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Review

A Review of Slaughter Practices and Their Effectiveness to Control Microbial – esp. *Salmonella* spp. – Contamination of Pig Carcasses

Arvo Viltrop [1,*], Tarmo Niine [1], Tijs Tobias [2,3], Elena Lucia Sassu [4], Ilaria Di Bartolo [5], Enrico Pavoni [6], Giovanni Loris Alborali [6], Elke Burow [7,†], Richard Piers Smith [8]

[1] *Estonian University of Life Sciences, Institute of Veterinary Medicine and Animal Sciences, Kreutzwaldi 62, Tartu 51006, Estonia*
[2] *Utrecht University, Faculty of Veterinary Medicine, Department of Population Health Sciences, Farm Animal Health Unit, Yalelaan 7, 3584CL Utrecht, the Netherlands*
[3] *Royal GD (Animal Health Service), P.O. Box 9, 7400 AA Deventer, the Netherlands*
[4] *Institute of Veterinary Disease Control, Austrian Agency for Health and Food Safety (AGES), Mödling, Austria*
[5] *Dept. of Food Safety, Nutrition and Veterinary Public Health, Istituto Superiore di Sanità, Viale Regina Elena 299, 00161 Roma, Italy*
[6] *Experimental Zooprophylactic Institute of Lombardy and Emilia Romagna, via Bianchi 7/9, 25124 Brescia, Italy*
[7] *German Institute for Risk Assessment (BfR), Department of Biological Safety, Max-Dohrn Str. 8-10, 10589 Berlin, Germany*
[8] *Department of Epidemiological Sciences, Animal and Plant Health Agency – Weybridge, Woodham Lane, New Haw, Addlestone, Surrey KT15 3NB, UK*

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ABSTRACT

The BIOPIGEE project (part of the One Health European Joint Programme under Horizon 2020) aimed to identify relevant measures to effectively control *Salmonella,* and another zoonotic pathogen, hepatitis E virus (HEV) within the pig meat food chain. The aim of this study was to identify biosecurity measures or management practices that are relevant for limiting *Salmonella* and/or HEV occurrence and spread within pig slaughterhouses. This was with the final goal of compiling a list of biosecurity measures for different processes and operations along the slaughter line with evidence of their effectiveness. To achieve this, a literature review was conducted on studies estimating the effectiveness of measures applied in slaughterhouses to reduce the microbial contamination of pig carcasses. Results of this literature search are discussed and presented in summary tables that could be used as a source of information for the pig slaughter industry to further develop their guidelines on hygienic slaughter.

Contents

* Corresponding author.
E-mail addresses: arvo.viltrop@emu.ee (A. Viltrop), tarmo.niine@emu.ee (T. Niine), T.J.Tobias@uu.nl (T. Tobias), elena-lucia.sassu@ages.at (E.L. Sassu), ilaria.dibartolo@iss.it (I. D. Bartolo), enrico.pavoni@izsler.it (E. Pavoni), giovanni.alborali@izsler.it (G.L. Alborali), elke.burow@mluk.brandenburg.de (E. Burow), Richard.p.smith@apha.gov.uk (R.P. Smith).
† Present address: Ministry of Agriculture, Environment and Climate Protection of the State of Brandenburg, Henning-von-Tresckow-Straße 2-13, 14467 Potsdam, Germany.

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The BIOPIGEE project (part of the One Health European Joint Programme under Horizon 2020) aimed to identify relevant measures to effectively control *Salmonella* and Hepatitis E virus (HEV) within the pig meat food chain for reducing the number of human cases. Slaughter as the step at the end of primary pig production is of particular importance for the prevention of the contamination of carcasses and pork cuts with *Salmonella,* thus reducing the risk of human infections (L. Alban & Stärk, 2005; De Busser et al., 2013). Similarly, slaughter hygiene may have an important role in preventing human HEV infections as cross-contamination of pig carcasses with excretions or blood from HEV-positive pigs may occur at slaughter (Di Bartolo et al., 2012; Forzan et al., 2021). Thus, biosecurity measures and working practices directed to mitigate the risks of infections and contamination of carcasses with pathogens within the slaughterhouse are of paramount importance in reducing the risks of foodborne human infections.

Salmonella is a zoonotic pathogen frequently occurring as a subclinical infection in pigs which may cause pork-associated foodborne gastrointestinal infections and disease in humans (Campos et al., 2019). A great deal of effort has been put into reducing the risk of infection in humans by applying control measures in primary production, as well as improving the hygienic procedures at the slaughterhouses (Andres & Davies, 2015; Arguello et al., 2013; Hugas & Beloeil, 2014) Nevertheless, *Salmonella* infections are still a significant health hazard for humans in Europe, including by exposure to contaminated pig meat (Roasto et al., 2022).

About 10% of slaughtered pigs in the European Union (EU) were found to be infected with *Salmonella* in a pan-European baseline survey in the early 2000s (EFSA, 2008), and pigs and pork were suggested to be responsible for between 10% and 20% of all human cases of salmonellosis in the EU (EFSA, 2010). The effort taken by the pig industry since then to control *Salmonella* infections in the EU seems to have resulted in considerable improvements. The summary of the results of studies from various EU member states demonstrates that the overall proportions of *Salmonella*-positive pig carcasses, based on samples taken by the competent authorities, ranged between 3.1% and 3.9% in the period from 2017 to 2020 (Roasto et al., 2022). Nevertheless, pork remains an important source of *Salmonella* for humans in the EU, particularly the serovar *S.* Typhimurium and its monophasic variants. During 2016–2019, 14.0% of *S.* Typhimurium and 26.6% of monophasic *S.* Typhimurium isolates from humans were associated with pork as the source, as reviewed by Roasto et al. (2022).

Hepatitis E virus (HEV) is an emerging zoonotic pathogen in Europe. In the last 10 years, an increasing number of autochthonous HEV cases have been detected, with no history of travel to endemic areas. In the European Union, the zoonotic HEV-3 and HEV-4 genotypes can be found in humans as well as in different animal reservoirs. Pigs and wild boar are the main reservoirs of HEV-3 and HEV-4 (Ricci et al., 2017). In Europe, foodborne is the main route of transmission and human cases have been associated with the consumption of raw or undercooked pork, liver sausages, and wild boar meat (Ricci et al., 2017; Izopet et al., 2019). Pigs sampled at slaughter show a high seroprevalence confirming wide exposure to the virus on farms (Chelli et al., 2021; Meester et al., 2022). The highest risk of transmission to humans has been attributed to pig liver (Ricci et al., 2017) which has been shown to contain infectious virus despite the muscles of the same pig being free of the virus (Chelli et al., 2021; García et al., 2019). Detection of HEV RNA in the diaphragm of slaughter pigs has been considered to be related to contamination from liver rather than infection of the muscle itself (Chelli et al., 2021; García et al., 2019). There are no formal requirements enforced on the EU level for HEV control in primary production or at slaughterhouse. The only measure to control HEV transmission before the processing steps of pork products has been recommended by the Dutch Meat Products Association, advising its members not to use pork diaphragm muscle in unheated products (Bouwknegt et al., 2017 reviewed by Boxman et al., 2020).

