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ORIGINAL ARTICLE

The resilience of the pork supply chain to a food safety outbreak: The case of dioxins

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Abstract

Food supply chains are constantly challenged by food safety hazards entering the chain. The ability of the supply chain to provide safe food within a reasonable time after such a food safety threat or shock can be investigated with the concept of resilience using food safety as an indicator. Resilience is then defined as the food safety performance deviation due to the shock and takes both the severity of the shock as well as the time to fully recover or reach a new equilibrium into account. This study developed a stochastic simulation model to evaluate the resilience of the Dutch pork supply chain to dioxin contamination in the feed. The resilience of the supply chain as well as the potential costs associated with the contamination are compared between several monitoring strategies with the aim to determine the optimal control points for dioxin monitoring. Model results show that collecting and analyzing samples at more than one control point along the pork supply chain, in particular at feed mills and fat melting facilities, resulted in the highest resilience and the lowest costs after a shock. This model and these results can be used by public and private decision makers to make proactive and informed decisions on the monitoring strategies to control dioxins in the pork supply chain that result in optimal resilience to a dioxin crises.

KEYWORDS
cost-effectiveness, food safety, modelling, monitoring

1 | INTRODUCTION

Food and feed supply chains are constantly challenged by the introduction of food safety hazards, potentially leading to food safety incidents. One of these food safety hazards recurrently leading to food and feed safety incidents is dioxins (R. Hoogenboom et al., 2015). Dioxins, including polychlorinated biphenyls (PCBs) and dioxin-like PCBs, are a group of structurally and chemically similar compounds belonging to the group "Persistent Organic Pollutants" (World Health Organization [WHO], 2016). Dioxins are highly toxic and cause cancer, problems to the immune system, hormonal issues, and reproductive and developmental problems (WHO, 2016). Humans are exposed to dioxins mainly via food consumption, in particular via food of animal origin. Dioxins accumulate in the body fat and liver of livestock and—to a lesser extent—in meat and might be excreted through milk and eggs (CODEX Alimentarius, 2006; Food & Agriculture Organization of the United Nations [FAO], 2008; WHO, 2016).

Dioxins are mainly a by-product of industrial processes such as the production of chemicals or the metallurgical industry, uncontrolled waste incinerators, agricultural burning of harvest residues, application of contaminated sewage sludge to agricultural land, or of natural processes such as volcanic eruptions or forest fires. Dioxins are released in the environment, adsorbing mineral and organic particles in the water and the soil. In the animal supply chain, dioxins can enter the chain at the farming stage where animals can be exposed to dioxins through their environment and feed. A (low) background level of dioxins is always present in meat products because there is a low, relatively stable, background dioxin level in the environment. High levels of dioxin contamination in meat products are mostly caused by contaminated feed.

Several dioxin incidents occurred in Northern Europe in the last decades: Contaminated citrus pulp from Brazil was included in animal feed produced in Germany in 1998; recycled oil and fat-containing transformer oil, a source of PCBs, were included in animal feed in Belgium in 1999; potato peels, sorted with dioxin contaminated kaolinic clay, were used as feed in the Netherlands in 2004; and recycled mineral oil was used as fuel in direct flame to dry bakery waste used as ingredient in animal feed in Ireland in 2008 (Heres et al., 2010; L. Hoogenboom et al., 2007; R. Hoogenboom et al., 2015). These dioxin contaminations resulted in large disruptions—food safety crises—in the pig supply chain in the European Union (EU) with large amounts of feed and pigs needed to be rendered and high costs (e.g., Casey et al., 2010; Marnane, 2012).

After the Belgian dioxin crisis of 1999, EU legislations regulating dioxins were implemented (Casey et al., 2010). Maximum limits (MLs) for the presence of dioxins in several food products were put in place to limit human exposure to these hazards (European Union [EU], 2011). In order to minimize the introduction in the animal production chain, MLs were also set for animal feed (EU, 2006a). Action levels (ALs) were set to encourage a proactive approach for reducing unwanted substances in food and feed (EU, 2006b). In Europe, following the General Food Law (EC/178/2002), food business operators are responsible for providing safe ingredients to the next link in the food chain, the ultimate aim being the production of safe end products. Safe in this case means a product with food safety hazards below the legal ML set. Toxic equivalents (TEQ) have been developed to sum up the toxicity of the different dioxin congeners, referred to as "dioxins." Legal limits are expressed in WHO-TEQs, for the sum of polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) and the sum of PCDDs, PCDFs, and PCBs (Barone et al., 2021).

An important food source of human dioxins exposure are pork products. For example, an Italian monitoring study, performed in 2019, showed dioxin levels of 1.39, 1.13, 1.11, and 1.02 pg WHO-TEQ/g lipid weight in pork loin, baked ham, salami, and raw ham, respectively (Barone et al., 2021). Therefore, it is relevant to control dioxins in the pig supply chain. To control dioxins in pig supply chains, interventions to reduce the likelihood of dioxins entering pig supply chains have been implemented, for example, through quality control systems demanding the use of products that have dioxin levels below set thresholds and/or through risk-based inspection and monitoring systems. The faster too high levels of dioxins in feed can be detected, the more likely it is that the crisis-to-be can be restricted, and the pig supply chain can return to normality. The extent to which the pig supply chain can withstand a contamination of feed with dioxins can be assessed by the supply chain resilience. Some studies are available that analyzed risk-based inspections and monitoring programs for dioxin in pig supply chain to prioritize efforts and allocate the resources as efficient as possible (Lascano-Alcoser et al., 2014; Ma & Ni, 2012). Such studies are very relevant because a structured and scientific approach at the national level is essential to avoid risk managers taking subjective decisions (Bonardi et al., 2021), and a cost-effective monitoring strategy is essential to use available resources as efficiently as possible (Focker et al., 2022). However, these studies did not consider supply chain resilience.

Tukamuhabwa et al. (2015) defined supply chain resilience as the adaptive capability of a supply chain to prepare for and/or respond to disruptions, either a shock or a stressor, to make a timely and cost-effective recovery, and therefore progress to a new equilibrium after the disruption. A shock is defined as "an abrupt event of differing probability of occurrence and severity of impact" and a stressor as "longer-term driver or condition that is more easily perceived and will influence change either directly or indirectly" (Zurek et al., 2022). Dioxin contamination in feed can be classified as a shock. Mu et al. (2021) reviewed studies on resilience to derive a framework that can be applied to food safety. The framework includes the specification of the context (resilience of what and to what?), and the resilience measurement, including the identification of the desired functions of the food system (which resilience factors and which associated indicators?). The three elements of resilience described are the time, the degree of impact caused by the shock, and the degree of recovery. As stated by Mu et al. (2021), multiple objectives can be considered, for example, social resilience, economic resilience, or environmental resilience. In addition, measures that improve the resilience can be assessed.

In our study, we use the pig supply chain in the Netherlands as a case study because the abovementioned dioxin crises caused serious disruptions in the Dutch pig sector. The Dutch pig sector is intensive, with pigs housed inside until a slaughter weight of around 115 kg live weight. Pigs get compound feed, sometimes in combination with liquid by-products from human food production. Many feed ingredients are sourced globally, for example, soy from the Americas, and there is a lively trade in feed ingredients between European countries. Feed composition is optimized based on cost-minimization while complying with nutritional and environmental requirements. Feed ingredients can differ between batches of feed. The Netherlands established a governmental monitoring program for dioxins in animal derived food, analyzing about 200−300 samples per year (Adamse et al., 2017) to first detect exceedances of action or legal limits and second to estimate the prevalence of dioxins over time. Feed materials and pork products are frequently tested by the government and the food business operators for the presence of dioxins; however, not all batches can be tested and a 100% guarantee for safety can never be achieved. Therefore, despite all precautionary measures, batches may still be contaminated. When a highly contaminated batch of raw feed material is processed into compound feed at a feed mill, it is delivered to numerous pig farms and fed to numerous pigs.

In this study, the resilience of the Dutch pig supply chain (resilience of what?) to dioxin contamination originating from the feed (resilience to what?) is estimated. The pig supply chain should place only those pig products on the market that have dioxin concentration below the ML set in the European Union (which resilience factors and which associated indicators?). This study focuses on different monitoring strategies enhancing the resilience of the pork supply chain (what enhances resilience?). This study aims to analyze the optimal monitoring strategy for dioxins in the pig supply chain based on supply chain resilience. For this purpose, a stochastic simulation model was developed, and several scenarios were calculated in order to come to an optimized monitoring strategy.

