DOI: 10.1111/risa.14141

ORIGINAL ARTICLE

Building a resilient pork supply chain to *Salmonella* spp

Wenjuan Mu[1] | **Esther van Asselt**[1] | **Coen van Wagenberg**[2] | **H. J van der Fels-Klerx**[1]

[1]Wageningen Food Safety Research, Wageningen University and Research, Wageningen, The Netherlands

[2]Wageningen Economic Research, Wageningen University and Research, Wageningen, The Netherlands

Correspondence
Wenjuan Mu, H. J van der Fels-Klerx, Wageningen Food Safety Research, 6700AE, Wageningen, The Netherlands.
Email: wenjuan.mu@wur.nl; ine.vanderfels@wur.nl

[Correction added on 06th July 2023, after first online publication: The author's name was changed from 'Ine van der Fels-Klerx' to 'H. J van der Fels-Klerx' in the author byline.]

Funding information
Ministry of Agriculture, Nature and Food Quality, the Netherlands, Grant/Award Number: KB-37-001-006

Abstract

Salmonella spp. control in pork supply chains has always been a challenging issue and insufficient control can lead to high social and economic consequences. Conventional risk management and risk management approaches and models are not sufficient to address potential food safety shocks caused by *Salmonella* spp., as they mainly focus on assessing measures to reduce *Salmonella* spp. risks instead of developing the resilience capability (e.g., flexibility to adapt to sudden changes in the risks). Our study is the first that incorporated the resilience concept to the quantitative modeling of *Salmonella* spp. spread in the pork supply chain. The objective of this study was to explore the resilience performance of the pork supply chain under different food safety shocks caused by *Salmonella* spp., and to investigate the effectiveness of interventions on reducing the impact of these shocks on the resilience performance of the chain. Scenario analysis indicated that the effectiveness of the investigated resilience strategies or interventions depended on the risk profile (i.e., default, minimum, maximum level of *Salmonella* spp. contamination) of the pork supply chain. For pork supply chains with minimum and default risk profiles, more attention should be paid to increasing resilience of pigs towards *Salmonella* spp. infection. For supply chains with maximum risk profile, the focus should be on improving the performance of the slaughterhouse, such as careful evisceration, logistic slaughtering. To conclude, enhancing resilience performance of the pork supply chain can contribute to a safe pork supply.

KEYWORDS
food safety, pathogen, quantitative microbial risk assessment model, resilience management, risk management

1 | INTRODUCTION

Salmonellosis has been identified as one of the most common zoonotic diseases in the European Union (EU). In 2019, about 88,000 salmonellosis cases were reported, resulting in high social and economic impacts (EFSA, 2019). Pig meat and products thereof have been listed as one of the most relevant vehicles with respect to foodborne salmonellosis outbreaks (Hdaifeh et al., 2020). The pig reservoir was estimated to be the cause of about a quarter of the human salmonellosis cases in the EU (Snary et al., 2016). *Salmonella* spp. can enter the pork supply chain at any stage, from farm to fork (Rodríguez & Suárez, 2014). The introduction and spread of *Salmonella* spp. can occur through different routes, for example, through external agents in the environment (e.g., rodents, people, trucks), via pig feed, and via spread from a sow to its piglets (vertical transfer) and from one pig to another within a herd (horizontal transfer) (Campos et al., 2019).

Several models have been developed to aid decision making about *Salmonella* spp. control in pork supply chains. For example, van der Gaag et al. (2004) developed a susceptible-infected-recovered (SIR) model considering the supply chain stages from pig finishing until slaughtering. Smid and colleagues (2012) developed a Bayesian belief network model to trace a *Salmonella* spp. contamination in the pork slaughtering process and to identify hotspots where data collection is most effective for biotracing. Snary et al. (2016) developed a quantitative microbiological risk assessment (QMRA) model considering the entire pig supply chain. They assessed the effectiveness of control measures on reducing the prevalence of *Salmonella* spp. accounting for differences in pork production systems and consumption patterns in different member states of the EU. These models simulated *Salmonella* spp. spread and prevalence in the pig supply chain and can be used to estimate a priori the effects of potential interventions, while taking a "normal" situation of operations as a starting point. However, prevalence of *Salmonella* spp. or other food safety hazards can suddenly increase through shocks, that is, changes in influencing factors inside and outside the pig supply chain to values outside normal operations. Conventional risk management and risk assessment models are not sufficient to address such potential food safety shocks caused by *Salmonella* spp., as the main focus of the current models is on assessing measures to reduce food safety risks instead of on developing the flexibility of the supply chain to adapt to sudden changes in food safety risks (Rodríguez & Suárez, 2014). Mu and colleagues (2021) argued that the concept of resilient food supply chain is more suitable in such a situation, because it includes the capacity to adapt and recover from shocks arising from the presence or emergence of the food safety risks. They defined resilience in the context of food safety as "the recovery capacity of the food supply chain to food safety shocks to allow the delivery of safe food over a reasonable lead time" (Mu et al., 2021). To improve the recovery capacity, supply chain actors can implement interventions that can enhance resilience. For example, interventions at farm level include having alternative suppliers for incoming piglets and feed, reducing on-farm spread of *Salmonella* spp. within and between pig herds, and, potentially, options that make pigs more resilient to a *Salmonella* spp. infection (Nakov et al., 2019). Interventions at slaughterhouse level include surveillance programs, good slaughter hygiene, flexibility of its slaughtering capacity to allow logistic slaughtering, as well as having alternative partners (e.g., pig suppliers) to allow the flexibility to recover from supply chain shocks (Alban et al., 2017). By applying simulation modeling, one can examine the resilience performance of the supply chain as a whole and for each of its stages specifically, the potential impact of food safety shocks, and the effectiveness of interventions for each stage of the supply chain in reducing the impacts caused by shocks and thereby contributing to the resilience of the pork supply chain.

The objective of this study was to develop a simulation model that can be used to explore the resilience performance of the pork supply chain under different food safety shocks caused by *Salmonella* spp., and to investigate the effectiveness of the interventions on reducing the impact of these shocks on the resilience performance of the chain.

2 | MATERIALS AND METHODS

The development of the resilience assessment model is described in subsection 2.1, whereas the resilience quantification method is introduced in subsection 2.2. Scenario analysis, described in subsection 2.3, was used to assess resilience performance of the pork supply chain in the given predefined scenarios that reflect possible food safety shocks and resilience enhancing interventions.