According to European Union regulation, the assessment of microbiological contamination of pig carcasses in slaughterhouses is based on microbiological testing of carcasses for the occurrence of *Salmonella* spp. and the quantification of *Enterobacteriaceae* and aerobic bacteria (EC, 2007). *Enterobacteriaceae* are considered useful indicators of contamination with enteric bacteria like *Escherichia coli (E. coli), Salmonella enterica,* and some *Yersinia* spp (Cavalheiro et al., 2022). Increased counts of *Enterobacteriaceae* on pig carcasses have been shown to be associated with the occurrence of *Salmonella* on carcasses (Biasino et al., 2018; Corbellini et al., 2016). Aerobic bacterial counts and counts of *E. coli* have not been found to be directly associated with *Salmonella* contamination (Biasino et al., 2018). However, they can and have been used as indicators of changes in contamination levels, such as for the assessment of the effectiveness of measures to reduce microbial contamination (e.g., comparing different decontamination procedures). As there are no formal requirements for HEV control in primary production or at slaughterhouse, the standards for assessing HEV contamination are also lacking.

The aim of the present study was to identify biosecurity measures that are relevant for limiting *Salmonella* and/or HEV occurrence and their spread within pig slaughterhouses by performing a literature review. The outcome of the present study would be used to determine best practices and to compile a list of biosecurity measures for different processes and operations along the slaughter line, providing quantitative evidence of their effectiveness. Such a list may serve as the orientation in optimizing individual slaughter management design.

The study questions addressed in the literature review were what measures and procedures are applied in different steps of the slaughter process and how effective they are in controlling microbial contamination of pig carcasses, with special emphasis on controlling *Salmonella* and hepatitis E virus.

Methods

The literature search was conducted in ISIWoS, PubMed, Scopus, and Google Scholar databases in January 2021 and repeated for later publications in May 2023 to find relevant sources of scientific information. Due to resource constraints, no full systematic review was performed. Nevertheless, a systematized process of literature search and review was employed and several systematic steps for literature searching, and data retrieval were followed.

The search was targeted, and specific keywords, in English, related to the review questions were used, combining short search terms (e.g., *Salmonella* AND slaughter AND pig). The names of specific slaughter steps were used as keywords to replace 'slaughter' in the term. The same searches were carried out with 'hepatitis E' replacing '*Salmonella*'. The reference lists of relevant review papers were checked, and papers meeting the inclusion criteria were selected for review. Google searches were also performed to find grey literature, such as reports and proceeding papers. The literature search, relevance confirmation, and data extraction steps were conducted by two researchers.

Publications on original research (experimental or observational studies) assessing the effectiveness of measures applied in slaughterhouses in Europe and countries with similar systems (North America, Brazil, and Australia) were included (together with reports from experiments conducted by slaughterhouses or related organizations – further referred as 'industry reports'). In case *Salmonella* contamination was not specifically addressed in a study, the reduction of contamination of carcasses with other enteric bacteria was considered as a proxy for evidence for the reduction of *Salmonella* contamination.

Any quantitative outcome measures like proportions, bacterial counts, odds ratio (OR), or regression coefficients (Coef) were considered relevant. Studies conducted from 1990 to the present were included with no language restrictions.

Table 1
Countries where studies on control of *Salmonella* or other enteric bacteria at slaughter were performed with a number of studies included

Country	No. of studies[a]
United States of America (USA)	6
Belgium	5
Ireland	5
Denmark	4
Canada	3
France	3
Spain	3
Sweden	3
the Netherlands	3
United Kingdom (UK)	3
Brazil	2
Australia	1
Germany	1
Italy	1
Norway	1
Portugal	1

[a] The total number is > 41 as in case of multi-country studies, the study was counted for every participating country.

A summary table, divided by slaughter process steps, with all identified measures and quantitative estimates of their effectiveness as well as other details of the study (sample size, country of origin, type of the publication) and recommendations based on observed evidence was compiled and is presented as Supplementary material to this paper. Relevant sections from the industry guidelines (UECBV, 2022) for the reduction of microbial contamination at slaughter were included in the summary table to highlight already recommended procedures.

Results

In total, 41 original research papers or reports were included in the review, which related to studies investigating the effectiveness of practices and measures to control *Salmonella* or other enteric bacteria or providing background information on risk factors for bacterial contamination along the slaughter line in pig slaughterhouses. Out of these, 29 papers contained quantitative evidence on the effectiveness of various measures and were used to retrieve the information presented in Tables 2–8 and the Supplementary table. Most of the studies (n = 37) originated from peer-reviewed research journals. Two were study

Table 2
Efficacy of procedures in slaughterhouse lairage to control bacterial contamination in slaughter pigs based on published study results

Procedure	Parameter measured	Result value	Reference
Arriving pigs	Detection of *Salmonella* contamination on carcasses of dirty on arrival pigs		Letellier et al., 2009
	Reference: clean pigs	OR[a] = 2.78	
Keeping pigs in lairage	*Salmonella* cecal contamination of a pig at slaughter		Belœil et al., 2004
	Length of time pigs kept in lairage	OR	
	Reference: < 3 h	-	
	3–6 h	3.3	
	> 6 h	13.1	
	Salmonella prevalence (%) 24 h after slaughter on carcass swabs of pigs kept **2–4** h in lairage	In clean pens = 1.7% In contaminated pens = 0.8%	Boes et al., 2001
	Salmonella prevalence in carcasses: Range of time spent in lairage pens: 0.5 to 2 h	No association	Delhalle et al,. 2008
	Recovery of pen-specific *Salmonella* serovars: Range of time spent in lairage pens: 1.9 to 5.3 h	No correlation between time and serovars	Rostagno et al., 2003
Adding formic acid in drinking water	*Salmonella* detection in carcasses after evisceration		Bernad-Roche et al., 2022
	Reference: Treatment group		
	Control group		
		OR = 2.75	
Spraying or misting of pigs in lairage	Change in carcass aerobic bacteria count (log CFU[b]/cm^2) when '**spraying is used only when the external temperature is considered hot**' when spraying is performed '**in relation to external temperature**' or spraying '**75% of the time during lairage**'.	Increase: Coef.[c] 0.63; SE[d] 0.13; $p < 0.001$	Delhalle et al., 2008
		No significant association	
	Change in *Salmonella* prevalence on the pigs' skin		Walia. Lynch, et al., 2017
	- after **misting with clean water**	Significant increase from 72.1 to 94.3%	
	- after **misting with 0.5% Virkon® S ly.** or **'no misting' group**.	No significant change	
Cleaning and disinfection of lairage pens	Proportion of *Salmonella*-positive pen samples	Significant difference	Rostagno et al., 2003
	- Abattoir A pens washed with high-pressure cold water,	$p < 0.05$	
	- Abattoir B pens never washed.	62.5%	
		90.3%	
	Carcass *E. coli* counts (log CFU/cm^2)	Coef. −0.56; SE 0.08; $p < 0.001$	Delhalle et al., 2008
	- water as the cleaning method (Yes *vs.* No)		
	- frequency of lairage disinfection (min. once a year max. once a day)		
		Coef −0.76; SE 0.15; $p < 0.001$	
	Probability of detection of *Salmonella* in the pen surfaces		Walia, Arguello, et al., 2017
	Most effective cleaning and disinfection protocols:		
	- High-Pressure Wash + Detergent + Chlorocresol Disinfectant		
	- Drying following High-Pressure Wash + Detergent + Quaternary ammonium compound (QAC) Disinfectant	Probability	
	- Drying following High-Pressure Wash + Detergent + Chlorocresol Disinfectant		
		2.2%	
		3.8%	
		1.2%	

[a] odds ratio.
[b] colony-forming unit.
[c] - regression coefficient.
[d] - standard error.

