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Salmonella enterica prevalence, serotype diversity, antimicrobial resistance and control in the European pork production chain

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ABSTRACT

Background: A risk assessment conducted by EFSA identified ***Salmonella enterica*** (*Salmonella*) as a high-risk hazard at the EU level in the context of meat inspection of swine. Despite pork being considered an important source of *S.* Typhimurium and its monophasic variant, Regulation (EC) No 2073/2005 does not set criteria for specific *Salmonella* **serotypes**. Enforcing specific criteria for *Salmonella* target **serotypes** could result in a reduction in the **prevalence** of *Salmonella* in the **pork production chain**, as has happened in broiler flocks.
Scope and approach: This study gives an overview of ***Salmonella enterica*** in the European pork chain, discussing **prevalence**, **serotype** diversity, **antimicrobial resistance** and epidemiological importance during the last 20 years. Additionally, future trends and recommendations regarding control of *Salmonella* in the European **pork production chain** are introduced.
Key findings and conclusions: The highest proportions of *Salmonella*-positive samples were observed at the fattening pig farm level, whereas the **prevalence** of *Salmonella* on pig carcasses was much lower. Among epidemiologically important **serotypes**, isolates of *S.* Typhimurium, and its monophasic variant were found to be resistant to ampicillin, sulfamethoxazole, streptomycin and tetracycline. Future *Salmonella* **control** in the **pork production chain** can preferably be conducted through a risk-based meat safety assurance system. In conclusion, a fit-for-purpose strategy applied to the **pork production chain** and adapted to the national epidemiological situation can deliver acceptable consumer safety.

1. Introduction

Salmonellosis was the second most commonly reported zoonosis and the most frequent cause of foodborne outbreaks in the EU during the last decade (EFSA & ECDC, 2021a). The notification rate of salmonellosis was 13.7 confirmed cases per 100,000 inhabitants with 52,702 total cases in humans in the EU in 2020 (EFSA & ECDC, 2021a). A notification rate of 20.0 cases per 100,000 inhabitants was reported in 2019 (EFSA & ECDC, 2021b). The difference between the two consecutive years is probably due to the COVID-19 pandemic. Salmonellosis is often characterised by gastroenteritis, with symptoms of diarrhoea, fever, vomiting and abdominal pain. Most cases of salmonellosis are mild, but in some people, particularly the immunocompromised, *Salmonella* infection can be severe, resulting in bacteraemia or other extra-intestinal infections (Arya et al., 2017).

The three most commonly reported serotypes isolated from humans in 2020 were *S.* Enteritidis, *S.* Typhimurium (4, [5],12:i:1,2) and its monophasic variant (1,4,[5],12:i:), which accounted for 48.7%, 12.4%

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and 11.1% of the confirmed human salmonellosis cases in the EU, respectively (EFSA & ECDC, 2021b). The proportion of human salmonellosis cases caused by *S.* Typhimurium (ST) and its monophasic variant (MST) ranged from 20.1% to 23.5% during the period from 2016 to 2020 (EFSA & ECDC, 2021b). Pork is considered an important source of ST and MST (Hauser et al., 2010). The public health impact of *Salmonella* is further aggravated by the emergence of antimicrobial resistance, especially to the highest priority clinically important antimicrobials, such as quinolones and 3rd and 4th generation cephalosporins (WHO, 2019). Jiang et al. (2019) demonstrated the presence of multiresistance to quinolones and beta-lactams in various serotypes of *Salmonella* isolated from slaughtered pigs, and the authors suggested that this pathogen could pose a risk for acquisition and dissemination of multidrug resistance (MDR) *via* the pork production chain.

In the EU, *Salmonella* control programmes in poultry production have shown a reduction in the prevalence of targeted *Salmonella* serotypes, particularly *S.* Enteritidis (EFSA, 2019). In pig production, some EU Member States (MSs) apply national surveillance and control programmes, which are not harmonised between MSs and do not necessarily set specific criteria for *Salmonella* as such or target serotypes. Analysis of the costs and benefits in the EU of setting a target for the reduction of *Salmonella* infections in slaughter pigs was carried out by the Food Control Consultants Ltd Consortium in 2010. The analyses revealed that none of the intervention scenarios had any economic gain, according to the cost-benefit analysis (FCC, 2010).