2 | MATERIALS AND METHODS

2.1 | The pork supply chain

A model was developed simulating the flow of pigs and their products throughout the pork supply chain from (compound) feed to retail. Only the finishing stage of pig farming was considered, since contamination at this stage will potentially lead to contaminated consumer products. A hypothetical pork supply chain was considered in which compound feed was produced and consumed by pigs in the same local area. Pigs were kept and slaughtered within this area, so import and export are not considered. Input data were taken from the pork supply chain in the Netherlands.

The Netherlands had 2767 pig farms (N_{FA}) with finishing pigs in 2021 (Statistics Netherlands [CBS], 2022). We assumed that several feed mills ($N_{\mathrm{FM}}= 20$) produced finishing pig feed (Rijkswaterstaat, 2022). Thus, we assumed that on average, each feed mill delivered finishing pig feed to 138 finising farms. We assumed that a feed mill had a stock of each feed ingredient for a 2-week production period. Each farm received feed from a fixed feed mill every 2 weeks. Pigs were therefore exposed to the same feed for 2 weeks. We assumed that once the feed was delivered, all finishing pigs at the farm were immediately fed with this feed only. Feed intake depended on the age of the pig, as indicated in Table 1 (I_{feed}). Since the feed intake also depended on the weight of each individual pig and weights differed between pigs of the same age, an uncertainty factor of ± 20% was added to the standard feed intake based on the age. A finishing pig farm kept on average 1902 pigs ($\mathrm{FA}_{\mathrm{pig}}$) (Statistics Netherlands [CBS], 2022). Assuming that a farm delivered finishing pigs to a slaughterhouse in same-sized groups weekly, one group contained 119 pigs, all with the same age. Each farm supplied pigs to one fixed slaughterhouse ($N_{\mathrm{SL}} = 20$) throughout one run of the model. A group of finishing pigs stayed together in one pen until slaughter. Assuming that the slaughterhouses had a similar size, each slaughterhouse was supplied by, on average, 138 finishing farms every week.

We assumed that in week 0, two feed mills received contaminated fatty ingredients, thereby initiating the dioxin incident. We assumed that after the recpetion of the ingredients, it took 2 weeks before the compounbd feed reached the farms. The finishing stage lasted 16 weeks (van Raamsdonk et al., 2007). Slaughtering, the initial processing (e.g., fat melting), and the further processing into ready-to-eat pork products sold at retail was assumed to last 1 week. The simulation period of the model was 26 weeks in total, covering a period of 6 months. Tables 1 and 2 summarize all inputs.

2.2 | Dioxins in the pork supply chain

The following dioxin contamination scenario was considered: Two feed mills, having the same supplier of fatty ingredients, received contaminated batches of these fatty ingredients. After mixing these contaminated fatty ingredients into the compound feed, the compound feed was assumed to have a level of 7.5 ng WHO-PCDD-F-TEQ/kg feed, including the background concentration, a concentration equal to 10 times the ML set in the EU for dioxins in compound feed (EU, 2006a). This concentration in feed leads to a maximum of 17 ng WHO-PCDD-F-TEQ/kg pig fat using the carry-over Equations 1 and 2 a concentration within the range of 2.5–132.9 ng WHO-PCDD/F-TEQ/kg fat observed during the Irish incident of 2008 (Heres et al., 2010). The background dioxin and PCB level in pig feed mentioned by Adamse et al. (2015) is 0.26 ng WHO-PCDD-F-PCB-TEQ/kg. Since the ML for dioxins and dioxin-like PCBs in compound feed is twice the ML for dioxins in compound feed (EU, 2006a), we assumed a background concentration for dioxins in pig feed of 0.13 WHO-PCDD-F-TEQ/kg. As a sensitivity analysis, a lower concentration (−50%) of 3.75 ng WHO-PCDD-F-TEQ in the contaminated compound feed was considered. Furthermore, the alternative scenario with only one feed mill (−50%) receiving contaminated fatty ingredients and delivering contaminated feed was considered.

Dioxins accumulate in pigs, mostly in the fatty tissue and the liver. The longer the exposure, the higher the accumulation. After exposure to high levels of dioxins, the concentration in the liver and fatty tissue declines slowly. To model the concentration in pig fat, during the 2 weeks of exposure, the following first equation was derived from data presented by L. A. P. Hoogenboom et al. (2004):

$$\text{if } w \leq T_{\mathrm{exp}}: \quad C_0 = 0.063 \times \sum_{w}^{T_{\mathrm{exp}}} C_{\mathrm{feed},w} \times I_{\mathrm{feed},w} \times 7\,, \qquad (1)$$

where w is the current week; T_{exp} is the exposure period in weeks, equal to two in our model; C_0 is the dioxin concentration in the pig fat at the end of week w; $C_{\mathrm{feed},w}$ is the dioxin concentration in the feed in week w; and $I_{\mathrm{feed},w}$ is the feed intake during week w.

After the pig's exposure to feed contaminated with dioxins stops (the contaminated compound feed is consumed by the pigs), the dioxin level in the pig decreases. Shen et al. (2012) suggest using an exponential equation to describe the dioxin concentration in pig fat over time. For our model, we fitted an exponential equation to the data collected by

TABLE 1 Input variables of the simulation model.

Variable	Abbreviation	Value	Reference/explanation
Feed mills (#)	FM	20	Twenty large companies produce 88% of the compound feed (Rijkswaterstaat, 2022)
Feed deliveries/month (#)		2	Lascano-Alcoser et al. (2014)
Finishing pig farms (#)	FA	2767	Finishing pig farms in 2021 (CBS, 2022a)
Slaughterhouses (#)	SL	20	Twenty slaughterhouses slaughter 90% of the pigs in the Netherlands (NVWA, 2021)
Average number of pigs per farm (#)	$\mathrm{FA}_{\mathrm{pig}}$	1902	Finishing pigs per farm in 2021 (Agrimatie, 2022a)
Pigs slaughtered per year (#)	$\mathrm{SL}_{\mathrm{pig}}$	17,236,800	Data for 2021 (CBS, 2022b)
Age start finishing stage (weeks)	$\mathrm{age}_{\mathrm{f}}$	11	van Raamsdonk et al. (2007)
Age slaughter (weeks)	$\mathrm{age}_{\mathrm{s}}$	27	van Raamsdonk et al. (2007)
Feed intake 11–12 weeks (kg/day)	I_{feed1}	1.07 ± 20%[a,b]	van Raamsdonk et al. (2007), assumption: uncertainty of +/-20%
			van Raamsdonk et al. (2007), assumption: uncertainty of +/-20%
Feed intake 13–17 weeks (kg/day)	I_{feed2}	1.94 ± 20%[a,b]	van Raamsdonk et al. (2007), assumption: uncertainty of +/-20%
Feed intake 18–27 weeks (kg/day)	I_{feed3}	2.22 ± 20%[a,b]	van Raamsdonk et al. (2007), assumption: uncertainty of +/-20%
Carcass weight (kg)	WC	94.6–101.5[ab]	Data for 2018–2020 (van der Linde, 2020)
Live weight (kg)	$125\% \times WC$	119 kg/95 kg (Vion Food Group, 2021)	
Batch size fatty ingredients (kg)	B_f	30,000	(Lascano-Alcoser et al., 2014)
Fatty ingredients in pig feed (%)	$\mathrm{fat}_{\mathrm{feed}}$	3.5%	Mean of 3.16% and 3.90% for low and high energy compound feed, respectively (van Raamsdonk et al., 2007)
Dioxin concentration contaminated feed	C_{feed}	7.5	Ten times the ML of 0.75 ng WHO-PCDD-F-TEQ/kg compound feed
Background level dioxins in feed	C_{feed}	0.13	(Adamse et al., 2015) 50% of dioxin and dl-PCBs
Feed production and delivery (weeks)	T_f	2	Assumption
Slaughter and initial processing (weeks)	T_{sl}	0.5	Assumption
Further processing (weeks)	T_{pr}	0.5	Assumption
Number of contaminated feed mills	$\mathrm{nb}_{\mathrm{FMI}}$	2	Scenario
Exposure to contaminated feed (weeks)	T_{exp}	2	Scenario
Sensitivity CALUX test	Sen	1	Assumption
Price finishing pig feed (€/kg)	P_{feed}	0.37	Mean between January and June 2022 (Agrimatie, 2022b)
Market price finishing pigs (€/kg)	P_{pig}	1.90	Prices July 2022 (PigBusiness, 2022)
Market price pig meat (€/kg)	P_{meat}	4.0	(van Galen et al., 2021) and expert opinion
Market price ready-to-eat pork products (€/kg)	P_{prod}	8.0	Assumption
Destruction/rendering costs (€/kg)	P_{rend}	0.45	€380 + €69,30 per container of 1 ton or 20,000 L (Rendac, 2022)

[a] Uniform distribution.