Table 3
Efficacy of scalding conditions and procedures to control bacterial contamination on pig carcasses, based on published study results

Procedure	Parameter measured	Result value	Reference
Bath scalding	*Salmonella* presence on carcasses when the scald water was *Salmonella*-free **Reference:** Not *Salmonella*-free.	OR[a] = 0.39	Letellier et al., 2009
	Presence of *Salmonella* in scalding water Scalding water temperature: between 60 and 62°C 60.3°C or lower 61 and 62°C	 Not detected Not detected 5.6% 1.1%	 Arguello et al., 2012Botteldoorn et al., 2003Hald et al., 2003Hald et al., 2003
Steam scalding	Reduction in *Salmonella* prevalence in carcasses: Steam scalding **Reference:** 'basin scalding'	 (univariable) Coef.[b] −1.68; SE[c] 0.67; p = 0.033	Delhalle et al., 2009
Plugging of carcasses	The *Enterobacteriaceae* counts around the anuses after the scalding and dehairing procedure unplugged carcasses plugged carcasses	 increased by 1.15 log CFU[d]/cm^2 no significant change	Purnell et al., 2010
	The percentage of carcasses with *Enterobacteriaceae* counts below the level of detection (<1 log) plugged carcasses unplugged carcasses	 23.5% 2.9%	Purnell et al., 2010
	Detection of *Salmonella*-positive carcasses at the end of slaughter line '*Salmonella* detected in scalding water and on carcass after plug removal' **Reference:** Other combinations of testing results	 OR = 3.63	Hald et al., 2003

[a] odds ratio.
[b] regression coefficient.
[c] standard error.
[d] colony-forming unit.

Table 4
Efficacy of singeing conditions and procedures to control bacterial contamination in pig carcasses based on published study results

Procedure	Parameter measured	Result value	Reference
Handheld singeing	Reduction in the prevalence of *Salmonella*	47.5% reduction	da Silva et al., 2012
Automated singeing system	Reduction in the prevalence of *Salmonella* Reduction in aerobic mesophilic counts, coliform, and coliform resuscitation counts. Reduction of aerobic plate counts	>80% reduction from 7% to 0% Reduction by 2.5 log10 CFU[a] cm − 2 from 1.34 to − 0.15 log10 CFU/cm^2	da Silva et al., 2012Pearce et al., 2004Pearce et al., 2004Yu et al., 1999

[a] colony-forming unit.

reports from the industry and available from internet sources and one conference proceeding paper was included, as other relevant sources could not be found, or available information was scarce on certain slaughter steps. Except for five studies, all were conducted under field conditions, mostly at relatively large-scale and technologically advanced slaughterhouses located in Europe, the United States, Canada, Brazil, or Australia. The list of countries where studies were performed with the number of studies included is presented in Table 1.

The number of studies by year of publishing aggregated into ten-year periods (excluding the period 2020–2023) is presented in Figure 1. Most studies (19/41) were from the period 2000–2009. The latest studies that could be included were from 2022. No relevant studies were identified beyond 2022.

The number of papers used to extract quantitative information on the effectiveness of biosecurity procedures to control *Salmonella* or bacterial contamination for each step of slaughter line is presented in Figure 2. Several studies addressed multiple steps of the slaughter process; thus, the total number of sources of information in Figure 2 is >29.

The largest number of studies addressed the lairage management (n = 7) followed by scalding and effectiveness of final decontamination of carcasses after carcass splitting (n = 6).

Out of the 29 studies used to derive quantitative evidence, 11 did not specifically use *Salmonella* to assess bacterial contamination. The bacteria in these studies were most frequently identified as *Enterobacteriaceae,* followed by aerobic bacteria and *E. coli.*

The search on the effectiveness of measures to specifically control HEV at slaughterhouse level identified one relevant paper demonstrating in one experiment the complete elimination of the HEV on the skin of pig carcasses after pasteurization step applied on carcasses after singeing (Jones & Johns, 2012).

The evidence related to the effectiveness of measures for specific steps in the slaughter process is discussed below.

Table 5
Efficacy of procedures related to polishing of pig carcasses to control bacterial contamination, based on published study results

Procedure	Parameter measured	Result value	Reference
Maintenance of polishing equipment	Recovery of *Salmonella* from a carcass:		Hald et al., 2003
	'*Salmonella* isolated from the polishing equipment'	OR[a] = 3.74	
	Reference: no detection		
Second singeing after polishing	Bacterial contamination of carcass		
	Aerobic bacteria	**Reduction**	
	Coliforms	from 2.24 to 0.60 log10 CFU[b]/cm^2	Yu et al., 1999
		from 0.97 to 0.45 log10 CFU/cm^2	
		Reduction	Montzey & Minvielle, 2002
	Total mesophilic flora at 30°C	by 2 Log CFU cm − 2	**(Industry report)**
	Enterobacteriaceae	by 0.5 Log CFU cm − 2	
Hot water treatment after polishing	The total number of spoilage bacteria and *E. coli*	**Reduction** by 2.5 log10 CFU cm − 2	Gill et al., 1995
	A total aerobic count - recovered from sites before and after pasteurization		Gill et al., 1997
	a) carcass surface except the anal area	log10 values for the mean total: a) Set 1: before 2.10 after 0.16 Set 2: before 1.97 after 0.19	
	b) anal area	b) Set 1: before 1.40 after 1.31 Set 2: before 1.81 after 1.16	
Steam pasteurization of carcasses before evisceration in a nonpressurized enclosed on-line chamber	Reduction of bacterial counts on carcasses after pasteurization		Conter et al., 2006
	reduction of the mean	2.00 log10 CFU/cm^2	
	AMC[c]	1.07 log10 CFU/cm^2	
	Coliforms counts	0.78 log10 CFU/cm^2	
	E. coli counts	$p < 0.05$	

[a] odds ratio.
[b] colony-forming unit.
[c] aerobic mesophilic count.