2.1 | Resilience assessment model

A discrete time stochastic state-transition resilience assessment simulation model was developed based on the stochastic susceptible-infected-recovered (SIR) model presented by van der Gaag et al. (2004) to simulate the *Salmonella* spp. spread along the pork supply chain from finishing pig farm to slaughterhouse. The pork supply chain in our model was based on the Dutch situation and starts at the finishing stage and ends at the slaughter stage, similar to the model of van der Gaag et al. (2004). In the Netherlands, piglets are often raised on specialized farms that sell piglets to specialized finishing pig farms. The resilience assessment model starts at the moment the piglets arrive at the finishing stage at a live weight of 25 kg (Funk et al., 2001) and finishes with chilled carcasses at the end of slaughtering with the unit of a carcass. The multiplying stage is not included, because it has only limited impact on the prevalence of *Salmonella* spp. in the pork supply chain (van der Gaag et al., 2004).

The SIR model was constructed with two components, that is, states and transition probabilities. States define the *Salmonella* spp. status of an individual pig. Six states were defined, two susceptible states (S1 and S2), three infectious states (I1, I2 and I3), and one carrier state I. Transition probabilities indicate the probability for each individual pig to change from one state to another in 1 day. Every day, the pig status was recalculated for each individual pig. Figure 1 illustrates the states and transitions for live pigs (A) and carcasses (B).

A live pig can, for example, start in state S1 (susceptible 1 that represents a *Salmonella* spp. free pig with negative serology) and then move to state I1, that is, the pig becomes infected with *Salmonella* spp. and becomes infectious (infectious 1, an infected and infectious pig with negative serology). After seroconversion, the pig can move to state I2 (infectious 2, an infected and infectious pig with positive serology). After losing the infectiousness, the pig changes from state I2 to C (carrier, a pig that is no longer shedding but has a positive serology). Upon recovery, the state of a pig can change to S2 (susceptible 2, a pig susceptible to *Salmonella* spp. again with positive serology). From S2, the state of a pig can change to S1 when the serology becomes negative. However, if the recovered pig (S2) is infected and infectious again, the state of the pig will change to I3 (infectious 3, a previously infected and infectious pig). Under certain circumstances, such as high stress level of the pig, the state of a pig can change directly from C to I3. The transition probability matrix $P(t)$ governs the state transition of the live pigs or carcasses in time step t, with t set as 1 day. The state transition matrix for the finishing stage is presented in Equation (1). For the biologically impossible state transitions, the probability was set as zero. The rows of the matrix represent the current states and the columns of the matrix represent the states to be transited to. Consequently, the row summation is equal to one.

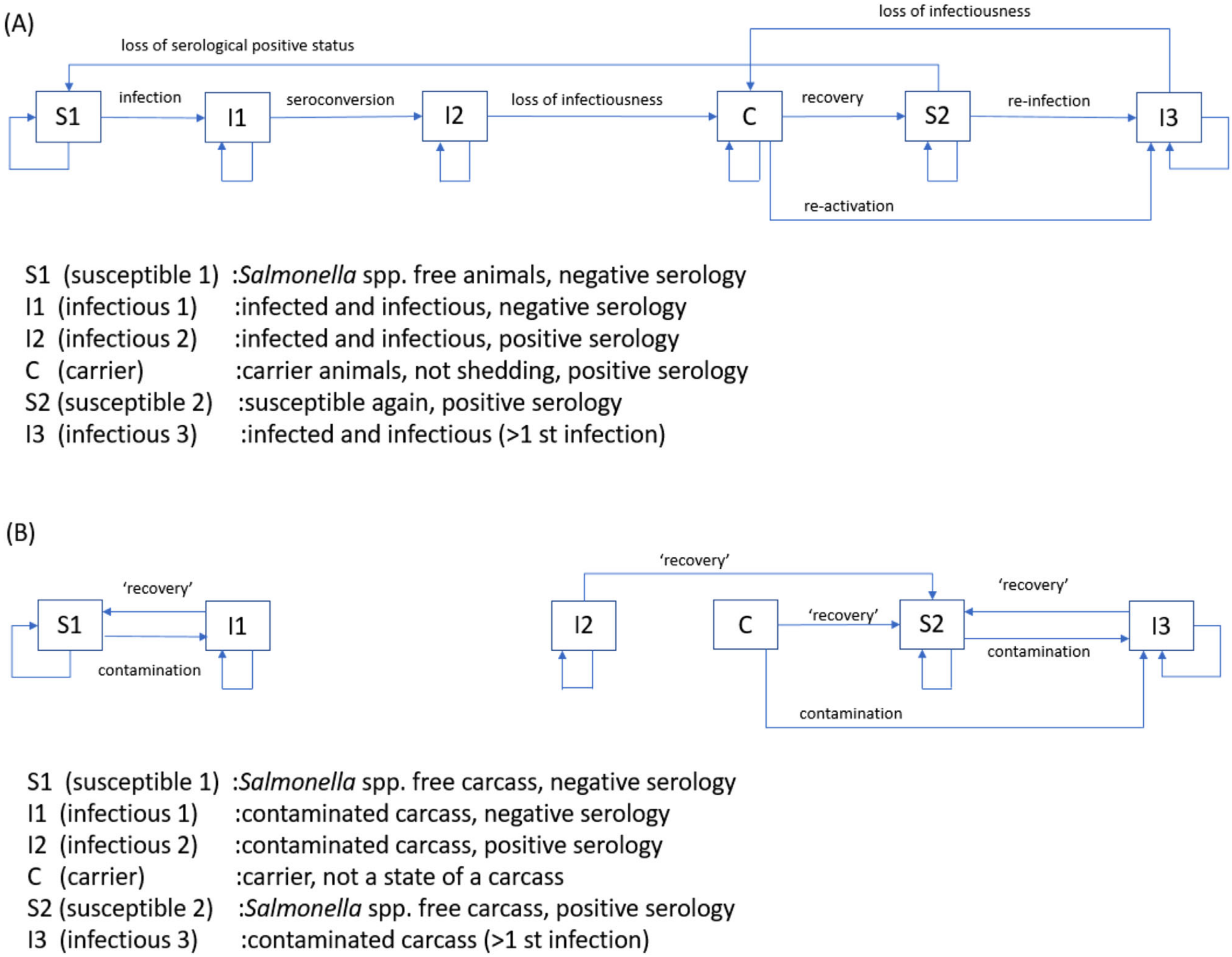

FIGURE 1 (A) States and transitions for live pigs; (B) States and transitions for carcasses. (*Source*: Van der Gaag et al., 2004).

$$\mathrm{P}(\mathrm{t}) = \begin{pmatrix} 1-P_{S1,I1} & P_{S1,I1} & 0 & 0 & 0 & 0 \\ 0 & 1-P_{I1,I2} & P_{I1,I2} & 0 & 0 & 0 \\ 0 & 0 & 1-P_{I2,C} & P_{I2,C} & 0 & 0 \\ 0 & 0 & 0 & 1-P_{C,I3}-P_{C,S2} & P_{C,S2} & P_{C,I3} \\ P_{S2,S1} & 0 & 0 & 0 & 1-P_{S2,S1}-P_{S2,I3} & P_{S2,I3} \\ 0 & 0 & 0 & P_{I3,C} & 0 & 1-P_{I3,C} \end{pmatrix} \quad (1)$$

The carrier state C does not exist for carcasses because, after slaughtering, the carcass of a pig with a carrier state is either contaminated (I3) or uncontaminated (S2). Some of the transitions for carcasses are different when compared to those for live pigs. For carcasses, serology conversion is no longer possible, which means the transitions from I1 to I2 and from S2 to S1 do not exist.