Hoogenboom et al. (2004) to model the concentrations in pig fat after exposure, resulting in the following equation:

$$\text{if } w > T_{\mathrm{exp}}: \quad C_w = C_0 \times e^{-0.2*\left(w - T_{\mathrm{exp}}\right)}, \tag{2}$$

where C_w is the dioxin concentration in the pig fat at week w.

At the end of each week, the amount of consumer end products, expressed in the number of slaughtered pigs on the market with dioxin concentrations in the fatty tissue below

TABLE 2 Deduced inputs.

Variable	Value	Calculation/explanation
Pigs/delivery to slaughterhouse (#)	Triangular (mode = 119, min = 59, max = 179)	$(\mathrm{FA}_{\mathrm{pig}}/(\mathrm{age}_{sl} - \mathrm{age}_{f})$; for the min and the max, +/-50% of the mode was considered; this number was set at week 0 and remained the same for the rest of the modelled period.
Number of clients (farms) per feed mill (#)	Triangular (mode = 138, min = 69, max = 207)	FA/FM; for the min and the max, +/-50% of the mode was considered; this number was set at week 0 and remained the same for the rest of the modelled period.
Number of suppliers (farms) per slaughterhouse (#)	Triangular (mode = 138, min = 69, max = 207)	FA/SL; for the min and the max, +/-50% of the mode was considered; this number was set at week 0 and remained the same for the rest of the modelled period.
Compound feed intake per 2 weeks for all finishing pigs over all farms (kg)	146,530,500	$((I_{\mathrm{feed1}} \times 14) + (I_{\mathrm{feed2}} \times 35) + (I_{\mathrm{feed3}} \times 63))$ / $((\mathrm{age}_{\mathrm{sl}} - \mathrm{age}_{\mathrm{f}})) \times 2 \times (\mathrm{FA} \times \mathrm{FA}_{\mathrm{pig}})$
Batches of fatty ingredients per 2 weeks (#)	171	$146{,}530{,}500 \times \mathrm{fat}_{\mathrm{feed}}/B_f$
Pigs slaughtered per week (#)	331,477	$\mathrm{SL}_{\mathrm{pig}}/52$
Finishing stage (weeks)	16	$(\mathrm{age}_{sl} - \mathrm{age}_{f})$
Batches of pork fat per year (#)	5200	$\mathrm{SL} \times 5 \times 52$

Abbreviations: explained in Table 1

and above the ML of 1 pg WHO-PCDD-F-TEQ/g fat (EU, 2011), was calculated.

2.3 | Resilience of the supply chain

As described by Mu et al. (2021), a supply chain is relatively resilient to a food safety incident, if the deviation in performance with the incident from the performance without the incident is small and the recovery after the incident to a pre-incident situation, or a new equilibrium, is fast. The factors influencing resilience are time, including the incubation time (the period between the production of contaminated feed and arrival of unsafe pork products on the market), the detection time (the difference in time between the production of unsafe feed and the detection of either unsafe feed or unsafe pork products on the market), the recovery time (the time between the incident and the recovery back to the pre-incident situation, or a new equilibrium), the degree of impact caused by the incident (quantity of unsafe products produced, number of ill people, quantity of destructed products, etc.), and the degree of recovery (capacity to recover back to the (new) steady state) (Mu et al., 2021).

As a measure of performance deviation, we used the weekly number of slaughtered pigs with dioxin concentration above the ML, not detected, divided by the weekly total number of slaughtered pigs times 100%. For example, if 100% slaughtered pigs had a concentration below the ML in a certain week, the performance in that week was set at 100%. This was calculated for each week. The resilience is a measure for withstanding a performance deviation due to a shock and was calculated for a period of 26 weeks, as 100% minus the performance deviation. In other words, the total number of pigs slaughtered during the period of 26 weeks (100%) minus the percentage of pigs slaughtered with a dioxin concentration above the ML. The resilience was expressed in percentage. The means were compared pairwise using Bonferroni's method.

2.4 | Management options: Monitoring

Dioxins contamination in the pork supply chain can mainly be managed, among others, through monitoring. The following three monitoring points along the supply chain were considered: at feed mill level, in the batches of fatty ingredients; at slaughterhouse level, in pig meat; or at fat melting facility level, in the melted fat. The total number of samples collected along the pork supply chain was based on the number of samples collected by the Netherlands Food and Consumer Product Safety Authority (NVWA) at feed mill and slaughterhouse levels. Between 2016 and 2020, the highest number of samples of fatty feed ingredients for dioxin analyses per year were collected in 2019, namely 161 samples (Netherlands Food & Consumer Product Safety Authority [NVWA] & Wageningen Food Safety Research [WFSR], 2019). Since about 35% of the total amount of compound feed produced in the Netherlands is pig feed (Nevedi, 2022), we assumed that 57 samples were collected from fatty ingredients to be used in pig feed production. In the same period, the highest number of samples of pig meat at slaughterhouse level in a year was collected in 2016, namely 118 samples (van Leeuwen et al., 2021). Taking these highest numbers of samples into consideration, both rounded, an estimated yearly total of 180 samples can be considered for the pork supply chain at both the level of the feed and the level of the end products. Samples were first analyzed using a CALUX test. If a sample was classified as suspect with the CALUX test, gas chromatography–mass spectrometry was used for confirmation. The sensitivity of the CALUX

TABLE 3 Monitoring options: The number of samples collected per year at the three stages of the pork supply chain.

Options	Feed ingredient at feed mill	Pork meat at Slaughterhouse	Pork fat at fat melting
Option 1	180	0	0
Option 2	0	180	0
Option 3	0	0	180
Option 4	60	60	60
Option 5	90	90	0
Option 6	90	0	90
Option 7	0	90	90

test was set to 100%, meaning that all samples with dioxin concentration above the ML were detected with the screening test. In a sensitivity analysis, we examined the impact of collecting 50% less (90) or 50% more (270) samples per year. In addition, samples from five pigs per group at slaughterhouse level, instead of the default one, were collected and analyzed.

To estimate at which control points along the supply chain collecting samples would be most optimal, these samples were distributed between the three control points considered, resulting in seven monitoring options, shown in Table 3. Random samples of fatty feed ingredients, pork meat and/or pork fat were collected weekly.

We assumed that in case contamination in a fatty ingredient was found at a feed mill, the contaminated feed was destroyed. Furthermore, in case contamination in a feed ingredient was found, tracking and tracing of the contamination were performed within 1 week, before any contaminated feed was delivered to farms. Thus, no pigs or pork products were contaminated nor needed to be recalled. If a contamination was detected at a certain feed mill, all other feed mills that received the same contaminated fatty ingredient were notified before having delivered the feed to any farm. These mills also destroyed the feed, and, consequently, pigs and pork products were not contaminated. If contamination was discovered at a slaughterhouse or fat melting facility, the carcasses and pork products of the contaminated batch were destroyed. Tracking and tracing were assumed to be performed within 1 week. After 1 week, all farms having received feed from the same feed supplier were blocked, and the present pigs were culled and destroyed. However, pigs on some of these farms that received the contaminated feed could already have been slaughtered prior to blocking and their meat products could have been placed on the market, if they were missed in the screening. The carcasses and pork products of these pigs that were not yet consumed were recalled and destroyed. The longer it took to detect a contamination, the more pig products with a dioxin concentration above the ML were placed on the market and, consequently, the more products needed to be recalled.