Table 6
Efficacy of procedures related to the evisceration of carcasses to control bacterial contamination in pig carcasses, based on published study results

Procedure	Parameter measured	Result value	Reference
Midline opening of the belly	*Enterobacteriaceae* contamination of different carcass parts		Biasino et al., 2018
	Using robot		
	Reference: manual opening.	Odds of contamination were 2.8–8.3-fold lower	
Using a plastic bag to seal the rectum	Reduction of carcass contamination (detection) with *Yersinia enterocolitica* on carcasses when eviscerating using a plastic bag		Nesbakken et al., 1994
	Reference: without using a plastic bag	Odds Ratio = 0.08	
Avoiding incision of tonsils	*Enterobacteriaceae* contamination of different carcass parts.		Biasino et al., 2018
	Association with incision of tonsils	**Elbow**	
	Reference: no incision	Coef.[a] 0.37 $p = 0.038$	
		Foreleg Coef. 0.39 $p = 0.017$	

[a] regression coefficient.

1. *Logistic slaughter*

Ordering the slaughter of pigs during the day or week according to the herds' *Salmonella* status (pigs from *Salmonella*-negative or low-risk category herds are slaughtered first followed by the pigs from herds with higher *Salmonella* risk category) has been recommended to reduce the *Salmonella* contamination of pig carcasses on the slaughter line. This practice, often called 'logistic slaughter', has been used in some EU countries like Denmark (L. Alban et al., 2012), Ireland (Duggan et al., 2010), Germany (Kühnel & Blaha, 2004), and the Netherlands (Swanenburg et al., 2001). This recommendation has been based on the logical assumption that, by restricting the bacterial contamination of the slaughterhouse environment, the cross-contamination of carcasses along the slaughter line will be reduced.

Table 7
Efficacy of procedures related to carcass splitting to control bacterial contamination in pig carcasses, based on published study results

Procedure	Parameter measured	Result value	Reference
Cleaning and disinfection of the splitting machine	Reduction of bacterial counts on pig carcasses when cleaning and disinfection of the splitting machine is done three times a day		Delhalle et al., 2008
	E. coli counts	Coef.[a] − 0.89; SE[b] 0.37; $p = 0.016$;	
	Aerobic bacteria count	Coef. − 0.76; SE 0.26; $p = 0.004$	
Head splitting	Detection of *Salmonella* on carcasses		Biasino et al., 2018
	Detection on sternum after splitting the head		
	Reference: head not split	OR[c] = 4.2	

[a] regression coefficient.
[b] standard error.
[c] odds ratio.

However, the evidence on the effectiveness of logistic slaughter in avoiding the cross-contamination of pig carcasses remains controversial and only a limited number of studies could be found where the effect of logistic slaughter on contamination of carcasses had been quantified. Swanenburg et al. (2001) found that the prevalence of *Salmonella* in pork samples of seronegative herds was lower than in samples of seropositive herds and *Salmonella* contamination of carcasses after slaughter was partially caused by *Salmonella*-infected herds that were slaughtered before, and partially by residential flora of the slaughterhouse. It was concluded by the authors that separate slaughter of seronegative pig herds can be useful to decrease the prevalence of *Salmonella*-contaminated pork after slaughter. However, the level of contamination of carcasses due to cross-contamination from other infected pigs at slaughter compared to contamination from residential flora of the slaughterhouse was not quantified in the above-mentioned study.

Boes et al. (2001) did not find clear evidence of the effect of slaughtering pigs separately from *Salmonella*-negative and infected herds. Carcass swabs collected 24 h after slaughter revealed a low degree of cross-contamination originating from contaminated lairage pens where pigs were kept for 2–4 h. The proportion of *Salmonella*-positive carcasses in an intervention group, which mimicked the conditions of logistic slaughter (clean lairage pens), was 1.7% whereas in a control group (with contaminated lairage pens), it was 0.8% and the difference was not statistically significant.

Similarly, in a study conducted in Spanish slaughterhouses, the results showed that the order of slaughter of batches with different *Salmonella* risk categories was not as important as the separation of animals of different *Salmonella* risk during the transport and in lairage. Carcass contamination in low-risk herds was associated with the contamination of lairage pens and the slaughter line activities (Argüello et al., 2014).

2. *Lairage*

The effect of keeping pigs in lairage before slaughter, combined with other lairage-related factors, has been extensively studied, and a lot of evidence has been produced to describe the effects of these factors on carcass *Salmonella* contamination. Seven studies were used to retrieve quantitative evidence, and the results are summarized in Table 2.

The cleanliness of pigs arriving at the slaughterhouse has been shown to be a significant factor associated with carcass *Salmonella* contamination. Pigs that were visibly dirty on arrival had a higher risk of being contaminated with *Salmonella* when compared to clean ones (odds ratio 2.78) (Letellier et al., 2009).

The contaminated lairage pens have been shown to be an important source of *Salmonella* infection for slaughtered pigs (Argüello et al., 2014). Thus, the effect of time in which the pigs are spending in lairage pens on carcass bacterial contamination has been addressed in several studies (Beloeil et al., 2004; Delhalle et al., 2008; Hurd et al., 2002; Rostagno et al., 2003). The general conclusion of these studies is that prolonged housing of slaughter pigs in abattoir lairage may result in the infection of pigs with *Salmonella* originating from the lairage environment. Beloeil et al. (2004) found that the odds for individual *Salmonella* cecal contamination of a pig at slaughter were 3.3 times higher for pigs kept in lairage for 3–6 h, and 13.1 times higher for pigs kept more than 6 h compared to those kept less than 3 h. However, a short time in the lairage (up to 6 h) evidently does not significantly increase the risk of infection. Delhalle et al (2008) found that a holding time of 30–120 min had no effect on carcass *E. coli* or aerobic bacteria count or on *Salmonella* prevalence, whereas Rostagno et al (2003) did not find a correlation between the time spent in lairage pens and the recovery of pen-specific serovars from the slaughter pigs when the average time was 3.5 h and the range 1.9–5.3 h.

The effect of cleaning and disinfection of lairage pens on carcass bacterial contamination has been demonstrated by Delhalle et al (2008). The carcass *E. coli* counts, in log colony-forming units (CFUs) per cm^2, decreased if water was used as the cleaning method for the lairage [regression coefficient (Coef.) −0.56; standard error (SE) 0.08; $p < 0.001$] and if lairage was disinfected more frequently (comparison groups – once a year, twice a year, once a month, once a week, once a day) (Coef −0.76; SE 0.15; $p < 0.001$) (Delhalle et al., 2008). Already washing the pens with high-pressure cold water before pigs had entered significantly reduced the proportion of *S.* Enterica-positive pen samples, suggesting that washing reduced the bacterial load (Rostagno et al., 2003). The extensive contamination of watering sources with *Salmonella* (33% of water samples) was discovered in a latter study indicating the need for cleaning and disinfection of watering equipment in the lairage. In a study comparing the effectiveness of eight cleaning and disinfection protocols for slaughterhouse lairages, washing with water alone did not have a significant effect on bacterial load on surfaces. The most effective protocol to eliminate *Salmonella* and reduce *Enterobacteriaceae* counts was ensuring that lairage pens were allowed to dry after intensive cleaning with a detergent and a chlorocresol-based disinfectant (Walia, Arguello, et al., 2017).