In this article, research and related statistics over the past 20 years conducted in the EU on *Salmonella* in the pork production chain are reviewed. Trends in *Salmonella* serotype diversity, antimicrobial resistance, epidemiological importance and surveillance and control options are discussed.

2. *Salmonella* prevalence in the pork production chain and serotype diversity

The EU-wide baseline study of *Salmonella* in slaughter pigs published in 2008 showed that 10.3% of slaughter pigs were *Salmonella*-positive, based on testing of ileocaecal lymph node samples, raising concerns over risks to human health and the need to control and reduce those risks (EFSA, 2008). Isolation of *Salmonella* serotypes from the ileocaecal lymph nodes is considered to replicate *Salmonella* prevalence on farms; however short-term exposure in the lairage can also lead to lymph node positivity (Arguello et al., 2013). In general, *Salmonella* isolates have been recovered from a higher percentage of ileocaecal lymph nodes than from carcasses. When piglets on farm are infected, this usually occurs after weaning. After the infectious phase, the pigs develop immunity. This implies that fewer pigs of slaughter age will harbour and excrete *Salmonella* from their intestines than would young animals (Kranker et al., 2003).

The *Salmonella* prevalence at different stages of the European pork production chain is presented in Table 1. NCBI PubMed literature database was searched on the October 5, 2022 using the specific search string (*salmonella AND (pork OR pig OR pigs) AND (prevalence OR prevalent OR detection OR resistance OR resistant OR serotype OR serotypes OR serovar OR serovars OR outbreak OR outbreaks)*) in combination with a time filter (starting from 2000). The initial search string returned 3409 research articles, which decreased to 2581 when the time filter was applied. Four manual screening steps were then performed by one researcher. The first manual screening was conducted using scientific paper titles to exclude non-European research (n = 523). The second manual screening was used to exclude all research papers with nonrelevant titles (n = 1422). In the third manual screening, abstracts were read, and all nonrelevant papers were excluded (n = 410). The fourth manual screening consisted of main text analysis and exclusion of all papers not related to outbreaks, prevalence, serotype or antibiotic resistance data (n = 15). After the above, a committee of three experts was created, and scientific research papers (n = 211) were only included when all three experts had come to the same conclusion that each paper contained relevant information regarding the prevalence and preferably also serotype with antimicrobial resistance data. Based on the previously mentioned criteria 31 high quality research papers were included in the prevalence analysis, 27 of them were further included in the serotype study and 8 out of those 27 were subsequently included in the antibiotic resistance analysis. Additionally, 17 outbreak-associated research publications were included based on the agreement of the expert committee.

The prevalence of *Salmonella* at farm, abattoir, meat cutting/processing and retail as reported by the studies are shown in Table 1. These prevalences should be carefully interpreted considering the diverse set of included studies, different sampling sites, materials and methods used. Also, the studies reported here were spread over a 20-year period, i.e., 2000–2020.

Based on samples taken by competent authorities (CAs), the overall proportions of *Salmonella*-positive pig carcasses in the EU ranged between 3.1 and 3.9% in the period from 2017 to 2020 (Table 2). However, there are big differences between European countries, and between the results of *Salmonella* testing in food business operator's (FBOs') own checks and CAs' official programmes. In 2020, the highest prevalence (14.3%) of *Salmonella*-positive pig carcasses was reported by the CA in Spain (EFSA & ECDC, 2021b). Some non-European countries have reported higher *Salmonella* prevalences in their pork chains than have been reported in Europe. For example, according to Yokozawa et al. (2016), the *Salmonella* prevalence on pig carcasses was 25.0% in Vietnam. Also, the *Salmonella* prevalence in pigs, including carcasses in commercial slaughterhouses in China was 22.9% (Jiu et al., 2020).