2.5 | The costs of extra resilience

A higher probability to detect dioxin contamination will, on the one hand, increase the supply chain resilience when food safety is used as an indicator and make the supply chain safer. On the other hand, it will result in additional costs, such as recall costs and lost revenues. In order to estimate the costs of extra resilience, the costs due to recalls or lost revenue for each of the monitoring options shown in Table 3 were estimated. Monitoring costs were considered to be similar for each option, since the total number of samples and analyses are similar in each option. Even though more positive screening tests lead to higher costs due to the high costs of the required confirmatory test, this aspect was not considered, as it was considered not to be significant relative to recall costs or revenue losses. Considering 180 samples collected and analyzed with a CALUX test, at a cost of about €280 per test (personal communication WFSR, 2022), a baseline cost for the initial screening was estimated to be €50,400. A confirmatory test costs about €600 per test (personal communication WFSR, 13 May 2022) and will be added to the baseline cost for the initial screening.

First, the costs for the feed mills were estimated. Internal recall costs were estimated in case contamination was found at the feed mill. These costs were estimated at 1.5 times the selling price of finishing pig feed. This price included the production costs of one extra batch, which we considered to be equal to the selling price since alternative raw materials had to be arranged quickly, leading to higher production costs. We assumed an additional 50% of the selling price accounts for destruction costs of the contaminated batch, extra administration costs, and cleaning costs.

$$\text{C\_feed} = 1.5 \times \text{CF} \times \text{SP\_feed}, \tag{3}$$

where C_feed is the total costs for the feed mills; CF is the amount of contaminated feed produced in kilograms, depending on the number of clients of the feed mill and the number of finishing pigs at these farms; and SP_feed is the selling costs of finishing pig feed.

Second, the costs for the farmers were estimated, including the lost revenue due to not being able to sell pigs to the slaughterhouse, and the additional costs of rendering pigs with dioxin levels above the ML.

$$\text{DC\_farm} = 1.25 \times WC_1 \times P_{\text{rend}}, \tag{4}$$

$$\text{RL\_farm} = WC_1 \times P_{\text{pig}}, \tag{5}$$

$$\text{C\_farm} = \text{DC\_farm} + \text{RL\_farm}, \tag{6}$$

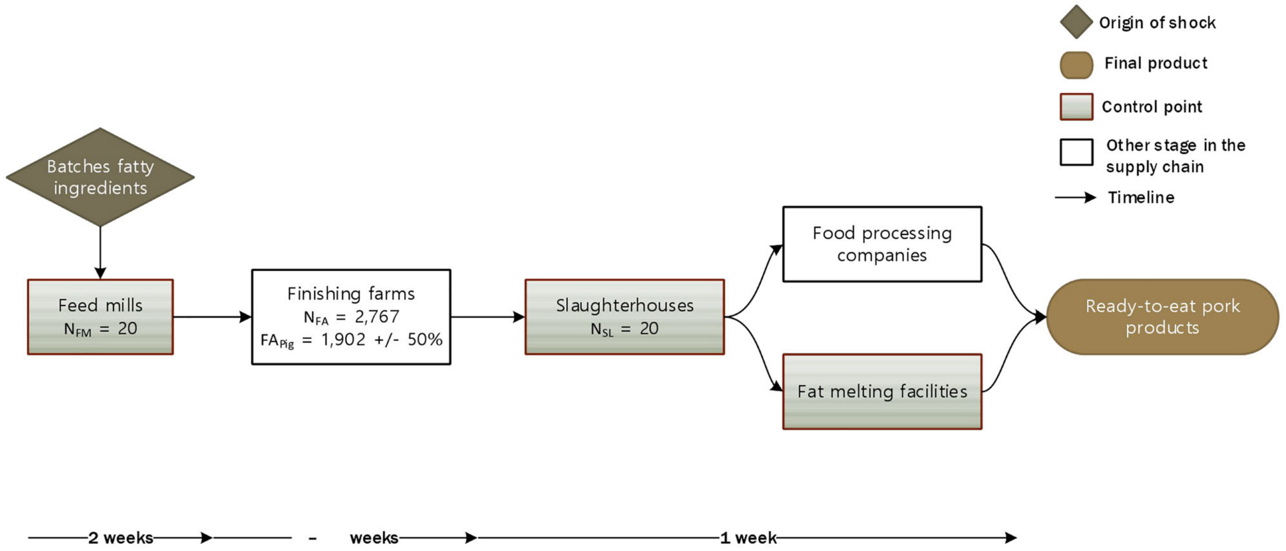

FIGURE 1 Pork supply chain: From the finishing stage to ready-to-eat products. N_{FM}, number of feed mills, N_{FA}, number of finishing farms, $\mathrm{FA}_{\mathrm{pig}}$, number of pigs per finishing farm, N_{SL}, number of slaughterhouses.

where DC_farm is the rendering costs of pigs with dioxin levels above the ML, not yet slaughtered; WC_1 is the carcass weight of these pigs; P_{rend} is the rendering costs per kilogram; RL_farm is the lost revenue of not being able to sell pigs with dioxin levels above the ML; P_{pig} is the price the slaughterhouses pay the farmers per kg of carcass; and C_farm is the total costs for the farms.

Third, the costs for the processors, that is, the slaughterhouses and the fat melting facilities, were estimated. These costs included the recall and destruction costs of the contaminated products placed on the market, the rendering costs of the contaminated carcasses present at the slaughterhouse, the lost revenue of the slaughterhouses and the other processors, including the fat melting facilities, due to not being able to buy and sell pigs or pig products from suppliers having contaminated pigs or products. In the model, we assumed one step of processing after slaughter (Figure 1).

$$\mathrm{RC\_proc} = 3 \times P_{\mathrm{meat}} \times WC_2, \tag{8}$$

$$\mathrm{DC\_proc} = WC_2 \times P_{\mathrm{rend}}, \tag{9}$$

$$\begin{aligned}\mathrm{RL\_proc} = {} & \left[(WC_1 \times P_{\mathrm{meat}}) - \left(WC_1 \times P_{\mathrm{pig}}\right)\right] \\ & + \left[\left(WC_1 \times P_{\mathrm{prod}}\right) - (WC_1 \times P_{\mathrm{meat}})\right],\end{aligned} \tag{10}$$

where RC_proc is the recall costs, P_{meat} is the selling price of meat, and WC_2 is the weight of pig carcasses recalled. Factor three comes from the study of Shiptsova et al. (2002), who estimated the recall costs for pork products to be three times the selling price of the products placed on the market.

DC_proc are the rendering costs; P_{rend} is the rendering costs per kilogram; RL_proc is the lost revenue; WC_1 is the carcass weight of all pigs, with dioxin levels above the ML th farmers cannot send to the slaughterhouses and further processor; P_{meat} is the selling price per kilogram of pig products after slaughter; P_{pig} is the price the slaughterhouse pays to the farmers per kilogram of carcass; and P_{prod} is the selling price per kilogram of ready-to-eat pork products. The assumptions made here were first that the entire carcass was used to produce products and second that the selling price of the products (meat, organs, fat, etc.) was similar and equal to the selling price of meat, meat consisting of 65% of the carcass (Vion Food Group, 2021). In a sensitivity analysis, we considered the fact that all costs for the processors could be less (−50%) or more (+50%) to show the effect of our assumptions on the results. The total costs were estimated by adding up the costs for the feed mills, the farmers, and the processors. The means of the total costs were compared pairwise using Bonferroni's method.

The model was coded in R (version 4.1.0; R Core Team, 2021). The model was run using 1000 iterations. These 1000 iterations were used to determine a 90% probability interval around the results. The code is available upon request.