Adding formic acid esterified in the form of glycerides in the drinking water of pigs kept in lairage has been shown to significantly reduce *Salmonella* infection in slaughtered pigs. The dosage used in the study (3 kg formic acid/1000 L) was higher than the dosage commonly used for pigs in farms as the exposure time was short (~15 h for all groups).

Table 8
Efficacy of decontamination procedures to control bacterial contamination on pig carcasses, based on published study results

Procedure	Parameter measured	Result value	Reference
Removal of fecal contamination from carcasses after evisceration	Reduction of aerobic colony counts (ACC) and *Enterobacteriaceae* count (ENT) after treatment	Reduction (log10 CFU[a]/cm^2)	Le Roux et al., 2008 (Paper in conference proceedings)
	by trimming	ACC 2.69 / ENT 3.39	
	skin	ACC 2.27 / ENT 2.60	
	meat	ACC 2.82 / ENT 3.59	
	by steam vacuum	ACC 2.10 / ENT 2.53	
	skin		
	meat		
Washing of carcasses before and after evisceration with cold potable water	Total aerobic bacterial counts on carcasses		Bolton et al., 2002
	pre-evisceration washing	increase by 2,5 log10 CFU cm − 2	
	post-evisceration washing	increase by 1 log10 CFU ml − 1	
Hot water treatment in a cabinet	Prevalence of *Salmonella*-positive carcasses	Reduction by 90–97%	Jensen, 2000 (Industry report)
	Reduction in *E. coli* counts on carcasses	On average 2 log10 CFU/1400 cm^2	
	The prevalence of *Salmonella* on carcasses		Hamilton et al., 2010
	Not treated	ND[b, A] / 16.0%[B]	
	Hot water treatment	ND[A] / 2.7%[B]	
	The prevalence of *E. coli* on carcasses	92.9%[A] / 69.3%[B]	
	Not treated	9.8%[A] / 22.0%[B]	
	Hot water treatment	0.89[A] / 0.45[B] CFU/gram	
	The mean log10 *E. coli* concentration	0.83[A] /−0.65[B] CFU/gram	
	Not treated	4.06[A] / 3.00[B] CFU/gram	
	Hot water treatment	1.81[A] / 2.10[B] CFU/gram	
	The mean log10 TVC[2]		
	Not treated		
	Hot water treatment		
	Salmonella prevalence in carcasses from pigs from herds with higher risk of *Salmonella*	0.9% (similar to the surveillance results from pork originating from all other pigs in Denmark)	Alban & Sørensen, 2010
Steam pasteurization of carcasses before evisceration in a nonpressurized enclosed on-line chamber	Reduction of bacterial counts on carcasses after pasteurization		Conter et al., 2006
	reduction of the mean	2.00 log10 CFU/cm^2	
	AMC[c]	1.07 log10 CFU/cm^2	
	Coliforms counts	0.78 log10 CFU/cm^2	
	E. coli counts	$p < 0.05$	
Acidified sodium chlorite (ASC) treatment (a low volume pressurized spray, approx. 4 l/side)	The prevalence of *Salmonella* on carcasses		Hamilton et al., 2010
	Not treated	ND[A] /16.0%[B]	
	ASC treatment	ND[A] / 7.0%[B]	
	The prevalence of *E. coli* on carcasses	92.9%[A] / 69.3%[B]	
	Not treated	12.5%[A] / 30.0%[B]	
	ASC treatment	0.89[A] / 0.45[B] CFU/gram,	
	The mean log10 *E. coli* concentration	−0.75[A] /−0.60[B] CFU/gram	
	Not treated	4.06[A] / 3.00[B] CFU/gram	
	ASC treatment	2.76[A] / 2.53[B] CFU/gram	
	The mean log10 TVC[d]		
	Not treated		
	ASC treatment		
A Lactic acid rinse (2–2.5% lactic acid applied to the carcasses in a cabinet before the chilling stage)	Proportion of *Salmonella*-positive carcasses		Larsen et al., 2003
	before treatment	14%	
	after treatment	7%	
		$p < 0.05$	

[a] colony-forming unit.
[b] Not detected.
[c] aerobic mesophilic count.
[d] total viable count.
[A] Abattoir A.
[B] Abattoir B.

The odds of detecting *Salmonella* in carcasses of untreated group of pigs after evisceration were 2.75 times higher compared to the treatment group (Bernad-Roche et al., 2022).

Spraying or misting of pigs kept in lairage to improve their welfare may have effects on the bacterial contamination of carcasses. Carcass aerobic bacterial count (log CFU/cm^2) increased when spraying was used 'only when the external temperature was considered hot' (Coef. 0.63; SE 0.13; $p < 0.001$) whereas there was no significant association when spraying was performed 'in relation to external temperature' or '75% of the time during lairage' (Delhalle et al., 2008). In another study, after misting with clean water, the *Salmonella* prevalence on the pigs increased from 72.1% to 94.3%, whereas after misting with 0.5% Virkon® S, the prevalence did not change significantly (Walia. Lynch, et al., 2017). These findings indicate that adding disinfectant to the spraying or misting water would be needed to avoid additional risk of infection.

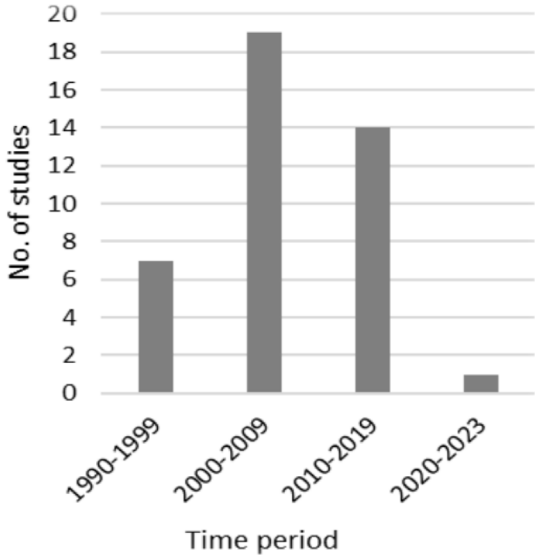

Figure 1. Number of studies included per year of publication.

3. *Scalding*

Scalding carcasses may be performed in a water bath or by steam and these processes are associated with different risks of carcass *Salmonella* contamination. Quantitative information was retrieved from six papers (Table 3).

Salmonella-contaminated scalding water in a scalding bath increased the risk of contamination of carcasses. In a study in Canada, the proportion of contaminated carcasses was 2.6 times higher when the scalding water was contaminated compared to water being *Salmonella*-free (Letellier et al., 2009). In a study conducted in Belgian slaughterhouses, the use of steam for scalding was protective against *Salmonella* contamination of carcasses in univariable analysis (Coef. −1.68; SE 0.67; $p = 0.033$) whereas in a multivariable model, the effect was nonsignificant (Delhalle et al., 2008).