Finland, Sweden and Norway have special EU trade guarantees concerning *Salmonella* in fresh pork. According to the Finnish *Salmonella* Control Programme, the prevalence of *Salmonella*-positive lymph node samples at slaughter was less than 0.1%, thus suggesting that *Salmonella* in pigs is not a food safety issue in Finland (Felin, 2019). In 2020, Finland and Switzerland reported no *Salmonella*-positive samples out of, respectively, 6197 and 1112 pig carcasses tested by the FBOs. Also, a very low prevalence of *Salmonella* on pig carcasses was reported by Norway and Sweden, 0.03% and 0.04%, respectively (EFSA & ECDC, 2021b).

From 2000 to 2020, the top three *Salmonella* serotypes in the European pork production chain were ST including MST, Derby and Rissen (Table 3). Within the last decade, MST has taken a high position among the most prevalent *Salmonella* serotypes in the pork production chain not only in Europe (Table 4) but also in the United States and Asia (Elnekave et al., 2018; Petrovska et al., 2016; Sun et al., 2020). ST and MST have become among the most common *Salmonella* serotypes responsible for animal and human infections, with pork considered an important source (Sun et al., 2020). Petrovska et al. (2016) explained the epidemiologic success of MST by the emergence of new epidemic clones with a novel genomic island encoding resistance to heavy metals and a composite transposon encoding AMR genes. In a recent five-year cross-sectional study in Estonia, *S.* Derby was the most frequently isolated serotype from all stages of pig production, but mostly at pig farm and abattoir levels, followed by ST and MST (Kuus et al., 2021).

In the present review, *S.* Rissen was primarily reported as detected at abattoir level, but seldom at retail level (Table 3). European studies have detected *S.* Rissen in slaughtered pigs (Arguello et al., 2013; Belsue et al., 2011). Also, the emergence of *S.* Rissen has been recognised in many countries worldwide (Elbediwi et al., 2021).

The question is whether the focus should be on all *Salmonella* serotypes or on those of public health significance e.g. ST and MST in pork. For example, the EU *Salmonella* Control Regulation (EC) No 2160/2003 laid down the following criteria for determining the public health significance of *Salmonella* serotypes: (a) frequency of the serotype in human salmonellosis; (b) route of infection and presence in relevant animal populations and feed; (c) rapid and recent emergence, spread and ability to cause disease in humans and animals and; (d) increased virulence such as invasiveness or AMR. However, the microbiological criteria

Table 1
Salmonella prevalences at different stages of the pork production chain in Europe from the period of 2000–2020 originating from included studies (n = 31).