3 | RESULTS

3.1 | The detection time

Figure 2 shows the performance of the supply chain between weeks 0 and 26. A performance of 100% is equal to no pork products with dioxin levels above the ML placed on the

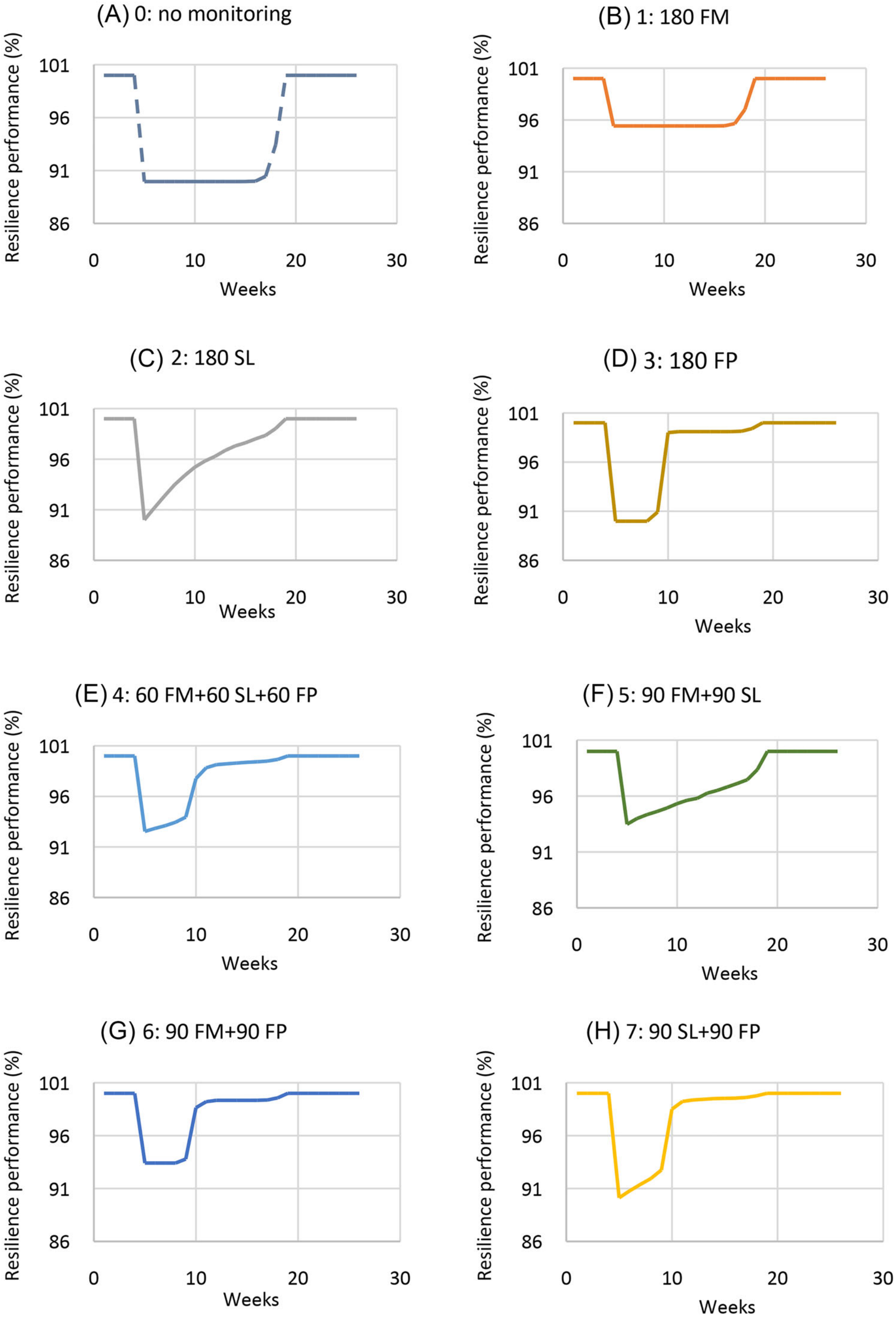

FIGURE 2 Resilience performance of the supply chain in terms of amount of pig products placed on the market with dioxin concentrations < ML. The averages for 1000 iterations are shown. FP, fat melting facilities; FM, feed mills; ML, maximum limits; SL, slaughterhouses.

market. At week 0, two feed processors received contaminated fatty ingredients. Contaminated pork products start to appear on the market from week 4 onward because we assumed that production and delivery of feed required 2 weeks. A pig needs to be fed for at least 1 week with contaminated feed before contamination can be detected, and slaughter and processing require 1 week to place ready-to-eat products on the market. In case of no monitoring, contaminated products are placed on the market from weeks 4 to 18. In case of the monitoring options that include monitoring at fat melting facilities, the majority of contaminated products were removed before week 10 (options 3, 4, 6, and 7 in Figure 2). This is because the probability of missing a contamination in feed is lower if fat melting facilities are monitored compared to when they are not monitored because fat comes from pigs from multiple groups and farms, which increases the probability to detect contamination. In case of the monitoring options that do not include monitoring at the

TABLE 4 Performance deviation and resilience of the supply chain in the different monitoring options.

		Percentage of pigs > ML on the market	Percentage of pigs > ML avoided on the market	No. of pigs recalled	Detection time (weeks)	Resilience (%)
0	No monitoring	5.24	–	–	–	94.8
		(4.06–6.47)				(93.5–95.9)
1	180 FM	2.58	2.52	–	8	97.4
		(0.00–6.13)	(0.00–5.81)		(0–16)	(93.5–97.6)
2	180 SL	2.45	2.96	81,100	4	97.6
		(0.72–4.59)	(0.63–5.15)	(34,600–116,200)	(1–11)	(95.4–99.3)
3	180 FP	2.28	3.10	87,400	5	97.7
		(1.52–4.17)	(2.02–4.00)	(58,100–111,600)	(5–5)	(95.8–98.5)
4	60 FM + 60 SL + 60 FP	**1.51**	**3.79**	65,100	**3**	**98.5**
		(0.00–3.62)	(2.12–5.60)	(0–115,200)	(0–6)	(96.4–100)
5	90 FM + 90 SL	2.31	3.00	41,200	4	97.7
		(0.00–5.33)	(0.00–5.75)	(0–110,900)	(0–16)	(94.7–100)
6	90 FM + 90 FP	**1.60**	**3.69**	58,500	**3**	**98.4**
		(0.00–4.19)	(2.02–5.65)	(0–111,600)	(0–6)	(95.8–100)
7	90 SL + 90 FP	**2.02**	**3.41**	90,000	**4**	**98.0**
		(1.05–3.77)	(2.11–4.78)	(58,300–115,900)	(1–6)	(96.2–98.9)

Note: The 90% probability interval is indicated in brackets. Results in bold are the top three best performing options.
Abbreviations: FM, feed mills; FP, fat melting facilities; SL, slaughterhouses.

fat melting facilities, so only at feed mills and/or slaughterhouses (options 1, 2, and 5), it can take up to 18 weeks before all contaminated pork products are removed from the market. The shortest average detection time (3 weeks) was for option 4, monitoring at all three stages, and for option 6, monitoring at both the feed mills and the fat melting facilities. In 90% of the model iterations, the contamination was detected between week 0 and 6 for both these options. For option 1, monitoring at the feed mills only, and option 5, monitoring at the feed mills and the slaughterhouses, the contamination remained undetected in more than 5% of the cases since the 95% percentile is week 16, the maximum duration of the finishing stage. For option 3, on the other hand, the contamination was always detected in week 5 in 90% of the model iterations (Table 4).

3.2 | The resilience of the supply chain

Option 4, collecting samples at all three control points, performs best in terms of (lowest) percentage of pigs with dioxin concentrations above the ML placed on the market and (highest) percentage avoided on the market, and thus in terms of resilience. Option 6, collecting samples at the feed mills and the fat melting facilities, is the second best option in terms of resilience. These options are also the options with the shortest average detection time. The third best performing option in terms of resilience is option 7, collecting samples at the slaughterhouses and fat melting facilities (Table 5 and Figure 3). The most resilient supply chain in terms of food safety is in general achieved when monitoring at the later stages of the supply chain, in particular at the fat melting facilities. This is because a contamination in feed might be missed in case the fat melting facilities are not monitored. In case contamination is missed, the resilience performance of the supply chain returns to 100% after 18 weeks, when all pork products with dioxin concentrations above the ML are sold to consumers. At feed level or slaughterhouse level, the number of samples is small compared to the number of potentially contaminated batches. At the level of the fat melting facilities, pigs from multiple groups, originating from multiple farms, are mixed together. Therefore, the total number of batches is reduced, and the probability of detecting a contamination increases significantly. In case of the monitoring option allocating all samples to the fat melting facilities (option 3), enough samples are collected to find a contamination at the finishing stage within 1 week.