In the following subsections, the key variables for constructing the SIR model are summarized for each stage of the supply chain (i.e., from finishing stage up to and including slaughtering). Detailed modeling information and calculation formulas can be found in Van der Gaag et al. (2004).

2.1.1 | Finishing

The model unit was one finishing pig farm, which was assumed to have 10 compartments with 100 pigs each (1,000 pigs in total at one farm). The farm was assumed to use an all-in-all-out management system on group level, so every group of 100 pigs (one compartment) is delivered as one unit to the slaughterhouse. We assumed that this group of 100 pigs also stayed together in the rest of the supply chain from being transported in one truck to the slaughterhouse, being kept together in the lairage at the slaughterhouse, to being slaughtered. The sojourn time for one group of pigs was assumed to be 113 days. The model started with an empty finishing farm. The farmer was assumed to buy the first group of 100 pigs from the multiplying stage at day 1 and a new group of pigs from the multiplying stage every 11 days until 1,000 pigs (i.e., 10 groups) were on the farm. To meet the 113 days sojourn time, the period between buying batch 10 (group 10) and batch 11 (group 1) was set at 14 days. After 113 days on the finishing farm, the farmer sells the 100 pigs of the first group to the slaughterhouse. No pigs were assumed to die during finishing. The pigs sold to the slaughterhouse were assumed to be replaced by a new group of 100 pigs the same day, with no empty days assumed between the consecutive groups. A simulation horizon of 1,000 days was used, with 79 batches in total.

Each pig entering the finishing phase at day 0 has either a state S1 or state I2, which was determined by using the probability of $P_{S1,I2}$ (the probability to go from S1 to I2) as a challenge, the same as in van der Gaag et al. (2004).

The probabilities in P(t) were determined by many different factors. For example, $P_{S1,I1}$ is the probability for a never-infected pig in the finishing farm to become infected on the current day. This probability was computed based on the infection rate from the pigs within the same group and within the same farm, as well as the infection rates from external sources such as feed, and people. The formulas for calculating the probabilities can be found in Van der Gaag et al. (2004). Model parameters used in these formulas are indicated in Table 1.

2.1.2 | Transport and lairage

In our model, the duration of the total transport and lairage period was assumed to be 1 day. It was not possible to explicitly model a shorter duration (e.g., 6 h) of transport from finishing pig farm to slaughterhouse as mostly seen in practice, due to the 1-day time step applied in the model. However, model parameter values set for these stages were based on the shorter durations seen in practice.

In the stages of transport from finishing farm to slaughterhouse and lairage in the slaughterhouse, the states and transitions for live pigs (Figure 1, panel A) were used but the parameter values differed from those in the finishing farm stage. Some transition probabilities were set to zero, due to the short duration of being in this stage. First, transitions to another serological state were assumed not to occur (i.e., $P_{I1,I2} = 0$ and $P_{S2,S1} = 0$). Second, infectious pigs were assumed to remain infectious during transportation and lairage (i.e., $P_{I2,C} = 0$ and $P_{I3,C} = 0$). The infection parameter (β_i) used to quantify the probability that a pig is infected by the pigs in the same group (PG) during transportation ($i = 2$) and lairage ($i = 3$) is much higher than the rate applied at the stage of finishing ($i = 1$; i.e., β_2 and β_3 are much higher than β_1).

$$\mathrm{PG} = 1 - e^{-(\beta_i * (I\mathrm{group}/N\mathrm{group}))} \tag{2}$$

PG = probability that a pig is infected by the pigs in the same group, where Igroup is the number of infectious pigs in a group, and Ngroup is the total number of pigs in a group. β_i is the infection parameter, that is, the rate at which a single infected pig infects susceptible pigs in a population of susceptible pigs. The index i indicates the stage in the supply chain, with $i = 1$ is farm, $i = 2$ transport, and $i = 3$ lairage.

The values for $P_{C,I3}$ in the stage of transportation were higher than those in the stage of finishing due to the higher level of stress of pigs during transport. The transmission probability in lairage was calculated recursively. Namely, the probability of a susceptible pig getting infected in lairage depends on the prevalence level of the current group and the prevalence level of the previous group. The larger the time span between the last and current group, the smaller the impact of the previous group is.

2.1.3 | Slaughter

In the slaughter stage, the slaughter process was divided in two steps, namely (1) the procedure of sticking till evisceration, and (2) the procedure of evisceration till chilling. In the slaughter stage, state transitions were governed as indicated in Figure 1 (panel B). The carrier state is not relevant in the slaughter stage. After the first step, pigs with a carrier state before the slaughtering process can turn into carcasses with state of S2 or I3. The probability to move from carrier state to S2 is equal to the recovery rate in the first step of the slaughtering, and the probability of carrier state to I3 is one minus the probability of carrier state to S2.

In the first step, contaminated carcasses can become susceptible, but *Salmonella* spp. free carcasses cannot be contaminated. In the second step, contaminated carcasses can become susceptible, and susceptible carcasses can also become contaminated. The probability that a *Salmonella* spp. free carcass is contaminated depends on the state of the preceding carcasses. More preceding contaminated carcasses increase the probability for a *Salmonella* spp. free carcass to become contaminated. Conversely, more preceding *Salmonella* spp. free carcasses decrease the probability for a *Salmonella* spp. free carcass to become contaminated.

2.2 | Risk profiles

We distinguished three risk profiles of the two supply chain actors (i.e., finishing pig farm, slaughterhouse), with the default risk profile representing the current average hygiene situation in the EU, and the minimum and maximum risk profiles representing the best and worst hygiene situations.

