%$, $p < .001$). The GRADE score for this outcome was very low due to risk of bias and very serious inconsistency and indirectness. The decontamination effect was minimal in all three subgroups. Subgrouping based on sample type helped address the heterogeneity, as zero heterogeneity was estimated for the subgroups of UV treatment of whole carcasses and skinless breast fillets. The lowest log reduction was observed for the UV treatment of whole carcasses (0.34 $\log_{10}$CFU; 95% CI: 0.28–0.40), implying that UV treatment may not be an effective solution for *Campylobacter* in broiler products and that its effectiveness is reduced even further if whole carcasses are treated in commercial settings.

3.4.8 | Rapid cooling (super-chilling)

Rapid cooling, also known as super-chilling, involves quickly freezing the skin of the product while keeping

the meat unfrozen. This process can reduce the number of *Campylobacter* on the skin due to cell injury during the freeze–thaw cycle and oxidative stress (Burfoot et al., 2016). Similar to processing aids, rapid cooling is applied by immersion or spraying of coolants such as liquid nitrogen. Rapid cooling by immersion of chicken skin or parts was reported by two studies in five before–after and four challenge trials as shown in Figure D.8 in the Supporting Information. Before–after trials in the laboratory with breast skin as the treatment unit were estimated to cause a 0.68 $\log_{10}$CFU (95% CI: 0.20–1.15) reduction; however, heterogeneity was highly significant ($I^2 = 97\%$, $p < .0001$), and the GRADE score was very low due to high risk of bias, very serious inconsistency, and very serious indirectness. The pooled effect of the remaining challenge tests on chicken wings was 1.06 $\log_{10}$CFU (95% CI: 0.38–1.32), also with highly significant heterogeneity ($I^2 = 99\%$, $p < .0001$) and a very low GRADE score due to very serious inconsistency, very serious indirectness, and serious imprecision. The discrepancy between the results of before–after and challenge trials implies that the effectiveness of super-chilling may be overestimated because of differences between natural and induced contamination in initial levels of contamination and strain characteristics. Burfoot et al. (2016) also reported prevalence changes for liquid N_2 immersion of breast skin samples in five before–after trials as shown in Figure D.13 in the Supporting Information. The majority of the trials indicated a considerable reduction in prevalence, as the OR estimates were less than one. The pooled OR estimate was 0.07 (95% CI: 0.02–0.23), with significant heterogeneity ($I^2 = 80\%$, $p < .0001$) and a very low GRADE score due to high risk of bias and very serious indirectness. Although the log reduction was not substantial, under real processing conditions it might be sufficient to reduce contamination to undetectable levels on the majority of units due to the relatively low contamination on carcasses that have reached the chilling step. In general, rapid cooling by immersion may contribute an additional log reduction but cannot be solely relied upon as an effective decontamination measure.

Spray rapid cooling treatment was reported in 28 before–after trials by Burfoot et al. (2016) in three subgroups using liquid N_2 in a patented rapid surface chilling system in the form of a continuous tunnel or batch cabinets as shown in Figure D.9 in the Supporting Information. The overall log reduction estimate was 0.69 $\log_{10}$CFU (95% CI: 0.50–0.89), with significant heterogeneity ($I^2 = 86\%$, $p < .001$). The GRADE score for this outcome was very low due to high risk of bias and very serious inconsistency. Continuous treatment in the tunnel system was noticeably more effective than batch cabinets in reducing contamination levels.

3.4.9 | Modified atmosphere packaging

Modified atmosphere packaging (MAP) has been suggested to control the growth of microorganisms and maintain freshness by changing the gas compositions in packaging and has been widely applied to numerous food products. A few studies have reported the effect of MAP on *Campylobacter* contamination during the refrigerated storage of chicken products. In this review, concentration changes during MAP storage were categorized into two groups; the first group included MAP applications with different ratios of N_2 and CO_2, and the second group included storage under vacuum and different ratios of N_2, O_2, and CO_2. Packaging with different ratios of N_2 and CO_2 and refrigeration for up to 17 days were reported by 63 challenge trials in two studies as shown in Figure D.10 in the Supporting Information. The overall log reduction offered by these trials was minimal (0.15 $\log_{10}$CFU; 95% CI: 0.09–0.21), and the heterogeneity within this dataset was very low ($I^2 = 8\%$, $p = .999$), with a very low GRADE score due to some concerns of risk of bias and very serious indirectness. Other gas combinations were reported by 38 challenge trials in three studies as shown in Figure D.11 in the Supporting Information. Similarly, the pooled log reduction estimate was minimal (0.30 $\log_{10}$CFU; 95% CI: 0.06–0.54), with significant heterogeneity ($I^2 = 92\%$, $p < .001$), and the GRADE score was very low due to some concerns of risk of bias, serious imprecision, and very serious inconsistency and indirectness. The most effective combination was 80:20 O_2:N_2, with a pooled estimate of 0.61 $\log_{10}$CFU (95% CI: 0.34–0.89), and the least effective was vacuum packing of chicken samples, with several trials by Olaimat et al. (2014) showing increased levels of contamination.

Byrd et al. (2011) reported nine before–after trials investigating the effects of different combinations of gases in MAP during refrigeration (Figure D.12 in the Supporting Information). The pooled log reduction estimate was 0.31 (95% CI: −0.11 to 0.75) with moderate heterogeneity ($I^2 = 56\%$, $p = .017$). The highest pooled log reduction was estimated for MAP with 100% O_2 (0.69; 95% CI: −0.10 to 1.47); however, only one of three trials showed a log reduction, whereas the other two indicated increased concentrations.

Two studies also reported prevalence changes during MAP storage with 11 before–after trials as summarized in Figure D.14 in the Supporting Information. The pooled OR was estimated as 0.62 (95% CI: 0.24–1.62), with significant heterogeneity ($I^2 = 74\%$, $p < .0001$). Some of the trials reported increases in prevalence, and the 95% CIs for majority of the trials and the pooled estimate indicated "no effect," likely due to their small sample sizes. Consequently, the direction of the effect was imprecise.

The reported increases in contamination levels and the effect of refrigeration in the absence of MAP imply that MAP may not affect bacterial contamination on carcasses compared with no intervention. Hence, its use is not recommended unless further research reports benefits.

3.5 | Overall quality of the studies and additional results

All of the included studies were published in reputable journals and passed rigorous assessment of their scientific merits. However, in general, some reporting issues should be taken into consideration for food science and technology research.

Risk of bias analysis (Appendix A in the Supporting Information) may suggest better reporting practices. The most common problem in reporting was randomization. In randomized controlled trials in human and animal medicine, the randomization process is typically reported, but most of the studies included in this review were published in food science-related journals and did not report randomization. For such studies, randomization was recorded as "convenience"-based selection. It is impossible to evaluate selection bias in the absence of information about how the samples were selected and whether the selection of samples was independent of the subsequent treatment allocation. In addition, information on intended outcomes and attrition was generally not reported, casting doubt on the assessment of biases in reporting or attrition. We urge investigators to be more transparent about these issues in food science and technology studies. Another important problem was the absence of background information that might be helpful for explaining heterogeneity, such as processing conditions and status of batches of broilers prior to processing. By contrast, the majority of studies were highly transparent and clear about their methodologies for sample preparation and microbiological measurement, including the detection and enrichment methods used.

Systematic reviews are useful tools for identifying reporting issues at the study level as well as overall context. In human medicine, the importance of complete and accurate reporting has long been documented, and several guidelines have been established for strengthening reporting, such as the Consolidated Standards of Reporting Trials (CONSORT) statement (Schulz et al., 2010) and the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) checklist (Knottnerus & Tugwell, 2008). Most recently, the REFLECT statement was developed as an extension of the CONSORT statement for application in veterinary medicine by accommodating differences between randomized clinical trials with human subjects versus livestock animals (O'Connor et al., 2010). Similarly, the findings of this review and other systematic reviews in relevant fields can build guidelines that improve reporting in food science and technology studies.