Stage	Sampling year	Country	Source	Total	Positive	Proportion (%)	CI95	Study
Farm	2016–2020	Estonia	Herds, fattening pigs	119	33	27.7	20.1–36.8	Kuus et al. (2021)
	2011–2012	Portugal	Multiple samples[a]	209	44	21.1	15.9–27.3	Fernandes et al. (2016)
	2008–2010	Germany	Fattening pigs[b]	700	51	7.3	5.5–9.5	Nathues et al. (2013)
	2008–2009	Belgium	Faecal samples, fattening pigs	2052	160	7.8	6.7–9.1	Rasschaert et al. (2012)
	2007	Portugal	Faecal samples, breeding and fattening pigs	1670	170	10.2	8.8–11.8	Correia-Gomes et al. (2012)
	2007	Portugal	Herds (production holdings)	134	61	45.5	37.0–54.3	Correia-Gomes et al. (2012)
	2007	Portugal	Herds (breeding holdings)	33	15	45.5	28.5–63.4	Correia-Gomes et al. (2012)
Transport	2009–2010	Spain	Trucks	56	13	23.2	13.4–36.7	Hernández et al. (2013)
Lairage	2013–2014	Italy	Lairage	67	33	49.3	37.0–61.6	Bonardi et al. (2016)
	2009–2010	Spain	Lairage	64	9	14.1	7.0–25.5	Hernández et al. (2013)
Slaughter	2016–2020	Estonia	Carcasses	1907	61	3.2	2.5–4.1	Kuus et al. (2021)
	2015–2016	Spain	Faecal, carcasses and environmental	315	107	34.0	28.8–39.5	Marin et al. (2020)
	2015	Italy	Raw meat	126	5	3.4	1.5–9.5	Carraturo et al. (2016)
	2014	Portugal	Carcasses	360	44	12.2	9.1–16.2	Cota et al. (2019)
	2014	Italy	Faecal, carcasses and environmental	671	135	20.1	17.2–23.4	Pesciaroli et al. (2017)
	2014	Croatia	Tonsils	78	2	2.6	0.4–9.8	Zdolec et al. (2015)
	2014	Croatia	Lymph nodes	78	0	0.0	0.0–5.9	Zdolec et al. (2015)
	2013–2014	Italy	Lymph nodes	201	40	20.0	14.8–26.2	Bonardi et al. (2016)
	2012–2013	Greece	Faecal, lymph nodes, tissue	492	14	2.9	1.6–4.9	Evangelopoulou et al. (2014)
	2009–2010	Spain	Carcasses, lymph nodes, tonsils, caecal	640	83	13.0	10.5–15.9	Hernández et al. (2013)
	2009–2010	Spain	Environment	320	18	5.6	3.5–8.9	Hernández et al. (2013)
	2007–2008	Portugal	Carcasses, lymph nodes, meat	345	60	17.4	13.6–21.9	Gomes-Neves et al. (2012)
	2006–2008	Italy	Carcasses, lymph nodes, caeca	425	64	15.1	11.9–18.9	Piras et al. (2011)
	2006–2008	Italy	Environment	41	13	31.7	18.6–48.2	Piras et al. (2011)
	2005–2008	Italy	Caecal content	451	97	21.5	17.9–25.7	Bonardi et al., 2013 [c]
	2005–2008	Italy	Tonsils	250	26	10.4	7.0–15.3	Bonardi et al., 2013 [c]
	2005–2008	Italy	Carcass swabs	451	49	10.9	8.2–14.2	Bonardi et al., 2013 [c]
	2005–2008	Italy	Scalding tank	34	0	0.0	0.0–12.6	Bonardi et al., 2013 [c]
	2007	Belgium	Lairage, carcasses, lymph nodes, faecal material, environmental etc.	1953	276	14.1	12.6–15.8	De Busser et al. (2011)
	2006–2007	United Kingdom	Carcass swabs, caecal content or lymph nodes	599	244	40.7	36.8–44.8	Marier et al. (2014)
	2005–2007	Ireland	Caecal content	193	87	45.1	38.0–52.4	Duggan et al., 2010 [d]
	2005–2007	Ireland	Rectal faeces	193	59	30.6	24.3–37.7	Duggan et al., 2010 [d]
	2005–2006	Ireland	Pork (meat samples)	720	24	33.3	21.9–49.9	Prendergast et al. (2008)
Meat cutting, processing	2016–2020	Estonia	Meat cutting	1290	14	1.1	0.6–1.9	Kuus et al. (2021)
	2015	Italy	Processing (ground pork)	150	21	14.0	9.1–20.8	Bonardi et al. (2017)
	2015	Italy	Processing (cured salami)	140	15	10.7	6.3–17.3	Bonardi et al. (2017)
	2009–2010	Spain	Quartering (meat cutting)	80	3	3.8	1.0–11.3	Hernández et al. (2013)
	2000–2004	Belgium	Meat cutting and minced meat	234	35	15.0	10.8–20.3	Delhalle et al. (2009)
	NS	Italy	Production (sausage)[b]	270	32	11.9	8.4–16.5	Piras et al. (2019)
Retail	2016–2018	Romania	Raw pork	146	33	22.6	16.3–30.4	Tîrziu et al. (2020)
	2016–2018	Romania	RTE pork	62	3	4.8	1.3–14.4	Tîrziu et al. (2020)
	2015	Italy	RTE pork	100	6	6.0	2.5–13.1	Bonardi et al. (2018)
	2011	Romania	Pork	208	48	23.1	17.7–29.5	Mihaiu et al. (2014)
	2007	Ireland	Butchers' shops and supermarkets (pork)	500	13	2.6	1.5–4.5	Prendergast et al. (2009)
	2006–2007	Italy	Pork	100	15	15.0	8.9–23.9	Bonardi et al. (2008)
	2006	Denmark	Butchers' shops and supermarkets (pork)	887	37	4.2	3.0–5.8	Hansen et al. (2010)
	2004–2005	Belgium	Minced meat	1475	58	3.9	3.0–5.1	Delhalle et al., 2009 [e]
	2003–2005	Belgium	Minced meat	1616	33	2.0	1.4–2.9	Delhalle et al., 2009 [e]
	2003–2005	United Kingdom	Pork	1440	56	3.9	3.0–5.1	Little et al. (2008)
	2004	Germany	Pork	250	1	0.4	0.02–2.6	Schwaiger et al. (2012)
	2004	Germany	Pork	250	1	0.4	0.02–2.6	Schwaiger et al. (2012)
	2002	Denmark	Butchers' shops and supermarkets (pork)	4498	52	1.2	0.9–1.5	Hansen et al. (2010)