TABLE 1 Model parameters used in the scenarios (*Source*: Van der Gaag et al., 2004)

Stage	Parameter	Default risk profile	Minimum risk profile	Maximum risk profile	Parameter description
Finishing farm	$P_{S1,I2}$	0.1	–	0.25	Probability a pig enters the finishing farm as an infected pig
	ζ	113	–	–	The sojourn time for groups at the finishing farm
	ψ	0.75	0.25	–	Immunization factor (difference in susceptibility between serological negative and serological positive animals)
	δ	1/12	–	–	Seroconversion period (in days)
	Φ	1/60	–	–	Period to become serological negative again (in days)
	β_f	0.05	–	–	Infection rate within a farm
	β_1	0.00005	–	–	Infection rate within a group
	$PE_{finishing}$	0.00002	–	0.0005	Probability to become infected by feed, visitors, or other external causes within a time step
	α_1	1/16	1/2	–	Infectious period after the first infection (in days)
	α_2	1/14	1/2	–	Infectious period after the second or third infection (in days)
	γ	1/60	1/5	–	Duration of the carrier period (in days)
Transport	Ψ	0.75	–	–	Immunization factor (difference in susceptibility between serological negative and serological positive animals)
	β_2	1.5	0.5	2.5	Infection rate within a group
	$PE_{transport}$	0.005	0.00005	0.05	Probability to become infected by visitors or other external causes within a time step
	$P_{C,I3}$	0.35	0.05	0.65	Probability that an animal in the carrier state will re-activate
Lairage	Ψ	0.75	–	–	Immunization factor (difference in susceptibility between serological negative and serological positive animals)
	β_3	1.5	0.5	2.5	Infection rate within a group
	$PE_{lairage}$	0.005	0.0005	0.002	Probability to become infected by visitors or other external causes within a time step
	Λ	0.5	1	0	Smoothing factor (determine the relative importance of the prevalence of newly introduced groups on the PF)
	$PFmin_{lairage}$	0.001	0	0.05	Minimum value of PF (one-fourth probability to become infected by the lairage within a time step)
	$PFmax_{lairage}$	0.1	0.05	0.5	Maximum value of PF
Slaughter	$PE_{slaughter}$	0.005	0.0005	0.05	Probability to become infected by visitors or other external causes within a time step
	Qevisc	0.75	0.9	0.1	Probability that a bacteriological positive carcass becomes bacteriological negative by evisceration
	Qproc	0.75	0.9	0.1	Probability that a bacteriological positive carcass becomes bacteriological negative after entire slaughter process
	$PFmin_{slaughter}$	0.001	0.0001	0.05	Minimum value of PF (¼probability to become contaminated by the slaughterline within a time step)
	$PFmax_{slaughter}$	0.25	0.05	0.5	Maximum value of PF

(Continues)

TABLE 1 (Continued)

Stage	Parameter	Default risk profile	Minimum risk profile	Maximum risk profile	Parameter description
	Qdown	0.05	0.5	0.1	Relative percentage the PF will decrease after a noncontaminated carcass passed the slaughterline
	Qup	0.1	0.01	0.5	Relative percentage the PF will increase after a contaminated carcass passed the slaughterline

Parameter values used in the minimum, default, and maximum risk profile are the minimum, most likely, and maximum values as defined in van der Gaag et al. (2004); these values are summarized in Table 1. Literature (Peeters, 2019) and consultation with experts confirmed that the parameter values for quantifying the *Salmonella* spp. spread at the farm level have not changed much in the past 15 years.

2.3 | Resilience quantification

Resilience deterioration in this study is quantified as the difference in *Salmonella* spp. prevalence on chilled carcasses before and after a shock:

$$\text{Resilience deterioration} = (\text{SP}_{\text{shock}} - \text{SP}_{\text{baseline}})/\text{SP}_{\text{baseline}} \times 100\% \quad (3)$$

where SP_{shock} is the *Salmonella* spp. prevalence on chilled carcasses after a shock, and $\text{SP}_{\text{baseline}}$ is the *Salmonella* spp. prevalence before the shock (i.e., baseline situation). The higher the resilience deterioration (with 100% as the maximum), the less resilient the supply chain is to the shock. A resilience deterioration of 0% indicates that the supply chain is fully resilient to the shock.

Intervention strategies can be applied to improve resilience performance of the pork supply chain to *Salmonella* spp. related shocks. The effectiveness of an intervention strategy to reduce *Salmonella* spp. prevalence after a shock occurred is indicated with Resilience performance improvement $(\text{RPI})_{\text{intervention}}$, and measured as the percentual improvement in *Salmonella* spp. prevalence between the situation with an intervention implemented compared to the situation without the intervention when a shock occurs:

$$\text{RPI}_{\text{intervention}} = (SP_{\text{shock}} - SP_{\text{intervention}})/SP_{\text{shock}} \times 100\% \quad (4)$$

Where $SP_{\text{intervention}}$ is the *Salmonella* spp. prevalence on chilled carcasses after the intervention strategy has been applied and a shock occurred. The higher $\text{RPI}_{\text{intervention}}$, the more effective the intervention is in mitigating the effect of a shock. An intervention resilience performance improvement of 0% indicates that an intervention does not mitigate any effect of a shock, whereas a value of 100% indicates that the intervention fully mitigates the impact of the chock.

2.4 | Scenarios

For each of the three risk profiles (default, minimum, maximum), we constructed 11 scenarios related to shocks and intervention strategies (baseline scenario and 10 alternative scenarios), resulting in 33 scenarios in total. The *Salmonella* spp. prevalence in the baseline (scenario 1) of each of the three risk profiles was used as a benchmark for evaluating the resilience performance of each particular risk profile in alternative scenarios. We defined 10 alternative scenarios, divided into shock scenarios (scenario 2 to 6) and shock + intervention scenarios (scenario 7 to 11). This was done to be able to analyze the impact of an intervention when a shock occurs. Because shocks can occur at different stages in the supply chain, we defined scenarios with farm-level shocks (scenario 2, 3, 7, 8) and with slaughterhouse-level shocks (scenario 4, 5, 9, 10). Finally, because shocks could occur simultaneously, we defined scenarios which combined all shocks (scenario 6, 11). We modeled the effect of a shock on *Salmonella* spp. prevalence rather than the shock itself. The detailed classification and description of the scenarios are illustrated in Table 2. For each scenario, the model was run with 100 iterations, each iteration representing 79 batches of 100 pigs moving through the supply chain. From the 100 iteration results, the mean and coefficient of variation of the *Salmonella* spp. prevalence on chilled carcasses were calculated.