A pairwise comparison of means estimated for the resilience using the Bonferroni method concludes that all options lead to statistically more resilient supply chains than the option without monitoring (Table 5). However, a few options are not statistically different from each other in terms of resilience: options 2 and 3, options 2 and 5, options 3 and 5, options 4 and 6, and options 6 and 7. The options in the top three (options 4, 6, and 7), although not significantly different from each other, are significantly different from the other options 1, 2, 3, and 5.

TABLE 5 Bonferroni pairwise comparison of means for the resilience.

	Options	0 No monitoring	1	2	3	4	5	6
1	180 FM	0.0000						
2	180 SL	0.0000	0.0000					
3	180 FP	0.0000	0.0000	1.0000				
4	60 FM + 60 SL + 60 FP	0.0000	0.0000	0.0000	0.0000			
5	90 FM + 90 SL	0.0000	0.0000	1.0000	1.0000	0.0000		
6	90 FM + 90 FP	0.0000	0.0000	0.0000	0.0000	0.7090	0.0000	
7	90 SL + 90 FP	0.0000	0.0000	0.0026	0.0000	0.0000	0.0018	0.1207

Note: The p-values are shown, in case $p < 0.05$ the options lead to significantly different results.
Abbreviations: FM, feed mills; FP, fat melting facilities; SL, slaughterhouses.

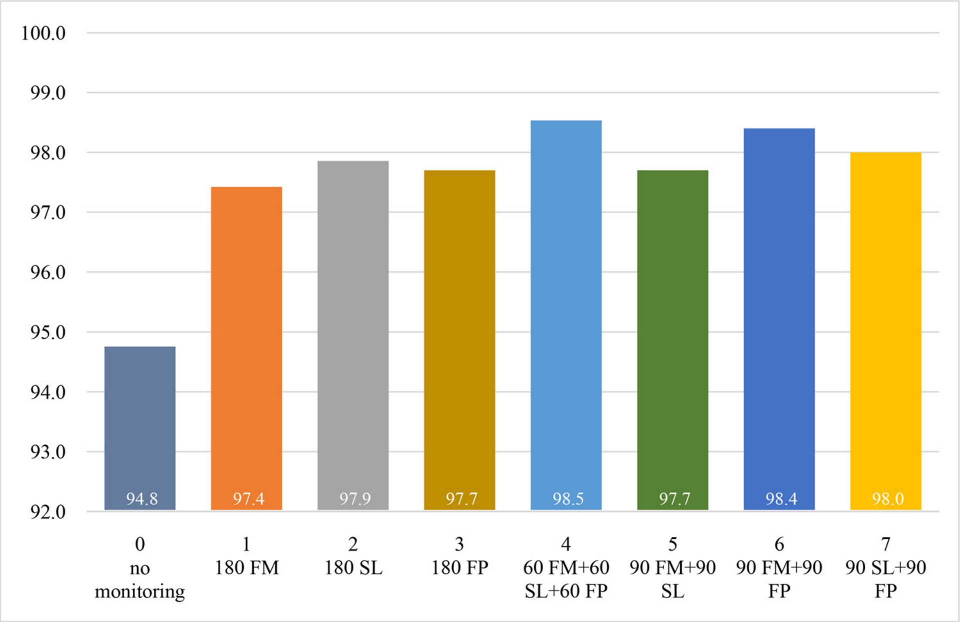

FIGURE 3 Resilience of the supply chain to dioxin contamination for the different monitoring options. The main bar represents the average resilience for 1000 iterations. The error bars 90% probability interval around the mean. FM, feed mills; FP, fat melting facilities; SL, slaughterhouses.

3.3 | Cost and effectiveness of monitoring options

Total costs in case contamination occurs vary widely from on average €4 million for monitoring option 1 to €314 million for monitoring option 7 (Table 6). Approximately 60% of these costs are for the processors, between 35% and 40% for the farmers, and between 0% and 5% for the feed mills, irrespective of the monitoring option. A pairwise comparison of means using the Bonferroni method shows that all monitoring options lead to significantly different costs in case of dioxin contamination. The further down the supply chain the contamination is detected, the higher the monitoring costs. Monitoring option 1 results in the lowest total costs because no recalls are performed later in the supply chain. However, option 1 also results in the lowest resilience performance (Figure 4) because it results in the highest number of pigs with dioxin concentrations above the ML on the market (Table 4), potentially resulting in the highest human health impact. As concluded in the previous section, options 4, 6, and 7 result in the highest supply chain resilience. The costs in case of contamination were lower for options 4 and 6 than for option 7 and also for many of the other options with a lower resilience performance (Figure 4). Therefore, options 4 and 6 would be the preferred options from a cost and effectiveness perspective.

3.4 | Sensitivity analysis

Lowering the number of samples collected by 50% lowers the resilience of the pork chain, by on average 0.7%. In contrast, increasing the number of samples collected by 50% increases the resilience of the pork chain by on average 0.5%.

TABLE 6 Results: Costs for each monitoring option (90% probability interval in brackets).

Monitoring option		Costs feed mills (internal recall + destruction + replacement) (*1000€)	Costs farmers (rendering costs + revenue loss) (*1,000€)	Costs processors (recall costs + rendering costs + revenue loss) (*1000€)	Total costs (*1000€)
1	180 FM	4143 (0–9552)	–	–	4143 (0–9552)
2	180 SL	–	59,523 (19,356–103,646)	217,774 (91,837–344,181)	277,297 (108,682–443,958)
3	180 FP	–	62,190 (40,911–79,119)	228,966 (150,733–291,597)	291,155 (191,155–371,018)
4	60 FM + 60 SL + 60 FP	2,238 (0–8956)	46,546 (0–86,308)	170,347 (0–306,714)	219,131 (6,970–389,856)
5	90 FM + 90 SL	2812 (0–9315)	23,577 (0–81,555)	91,150 (0–278,634)	117,540 (6,550–362,081)
6	90 FM + 90 FP	2673 (0–9341)	39,407 (0–76,961)	146,187 (0–283,851)	188,267 (6786–360,548)
7	90 SL + 90 FP	–	67,876 (41,550–93,031)	246,577 (156,627–321,715)	314,453 (198,369–411,854)

*means times
Abbreviations: FM, feed mills; FP, fat melting facilities; SL, slaughterhouses.

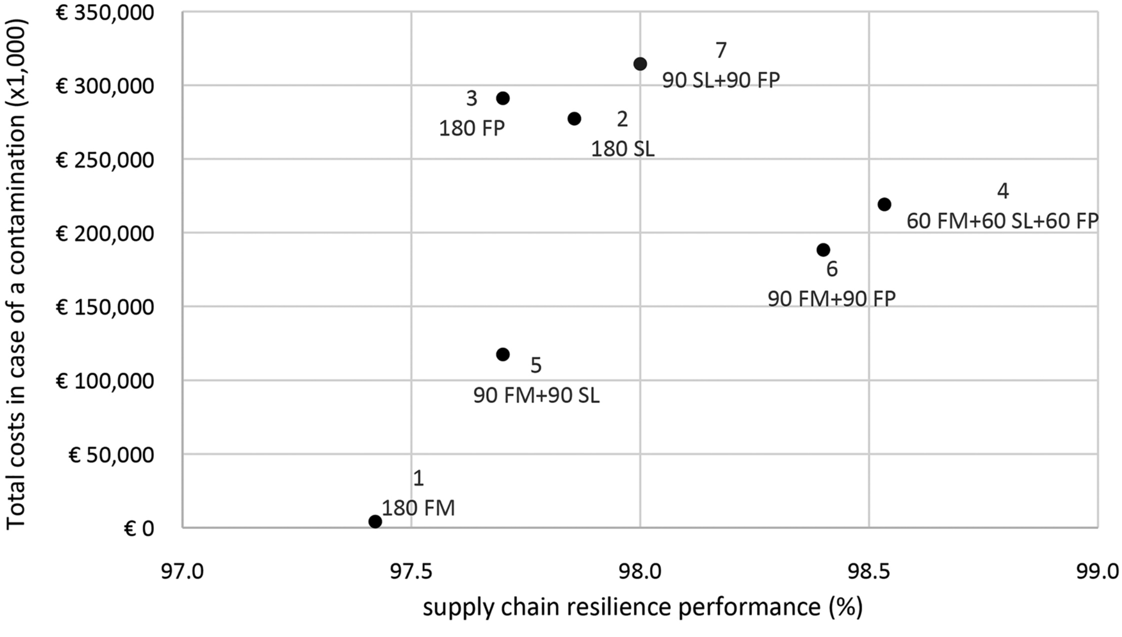

FIGURE 4 Costs and effectiveness of the different monitoring options. The labels show the number of samples collected at each stage of the pork supply chain. FM, feed mills; FP, fat melting facilities; SL, slaughterhouses.