At the outcome level, the included studies cover the full chain of broiler production. However, the number of trials covering concentration changes was much greater than the number of trials assessing prevalence changes, which limits the interpretation of prevalence changes. Both concentration and prevalence are crucial for tracking microbial change throughout the chain and for feeding QMRA models for systematic food safety decision-making. In each processing step, microbial changes can be viewed as the effects of one or more of six basic phenomena (i.e., growth, inactivation, mixing, partitioning, removal, and cross-contamination) as suggested by Nauta et al. (2005), and neither concentration nor prevalence fully represents the impact of these phenomena. Furthermore, although most of the included studies reported concentration only on *Campylobacter*-positive samples, a portion of them did not report if the negative samples were included in the measurements or not, which may cause bias in the composite estimates. Future studies should report both outcomes by conducting more processing or pilot plant studies with natural contamination on carcasses, rather than focusing only on concentrations of *Campylobacter* and other important microorganisms.

Some limitations also exist based on the common methodology for systematic reviews and meta-analyses. Current methods and quality assessment procedures were mainly developed with the healthcare setting in mind, and food safety studies frequently differ significantly from healthcare studies in terms of randomization, allocation, and sample sizes. At the data analysis level, heterogeneity is the most common indicator of the usability or applicability of the results in decision-making or future studies. IntHout et al. (2015) pointed out that heterogeneity could be larger between small studies compared with larger studies. Many of the studies included in the present review were small, so their inclusion might induce high heterogeneity and consequently negatively affect the confidence of the effect size estimates. Moreover, studies with small sample sizes might mask potential inconsistencies, which can be confounded by measures of imprecision. Imprecision was determined when high variance occurred; however, the results across studies may seem consistent due to overlapping, wide CIs. In the current GRADE scheme, heterogeneity and imprecision are often evaluated independently, which overlooks the relationship between these two measures. Hence, the risk of falsely identifying heterogeneous datasets as nonheterogeneous should not be overlooked when discussing and implementing meta-analysis studies where the imprecision is very severe.

4 | CONCLUSIONS

The present systematic review provides a comprehensive summary and critical analysis of current knowledge in the literature on changes in the concentration and prevalence of *Campylobacter* in broiler chicken along the full processing chain attributable to various processing stages and microbial intervention strategies. In general, the results indicate that processing stages can either reduce or increase *Campylobacter* contamination on broiler carcasses. Scalding and chilling can reduce both prevalence and concentration. However, it is advisable to augment their control efficacy by integrating the application of processing aids to control possible cross-contamination between carcasses and contamination from feces. Although preferred for some quality aspects, air chilling may not provide as much control as immersion chilling; therefore, combining air chilling with other control measures such as processing aids may ensure further reduction in prevalence and concentration. As downstream steps, refrigeration and freezing will prevent growth and provide reduction in both concentration and prevalence. By contrast, evisceration and defeathering are likely to increase prevalence or concentration, and these stages should be closely monitored and targeted by interventions if necessary. Chemical and physical interventions can reduce broiler contamination by up to 1–2 logs and are mostly effective in reducing prevalence. However, discrepancies between before–after and challenge trials indicate that the effectiveness of these interventions might be limited under commercial conditions.

This review provides composite estimates for processing stages and interventions, and a comprehensive list of observed effects in individual studies that can be used for future studies. Although risk management can gain valuable information from the results, it should be noted that the cumulative effects of processing stages and interventions, and risk estimates can only be estimated by following a QMRA. Risk management should also consider the processing chain as a whole, as the individual effects of stages and interventions are highly variable and dependent on the characteristics of each processor; therefore, an integrated approach for food safety should be followed to minimize the risk of campylobacteriosis through the consumption and handling of broiler chicken products.

The included studies provided limited information about study design, pre- and postharvest conditions, and possible confounders, which highlights the need for the development of best practices in reporting scientific data in food science and technology studies. At the outcome level, unexplained heterogeneity was the main limiting factor. To overcome this issue, better reporting of processing conditions and other factors in future studies is suggested.

The findings of this systematic review and meta-analysis are expected to be useful for evidence-based decision-making by government and industry risk managers and risk assessors. Although newly adopted for food safety practices, systematic evidence collection can provide unbiased and transparent estimations for processing stages and interventions for more accurate and reliable decisions on food safety management and public health protection.

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AUTHOR CONTRIBUTIONS

Onay Dogan: Data curation; Formal analysis; Methodology; Software; Validation; Visualization; Writing-original draft. Anand Aditya: Data curation; Methodology; Software. Juan Ortuzar: Data curation; Software. Jennifer Clarke: Conceptualization; Supervision; Writing-review & editing. Bing Wang: Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Writing-original draft.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

Abu-Ruwaida, A. S., Sawaya, W. N., Dashti, B. H., Murad, M., & Al-Othman, H. A. (1994). Microbiological quality of broilers during processing in a modern commercial slaughterhouse in Kuwait. *Journal of Food Protection*, *57*(10), 887–892.

Aiassa, E., Higgins, J. P. T., Frampton, G. K., Greiner, M., Afonso, A., Amzal, B., Deeks, J., Dorne, J.-L., Glanville, J., Lövei, G. L., Nienstedt, K., O'connor, A. M., Pullin, A. S., Rajić, A., & Verloo, D. (2015). Applicability and feasibility of systematic review for performing evidence-based risk assessment in food and feed safety. *Critical Reviews in Food Science and Nutrition*, *55*(7), 1026–1034. https://doi.org/10.1080/10408398.2013.769933

Allen, V. M., Bull, S. A., Corry, J. E. L., Domingue, G., Jorgensen, F., Frost, J. A., Whyte, R., Gonzalez, A., Elviss, N., & Humphrey, T. J. (2007). Campylobacter spp. contamination of chicken carcasses during processing in relation to flock colonisation. *International Journal of Food Microbiology*, *113*(1), 54–61. https://doi.org/10.1016/j.ijfoodmicro.2006.07.011

Arritt, F. M., Eifert, J. D., Pierson, M. D., & Sumner, S. S. (2002). Efficacy of antimicrobials against *Campylobacter jejuni* on chicken breast skin. *Journal of Applied Poultry Research*, *11*(4), 358–366. https://doi.org/10.1093/japr/11.4.358

Baker, R. C., Paredes, M. D., & Qureshi, R. A. (1987). Prevalence of *Campylobacter jejuni* in eggs and poultry meat in New York State. *Poultry Science*, *66*(11), 1766–1770.

Bashor, M. P., Curtis, P. A., Keener, K. M., Sheldon, B. W., Kathariou, S., & Osborne, J. A. (2004). Effects of carcass washers on *Campylobacter* contamination in large broiler processing plants. *Poultry Science*, *83*(7), 1232–1239.

Bauermeister, L. J., Bowers, J. W. J., Townsend, J. C., & McKee, S. R. (2008). Validating the efficacy of peracetic acid mixture as an antimicrobial in poultry chillers. *Journal of Food Protection*, *71*(6), 1119–1122.

Beers, K., Rheinigans, J., Chinault, K., Cook, P., & Waldroup, A. (2006). Microbial efficacy of commercial application of Cecure® CPC antimicrobial to ingesta-contaminated pre-chill broiler carcasses. *International Journal of Poultry Science*, *5*(8), 698–703.

Berghaus, R. D., Thayer, S. G., Law, B. F., Mild, R. M., Hofacre, C. L., & Singer, R. S. (2013). Enumeration of *Salmonella* and *Campylobacter* spp. in environmental farm samples and processing plant carcass rinses from commercial broiler chicken flocks. *Applied and Environmental Microbiology*, *79*(13), 4106–4114. https://doi.org/10.1128/aem.00836-13

Berndtson, E., Danielsson-Tham, M., & Engvall, A. (1996). *Campylobacter* incidence on a chicken farm and the spread of *Campylobacter* during the slaughter process. *International Journal of Food Microbiology*, *32*(1/2), 35–47. https://doi.org/10.1016/0168-1605(96)01102-6

Berrang, M. E., & Bailey, J. S. (2009). On-line brush and spray washers to lower numbers of *Campylobacter* and *Escherichia coli* and presence of *Salmonella* on broiler carcasses during processing. *Journal of Applied Poultry Research*, *18*(1), 74–78. https://doi.org/10.3382/japr.2008-00067

Berrang, M. E., Buhr, R. J., Cason, J. A., & Dickens, J. A. (2001). Broiler carcass contamination with *Campylobacter* from feces during defeathering. *Journal of Food Protection*, *64*(12), 2063–2066. https://doi.org/10.4315/0362-028X-64.12.2063

Berrang, M. E., & Dickens, J. A. (2000). Presence and level of *Campylobacter* spp. on broiler carcasses throughout the processing plant. *Journal of Applied Poultry Research*, *9*(1), 43–47.