2.4.1 | Baseline scenario

To construct the baseline scenario 1 for a certain risk profile, the parameter values in transport, lairage, and slaughtering stages corresponding to that risk profile were combined with the farm-stage parameter values from the default risk profile. For example, the baseline scenario with the minimum risk profile consisted of the minimum risk profile parameter values of the transport, lairage, and slaughtering stages combined with the default farm-level parameter values.

2.4.2 | Shock scenarios

Farm-level shocks

In scenario 2, a shock was simulated of a higher probability $P_{S1,I2}$ that a pig entering the finishing farm is infected. This

TABLE 2 Scenario design for three risk profiles

	Baseline scenario	Shock scenarios					Shock + Intervention scenarios				
	Scenario 1	**Scenario 2†**	**Scenario 3†**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**	**Scenario 9**	**Scenario 10**	**Scenario 11**
Profiles	**Baseline**	**Higher prevalence in purchased piglets in Finishing stage**	**Increase PE_finishing****	**Increase PE_slaughter*****	**Slaughterhouse recover (Q) shock**	**All shocks**	**Scenario 2 + Improve slaughterhouse recover (Q)**	**Scenario 3 + Improve slaughterhouse recover (Q)**	**Scenario 4 + resilient pigs**	**Scenario 5 + resilient pigs**	**Scenario 6 + resilient pigs**
Minimum profile	Default farm values + minimum values in other stages from VG (2004)*	$P_{S1,I2} = 0.25$ instead of 0.1	PE_finishing = 0.0005 instead of 0.00002	PE_slaughter = 0.05 instead of 0.0005	Q = 0.1 instead of 0.9	All shocks	Scenario 2 + Q = 0.95 instead of 0.9	Scenario 3 + Q = 0.95 instead of 0.9	Scenario 4 + resilient pigs	Scenario 5 + resilient pigs	Scenario 6 + resilient pigs
Default profile	Default values from VG (2004)	$P_{S1,I2} = 0.25$ instead of 0.1	PE_finishing = 0.0005 instead of 0.00002	PE_slaughter = 0.05 instead of 0.005	Q = 0.1 instead of 0.75	All shocks	Scenario 2 + Q = 0.9 instead of 0.75	Scenario 3 + Q = 0.9 instead of 0.75	Scenario 4 + resilient pigs	Scenario 5 + resilient pigs	Scenario 6 + resilient pigs
Maximum profile	Default farm values + maximum values in other stages from VG (2004)	$P_{S1,I2} = 0.25$ instead of 0.1	PE_finishing = 0.0005 instead of 0.00002	PE_slaughter = 0.1 instead of 0.05	Slaughterhouse recover shock: Q = 0.05 instead of 0.1	All shocks	Scenario 2 + Q = 0.9 instead of 0.1	Scenario 3 + Q = 0.9 instead of 0.1	Scenario 4 + resilient pigs	Scenario 5 + resilient pigs	Scenario 6 + resilient pigs

*VG (2004): Van der Gaag et al. (2004).
**PE_finishing is the probability of a pig to be infected in the finishing farm caused by the external causes e.g., feed, visitors.
***PE_slaughter is the probability of a carcass to be contaminated in the slaughter caused by external causes e.g., visitors.
†All three risk profiles used the same value, because all three risk profiles used the farm-stage parameter values of the default risk profile.

was included in the model by changing the *Salmonella* spp. prevalence at the beginning of the finishing stage from 0.1 to 0.25 (maximum value of prevalence level in van der Gaag et al., 2004). All three risk profiles used this value, because all three risk profiles used the farm-stage parameter values of the default risk profile. The other parameters at the farm level values were kept at default value.

In scenario 3, a shock was simulated consisting of a higher probability of a pig on the finishing farm ($PE_{\_finishing}$) to become infected by external causes, for example, by feed or visitors. For all three risk profiles, $PE_{\_finishing}$ increased from 0.00002 to 0.0005 (maximum parameter value in van der Gaag et al., 2004). Again, all three risk profiles used this value, because all three risk profiles used the farm-stage parameter values of the default risk profile. The other parameters at the farm level values were kept at default value.

Slaughterhouse-level shocks

In scenario 4, a shock was simulated consisting of a higher probability of a carcass ($PE_{\_slaughter}$) to become infected by external causes, for example, by bad lairage cleaning or low hygiene of personnel or visitors in the slaughterhouse. For the minimum risk profile, $PE_{\_slaughter}$ was increased from 0.0005 to 0.05; for the default risk profile, from 0.005 to 0.05; and for the maximum risk profile, from 0.05 to 0.1.

In scenario 5, a shock was simulated of lower recovery capability (Q) of the slaughterhouse. This can be caused by, for example, improper evisceration. There are two recovery possibilities in the slaughterhouse: the probability that a bacteriological positive carcass becomes bacteriological negative by evisceration (Qevisc) and the probability that a bacteriological positive carcass becomes bacteriological negative after the entire slaughter process (Qproc) . Qevisc has the same value as Qproc according to van der Gaag et al. (2004), so recovery rate (Q) was used to represent Qevisc and Qproc in Table 2. For the minimum risk profile, Q drops from 0.9 to 0.1; for the default risk profile, from 0.75 to 0.1; and for the maximum risk profile, from 0.1 to 0.05.

All shocks

In scenario 6, all aforementioned shocks were assumed to happen at the same time.

2.4.3 | Shock + intervention scenarios

The following scenarios involved both shocks and corresponding interventions for mitigating the shocks.

Farm-level shocks + slaughterhouse level interventions

In scenario 7, scenario 2 was combined with the intervention of improving slaughterhouse recovery capability (Q). Recovery capacity can be improved, for example, by double singeing with a temperature of 800–1000°C, good regular cleaning of the equipment with washes containing organic acids and/or logistic slaughter combined with dedicated processing lines for pigs positive for *Salmonella* spp. (EFSA, 2006). For the minimum risk profile, Q was improved from 0.9 to 0.95; for the default risk profile, from 0.75 to 0.9; and for the maximum risk profile, from 0.1 to 0.9.

In scenario 8, scenario 3 was combined with the intervention of improving slaughterhouse recovery capability (Q) as described in scenario 7.

Slaughterhouse-level shocks + farm intervention (i.e., resilient pigs)

In scenario 9, scenario 4 was combined with an intervention of pigs that are more resilient to *Salmonella* spp., for example by vaccinating against *Salmonella* spp. or using probiotic feed additives. To simulate resilient pigs, several resilience associated parameters (i.e., $\alpha1$, $\alpha2$, γ, and Ψ) were set at the optimal values presented in Van der Gaag et al. (2004). $\alpha1$ and $\alpha2$ represent the infectious period after the first infection and the infectious period after the second or third infection, respectively, and were assumed to be as short as possible (i.e., both 1/2). γ reflects the duration of the carrier period, and was assumed to be as short as possible (i.e., 1/5). The immunization factor Ψ is the difference in susceptibility between serological negative and serological positive pigs, and was assumed to be as small as possible (i.e., 0.25).