The temperature of the scalding water is also crucial both for the quality of scalding and in avoiding the contamination of the water with living bacteria. It has been shown in several studies that the temperature of the scalding water should always be between 60 and 62°C to keep the scalding water *Salmonella*-free (Arguello et al., 2012; Botteldoorn et al., 2003; Hald et al., 2003). The temperature of scalding water should be continuously monitored to ensure a constantly high temperature in the tank. Plugging the anus before scalding in water reduces the level of carcass skin contamination with enteric bacteria. It has been demonstrated that the *Enterobacteriaceae* counts around the anuses of unplugged carcasses increased by 1.15 log CFU/cm^2 after the scalding and dehairing procedure, while counts from plugged carcasses showed no significant change. The percentage of plugged carcasses with *Enterobacteriaceae* counts below the level of detection (<1 log) was 23.5%, whereas only 2.9% of unplugged carcasses were below this level (Purnell, James, Wilkin, & James, 2010).

4. *Singeing*

Three studies on the effectiveness of singeing conditions and procedures to control bacterial contamination providing quantitative information were used for data retrieval, and the results are shown in Table 4.

Besides its main purpose of removing any remaining hair, the singeing of carcasses reduces the bacterial contamination of the carcass surface. It has been found to be the most effective step for *Salmonella* reduction over the slaughter line resulting in a reduction of the number of *Salmonella*-positive carcasses by 47.5–80% (da Silva et al., 2012). In other studies, up to 100% reduction has been observed (Davies et al., 1999; Pearce et al., 2004). The degree of reduction of the *Salmonella*-contaminated carcasses depends on the singeing procedure and the type of singeing equipment used (da Silva et al., 2012; Davies et al., 1999). Automated singeing systems seem to be more efficient in reducing the number of *Salmonella*-positive carcasses compared to handheld singeing (da Silva et al., 2012). Immediate washing after singeing has been reported to reduce the effect of singeing (Davies et al., 1999).

5. *Polishing*

The polishing procedure after singeing of carcasses has been shown to be a site for bacterial recontamination of the carcasses (Hald et al., 2003; Pearce et al., 2004; Rahkio et al., 1992; Yu et al., 1999). This may happen due to the survival of bacteria in deeper skin folds or in the hair follicles that could be then redistributed over the carcass by the rotating flails and brushes of the polisher, or the bacteria may orig-

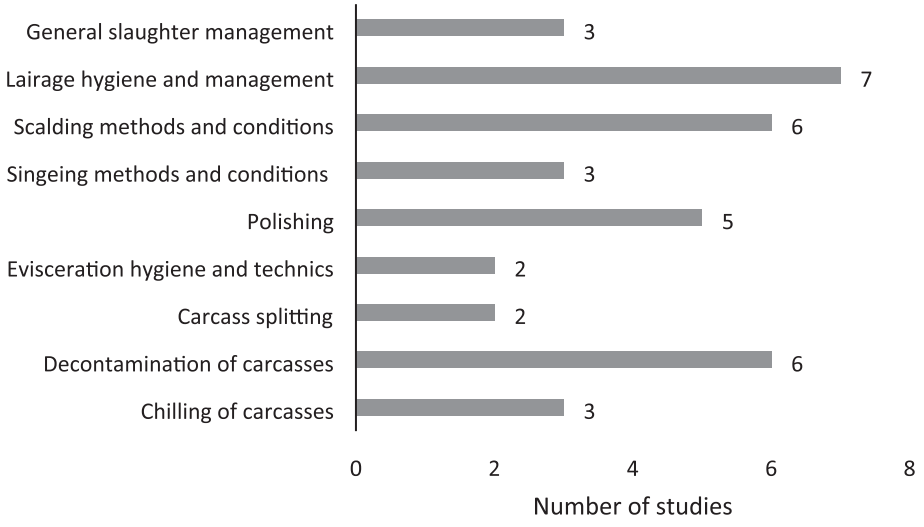

Figure 2. Number of studies used to derive quantitative evidence on the effectiveness of measures to control bacterial contamination of pig carcasses at slaughterhouse.

inate from the contaminated polisher (Lo Fo Wong et al., 2002). Quantitative data on the effectiveness of measures related to polishing to reduce contamination were extracted from five studies and are presented in Table 5.

Hald et al. (2003) have found that if the polishing equipment was contaminated with *Salmonella,* the odds of a pig carcass to be contaminated at the end of slaughter line were 3.74 times higher compared to the situation where *Salmonella* could not be isolated from the polisher.

To eliminate or reduce microbial contamination originating from the polisher, the pasteurization of polished un-eviscerated carcasses with hot water or steam has been shown to be effective. Application of sheets of water at 85°C onto polished pig carcasses for 15 s reduced the numbers of nonthermotolerant bacteria on carcasses, including coliforms and *Escherichia coli* by about two orders of magnitude (Gill et al., 1997; Gill et al., 1995; Yu et al., 1999). Steam pasteurization of carcasses in a nonpressurized enclosed on-line chamber significantly reduced counts of aerobic mesophilic bacteria as well as coliforms and *E. coli* (Conter et al., 2006).

Another option shown to be effective in reducing the contamination is the application of a second flaming of the carcasses after polishing. The repeated flaming improved decontamination of carcass surface on average by 2 Log in total mesophilic flora counts at 30°C and by 0.5 Log in *Enterobacteriaceae* (Montzey & Minvielle, 2002).

6. *Evisceration*

Evisceration has been shown to be a critical control point on the slaughter line in relation to carcass *Salmonella* contamination (Delhalle et al., 2008; Pearce et al., 2004). Contamination can happen mainly because of the accidental rupture of intestines or incision into tissues (e.g., lymphatic organs) during opening of the belly and the removal of internal organs (Crotta et al., 2019). As an example, incision of the tonsils during pluck set removal was associated with higher *Enterobacteriaceae* numbers at the elbow and foreleg (Biasino et al., 2018). Therefore, practices reducing these risks should be implemented. In Table 6, the quantitative information on effectiveness of evisceration practices to control bacterial contamination derived from two sources are presented.

Opening of the belly using a robot was significantly associated with a decrease in *Enterobacteriaceae* contamination of carcasses. The odds of contamination of different carcass parts were between 2.8 and 8.3-fold lower compared to manual opening (Biasino et al., 2018).

Another source of bacterial contamination during evisceration can be the extraction of feces from the rectum. Therefore, wrapping the loosened bung into the plastic bag until the intestines are removed is recommended (UECBV, 2022). As no study specifically addressing Salmonella contamination in this context could not be found in literature search data on other enteric bacterium, *Yersinia enterocolitica* is presented hereby. The odds of recovery of *Y. enterocolitica* from carcasses eviscerated using a plastic bag to seal the rectum were 8% of the odds of recovery of the bacterium from carcasses eviscerated without sealing the rectum (OR = 0.08) (Nesbakken, Nerbrink, Røtterud, & Borch, 1994). In a study conducted in 12 industrial slaughterhouses in five EU member states (Hald et al., 2003), the bung loosening or the evisceration was not identified as risk factors for carcass contamination. According to the authors' opinion, this could be due to seven of the slaughterhouses sealing the rectum with a plastic bag to prevent fecal contamination. In three slaughterhouses, where no such preventive measures were taken, the level of contamination during evisceration was higher.