Berrang, M. E., Dickens, J. A., & Musgrove, M. T. (2000). Effects of hot water application after defeathering on the levels of *Campylobacter*, coliform bacteria, and *Escherichia coli* on broiler carcasses. *Poultry Science*, *79*(11), 1689–1693.

Berrang, M. E., Meinersmann, R. J., & Adams, E. S. (2018). Shredded sponge or paper as a cloacal plug to limit broiler carcass *Campylobacter* contamination during automated defeathering. *Journal of Applied Poultry Research*, *27*(4), 483–487. https://doi.org/10.3382/japr/pfy051

Berrang, M. E., Meinersmann, R. J., Buhr, R. J., Reimer, N. A., Philips, R. W., & Harrison, M. A. (2003). Presence of *Campylobacter* in the respiratory tract of broiler carcasses before and after commercial scalding. *Poultry Science*, *82*(12), 1995–1999.

Berrang, M. E., Meinersmann, R. J., Cox, N. A., & Fedorka-Cray, P. J. (2011). Application of chlorine dioxide to lessen bacterial contamination during broiler defeathering. *Journal of Applied Poultry Research*, *20*(1), 33–39. https://doi.org/10.3382/japr.2010-00178

Berrang, M. E., Smith, D. P., & Hinton, A., Jr. (2006a). Application of distilled white vinegar in the cloaca to counter the increase in *Campylobacter* numbers on broiler skin during feather removal. *Journal of Food Protection*, *69*(2), 425–427.

Berrang, M. E., Smith, D. P., & Hinton, A., Jr. (2006b). Organic acids placed into the cloaca to reduce *Campylobacter* contamination of broiler skin during defeathering. *Journal of Applied Poultry Research*, *15*(2), 287–291.

Berrang, M. E., Windham, W. R., & Meinersmann, R. J. (2011). *Campylobacter*, *Salmonella*, and *Escherichia coli* on broiler carcasses subjected to a high pH scald and low pH postpick chlorine dip. *Poultry Science*, *90*(4), 896–900. https://doi.org/10.3382/ps.2010-00900

Bhaduri, S., & Cottrell, B. (2004). Survival of cold-stressed *Campylobacter jejuni* on ground chicken and chicken skin during frozen storage. *Applied and Environmental Microbiology*, *70*(12), 7103–7109. https://doi.org/10.1128/aem.70.12.7103-7109.2004

Borges, K. A., Cisco, I. C., Furian, T. Q., Tedesco, D. C., Rodrigues, L. B., Do Nascimento, V. P., & Dos Santos, L. R. (2020). Detection and quantification of *Campylobacter* spp. in Brazilian poultry processing plants. *Journal of Infection in Developing Countries*, *14*(1), 109–113. https://doi.org/10.3855/jidc.11973

Boysen, L., & Rosenquist, H. (2009). Reduction of thermotolerant *Campylobacter* species on broiler carcasses following physical decontamination at slaughter. *Journal of Food Protection*, *72*(3), 497–502. https://doi.org/10.4315/0362-028x-72.3.497

Boysen, L., Wechter, N. S., & Rosenquist, H. (2013). Effects of decontamination at varying contamination levels of *Campylobacter jejuni* on broiler meat. *Poultry Science*, *92*(5), 1425–1429. https://doi.org/10.3382/ps.2012-02889

Bucher, O., Farrar, A. M., Totton, S. C., Wilkins, W., Waddell, L. A., Wilhelm, B. J., McEwen, S. A., Fazil, A., & Rajić, A. (2012). A systematic review-meta-analysis of chilling interventions and a meta-regression of various processing interventions for *Salmonella* contamination of chicken. *Preventive Veterinary Medicine*, *103*(1), 1–15. https://doi.org/10.1016/j.prevetmed.2011.09.017

Bucher, O., Waddell, L., Greig, J., & Smith, B. A. (2015). Systematic review-meta-analysis of the effect of chilling on *Campylobacter* spp. during primary processing of broilers. *Food Control*, *56*, 211–217. https://doi.org/10.1016/j.foodcont.2015.03.032

Buczinski, S., & Vandeweerd, J. M. (2016). Diagnostic accuracy of refractometry for assessing bovine colostrum quality: A systematic review and meta-analysis. *Journal of Dairy Science*, *99*(9), 7381–7394. https://doi.org/10.3168/jds.2016-10955

Buhr, R. J., Berrang, M. E., & Cason, J. A. (2003). Bacterial recovery from breast skin of genetically feathered and featherless broiler carcasses immediately following scalding and picking. *Poultry Science*, *82*(10), 1641–1647.

Burfoot, D., Hall, J., Nicholson, K., Holmes, K., Hanson, C., Handley, S., & Mulvey, E. (2016). Effect of rapid surface cooling on *Campylobacter* numbers on poultry carcasses. *Food Control*, *70*, 293–301. https://doi.org/10.1016/j.foodcont.2016.05.041

Byrd, J. A., Sams, A. R., Hargis, B. M., & Caldwell, D. J. (2011). Effect of selected modified atmosphere packaging on *Campylobacter* survival in raw poultry. *Poultry Science*, *90*(6), 1324–1328. https://doi.org/10.3382/ps.2010-00746

Carroll, C. D., & Alvarado, C. Z. (2008). Comparison of air and immersion chilling on meat quality and shelf life of marinated broiler

breast fillets. *Poultry Science*, *87*(2), 368–372. https://doi.org/10.3382/ps.2007-00213

Chaine, A., Arnaud, E., Kondjoyan, A., Collignan, A., & Sarter, S. (2013). Effect of steam and lactic acid treatments on the survival of *Salmonella* Enteritidis and *Campylobacter jejuni* inoculated on chicken skin. *International Journal of Food Microbiology*, *162*(3), 276–282. https://doi.org/10.1016/j.ijfoodmicro.2013.01.012

Chantarapanont, W., Berrang, M. E., & Frank, J. F. (2004). Direct microscopic observation of viability of *Campylobacter jejuni* on chicken skin treated with selected chemical sanitizing agents. *Journal of Food Protection*, *67*(6), 1146–1152.

Chapman, B., Otten, A., Fazil, A., Ernst, N., & Smith, B. A. (2016). A review of quantitative microbial risk assessment and consumer process models for *Campylobacter* in broiler chickens. *Microbial Risk Analysis*, *2–3*, 3–15. https://doi.org/10.1016/j.mran.2016.07.001

Corry, J. E. L., James, S. J., Purnell, G., Barbedo-Pinto, C. S., Chochois, Y., Howell, M., & James, C. (2007). Surface pasteurisation of chicken carcasses using hot water. *Journal of Food Engineering*, *79*(3), 913–919. https://doi.org/10.1016/j.jfoodeng.2006.03.018

Cortez, A. L. L., Carvalho, A. C. F. B., Scarcelli, E., Miyashiro, S., Vidal-Martins, A. M. C., & Burger, K. P. (2006). Survey of chicken abattoir for the presence of *Campylobacter jejuni* and *Campylobacter coli*. *Revista do Instituto de Medicina Tropical de Sao Paulo*, *48*(6), 307–310. https://doi.org/10.1590/s0036-46652006000600001

Cox, J. M., & Pavic, A. (2010). Advances in enteropathogen control in poultry production. *Journal of Applied Microbiology*, *108*(3), 745–755. https://doi.org/10.1111/j.1365-2672.2009.04456.x

Dan, S. D., Mihaiu, M., Mihaiu, R., Jecan, C., & Lapusan, A. (2012). The effect of acetic and lactic acid for reducing the prevalence of pathogen load on poultry. *Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca: Veterinary Medicine*, *69*(1/2), 335–343.