Lowering the initial dioxin concentration in the feed or the amount of contaminated feed mills results in a higher estimated resilience due to the fact that less pigs with a dioxin concentration in their body fat above the ML are placed on the market. The effect of collecting samples from five pigs per group instead of one is negligeable. The time window in which pigs from one group could either have dioxin concentrations in their body fat just below or above the ML is small (about 2 weeks). During this time window only, selecting five pigs instead of one per group potentially decreases the rate of false negatives. Before and after this time frame, all pigs within a group will have a dioxin concentration above or below the ML. Therefore, selecting one or five pigs does not lead to different results. Increasing or decreasing the costs for processors in case dioxins was found to be above the ML, leading to higher or lower total costs in case of such an incident for options 2–7. However, different scenarios or changes in the inputs parameters considered in the sensitivity analysis lead to the same top three options in terms of resilience and costs (Tables 7 and 8). The only change in the top three is seen when increasing the number of samples collected: in terms of resilience, the top three options are options 4, 6, and 5, instead of options 4, 6, and 7. Detecting contamination before the fat melting stage leads to a more resilient supply chain. However, more samples are required to detect a contamination with a high probability at earlier stages since the number of batches is higher at these stages. Increasing the number of samples increases the probability of detecting a contamination earlier in the supply chain. Therefore, option 5, collecting samples before the fat melting stage, will enter the top three options.

4 | DISCUSSION

4.1 | The resilience of the supply chain

The options leading to the most resilient supply chains in terms of safety are those that include collecting samples at the fat melting facilities (fat melting facilities only and in combination with slaughterhouses and feed mills). The research of Wang et al. (2020) optimizing monitoring options for dioxins in the dairy supply chain resulted in a similar conclusion. They considered the control points feed mills, dairy farms, and milk trucks, mixing milk from multiple farms, which resemble our control points feed mills, slaughterhouses, and fat melting facilities, mixing fat from multiple pig farms. Wang et al. (2020) concluded that it was optimal to allocate most budget to dairy farms and milk trucks when to minimize the human health impact measured by the Disability Adjusted Life Years due to contaminated milk placed on the market, and thereby maximizing supply chain resilience. Our study also showed high resilience for option 7, sampling at slaughterhouses and fat melting facilities (Table 4). However, this option results in high costs in case of an incident (Table 6), an aspect not considered by Wang et al. (2020).

Since the three best performing options in terms of resilience (options 4, 6, and 7) are not statistically different from each other, either option could be chosen as "best performing," and the final choice will depend on other factors. One of these factors could be the spread of the results (the 90% probability interval around the mean). This spread is smaller when collecting samples at all the stages of the supply chain compared to the option dividing the samples over the slaughterhouses and the fat melting facilities. Therefore, in case one would be risk averse, monitoring at all stages of the supply chain would be the preferred option. Another factor influencing the choice of the optimal monitoring option could be the costs, as discussed in the next section.

4.2 | Cost effectiveness of monitoring options

Effective monitoring for dioxins in the pork chain at lowest costs was previously studied by Lascano-Alcoser et al. (2014), who stated that "sharing the responsibility of monitoring dioxins along the supply chain reduced the total costs." Our study leads to the same conclusion that sharing responsibility is needed to effectively reach high resilience at lowest costs. Lascano-Alcoser et al. (2014) concluded that it is cost-effective to allocate most resources on monitoring dioxins at the feed mill. This result is similar when looking at the average results obtained in the current study. However, the model of Lascano-Alcoser et al. (2014) did have a few differences with our model: Tracking and tracing costs in case of contamination were considered, and variability of the results was not considered. As shown by our model, the variability in results obtained when monitoring at the feed mill only shows that a contamination can easily be missed, and because it will not be discovered further downstream the supply chain, it could result in severe consequences for public health. Because of the huge volumes of feed ingredients and processed animal feed on the global market, only analyses of a very high number of samples in feed (ingredients) can assure early detection (Malisch & Kotz, 2014). The model described in this study considered the origin of dioxin contamination to be the fatty ingredients. However, as shown by incidents in the past, the origin could also be other feed ingredients such as potato peel, bakery waste, or citrus pulp (R. Hoogenboom et al., 2015), leading to a much higher number of potentially contaminated batches of ingredients than only the batches of fatty ingredients considered in this model. In case more ingredients could potentially be the source of contamination, the probability of missing the contamination with the number of samples at the feed mill considered in this model would be higher.

Depending on the nature of the incident considered, in addition to the food safety resilience, the economic resilience is also an important aspect to consider. This is demonstrated by the high costs for the supply chain in case of an incident. For the fictive incident considered in this study, in case the contamination was not detected at the level of the feed, based on the assumption previously listed, the estimated average total costs are between €109 and €444 million (Table 6, options 2, 3, and 7), with about 450,000 affected pigs. In contrast, the Irish incident of 2008 was discovered with routine sampling of pork fat from slaughtered pigs as part of the national residue control plan, and the costs were estimated to be €120 million, with about 30,000 tons of recalled pork products (Marnane, 2012). Furthermore, approximately 170,000 pigs were slaughtered and rendered (Marnane, 2012).

4.3 | Implication of the model

Mu et al. (2021) applied the concept of resilience in food safety to compare the effect of several management options

TABLE 7 Sensitivity analysis: The resilience of the pork supply chain to dioxin contamination.

	Monitoring options	**Baseline** **180 samples** **7.5 μg/kg** **Two feed mills** **One pig per group** **Base costs**[a]	**Sensitivity 1** **90 samples** **7.5 μg/kg** **Two feed mills** **One pig per group** **Base costs**[a]	**Sensitivity 2** **270 samples** **7.5 μg/kg** **Two feed mills** **One pig per group** **Base costs**[a]	**Sensitivity 3** **180 samples** **3.75 μg/kg** **Two feed mills** **One pig per group** **Base costs**[a]	**Sensitivity 4** **180 samples** **7.5 μg/kg** **One feed mill** **One pig per group** **Base costs**[a]	**Sensitivity 5** **180 samples** **7.5 μg/kg** **Two feed mills** **Five pigs per group** **Base costs**[a]	**Sensitivity 6** **180 samples** **7.5 μg/kg** **Two feed mills** **One pig per group** **50% base costs**[a]	**Sensitivity 7** **180 samples** **7.5 μg/kg** **Two feed mills** **One pig per group** **150% base costs**[a]
1	180 FM[b]	97.4 (93.5–97.6)	96.5 (93.8–100)	98.4 (94.1–100)	98.1 (95.3–100)	98.1 (96.6–100)	97.4 (93.9–100)	97.4 (93.5–97.6)	97.4 (93.5–97.6)
2	180 SL[b]	97.6 (95.4–99.3)	96.5 (94.6–98.7)	98.9 (98.1–99.5)	97.7 (96.0–99.3)	98.8 (97.1–99.0)	97.8 (95.9–99.3)	97.6 (95.4–99.3)	97.6 (95.4–99.3)
3	180 FP	97.7 (95.8–98.5)	97.5 (95.6–98.5)	97.7 (95.9–98.5)	97.8 (96.6–98.5)	99.0 (98.7–99.3)	97.7 (95.9–98.5)	97.7 (95.8–98.5)	97.7 (95.8–98.5)
4	60 FM + 60 SL + 60 FP	98.5 (96.4–100)	97.9 (95.5–100)	98.7 (96.8–100)	98.5 (96.8–100)	99.1 (98.5–100)	98.5 (96.3–100)	98.5 (96.4–100)	98.5 (96.4–100)
5	90 FM + 90 SL	97.7 (94.7–100)	96.5 (94.1–100)	98.4 (95.3–100)	98.0 (95.7–100)	98.5 (96.9–100)	97.9 (94.9–100)	97.7 (94.7–100)	97.7 (94.7–100)
6	90 FM + 90 FP	98.4 (95.8–100)	97.8 (95.6–100)	98.7 (96.0–100)	98.7 (96.7–100)	99.1 (98.6–100)	98.4 (96.0–100)	98.4 (95.8–100)	98.4 (95.8–100)
7	90 SL + 90 FP	98.0 (96.2–98.9)	97.7 (95.9–98.7)	98.2 (96.8–99.0)	98.1 (96.7–99.0)	99.1 (98.6–99.8)	98.1 (96.8–99.1)	98.0 (96.2–98.9)	98.0 (96.2–98.9)

Note: The 90% probability interval is indicated in brackets.