NS, Not specified.
[3]swabs before holding pigs.
[a] all production cycle including farrowing, weaning and finishing pigs.
[b] including environmental.
[c] Two sampling periods.
[d] Same pigs with different sampling material.
[e] Calculated backwards using % and Table 4.

Table 2
Proportions of *Salmonella*-positive single samples from pig carcasses in the EU, 2017–2020[a].

	Competent Authority[b]		Food Business Operator[b]	
	Positive %	CI95%	Positive %	CI95%
2017	3.1	2.8–3.4	2.6	2.0–2.7
2018	3.4	3.1–3.7	1.8	1.7–2.0
2019	3.9	3.6–4.2	1.1	1.0–1.2
2020	3.6	3.3–3.9	1.8	1.7–2.0

[a] EFSA & ECDC, 2019; 2021a; 2021b.
[b] Total number of samples was calculated considering only member states that provided data from both the competent authority and the food business operators.

Table 3
Pork production chain-related serotypes originating from included studies (n = 27) conducted in Europe in the period of 2000–2020[a].

Serotype	Pork production chain level				Total (%)
	Farm	Abattoir	Processing	Retail	
Typhimurium	205	591	28	65	889 (34.8)
Derby	69	429	34	12	544 (21.3)
Rissen	33	177	10	10	230 (9.0)
Monophasic Typhimurium	54	159	7	2	222 (8.7)
Reading	ND	68	ND	ND	68 (2.7)
Agona	54	12	ND	1	67 (2.6)
London	26	31	4	1	62 (2.4)
Bredeney	1	47	1	2	51 (2.0)
Brandenburg	13	23	4	4	44 (1.7)
Panama	ND	40	1	ND	41 (1.6)
Other	60	220	16	40	336 (13.2)
Total (%)	515 (20.2)	1797 (70.3)	105 (4.1)	137 (5.4)	2554 (100)

ND, Not determined.
[a] Bonardi et al., 2013; Bonardi et al., 2016; Bonardi et al., 2017; Bonardi et al., 2018; Correia-Gomes et al., 2012; Cota et al., 2019; De Busser et al., 2011; Delhalle et al., 2009; Duggan et al., 2010; Evangelopoulou et al., 2014; Fernandes et al., 2016; Gomes-Neves et al., 2012; Hansen et al., 2010; Hernández et al., 2013; Kuus et al., 2021; Little et al., 2008; Marier et al., 2014; Marin et al., 2020; Pesciaroli et al., 2017; Piras et al., 2011; Piras et al., 2019; Prendergast et al., 2008; Prendergast et al., 2009; Rasschaert et al., 2012; Schwaiger et al., 2012; Tîrziu et al., 2020; Zdolec et al., 2015.

regulation (Commission Regulation (EC) No 2073/2005) for carcasses and minced meat and processed products includes all *Salmonella* serotypes. This indicates a stricter approach the closer one gets to the consumption level. However, focusing on hygiene during slaughter and processing will target and hereby help prevent all *Salmonella* serotypes.