Demirok, E., Veluz, G., Stuyvenberg, W. V., Castaneda, M. P., Byrd, A., & Alvarado, C. Z. (2013). Quality and safety of broiler meat in various chilling systems. *Poultry Science*, *92*(4), 1117–1126. https://doi.org/10.3382/ps.2012-02493

Dickens, J. A., Berrang, M. E., & Cox, N. A. (2000). Efficacy of an herbal extract on the microbiological quality of broiler carcasses during a simulated chill. *Poultry Science*, *79*(8), 1200–1203.

Dickens, J. A., & Ingram, K. D. (2001). Efficacy of an herbal extract, at various concentrations, on the microbiological quality of broiler carcasses after simulated chilling. *Journal of Applied Poultry Research*, *10*(2), 194–198.

Dickens, J. A., & Whittemore, A. D. (1997). Effects of acetic acid and hydrogen peroxide application during defeathering on the microbiological quality of broiler carcasses prior to evisceration. *Poultry Science*, *76*(4), 657–660. https://doi.org/10.1093/ps/76.4.657

Dogan, O. B., Clarke, J., Mattos, F., & Wang, B. (2019). A quantitative microbial risk assessment model of *Campylobacter* in broiler chickens: Evaluating processing interventions. *Food Control*, *100*, 97–110. https://doi.org/10.1016/j.foodcont.2019.01.003

Duarte, A. S. R., Nauta, M. J., & Aabo, S. (2016). Variation in the effect of carcass decontamination impacts the risk for consumers. *Food Control*, *59*, 12–19. https://doi.org/10.1016/j.foodcont.2015.05.015

Duffy, L. L., Blackall, P. J., Cobbold, R. N., & Fegan, N. (2014). Quantitative effects of in-line operations on *Campylobacter* and *Escherichia coli* through two Australian broiler processing plants. *International Journal of Food Microbiology*, *188*, 128–134. https://doi.org/10.1016/j.ijfoodmicro.2014.07.024

EFSA Panel on Biological Hazards, Koutsoumanis, K., Allende, A., Alvarez-Ordóñez, A., Bolton, D., Bover-Cid, S., Davies, R., Cesare, A. D., Herman, L., Hilbert, F., Lindqvist, R., Nauta, M., Peixe, L., Ru, G., Simmons, M., Skandamis, P., Suffredini, E., Alter, T., Crotta, M., … Chemaly, M. (2020). Update and review of control options for *Campylobacter* in broilers at primary production. *EFSA Journal*, *18*(4), e06090. https://doi.org/10.2903/j.efsa.2020.6090

European Food Safety Authority (EFSA). (2005). Opinion of the Scientific Panel on food additives, flavourings, processing aids and materials in contact with food (AFC) related to Treatment of poultry carcasses with chlorine dioxide, acidified sodium chlorite, trisodium phosphate and peroxyacids. *EFSA Journal*, *297*, 1–27. https://doi.org/10.2903/j.efsa.2006.297

European Food Safety Authority (EFSA). (2008). Assessment of the possible effect of the four antimicrobial treatment substances on the emergence of antimicrobial resistance - Scientific Opinion of the Panel on Biological Hazards. *EFSA Journal*, *6*(4), 1–26. https://doi.org/10.2903/j.efsa.2008.659

European Food Safety Authority (EFSA). (2010). Application of systematic review methodology to food and feed safety assessments to support decision making. *EFSA Journal*, *8*(6), 1637. https://doi.org/10.2903/j.efsa.2010.1637

European Food Safety Authority (EFSA). (2014). Scientific Opinion on the evaluation of the safety and efficacy of peroxyacetic acid solutions for reduction of pathogens on poultry carcasses and meat. *EFSA Journal*, *12*(3), 1–60. https://doi.org/10.2903/j.efsa.2014.3599

Franchin, P. R., Ogliari, P. J., & Batista, C. R. V. (2007). Frequency of thermophilic *Campylobacter* in broiler chickens during industrial processing in a Southern Brazil slaughterhouse. *British Poultry Science*, *48*(2), 127–132. https://doi.org/10.1080/00071660701261286

Georgsson, F., Porkelsson, A. E., Geirsdottir, M., Reiersen, J., & Stern, N. J. (2006). The influence of freezing and duration of storage on *Campylobacter* and indicator bacteria in broiler carcasses. *Food Microbiology*, *23*(7), 677–683. https://doi.org/10.1016/j.fm.2005.10.003

Golden, C. E., & Mishra, A. (2020). Prevalence of *Salmonella* and *Campylobacter* spp. in alternative and conventionally produced chicken in the United States: A systematic review and meta-analysis. *Journal of Food Protection*, *83*(7), 1181–1197. https://doi.org/10.4315/JFP-19-538

González-Fandos, E., & Maya, N. (2016). Efficacy of malic acid against *Campylobacter jejuni* attached to chicken skin during refrigerated storage. *Journal of Food Processing and Preservation*, *40*(4), 593–600. https://doi.org/10.1111/jfpp.12637

Gonzalez-Fandos, E., Maya, N., Martinez-Laorden, A., & Perez-Arnedo, I. (2020). Efficacy of lactic acid and modified atmosphere packaging against *Campylobacter jejuni* on chicken during refrigerated storage. *Foods*, *9*(1), 109. https://doi.org/10.3390/foods9010109

Gonzalez-Fandos, E., Maya, N., & Perez-Arnedo, I. (2015). Effect of propionic acid on *Campylobacter jejuni* attached to chicken skin during refrigerated storage. *International Microbiology*, *18*, 171–175. https://doi.org/10.2436/20.1501.01.247

Guerin, M. T., Sir, C., Sargeant, J. M., Waddell, L., O'Connor, A. M., Wills, R. W., Bailey, R. H., & Byrd, J. A. (2010). The change in prevalence of *Campylobacter* on chicken carcasses during processing: A systematic review. *Poultry Science*, *89*(5), 1070–1084. https://doi.org/10.3382/ps.2009-00213

Gumhalter Karolyi, L., Medić, H., Vidaček, S., Petrak, T., & Botka–Petrak, K. (2003). Bacterial population in counter flow and parallel flow water chilling of poultry meat. *European Food Research and Technology*, *217*(5), 412–415. https://doi.org/10.1007/s00217-003-0772-6

Guyatt, G., Oxman, A. D., Akl, E. A., Kunz, R., Vist, G., Brozek, J., Norris, S., Falck-Ytter, Y., Glasziou, P., & DeBeer, H. (2011). GRADE guidelines: 1. Introduction—GRADE evidence profiles and summary of findings tables. *Journal of Clinical Epidemiology*, *64*(4), 383–394. https://doi.org/10.1016/j.jclinepi.2010.04.026

Haughton, P. N., Lyng, J. G., Cronin, D. A., Morgan, D. J., Fanning, S., & Whyte, P. (2011). Efficacy of UV light treatment for the microbiological decontamination of chicken, associated packaging, and contact surfaces. *Journal of Food Protection*, *74*(4), 565–572. https://doi.org/10.4315/0362-028x.jfp-10-356

Haughton, P. N., Lyng, J. G., Cronin, D. A., Morgan, D. J., Fanning, S., & Whyte, P. (2012). Efficacy of pulsed electric fields for the inactivation of indicator microorganisms and foodborne pathogens in liquids and raw chicken. *Food Control*, *25*(1), 131–135. https://doi.org/10.1016/j.foodcont.2011.10.030

Havelaar, A. H., Mangen, M. J. J., De Koeijer, A. A., Bogaardt, M. J., Evers, E. G., Jacobs-Reitsma, W. F., Pelt, W. V., Wagenaar, J. A., Wit, G. A. D., Zee, H. V. D., & Nauta, M. J. (2007). Effectiveness and efficiency of controlling *Campylobacter* on broiler chicken meat. *Risk Analysis*, *27*(4), 831–844. https://doi.org/10.1111/j.1539-6924.2007.00926.x

Hedges, L. V., & Olkin, I. (2014). *Statistical methods for meta-analysis*. Elsevier Science.

Higgins, J. P., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine*, *21*(11), 1539–1558. https://doi.org/10.1002/sim.1186

Higgins, J. P. T., & Green, S. (Eds.). (2011). *Cochrane handbook for systematic reviews of interventions, Version 5.1.0* (Updated March 2011). The Cochrane Collaboration. www.handbook.cochrane.org

Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., & Welch, V. A. (2019). *Cochrane handbook for systematic reviews of interventions*. Wiley.