Abbreviations: FM, feed mills; FP, fat melting facilities; SL, slaughterhouses.

[a] For processors in case the dioxin concentrations are above the maximum limit.

[b] For the sensitivity analyses 1 and 2, the total number of samples is different than the baseline: In the description of the monitoring options: 180 samples are thus 90 or 270, respectively; 60 samples 30 or 90, respectively; and 90 samples 45 or 135, respectively.

TABLE 8 Sensitivity analysis: The costs of the different monitoring options.

		Baseline **180 samples** **7.5 μg/kg** **Two feed mills** **One pig per group** **Base costs**[a]	**Sensitivity 1** **90 samples**[b] **7.5 μg/kg** **Two feed mills** **One pig per group** **Base costs**[a]	**Sensitivity 2** **270 samples**[b] **7.5 μg/kg** **Two feed mills** **One pig per group** **Base costs**[a]	**Sensitivity 3** **180 samples** **3.75 μg/kg** **Two feed mills** **One pig per group** **Base costs**[a]	**Sensitivity 4** **180 samples** **7.5 μg/kg** **One feed mill** **One pig per group** **Base costs**[a]	**Sensitivity 5** **180 samples** **7.5 μg/kg** **Two feed mills** **Five pigs per group** **Base costs**[a]	**Sensitivity 6** **180 samples** **7.5 μg/kg** **Two feed mills** **One pig per group** **50% base costs**[a]	**Sensitivity 7** **180 samples** **7.5 μg/kg** **Two feed mills** **One pig per group** **150% base costs**[a]
1	180 FM[b]	4143	2375	5205	4143	1204	4059	4186	4014
		(0–9,552)	(0–9,066)	(0–9,547)	(0–9,552)	(0–4,787)	(0–9,438)	(0–9,541)	(0–9511)
2	180 SL[b]	277,297	183,955	322,242	198,320	135,518	248,695	202,470	339,898
		(108,682–443,958)	(0–385,152)	(152,887–465,901)	(30,517–337,867)	(0–247,602)	(82,949–447,596)	(56,567–314,015)	(94,207–564,446)
3	180 FP	291,155	278,268	293,273	214,811	160,206	291,148	216,760	366,303
		(191,155–371,018)	(181,407–367,288)	(195,693–378,373)	(142,066–279,435)	(107,360–215,023)	(190,009–370,369)	(146,042–271,416)	(243,476–467,758)
4	60 FM + 60 SL + 60 FP	219,131	233,978	205,317	166,294	134,030	221,470	168,172	281,784
		(6970–389,856)	(7503–374,634)	(6771–407,909)	(6778–298,460)	(3368–219,386)	(6795–388,549)	(7254–290,824)	(6975–507,423)
5	90 FM + 90 SL	117,540	83,540	135,139	93,380	73,741	143,199	95,906	149,547
		(6550–362,081)	(0–284,577)	(6432–384,355)	(0–276,507)	(0–227,069)	(5627–391,945)	(0–279,529)	(0–453,953)
6	90 FM + 90 FP	188,267	209,842	168,295	142,573	131,339	182,922	143,562	239,459
		(6786–360,548)	(7252–359,690)	(6488–360,431)	(6746–258,423)	(2785–210,450)	(6754–358,277)	(6855–263,374)	(6586–454,697)
7	90 SL + 90 FP	314,453	295,741	323,314	235,063	164,380	324,085	229,226	398,668
		(198,369–411,854)	(185,237–394,276)	(222,669–417,989)	(153,018–319,201)	(104,702–232,035)	(220,613–427,353)	(157,968–295,017)	(268,246–532,317)

Note: The 90% probability interval is indicated in brackets.

Abbreviations: FM, feed mills, FP, fat melting facilities; SL, slaughterhouses.

[a] For processors in case the dioxin concentrations are above the maximum limit.

[b] For the sensitivity analyses 1 and 2, the total number of samples is different than the baseline: In the description of the monitoring options: 180 samples are thus 90 or 270, respectively; 60 samples 30 or 90, respectively; and 90 samples 45 or 135, respectively.

to control *Salmonella* spp., a microbiological food safety hazard, in the pork supply chain. Several management options were available to increase the resilience of the pork supply chain, such as limiting visitors to the farm or the slaughterhouse, regular cleaning of the equipment, or the vaccination of pigs. For chemical hazards, such as dioxins, management options to increase the resilience of the pork supply chain to dioxin contamination are less diverse: monitoring is the main management option available against dioxins. However, the same principles can be applied to estimate the resilience of a supply chain to both a microbiological hazard and a chemical hazard.

Ge et al. (2016) argued for stronger adoption of resilience thinking into research on bio-based production systems to focus on multiple aspects: system resilience, adaptability, and transformability. This study estimates the extent to which the pig supply chain can withstand a contamination of the feed with dioxins. Using the concept of food resilience enables to base the decision in this case on both the degree of impact caused by the shock and the time to recover. Furthermore, although the main indicator used in this study was food safety, the indicator "costs" was also considered. More indicators could be added to the model if necessary such as a social indicator, for example, public perception or sustainability. For example, option 5, although not included in the top three option in terms of resilience when focusing on the indicator "food safety," does lead to the lowest number of pigs culled; therefore, scoring best when the number of pigs culled would be used as an indicator for sustainability.

This model can be used by governmental decision makers or food business operators along the supply chain to make objective decisions on the control of dioxins in the pork supply chain. The amount of non-compliant pig products placed on the market, the detection time, and the potential costs in case of an incident can be compared between monitoring strategies. Furthermore, the spread in results can show the impact of uncertainty on the resilience outcomes. This type of model can be used to improve food safety by identifying critical control points and the most effective management options for optimal resilience at the lowest costs. The model allows to be more proactive and to implement dioxin control measures in the pork supply chain resulting in optimal supply chain resilience.

4.4 | Limitations

Our study used a stylized version of the Dutch pig supply chain with fixed size of feed mills, farms, slaughterhouses, and fat melting facilities. Expanding the model to include different sizes could make the model resemble reality more closely and thereby improve model outcomes. Furthermore, our study was aimed at monitoring to detect dioxin concentrations above the ML, not to estimate the prevalence over time, and it considered a fixed distribution of the samples between the three control points. In case one wishes to derive an optimal monitoring plan from this study to apply in practice, the distribution of the samples between the control points needs to be further finetuned using an optimization model with as constraints a budget for monitoring for the entire supply chain and a minimum required resilience. An optimization model would also allow to compare Pareto-optimal options, options where resilience cannot be improved without increasing the costs or options where the costs cannot be lowered without lowering resilience. The sensitivity analysis touched upon the effect of changing the budget available for monitoring. The analysis showed that collecting 50% of the initial number samples leads to a lower resilience of the supply chain and a longer detection time. Collecting 150% of the initial number of samples leads to a higher resilience of the supply chain. Consequently, resilience can be improved by increasing the number of samples collected and thus the budget available for sampling and analyses.

5 | CONCLUSION

The model developed in this study showed that monitoring can be effective in increasing the resilience of the pork supply chain to a potential dioxin contamination, taking into account the severity of the food safety incident, the time required to return to the performance of the supply chain before the incident or to achieve a new equilibrium, and the degree of recovery. Collecting and analyzing samples at fat melting facilities in combination with sampling at feed mills, or slaughterhouses, or both, resulted in the highest resilience. Also taking costs into account, collecting and analyzing samples at fat melting facilities and feed mills or at all three stages were found to be most cost-effective. This model and these results can be used by public and private decision makers to make proactive and informed decisions on the monitoring strategies to control dioxins in the pork supply chain that result in optimal resilience to a dioxin crises.

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