In scenario 10, respectively scenario 5 was combined with the intervention of resilient pigs as described in scenario 9.

All shocks + farm intervention (i.e., resilient pigs)

In scenario 11, scenario 6 was combined with the intervention of resilient pigs as described in scenario 9.

3 | RESULTS

Table 3 shows the mean *Salmonella* spp. prevalence and the coefficient of variation across different risk profiles and scenarios. In the baseline scenario, the *Salmonella* spp. prevalence after the slaughter process was 0.3, 5.6, and 57.4% for the minimum, default, and maximum risk profile, respectively. For the purpose of better comparison with the alternative scenarios, the order of the alternative scenarios in the table was adjusted to place interventions in combination with a shock next to the shock itself. For example, scenario 7 was placed after scenario 2 in order to see the clear impact of improving the recovery rate in the slaughterhouse stage on the final prevalence when there is a shock caused by the higher *Salmonella* spp. prevalence in piglets entering the finishing farm stage. Comparing the results of the alternative scenarios to the baseline scenario showed that even with the all-shock scenario (i.e., scenario 6), the *Salmonella* spp. prevalence in the minimum risk profile of 27.8% was about half the prevalence of 57.4% in the baseline scenario of the maximum risk profile.

Comparisons between the shock (scenarios 2 to 6) and the baseline (scenario 1) were calculated using Equation (3) and results were summarized in Table 4. When comparing the shock scenarios with the baseline scenario, except for scenario 6 (i.e., all shocks), the shock caused by the drop

TABLE 3 *Salmonella* spp. prevalence (%) as a result of various scenarios for three risk profiles

		Scenario 1	Scenario 2	Scenario 7	Scenario 3	Scenario 8	Scenario 4	Scenario 9	Scenario 5	Scenario 10	Scenario 6	Scenario 11
Risk profile	**Prevalence**	**Baseline**	**Higher prevlanece in purchased piglets in finishing stage**	**Scenario 2 + Q improvement**	**PE_finishing increase**	**Scenario 3 + Q improvement**	**PE_slaughter increase**	**Scenario 4 + resilient pigs**	**Slaughter recovery shock**	**Scenario 5 + resilient pigs**	**All shocks**	**Scenario 6 + resilient pigs**
Minimum profile	Mean prevalence	0.3%	0.3%	0.1%	0.3%	0.1%	0.5%	0.4%	20.9%	0.3%	27.8%	6.1%
	Coefficient of variation	0.21	0.17	0.18	0.13	0.06	0.02	0.35	0.32	0.16	0.38	0.05
Default profile	Mean prevalence	5.6%	5.9%	2.1%	6.6%	2.3%	6.5%	2.7%	36.8%	3.0%	43.2%	13.4%
	Coefficient of variation	0.07	0.05	0.05	0.05	0.04	0.02	0.07	0.08	0.08	0.16	0.06
Maximum profile	Mean prevalence	57.4%	58.7%	13.7%	61.2%	13.9%	58.1%	37.3%	61.4%	35.7%	65.3%	44.7%
	Coefficient of variation	0.02	0.01	0.01	0.02	0.02	0.01	0.03	0.03	0.02	0.02	0.02

in recovery rate at the slaughterhouse (scenario 5) had the largest impact on the resilience performance for all three risk profiles. For a slaughterhouse with a minimum risk profile, the increase in *Salmonella* spp. prevalence (from 0.3 to 20.9%) was larger than for a slaughterhouse with a maximum risk profile (from 57.4 to 61.4%). The other shocks, that is, higher prevalence at the finishing stage caused by purchased pigs with higher prevalence (scenario 2), higher probability of contamination caused by external factors at the finishing stage (scenario 3) or at the slaughter stage (scenario 4), resulted in a smaller increase. In these cases, *Salmonella* spp. prevalence doubled at the highest, as compared to the baseline scenario for all risk profiles. For the minimum risk profile, the reductions on the resilience performance due to different shocks were largest across different risk profiles. This was caused by the difference in the severity of shocks across different risk profiles. For example, for the minimum risk profile, the slaughter recovery rate dropped from 0.9 to 0.1 (drop of 89%), while for the maximum risk profile, the slaughter recovery rate dropped from 0.1 to 0.05 (drop of 50%). The increase in prevalence level in the maximum risk profile after the shock was relatively small, because the pre-shock situation in the maximum risk profile had already a high *Salmonella* spp. prevalence, which can be seen from the many parameters that have the worst scenario values. Therefore, this does not imply that the slaughter with the high-risk profile is more resilient.

Figure 2 presented the effectiveness of resilient interventions to reduce the prevalence level if a shock occurs for three risk profiles. When comparing intervention effectiveness across different shock scenarios, both increasing slaughter recovery capacity and introducing resilient pigs on the farm played an important role in reducing the final prevalence level. Improving the recovery capacity Q at slaughter can mitigate around 65 to 77% of the effects of farm-level shocks, irrespective of the risk profile. In contrast, when increasing pigs' resilience to mitigate the effects of slaughterhouse level shocks, large variations were apparent between risk profiles. With a shock caused by external factors in the slaughterhouse, the intervention of resilient pigs (scenario 9) showed the largest improvement (58.3%) for the default risk profile, whereas in the other risk profiles the effectiveness was around 24 to 36%. When a shock is caused by a drop in the slaughterhouse's recovery capability, with the concept of increasing resilience of pigs, the maximum risk profiles (scenario 10) showed effectiveness of 41.8% as compared to the over 90% improvements with the minimum risk profile (98.5%) and default risk profile (91.9%). When all slaughterhouse level shocks happened together, the effectiveness of increasing resilience of pigs (scenario 11) was higher under the minimum risk profile (78.1%) and default risk profile (69.0%) than under the maximum risk profile (31.6%).