Hinton, A., Jr., Cason, J. A., Buhr, R. J., & Liljebjelke, K. (2009). Bacteria recovered from whole-carcass rinsates of broiler carcasses washed in a spray cabinet with lauric acid-potassium hydroxide. *International Journal of Poultry Science*, *8*(11), 1022–1027.

Hinton, A., Jr., Cason, J. A., Hume, M. E., & Ingram, K. D. (2004a). Use of MIDI-fatty acid methyl ester analysis to monitor the transmission of *Campylobacter* during commercial poultry processing. *Journal of Food Protection*, *67*(8), 1610–1616.

Hinton, A., Jr., Cason, J. A., Hume, M. E., & Ingram, K. D. (2004b). Spread of *Campylobacter* spp. during poultry processing in different seasons. *International Journal of Poultry Science*, *3*(7), 432–437.

Hinton, A., Jr., & Ingram, K. D. (2000). Use of oleic acid to reduce the population of the bacterial flora of poultry skin. *Journal of Food Protection*, *63*(9), 1282–1286.

Hinton, A., Jr., & Ingram, K. D. (2003). Bactericidal activity of tripotassium phosphate and potassium oleate on the native flora of poultry skin. *Food Microbiology*, *20*(4), 405–410. https://doi.org/10.1016/s0740-0020(02)00151-x

Hinton, A., Jr., & Ingram, K. D. (2006). Antimicrobial activity of potassium hydroxide and lauric acid against microorganisms associated with poultry processing. *Journal of Food Protection*, *69*(7), 1611–1615.

Huang, J., Zang, X., Zhai, W., Guan, C., Lei, T., & Jiao, X. (2017). Quantitative analysis of *Campylobacter* spp. contamination in chicken slaughtering lines by "label tracking method" in eastern China. *Food Control*, *80*, 67–73. https://doi.org/10.1016/j.foodcont.2017.03.052

Hue, O., Le Bouquin, S., Laisney, M.-J., Allain, V., Lalande, F., Petetin, I., Rouxel, S., Quesne, S., Gloaguen, P.-Y., Picherot, M., Santolini, J., Salvat, G., Bougeard, S., & Chemaly, M. (2010). Prevalence of and risk factors for *Campylobacter* spp. contamination of broiler chicken carcasses at the slaughterhouse. *Food Microbiology*, *27*(8), 992–999. https://doi.org/10.1016/j.fm.2010.06.004

Huezo, R., Northcutt, J. K., Smith, D. P., Fletcher, D. L., & Ingram, K. D. (2007). Effect of dry air or immersion chilling on recovery of bacteria from broiler carcasses. *Journal of Food Protection*, *70*(8), 1829–1834.

Huezo, R., Smith, D. P., Northcutt, J. K., & Fletcher, D. L. (2007). Effect of immersion or dry air chilling on broiler carcass moisture retention and breast fillet functionality. *Journal of Applied Poultry Research*, *16*(3), 438–447. https://doi.org/10.1093/japr/16.3.438

Hulankova, R., Borilova, G., Abdullah, F. A. A., & Buchtova, H. (2018). Microbiological quality of organic chicken meat during refrigerated storage in air and modified atmospheres. *British Poultry Science*, *59*(5), 506–513. https://doi.org/10.1080/00071668.2018.1496399

Hwang, H., & Singer, R. S. (2020). Survey of the U.S. broiler industry regarding pre- and postharvest interventions targeted to mitigate *Campylobacter* contamination on broiler chicken products. *Journal of Food Protection*, *83*(7), 1137–1148. https://doi.org/10.4315/JFP-19-527

Interagency Food Safety Analytics Collaboration (IFSAC). (2018). Foodborne illness source attribution estimates for 2016 for Salmonella, Escherichia coli O157, Listeria monocytogenes, and Campylobacter using multi-year outbreak surveillance data, United States. http://www.cdc.gov/foodsafety/ifsac/index.html

IntHout, J., Ioannidis, J. P. A., Borm, G. F., & Goeman, J. J. (2015). Small studies are more heterogeneous than large ones: A meta-meta-analysis. *Journal of Clinical Epidemiology*, *68*(8), 860–869. https://doi.org/10.1016/j.jclinepi.2015.03.017

Isohanni, P. M. I., & Lyhs, U. (2009). Use of ultraviolet irradiation to reduce *Campylobacter jejuni* on broiler meat. *Poultry Science*, *88*(3), 661–668. https://doi.org/10.3382/ps.2008-00259

James, C., Göksoy, E. O., Corry, J. E. L., & James, S. J. (2000). Surface pasteurisation of poultry meat using steam at atmospheric pressure. *Journal of Food Engineering*, *45*(2), 111–117. https://doi.org/10.1016/S0260-8774(00)00048-0

James, C., James, S. J., Hannay, N., Purnell, G., Barbedo-Pinto, C., Yaman, H., Araujo, M., Gonzalez, M. L., Calvo, J., Howell, M., & Corry, J. E. L. (2007). Decontamination of poultry carcasses using steam or hot water in combination with rapid cooling, chilling or freezing of carcass surfaces. *International Journal of Food Microbiology*, *114*(2), 195–203. https://doi.org/10.1016/j.ijfoodmicro.2006.09.019

James, C., Vincent, C., de Andrade Lima, T. I., & James, S. J. (2006). The primary chilling of poultry carcasses—A review. *International Journal of Refrigeration*, *29*(6), 847–862. https://doi.org/10.1016/j.ijrefrig.2005.08.003

Jozwiak, A., Reichart, O., & Laczay, P. (2006). The occurrence of *Campylobacter* species in Hungarian broiler chickens from farm to

slaughter. *Journal of Veterinary Medicine Series B*, *53*(6), 291–294. https://doi.org/10.1111/j.1439-0450.2006.00958.x

Juven, B. J., & Rogol, M. (1986). Incidence of *Campylobacter jejuni* and *Campylobacter coli* serogroups in a chicken processing factory. *Journal of Food Protection*, *49*(4), 290–292.

Kameyama, M., Chuma, T., Nishimoto, T., Oniki, H., Yanagitani, Y., Kanetou, R., Gotou, K., Shahada, F., Iwata, H., & Okamoto, K. (2012). Effect of cooled and chlorinated chiller water on *Campylobacter* and coliform counts on broiler carcasses during chilling at a middle-size poultry processing plant. *Journal of Veterinary Medical Science*, *74*(1), 129–133. https://doi.org/10.1292/jvms.11-0167

Keener, K. M., Bashor, M. P., Curtis, P. A., Sheldon, B. W., & Kathariou, S. (2004). Comprehensive review of *Campylobacter* and poultry processing. *Comprehensive Reviews in Food Science and Food Safety*, *3*(2), 105–116. https://doi.org/10.1111/j.1541-4337.2004.tb00060.x

Kemp, G. K., Aldrich, M. L., Guerra, M. L., & Schneider, K. R. (2001). Continuous online processing of fecal- and ingesta-contaminated poultry carcasses using an acidified sodium chlorite antimicrobial intervention. *Journal of Food Protection*, *64*(6), 807–812.

Khalafalla, F. A., Abdel-Atty, N. S., Soad, A. N., & Hanafy, A. S. (2019). Potential microbiological hazards in broiler chickens during processing. *Assiut Veterinary Medical Journal*, *65*(160), 7–15.

Klein, G., Jansen, W., Kittler, S., & Reich, F. (2015). Mitigation strategies for *Campylobacter* spp. in broiler at pre-harvest and harvest level. *Berliner Und Munchener Tierarztliche Wochenschrift*, *128*(3-4), 132–140.

Knottnerus, A., & Tugwell, P. (2008). STROBE-A checklist to STrengthen the Reporting of OBservational studies in Epidemiology. *Journal of Clinical Epidemiology*, *61*(4), 323–323. https://doi.org/10.1016/j.jclinepi.2007.11.006

Koolman, L., Whyte, P., Meade, J., Lyng, J., & Bolton, D. (2014a). Use of chemical treatments applied alone and in combination to reduce *Campylobacter* on raw poultry. *Food Control*, *46*, 299–303. https://doi.org/10.1016/j.foodcont.2014.05.041

Koolman, L., Whyte, P., Meade, J., Lyng, J., & Bolton, D. (2014b). A combination of chemical and ultrasonication treatments to reduce *Campylobacter jejuni* on raw poultry. *Food and Bioprocess Technology*, *7*(12), 3602–3607.