Carcasses may also be cross-contaminated through operators' hands or instruments, i.e., knives. The hands of the evisceration operator were contaminated with *Salmonella* on two occasions in two different plants in a study from Ireland and were subsequently linked to carcass contamination based on molecular tracking of the isolates (Duggan et al., 2010).

7. *Carcass splitting*

Contaminated slaughter equipment, like the carcass splitter, can serve as a source of *Salmonella* cross-contamination. Samples taken from carcass splitters were found to frequently harbor *Salmonella* (Van Hoek et al., 2012). Data on the effectiveness of measures to control bacterial contamination at carcass splitting are presented in Table 7.

Complete cleaning and disinfection of the splitting machine three times a day significantly reduced *E. coli* and aerobic bacteria counts on pig carcasses (Coef. −0.89; SE 0.37; $p = 0.016$; Coef. − 0.76; SE 0.26; $p = 0.004$) (Delhalle et al., 2008).

It has been found that when the head is split, the risk of contamination of the carcass is higher compared to when the head remains intact. When the head was split, the odds of finding *Salmonella* on the sternum were higher by 4.2 times (Biasino et al., 2018).

8. *Decontamination*

Data on the effectiveness of decontamination of carcasses at or post-evisceration could be retrieved from seven studies and are presented in Table 8.

In case of fecal contamination of the carcass, measures should be taken to remove the contamination and to prevent the spread of microbes to other carcasses. This can be done during the trimming of the carcass either by knife or using steam vacuum technology-based systems. The latter has been shown to be more effective in reducing the bacterial load on beef carcasses (Reagan et al., 1996). In a study from Denmark, the steam vacuum technology applied on beef carcasses reduced the Aerobic Plate Count and *E. coli* by 1.31 log10 CFU/cm^2 to 1.74 log10 CFU/cm^2 for treatment of 10 and 30 s respectively from an initial value of 3.23 log10 CFU/cm^2 for knife trimming. The proportion of *E. coli*-positive samples were reduced from 50.6% to 6.7% and 3.3% for treatment of 10 and 30 s, respectively (Steenberg, Dalsgaard, Teilmann, & Christensen, 2006). There are fewer studies on the performance of this technology on pig carcasses. In a French study on pig carcasses, it was found that the efficacy of the steam vacuum technology was equivalent to trimming by knife in reduction of the bacterial contamination, but caused less damage to the carcass, thus having extra benefit for the producer (Le Roux et al., 2008).

The washing of carcasses has been used as an additional measure to remove bacterial contamination. The washing of carcasses with cold drinking water before and after evisceration (final wash), however, did not have any perceivable decontamination effects in a study from Ireland. Instead, pre-evisceration washing was associated with an increase in bacterial counts by 2.5 log10 CFU cm^{-2}, while post-evisceration washing was associated with an increase of 1 log10 CFU/mL (Bolton et al., 2002).

In contrast, hot water treatment (HWD) has been shown in several studies to significantly reduce the concentration of bacteria on carcasses and decrease the prevalence of *Salmonella*-positive carcasses.

A Danish experimental study of HWD in a cabinet with 80°C applied for 15 s reported an average of 2 log10 CFU/1400 cm^2 reduction in *E. coli* from an average of 3 log CFU/1400 cm^2 and suggested a decrease in the prevalence of *Salmonella*-positive carcasses by a factor of 10 to 40, i.e., a reduction by 90–97% (Jensen, 2000). Furthermore, HWD of carcasses from herds with a higher risk of *Salmonella* resulted in a carcass prevalence of 0.9%, similar to the surveillance results from pork originating from all other pigs in Denmark (Lis Alban & Sørensen, 2010). In a study from Australia, the prevalence of *E. coli* on control carcasses was 92.9% compared with 9.8% for HWD carcasses in one abattoir and the prevalence of *Salmonella* on control carcasses as 16% compared with 2.7% for HWD carcasses in a second one (Hamilton et al., 2010; Larsen et al., 2003).

Table 9
Efficacy of procedures and conditions related to the chilling of carcasses on the control of bacterial contamination in pig carcasses, based on published study results

Procedure	Parameter measured	Result value	Reference
Changing the carcass hooks before chilling	*E. coli* counts on carcasses: Changing of carcass hooks **Reference:** not changed	Reduction: Coef.[a] −0.69; SE[b] 0.08, $p < 0.001$	Delhalle et al., 2008
Cooling down the carcasses	Association of chilling time to reach 7°C of carcass internal temperature with aerobic bacterial counts on the surface of the carcass Longer time associated with increase in bacterial counts	Per hour Coef. 0.005; SE 0.002; $p = 0.0046$	Delhalle et al., 2008
Storage in chilling room	Change in proportion of *Salmonella*-positive carcasses Time of storage: 12–20 h more than 50 h	Reduction 3.8-fold average 4–7-fold	Arguello et al., 2012
	Contact time to transfer microorganisms between meat surfaces by direct contact	<1 min	Dickson, 1990

[a] regression coefficient.
[b] standard error;

The acidified sodium chlorite and lactic acid rinse have been shown to be effective methods for carcass decontamination in Australia and USA (Hamilton et al., 2010; Larsen et al., 2003), though these are not allowed in the EU.

9. *Chilling*

Chilling and cool storage (at −1 to 4°C) have been shown to reduce the bacterial contamination of carcasses. Data on the effectiveness of chilling and related processes are summarized in Table 9.

Twelve-to-twenty-hour cool storage resulted in on average 3.8-fold reduction and more than 50 h storing in 4–7-fold reduction in a proportion of *Salmonella*-positive carcasses in a study from Spain (Arguello et al., 2012). Rapid chilling is needed to prevent bacterial growth on carcasses. A longer chilling time to reach a 7°C carcass internal temperature meant higher aerobic bacterial counts on the surface of the carcass (per hour increase Coef. 0.005; SE 0.002; $p = 0.0046$) (Delhalle et al., 2008). Changing the carcass hooks just before chilling seemed to be protective against *E. coli* contamination (Delhalle et al., 2008).

Finally, physical contact between the carcasses during transportation on the slaughter line and at storage should be avoided. The transfer of microorganisms between meat surfaces by direct contact has been demonstrated with contact times of less than 1 min (Dickson, 1990).

Discussion

The search for evidence on the effectiveness of slaughterhouse biosecurity measures has shown that the majority of the procedures and measures in pig slaughter have been studied for their effect on fecal or bacterial contamination, with some special emphases on limiting the *Salmonella* contamination on carcasses.

The largest number of studies in this respect has been published on the decontamination of carcasses, a step specifically designed to eliminate or inactivate bacterial contamination from the surfaces of the carcass at various stages of slaughter process. The steam vacuum method has been recommended to eliminate fecal contamination from carcasses by the European Livestock and Meat Trades Union (UECBV, 2022). However, the published evidence of effectiveness of the method on pig carcasses is limited to one report in conference proceedings (Le Roux et al., 2008). Nevertheless, the method has been extensively validated on beef carcasses and we may speculate that the recommendation given by UECBV is based on these studies. Hot water treatment (HWT), as well as treatment with lactic acid or ASC, have been shown to be highly effective for the final decontamination of carcasses while HWT seems to surpass the other two methods in comparison.