4 | DISCUSSION

This study is the first study that incorporated a resilience concept in managing *Salmonella* spp. prevalence in the pork

TABLE 4 Resilience performance of three risk profiles under different shocks

Prevalence/ Risk profile	Scenario 2 Higher prevlanece in purchased piglets in finishing stage	Scenario 3 PE_finishing increase	Scenario 4 PE_slaughter increase	Scenario 5 Slaughter recovery shock	Scenario 6 All shocks
Minimum profile	12.3%	24.5%	104.0%	7774.8%	10360.5%
Default profile	6.3%	17.7%	16.8%	558.3%	674.2%
Maximum profile	2.2%	6.6%	1.2%	7.0%	13.7%

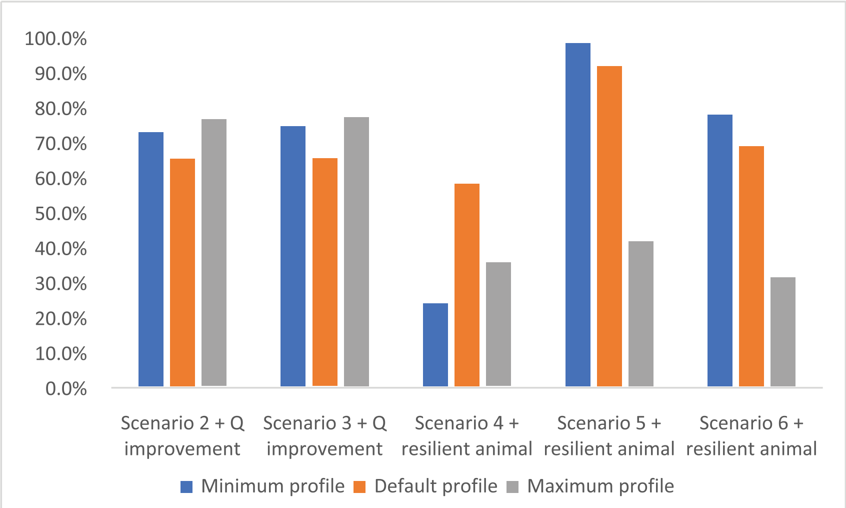

FIGURE 2 Effectiveness of resilient interventions on the prevalence level for three risk profiles.

supply chain. On top of a simulation model for mimicking the spread of *Salmonella* spp. prevalence in the pork supply chain, different shock scenarios with intervention strategies were constructed to test the resilience performance of the pork supply chain with different risk profiles. The *Salmonella* spp. prevalence, predicted using the modeling approach described in this study, are in line with previous findings. The minimum risk profile results in the baseline scenario (*Salmonella* spp. prevalence of 0.3%) are in line with the *Salmonella* spp. prevalence in EU countries with specific national guarantee plans; for example, for Denmark and Sweden, where *Salmonella* spp. prevalence has dropped to nearly zero (Primavilla et al., 2021). The results of the default risk profile (*Salmonella* spp. prevalence of 5.6%) are in line with Snary et al. (2016), who stated that there were slaughterhouses in Europe with a prevalence level around 5%. Also, EFSA (2019) indicated that the average prevalence in slaughterhouses across different Member States was 3.4%. The maximum risk profile (*Salmonella* spp. prevalence of 57.4%) reflects the worst-case slaughterhouse situation with poor hygiene conditions. Such a situation can be seen more often in developing countries where food safety can be a big concern. However, this may also occur in developed countries. For example, a study reported a *Salmonella* spp. prevalence of over 50% at one Belgian pig slaughterer (Botteldoorn et al., 2003). Similar cases were also found in Spain and Italy (Bonardi, 2017).

The effectiveness of the intervention strategies varied across different shocks and risk profiles, and between the interventions. Across different risk profiles, interventions at the slaughterhouse can improve resilience to shocks at farm level. For example, a slaughterhouse could introduce regular cleaning and disinfection procedures, use machines and equipment that have a lower probability to maintain *Salmonella* spp. strains, and use more intensive monitoring schemes (Hdaifeh et al., 2020). Another interesting finding is that resilient pigs could mitigate the impact of a bad performing slaughterhouse. Examples of practices that could increase the resilience of pigs are adopting vaccination, or using a probiotic feed additive to boost the immune system of the pigs (Peeters, 2019), breeding pigs that are resilient to *Salmonella* spp. (Knap & Doeschl-Wilson, 2020), and improving pig welfare (e.g. better housing, feeding schemes) to reduce stress in pigs thereby improving their immune system in resisting *Salmonella* spp. infection or recovering faster from an infection (Nakov et al., 2019; van Dixhoorn et al., 2021).

Although this study opens the field of incorporating resilience thinking in food safety control in the pork supply chain with a quantitative hazard simulation model, there are some limitations in the current study. Due to the lack of access to real monitoring data related to *Salmonella* spp. outbreaks, literature data and expert opinions were used to mimic the real situation. To reduce this limitation to reflect the real-life *Salmonella* spp. prevalence, different scenarios were constructed to represent the variation in *Salmonella* spp. prevalence seen in practice, and to assess worst- and best-case situations. Nevertheless, future studies are suggested to use real data on the food safety shocks, as well as data on the interventions applied after the shocks and recovery of the shocks, to derive more practical and case specific intervention strategies. Speed of recovery for example was not addressed in the modeling process due to lack of data, but should be included in the future studies when more data are available to better capture the resilience circle. Moreover, assumptions were used in this study for simulating resilient pigs, because only limited knowledge was available in this new research area. When more knowledge becomes available, estimates of the parameters to simulate resilient pigs can be improved, such as factors (e.g., housing factors, gut microbiome composition) that influence immunity and recovery of pigs with regard to coping with *Salmonella* spp.

Despite the aforementioned limitations of the current study, the resilience management, as an emerging concept in food safety domain, has shown its vital value in enhancing the safe food supply (Mu et al., 2021). Compared to the classical food safety risk assessment models, food safety resilience assessment models have the following added values: (1) emphasis on developing the capacity to make adaptations (e.g., having alternative supply chain network) or transformations (e.g., smart digital production systems) to cope with the food safety risks instead of putting minimizing food safety risks as the main objectives; (2) focusing on long-term coping strategies (e.g., resilient animals) instead of only seeking for short term solutions (e.g., use of antibiotics) to mitigate the impacts caused by the food safety risks.

In our study, *Salmonella* spp. was considered as the food safety hazard in the pork supply chain. However, to achieve the goal of building a resilient food supply chain to food safety shocks, analyses of other food safety hazards in the pork supply chain as well as in other food products should be performed. Due to the huge difference in the spreading pathways and mechanisms, different interventions are expected. The developed model for the pork supply chain's resilience performance to *Salmonella* spp. could be used as a starting point to quantitatively analyze resilience performance to other food safety hazards in the pork supply chain or to other food supply chains.