Kure, C. F., Axelsson, L., Carlehog, M., Mage, I., Jensen, M. R., & Holck, A. (2020). The effects of a pilot-scale steam decontamination system on the hygiene and sensory quality of chicken carcasses. *Food Control*, *109*, 106948. https://doi.org/10.1016/j.foodcont.2019.106948

Lee, S. K., Park, H. J., Lee, J. H., Lim, J. S., Seo, K. H., Heo, E. J., Kim, Y.-J., Wee, S.-H., & Moon, J. S. (2017). Distribution and molecular characterization of *Campylobacter* species at different processing stages in two poultry processing plants. *Foodborne Pathogens and Disease*, *14*(3), 141–147. https://doi.org/10.1089/fpd.2016.2218

Li, K., Lemonakis, L., Glover, B., Moritz, J., & Shen, C. (2017). Impact of built-up-litter and commercial antimicrobials on *Salmonella* and *Campylobacter* contamination of broiler carcasses processed at a pilot mobile poultry-processing unit. *Frontiers in Veterinary Science*, *4*, 88. https://doi.org/10.3389/fvets.2017.00088

Loretz, M., Stephan, R., & Zweifel, C. (2010). Antimicrobial activity of decontamination treatments for poultry carcasses: A literature survey. *Food Control*, *21*(6), 791–804. https://doi.org/10.1016/j.foodcont.2009.11.007

Mavri, A., & Smole Možina, S. (2013). Development of antimicrobial resistance in *Campylobacter jejuni* and *Campylobacter coli* adapted to biocides. *International Journal of Food Microbiology*, *160*(3), 304–312. https://doi.org/10.1016/j.ijfoodmicro.2012.11.006

McCrea, B. A., Tonooka, K. H., VanWorth, C., Boggs, C. L., Atwill, E. R., & Schrader, J. S. (2006). Prevalence of *Campylobacter* and *Salmonella* species on farm, after transport, and at processing in specialty market poultry. *Poultry Science*, *85*(1), 136–143.

McGuinness, L. A., & Higgins, J. P. T. (2021). Risk-of-bias VISualization (robvis): An R package and Shiny web app for visualizing risk-of-bias assessments. *Res Synth Methods*, *12*(1), 55–61. https://doi.org/10.1002/jrsm.1411

Mead, G. C., Allen, V. M., Burton, C. H., & Corry, J. E. L. (2000). Microbial cross-contamination during air chilling of poultry. *British Poultry Science*, *41*(2), 158–162. https://doi.org/10.1080/713654915

Meredith, H., Valdramidis, V., Rotabakk, B. T., Sivertsvik, M., McDowell, D., & Bolton, D. J. (2014). Effect of different modified atmospheric packaging (MAP) gaseous combinations on *Campylobacter* and the shelf-life of chilled poultry fillets. *Food Microbiology*, *44*, 196–203. https://doi.org/10.1016/j.fm.2014.06.005

Meredith, H., Walsh, D., McDowell, D. A., & Bolton, D. J. (2013). An investigation of the immediate and storage effects of chemical treatments on *Campylobacter* and sensory characteristics of poultry meat. *International Journal of Food Microbiology*, *166*(2), 309–315. https://doi.org/10.1016/j.ijfoodmicro.2013.07.005

Mild, R. M., Joens, L. A., Friedman, M., Olsen, C. W., McHugh, T. H., Law, B., & Ravishankar, S. (2011). Antimicrobial edible apple films inactivate antibiotic resistant and susceptible *Campylobacter jejuni* strains on chicken breast. *Journal of Food Science*, *76*(3), M163–M168. https://doi.org/10.1111/j.1750-3841.2011.02065.x

Musavian, H. S., Krebs, N. H., Nonboe, U., Corry, J. E. L., & Purnell, G. (2014). Combined steam and ultrasound treatment of broilers at slaughter: A promising intervention to significantly reduce numbers of naturally occurring *Campylobacter*s on carcasses. *International Journal of Food Microbiology*, *176*, 23–28. https://doi.org/10.1016/j.ijfoodmicro.2014.02.001

Musgrove, M. T., Cason, J. A., Fletcher, D. L., Stern, N. J., Cox, N. A., & Bailey, J. S. (1997). Effect of cloacal plugging on microbial recovery from partially processed broilers. *Poultry Science*, *76*(3), 530–533.

Nauta, M., Hill, A., Rosenquist, H., Brynestad, S., Fetsch, A., van der Logt, P., Fazil, A., Christensen, B., Katsma, E., Borck, B., & Havelaar, A. (2009). A comparison of risk assessments on *Campylobacter* in broiler meat. *International Journal of Food Microbiology*, *129*(2), 107–123. https://doi.org/10.1016/j.ijfoodmicro.2008.12.001

Nauta, M., Jacobs-Reitsma, W. F., & Havelaar, A. H. (2007). A risk assessment model for *Campylobacter* in broiler meat. *Risk Analysis*, *27*(4), 845–861. https://doi.org/10.1111/j.1539-6924.2006.00834.x

Nauta, M., van der Fels-Klerx, I., & Havelaar, A. (2005). A poultry-processing model for quantitative microbiological risk assessment. *Risk Analysis*, *25*(1), 85–98. https://doi.org/10.1111/j.0272-4332.2005.00569.x

Northcutt, J. K., Berrang, M. E., Dickens, J. A., Fletcher, D. L., & Cox, N. A. (2003). Effect of broiler age, feed withdrawal, and transportation on levels of coliforms, *Campylobacter*, *Escherichia coli* and *Salmonella* on carcasses before and after immersion chilling. *Poultry Science*, *82*(1), 169–173.

Northcutt, J. K., Smith, D., Huezo, R. I., & Ingram, K. D. (2008). Microbiology of broiler carcasses and chemistry of chiller water

as affected by water reuse. *Poultry Science*, *87*(7), 1458–1463. https://doi.org/10.3382/ps.2007-00480

O'Connor, A. M., Sargeant, J. M., Gardner, I. A., Dickson, J. S., Torrence, M. E., Dewey, C. E., Dohoo, I. R., Evans, R. B., Gray, J. T., Greiner, M., Keefe, G., Lefebvre, S. L., Morley, P. S., Ramirez, A., Sischo, W., Smith, D. R., Snedeker, K., Sofos, J., Ward, M. P., & Wills, R. (2010). The REFLECT statement: Methods and processes of creating reporting guidelines for randomized controlled trials for livestock and food safety. *Journal of Swine Health and Production*, *18*(1), 18–26.

Olaimat, A. N., Fang, Y., & Holley, R. A. (2014). Inhibition of *Campylobacter jejuni* on fresh chicken breasts by kappa-carrageenan/chitosan-based coatings containing allyl isothiocyanate or deodorized oriental mustard extract. *International Journal of Food Microbiology*, *187*, 77–82. https://doi.org/10.1016/j.ijfoodmicro.2014.07.003

Oosterom, J., Notermans, S., Karman, H., & Engels, G. B. (1983). Origin and prevalence of *Campylobacter* in poultry processing. *Journal of Food Protection*, *46*(4), 339–344.

Osiriphun, S., Iamtaweejaloen, P., Kooprasertying, P., Koetsinchai, W., Tuitemwong, K., Erickson, L. E., & Tuitemwong, P. (2011). Exposure assessment and process sensitivity analysis of the contamination of *Campylobacter* in poultry products. *Poultry Science*, *90*(7), 1562–1573. https://doi.org/10.3382/ps.2009-00577

Osiriphun, S., Tuitemwong, P., Koetsinchai, W., Tuitemwong, K., & Erickson, L. E. (2012). Model of inactivation of *Campylobacter jejuni* in poultry scalding. *Journal of Food Engineering*, *110*(1), 38–43. https://doi.org/10.1016/j.jfoodeng.2011.12.011

Oyarzabal, O. A., Hawk, C., Bilgili, S. F., Warf, C. C., & Kemp, G. K. (2004). Effects of postchill application of acidified sodium chlorite to control *Campylobacter* spp. and *Escherichia coli* on commercial broiler carcasses. *Journal of Food Protection*, *67*(10), 2288–2291.