Despite the effectiveness of the decontamination step, the measures to reduce the bacterial contamination in preceding steps on the slaughter line are also important, as demonstrated in numerous studies reviewed in this paper. Lairage management and scalding are the other two steps in the slaughter process which have been researched several times, possibly because the infection of pigs or the contamination of their carcasses at these stages can be carried throughout the whole slaughter process.

In the management of pigs in the slaughterhouse lairage, the keeping time appears to be of crucial importance. Even if the lairage pens are contaminated, the infection of pigs can be avoided if they are moved to slaughter within the first 4–6 h upon arrival.

Steam scalding has been shown to be superior compared to scalding in a bath, in regards to the reduction of bacterial contamination, whereas the effectiveness of bath scalding is dependent on the maintenance of optimal water temperature (60–62°C) in the scalding tank. The plugging of carcasses seems to be an important extra measure to avoid bacterial contamination during bath scalding.

Singeing has been shown to be very effective in the removal of bacterial contamination. However, during the following polishing step, the carcasses tend to be recontaminated by the flails and brushes of the polisher. Therefore, a decontamination step after polishing (second singeing or pasteurization) can be introduced to remove this contamination. Regular cleaning and disinfection of polishing equipment have been shown to be beneficial in reducing the contamination as well.

The following evisceration and carcass splitting steps involve manipulations which comprise a higher risk of recontamination of the carcass. Opening the carcass by robot reduces the risk of contamination substantially and therefore is highly recommended. Sealing the rectum with a plastic bag is another cheap but effective measure to reduce the risk of contamination of the carcass. The recontamination of the carcass through splitting equipment is apparently the most common flaw at the splitting step; therefore, frequent disinfection of the equipment has been shown to reduce the risk significantly.

Finally, in the chilling step, a longer period of time for keeping the carcass in the cool room seems to have the biggest effect on the reduction of bacterial contamination.

The number of identified specific studies on controlling HEV at slaughter was limited to one. There are no studies assessing the ability of HEV to survive in the slaughterhouse environment (surfaces, utensils) or on pig carcasses if cross-contamination occurs along the slaughter line. Studies conducted so far proved a high resistance of the HEV at room temperature for up to 28 days and up to 21 days at 37°C in

culture medium (Johne, Trojnar, Filter, & Hofmann, 2016), suggesting the ability of a long persistence of the virus in the environment. The virus remains infectious and only a reduction in infectivity was observed, for 4 weeks at 23°C if dried on steel, wood, plastics, and ceramics (Wolff, Günther, & Johne, 2022). The virus is inactivated in liver patè heated at a temperature of >71°C for 20 min, but remains infectious at 62°C (Barnaud, Rogée, Garry, Rose, & Pavio, 2012). If the virus is not embedded in any matrices or food, it is inactivated at 65°C in 5 min and at 80°C in 1 m.

Although the experiments are hampered by a lack of an efficient cell culture, which could interfere with the estimation of residual infectivity, results suggest the resistance of HEV in the environment of the abattoir within lairage pens and on equipment used in the slaughterhouse. The cross-contamination of carcasses in slaughter line could occur through feces of shedder pigs or during evisceration in case of accidental rupture of gall bladder and bile release. It is unknown how long the virus can survive on pig skin or on other surfaces, leaving open the question on this issue. Conversely, the risk of virus survival on the skin after scalding and singeing has been determined to be negligible (Crotta et al., 2021; Jones & Johns, 2012). The available information on HEV in the slaughter environment so far is limited and further influenced by the variable prevalence in animals when entering the slaughter line. Nevertheless, the studies on spread and risk factors of HEV contamination in pork and pork products conducted so far are a necessary starting point for the development of interventions. First recommendations regarding the use of pork products of higher risk have been issued showing that work is ongoing in this regard. Future studies should show whether the present measures of hygienic slaughter aimed at limiting the bacterial contamination are sufficient to control viral (HEV) contamination of pig carcasses, pork, and pork products.

In this literature search, we focused strictly on the effectiveness of measures applied in slaughterhouses to limit microbial contamination (primarily *Salmonella, Enterobacteriaceae,* and HEV) on pig carcasses extracted from explorative studies and primary literature. Other considerations, like animal welfare or food quality aspects, were not evaluated. Importantly, some measures that were designated as effective in this study (e.g., decontamination of carcasses using disinfecting substances) may not be applied or legally accepted in EU countries, as our search included studies, which addressed slaughter systems used in EU member states, but were not performed in only European countries.

The studies included in this review were conducted in a total of 16 countries including, beside European countries, Australia, Brazil, Canada, and USA. According to our best knowledge, the slaughter and quality control systems in these countries are compatible, thus, any effect due to very different slaughter systems in the countries could be presumably avoided. When comparing the results of similar studies conducted in different countries, no drastic differences could be seen, indicating that the measures are having a similar effect independent of the country location of the slaughterhouse. Nevertheless, it cannot be excluded that in different slaughter systems (e.g., small-scale, less mechanized slaughterhouses), the effects may be different or nonexistent.

The literature search was not conducted in a systematic way, and it is possible that we may have missed some sources of information. Nevertheless, we have a reason to believe that we have been able to reach most of the relevant papers with the identified 41, as shown by a systematic review with a similar review question conducted in 2015. This included papers from 1990 to 2015, and the number of relevant papers found was 37, but it also included literature reviews and meta-analyses, modelling and risk assessment papers, as well as papers considering measures in meat cutting and packaging stage (excluded from our review), and papers originating from all continents (Young et al., 2016). Our search revealed an additional five papers from the period 2016 to May 2023.

There is a substantial body of scientific evidence on the effectiveness of biosecurity measures in slaughterhouses obtained over recent decades. Based on that, the relevant practices for slaughter hygiene have been established and many of them are reflected in guidelines of the industry organizations like European Livestock and Meat Trades Union (UECBV, 2022). We hope that the present compilation of quantitative evidence will help the industry to further develop their guidelines on hygienic slaughter, perhaps also contribute to awareness and motivate to implement changes in the techniques, as well as quantify the effects of their actions. It could also help to direct the surveillance and monitoring efforts to ensure compliance with measures in most critical steps on slaughter line. However, it should not be forgotten that the measures implied along the slaughter line have combined effect and corrective measures in single step may not be sufficient to improve the situation. As shown in computer simulations, an improvement of individual factors had a limited effect on the *Salmonella* prevalence of the final carcass. The reduction was largest when several factors were improved concurrently (L. Alban & Stärk, 2005).

Authors' contribution

Initial literature search, relevance confirmation, and data extraction – AV and TN; providing additional literature sources – all authors; writing and editing the manuscript: all authors.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jfp.2023.100171.

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