5 | CONCLUSION

This study is the first study that incorporates the resilience concept to the quantitative modeling of the *Salmonella* spp. spread in the pork supply chain. Results showed that the effectiveness of the intervention strategies in improving resilience performance varied across different shocks and risk profiles (i.e., default, minimum, maximum). For pork supply chains with minimum and default risk profiles, increasing resilience of pigs towards *Salmonella* spp. infection was the most effective intervention, whereas for supply chains with maximum risk profile, this was improving the performance of the slaughterhouse (e.g., careful evisceration, logistic slaughtering). Future studies are suggested to use data from a real outbreak of a food safety incident, and data related to effects of intervention strategies, as well as investigating other food safety hazards (e.g., other bacterial, virus and bacterial hazards) or other food supply chains to build a resilient food supply chain to food safety shocks.

ACKNOWLEDGMENTS

The study presented in this paper has been funded by the Ministry of Agriculture, Nature and Food Quality, the Netherlands (through the knowledgebase project KB-37-001-006).

ORCID

Wenjuan Mu https://orcid.org/0000-0003-0166-2789

REFERENCES

Alban, L., Häsler, B., Nielsen, L., & Rüegg, S. (2017). Resilience in the pork supply chain from the food safety perspective. 12th International Symposium on the Epidemiology and Control of Biological, Chemical and Physical Hazards in Pigs and Pork. August 21-24, Foz do Iguaçu - Brazil. https://core.ac.uk/download/pdf/128982226.pdf

Bonardi, S. (2017). Salmonella in the pork production chain and its impact on human health in the European Union. *Epidemiology and Infection*, *145*(8), 1513–1526. https://doi.org/10.1017/s095026881700036x

Botteldoorn, N., Heyndrickx, M., Rijpens, N., Grijspeerdt, K., & Herman, L. (2003). Salmonella on pig carcasses: positive pigs and cross contamination in the slaughterhouse. *Journal of Applied Microbiology*, *95*(5), 891–903. https://doi.org/10.1046/j.1365-2672.2003.02042.x

Campos, J., Mourão, J., Peixe, L., & Antunes, P. (2019). Non-typhoidal salmonella in the pig production Chain: A comprehensive analysis of its impact on human health. *Pathogens*, *8*(1), 19.

EFSA. (2006). Opinion of the scientific panel on biological hazards (BIOHAZ) related to "Risk assessment and mitigation options of Salmonella in pig production". *EFSA Journal*, *4*(4), 341.

EFSA. (2019). The European Union one health 2019 zoonoses report. *EFSA Journal*, *19*(2), e06406. https://doi.org/10.2903/j.efsa.2021.6406

Funk, J. A., Davies, P. R., & Nichols, M. A. (2001). Longitudinal study of Salmonella enterica in growing pigs reared in multiple-site swine production systems. *Veterinary Microbiology*, *83*(1), 45–60. https://doi.org/10.1016/S0378-1135(01)00404-7

Hdaifeh, A., Khalid, T., Boué, G., Cummins, E., Guillou, S., Federighi, M., & Tesson, V. (2020). Critical analysis of pork QMRA Focusing on slaughterhouses: Lessons from the past and future trends. *Foods*, *9*(11). https://doi.org/10.3390/foods9111704

Knap, P. W., & Doeschl-Wilson, A. (2020). Why breed disease-resilient livestock, and how? *Genetics Selection Evolution*, *52*(1), 60. https://doi.org/10.1186/s12711-020-00580-4

Mu, W., van Asselt, E. D., & van der Fels-Klerx, H. J. (2021). Towards a resilient food supply chain in the context of food safety. *Food Control*, *125*, 107953. https://doi.org/10.1016/j.foodcont.2021.107953

Nakov, D., Hristov, S., Stankovic, B., Pol, F., Dimitrov, I., Ilieski, V., Mormede, P., Hervé, J., Terenina, E., Lieubeau, B., Papanastasiou, D. K., Bartzanas, T., Norton, T., Piette, D., Tullo, E., & van Dixhoorn, I. D. E. (2019). Methodologies for Assessing Disease Tolerance in Pigs. *Frontiers in Veterinary Science*, *5*(329). https://doi.org/10.3389/fvets.2018.00329

Peeters, L. (2019). *On-farm control measures against Salmonella Typhimurium infections in pigs: Focus on vaccination with an attenuated vaccine and the application of a probiotic feed additive*. Ghent University.

Primavilla, S., Roila, R., Zicavo, A., Ortenzi, R., Branciari, R., Shtylla Kika, T., Valiani, A., & Ranucci, D. (2021). *Salmonella* spp. in pigs slaughtered in small and medium-sized abattoirs in Central Italy: Preliminary results on occurrence and control strategies. *Applied Sciences*, *11*(16), 7600.

Rodríguez, D. M., & Suárez, M. C. (2014). Salmonella spp. in the pork supply chain: A risk approach. *Revista Colombiana De Ciencias Pecuarias*, *27*, 65–75.

Smid, J. H., Heres, L., Havelaar, A. H., & Pielaat, A. (2012). A biotracing model of *Salmonella* in the pork production chain. *Journal of*

Food Protection, *75*(2), 270–280. https://doi.org/10.4315/0362-028x.Jfp-11-281

Snary, E. L., Swart, A. N., Simons, R. R. L., Domingues, A. R. C., Vigre, H., Evers, E. G., Hald, T., & Hill, A. A. (2016). A quantitative microbiological risk assessment for *Salmonella* in pigs for the European Union. *Risk Analysis*, *36*(3), 437–449. https://doi.org/10.1111/risa.12586

van der Gaag, M. A., Vos, F., Saatkamp, H. W., van Boven, M., van Beek, P., & Huirne, R. B. M. (2004). A state-transition simulation model for the spread of Salmonella in the pork supply chain. *European Journal of Operational Research*, *156*(3), 782–798. https://doi.org/10.1016/S0377-2217(03)00141-3

van Dixhoorn, I. D. E., te Beest, D. E., Bolhuis, J. E., Parmentier, H. K., Kemp, B., van Mourik, S., Stockhofe-Zurwieden, N., van Reenen, C. G., & Rebel, J. M. J. (2021). Animal-based factors prior to infection predict histological disease outcome in porcine reproductive and respiratory syndrome virus- and *Actinobacillus pleuropneumoniae*-infected pigs. *Frontiers in Veterinary Science*, *8*, https://doi.org/10.3389/fvets.2021.742877

How to cite this article: Mu, W., van Asselt, E., van Wagenberg, C., & van der Fels-Klerx, H. J. (2023). Building a resilient pork supply chain to salmonella spp. *Risk Analysis*, 1–12. https://doi.org/10.1111/risa.14141