Ozdemir, H., Gucukoglu, A., & Koluman, A. (2006). Acidified sodium chlorite, trisodium phosphate and populations of *Campylobacter jejuni* on chicken breast skin. *Journal of Food Processing and Preservation*, *30*(5), 608–615. https://doi.org/10.1111/j.1745-4549.2006.00091.x

Park, H., Hung, Y. C., & Brackett, R. E. (2002). Antimicrobial effect of electrolyzed water for inactivating *Campylobacter jejuni* during poultry washing. *International Journal of Food Microbiology*, *72*(1/2), 77–83. https://doi.org/10.1016/s0168-1605(01)00622-5

Perez-Arnedo, I., & Gonzalez-Fandos, E. (2019). Prevalence of *Campylobacter* spp. in poultry in three Spanish farms, a slaughterhouse and a further processing plant. *Foods*, *8*(3), 111. https://doi.org/10.3390/foods8030111

Pires, S. M., Vigre, H., Makela, P., & Hald, T. (2010). Using outbreak data for source attribution of human *Salmonellosis* and *Campylobacter*iosis in Europe. *Foodborne Pathogens and Disease*, *7*(11), 1351–1361. https://doi.org/10.1089/fpd.2010.0564

Potturi-Venkata, L.-P., Backert, S., Vieira, S. L., & Oyarzabal, O. A. (2007). Evaluation of logistic processing to reduce cross-contamination of commercial broiler carcasses with *Campylobacter* spp. *Journal of Food Protection*, *70*(11), 2549–2554.

Purnell, G., James, C., James, S. J., Howell, M., & Corry, J. E. L. (2014). Comparison of acidified sodium chlorite, chlorine dioxide, peroxyacetic acid and tri-sodium phosphate spray washes for decontamination of chicken carcasses. *Food and Bioprocess Technology*, *7*(7), 2093–2101. https://doi.org/10.1007/s11947-013-1211-8

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rahimi, E., Momtaz, H., Ameri, M., Ghasemian-Safaei, H., & Ali-Kasemi, M. (2010). Prevalence and antimicrobial resistance of *Campylobacter* species isolated from chicken carcasses during processing in Iran. *Poultry Science*, *89*(5), 1015–1020. https://doi.org/10.3382/ps.2009-00090

Ravel, A., Hurst, M., Petrica, N., David, J., Mutschall, S. K., Pintar, K., Taboada, E. N., & Pollari, F. (2017). Source attribution of human *campylobacter*iosis at the point of exposure by combining comparative exposure assessment and subtype comparison based on comparative genomic fingerprinting. *PLoS ONE*, *12*(8), e0183790. https://doi.org/10.1371/journal.pone.0183790

Reich, F., Atanassova, V., Beckmann, L., & Klein, G. (2006). *Critical processing steps in the slaughterhouse for the control of Campylobacter in broilers*. EPC 2006 - 12th European Poultry Conference, Verona, Italy, 10–14 September, 2006, paper 220.

Reich, F., Atanassova, V., Haunhorst, E., & Klein, G. (2008). The effects of *Campylobacter* numbers in caeca on the contamination of broiler carcasses with *Campylobacter*. *International Journal of Food Microbiology*, *127*(1-2), 116–120. https://doi.org/10.1016/j.ijfoodmicro.2008.06.018

Reiter, M. G. R., Bueno, C. M. M., Lopez, C., & Jordano, R. (2005). Occurrence of *Campylobacter* and *Listeria monocytogenes* in a poultry processing plant. *Journal of Food Protection*, *68*(9), 1903–1906.

Rejab, S. B. M., Zessin, K. H., Fries, R., & Patchanee, P. (2012a). *Campylobacter* in chicken carcasses and slaughterhouses in Malaysia. *Southeast Asian Journal of Tropical Medicine and Public Health*, *43*(1), 96–104.

Rejab, S. B. M., Zessin, K. H., Fries, R., & Patchanee, P. (2012b). Comparison of *Campylobacter* contamination levels on chicken carcasses between modern and traditional types of slaughtering facilities in Malaysia. *Journal of Veterinary Medical Science*, *74*(1), 121–124. https://doi.org/10.1292/jvms.11-0145

Riedel, C. T., Brondsted, L., Rosenquist, H., Haxgart, S. N., & Christensen, B. B. (2009). Chemical decontamination of *Campylobacter jejuni* on chicken skin and meat. *Journal of Food Protection*, *72*(6), 1173–1180.

Rosenquist, H., Nielsen, N. L., Sommer, H. M., Nørrung, B., & Christensen, B. B. (2003). Quantitative risk assessment of human *campylobacter*iosis associated with thermophilic *Campylobacter* species in chickens. *International Journal of Food Microbiology*, *83*(1), 87–103. https://doi.org/10.1016/S0168-1605(02)00317-3

Rosenquist, H., Sommer, H. M., Nielsen, N. L., & Christensen, B. B. (2006). The effect of slaughter operations on the contamination of chicken carcasses with thermotolerant *Campylobacter*. *International Journal of Food Microbiology*, *108*(2), 226–232. https://doi.org/10.1016/j.ijfoodmicro.2005.12.007

Sargeant, J. M., & O'Connor, A. M. (2014). Conducting systematic reviews of intervention questions II: Relevance screening, data extraction, assessing risk of bias, presenting the results and interpreting the findings. *Zoonoses and Public Health*, *61*(S1), 39–51. https://doi.org/10.1111/zph.12124

Sargeant, J. M., Rajic, A., Read, S., & Ohlsson, A. (2006). The process of systematic review and its application in agri-food public-health. *Preventive Veterinary Medicine*, *75*(3–4), 141–151.

Sarjit, A., & Dykes, G. A. (2015). Trisodium phosphate and sodium hypochlorite are more effective as antimicrobials against *Campylobacter* and *Salmonella* on duck as compared to chicken meat. *International Journal of Food Microbiology*, *203*, 63–69. https://doi.org/10.1016/j.ijfoodmicro.2015.02.026

Scallan, E., Hoekstra, R. M., Mahon, B. E., Jones, T. F., & Griffin, P. M. (2015). An assessment of the human health impact of seven leading foodborne pathogens in the United States using disability adjusted life years. *Epidemiology and Infection*, *143*(13), 2795–2804. https://doi.org/10.1017/S0950268814003185

Schulz, K. F., Altman, D. G., & Moher, D. (2010). CONSORT 2010 Statement: Updated guidelines for reporting parallel group randomised trials. *BMJ*, *340*, c332. https://doi.org/10.1136/bmj.c332

Seliwiorstow, T., Baré, J., Berkvens, D., Van Damme, I., Uyttendaele, M., & De Zutter, L. (2016). Identification of risk factors for *Campylobacter* contamination levels on broiler carcasses during the slaughter process. *International Journal of Food Microbiology*, *226*, 26–32. https://doi.org/10.1016/j.ijfoodmicro.2016.03.010

Seliwiorstow, T., Baré, J., Van Damme, I., Algaba, I. G., Uyttendaele, M., & De Zutter, L. (2016). Transfer of *Campylobacter* from a positive batch to broiler carcasses of a subsequently slaughtered negative batch: A quantitative approach. *Journal of Food Protection*, *79*(6), 896–901. https://doi.org/10.4315/0362-028x.jfp-15-486

Seliwiorstow, T., Bare, J., Van Damme, I., Uyttendaele, M., & De Zutter, L. (2015). *Campylobacter* carcass contamination throughout the slaughter process of *Campylobacter*-positive broiler batches. *International Journal of Food Microbiology*, *194*, 25–31. https://doi.org/10.1016/j.ijfoodmicro.2014.11.004

Sexton, M., Raven, G., Holds, G., Pointon, A., Kiermeier, A., & Sumner, J. (2007). Effect of acidified sodium chlorite treatment on chicken carcases processed in South Australia. *International Journal of Food Microbiology*, *115*(2), 252–255. https://doi.org/10.1016/j.ijfoodmicro.2006.10.023

Shrestha, S., Wagle, B. R., Upadhyay, A., Arsi, K., Donoghue, D. J., & Donoghue, A. M. (2019). Carvacrol antimicrobial wash treatments reduce *Campylobacter jejuni* and aerobic bacteria on broiler chicken skin. *Poultry Science*, *98*(9), 4073–4083. https://doi.org/10.3382/ps/pez198

Shrestha, S., Wagle, B. R., Upadhyay, A., Arsi, K., Upadhyaya, I., Donoghue, D. J., & Donoghue, A. M. (2019). Edible coatings fortified with carvacrol reduce *Campylobacter jejuni* on chicken wingettes and modulate expression of select virulence genes. *Frontiers in Microbiology*, *10*, 583. https://doi.org/10.3389/fmicb.2019.00583

Slavik, M. F., Jeon-Weon, K., Pharr, M. D., Raben, D. P., Tsai, S., & Lobsinger, C. M. (1994). Effect of trisodium phosphate on *Campylobacter* attached to post-chill chicken carcasses. *Journal of Food Protection*, *57*(4), 324–326.

Smith, J., Corkran, S., McKee, S. R., Bilgili, S. F., & Singh, M. (2015). Evaluation of post-chill applications of antimicrobials against *Campylobacter jejuni* on poultry carcasses. *Journal of Applied Poultry Research*, *24*(4), 451–456. https://doi.org/10.3382/japr/pfv046

Son, I., Englen, M. D., Berrang, M. E., Fedorka-Cray, P. J., & Harrison, M. A. (2007). Prevalence of *Arcobacter* and *Campylobacter* on broiler carcasses during processing. *International Journal of Food Microbiology*, *113*(1), 16–22. https://doi.org/10.1016/j.ijfoodmicro.2006.06.033

Stern, N. J., & Robach, M. C. (2003). Enumeration of *Campylobacter* spp. in broiler feces and in corresponding processed carcasses. *Journal of Food Protection*, *66*(9), 1557–1563.

Sterne, J. A. C., Savović, J., Page, M. J., Elbers, R. G., Blencowe, N. S., Boutron, I., Cates, C. J., Cheng, H.-Y., Corbett, M. S., Eldridge, S. M., Emberson, J. R., Hernán, M. A., Hopewell, S., Hróbjartsson, A., Junqueira, D. R., Jüni, P., Kirkham, J. J., Lasserson, T., Li, T., … Higgins, J. P. T. (2019). RoB 2: A revised tool for assessing risk of bias in randomised trials. *BMJ*, *366*, l4898. https://doi.org/10.1136/bmj.l4898

Thames, H. T., & Theradiyil Sukumaran, A. (2020). A review of *Salmonella* and *Campylobacter* in broiler meat: Emerging challenges and food safety measures. *Foods*, *9*(6), 776–776. https://doi.org/10.3390/foods9060776

Thomas, N. L. (1977). The continuous chilling of poultry in relation to EEC requirements. *International Journal of Food Science & Technology*, *12*(2), 99–114. https://doi.org/10.1111/j.1365-2621.1977.tb00092.x

Thormar, H., Hilmarsson, H., Thrainsson, J. H., Georgsson, F., Gunnarsson, E., & Dadadottir, S. (2011). Treatment of fresh poultry carcases with emulsions of glycerol monocaprate (monocaprin) to reduce contamination with *Campylobacter* and psychrotrophic bacteria. *British Poultry Science*, *52*(1), 11–19. https://doi.org/10.1080/00071668.2010.537308

Thung, T. Y., Lee, E., Mahyudin, N. A., Radzi, C., Mazlan, N., Tan, C. W., & Radu, S. (2020). Partial characterization and in vitro evaluation of a lytic bacteriophage for biocontrol of *Campylobacter jejuni* in mutton and chicken meat. *Journal of Food Safety*, *6*, e12770. https://doi.org/10.1111/jfs.12770

Tong, Z., Ezeike, G. O. I., Doyle, M. P., Yen-Con, H., & Howell, R. S. (2003). Reduction of *Campylobacter jejuni* on poultry by low-temperature treatment. *Journal of Food Protection*, *66*(4), 652–655.

U.S. Department of Agriculture (USDA). (2020). Poultry slaughter 2020 summary. https://www.nass.usda.gov/Publications/Todays_Reports/reports/psla0420.pdf

Vashin, I. T., & Stoyanchev, T. T. (2004). Incidence and microbial diversity of *Campylobacter* spp. isolates during the slaughterhouse processing of poultry and critical control points of the process. *Bulgarian Journal of Veterinary Medicine*, *7*(3), 173–179.

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, *36*(3), 1–48.

Wagenaar, J. A., French, N. P., & Havelaar, A. H. (2013). Preventing *Campylobacter* at the source: Why is it so difficult? *Clinical Infectious Diseases*, *57*(11), 1600–1606. https://doi.org/10.1093/cid/cit555

Wagle, B. R., Arsi, K., Shrestha, S., Upadhyay, A., Upadhyaya, I., Bhargava, K., Donoghue, A., & Donoghue, D. J. (2019). Eugenol as an antimicrobial wash treatment reduces *Campylobacter jejuni* in postharvest poultry. *Journal of Food Safety*, *39*(6), e12704. https://doi.org/10.1111/jfs.12704

Wagle, B. R., Upadhyay, A., Shrestha, S., Arsi, K., Upadhyaya, I., Donoghue, A. M., & Donoghue, D. J. (2019). Pectin or chitosan coating fortified with eugenol reduces *Campylobacter jejuni* on chicken wingettes and modulates expression of critical survival genes. *Poultry Science*, *98*(3), 1461–1471. https://doi.org/10.3382/ps/pey505

Wempe, J. M., Genigeorgis, C. A., Farver, T. B., & Yusufu, H. I. (1983). Prevalence of *Campylobacter jejuni* in two California chicken processing plants. *Applied and Environmental Microbiology*, *45*(2), 355–359.

Whyte, P., Collins, J. D., McGill, K., Monahan, C., & O'Mahony, H. (2001). Quantitative investigation of the effects of chemical decontamination procedures on the microbiological status of broiler carcasses during processing. *Journal of Food Protection*, *64*(2), 179–183.

Whyte, P., McGill, K., & Collins, J. D. (2003). An assessment of steam pasteurization and hot water immersion treatments for the microbiological decontamination of broiler carcasses. *Food Microbiology*, *20*(1), 111–117. https://doi.org/10.1016/s0740-0020(02)00084-9

World Health Organization (WHO). (2015). *WHO estimates of the global burden of foodborne diseases: Foodborne disease burden epidemiology reference group 2007–2015*. Author.

Yang, H., Li, Y., Griffis L. , C., & Waldroup L. , A. (2002). A probability model for cross–contamination by *Campylobacter jejuni* and *Salmonella* Typhimurium in poultry chilling process. *Applied Engineering in Agriculture*, *18*(6), 717–724. https://doi.org/10.13031/2013.11313

Zhang, L., Jeong, J. Y., Janardhanan, K. K., Ryser, E. T., & Kang, I. (2011). Microbiological quality of water immersion-chilled and air-chilled broilers. *Journal of Food Protection*, *74*(9), 1531–1535. https://doi.org/10.4315/0362-028x.jfp-11-032

Zhang, X. Y., Tang, M. J., Zhou, Q., Zhang, J., Yang, X. X., & Gao, Y. S. (2018). Prevalence and characteristics of *Campylobacter* throughout the slaughter process of different broiler batches. *Frontiers in Microbiology*, *9*, 2092. https://doi.org/10.3389/fmicb.2018.02092

Zhao, T., & Doyle, M. P. (2006). Reduction of *Campylobacter jejuni* on chicken wings by chemical treatments. *Journal of Food Protection*, *69*(4), 762–767.

Zhuang, H., Rothrock, M. J., Hiett, K. L., Lawrence, K. C., Gamble, G. R., Bowker, B. C., & Keener, K. M. (2019). In-package antimicrobial treatment of chicken breast meat with high voltage dielectric barrier discharge-electric voltage effect. *Journal of Applied Poultry Research*, *28*(4), 801–807. https://doi.org/10.3382/japr/pfz036

Zweifel, C., Althaus, D., & Stephan, R. (2015). Effects of slaughter operations on the microbiological contamination of broiler carcasses in three abattoirs. *Food Control*, *51*, 37–42.

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