3. *Salmonella* serotypes in humans

According to EFSA and ECDC (2019; 2021b), in 2016–2020, the most frequently reported *Salmonella* serotypes in humans were *S*. Enteritidis, ST, MST, *S*. Infantis and *S*. Derby (Table 5). Some of these serotypes, especially ST and MST, are associated with pork consumption (Alt et al., 2015; Arnedo-Pena et al., 2016; Helmuth et al., 2019; Kuhn et al., 2013; Mandilara et al., 2021). Also, these most frequent serotypes were associated with both sporadic and outbreak cases of human salmonellosis (Alt et al., 2015). In the EU, the number of reported confirmed cases of human salmonellosis caused by MST increased in the years from 2016 to 2019 (Table 5). During the same period, among serotyped isolates originating from pork, ST and MST accounted for 14.0% and 26.6%, respectively (EFSA & ECDC, 2021b). Among 18 salmonellosis outbreaks linked to pork consumption, most (61.1%) were caused by ST and MST (Table 6). Also, serotypes Derby, Infantis, Goldcoast, Ohio and Muenchen were detected in eight salmonellosis outbreaks caused by the consumption of contaminated pork products. The emergence of MST-related human salmonellosis cases could be linked to the countries in which pork is among the most commonly consumed meat (Andreoli et al., 2017; Kuus et al., 2021). In 2020, the fifth most common serotype responsible for human infections was *S*. Derby (EFSA & ECDC, 2021b). According to the EU One Health 2019 Zoonoses Report, *S*. Derby accounted for 21.3% of all serotyped *Salmonella* isolates from pork (EFSA & ECDC, 2021a). Despite the high prevalence of *S*. Derby in pig carcasses and raw pork products, the incidence of human salmonellosis infections caused by *S*. Derby has been relatively low (Table 5). According to EFSA & ECDC (2021b), only 1.2% of human salmonellosis infections were caused by *S*. Derby. Other less common serotypes, such as Goldcoast and Muenchen, have been associated with pork-related *Salmonella* human infections (Scavia et al., 2013; Schielke et al., 2017). However, in the EU, the current *Salmonella* food safety problem in pigs relates mostly to ST and MST (EFSA and ECDC, 2021b).

Currently, it is not yet possible to use the genetic basis for *Salmonella* virulence as a predictor for which *Salmonella* serotypes are a food safety and public health risk and, therefore, should be controlled. However, recent advances in whole-genome sequencing (WGS) (Allard et al., 2018) are promising and could enable reliable predictions of the virulence and, thereby, the human health risk from exposure. Nevertheless, for post-harvest applications, the focus should be on hygiene, whereby

Table 4
The proportions of pork production chain-related *Salmonella* serotypes originating from included studies (n = 27) within two decades in Europe[a].

Serotype	2011–2020	Proportion (%)	Serotype	2000–2010	Proportion (%)
Derby	186	29.8	Typhimurium	863	44.7
Monophasic Typhimurium	184	29.5	Derby	358	18.5
Rissen	86	13.8	Rissen	144	7.5
Typhimurium	26	4.2	Agona	62	3.2
Infantis	15	2.4	Reading	56	2.9
Arizonae	14	2.2	London	50	2.6
London	12	1.9	Bredeney	47	2.4
Reading	12	1.9	Monophasic Typhimurium	38	2.0
Brandenburg	11	1.8	Brandenburg	33	1.7
Panama	8	1.3	Give	28	1.5
Others	70	11.2	Others	251	13.0
Total	624	100	Total	1930	100

[a] Bonardi et al., 2013; Bonardi et al., 2016; Bonardi et al., 2017; Bonardi et al., 2018; Correia-Gomes et al., 2012; Cota et al., 2019; De Busser et al., 2011; Delhalle et al., 2009; Duggan et al., 2010; Evangelopoulou et al., 2014; Fernandes et al., 2016; Gomes-Neves et al., 2012; Hansen et al., 2010; Hernández et al., 2013; Kuus et al., 2021; Little et al., 2008; Marier et al., 2014; Marin et al., 2020; Pesciaroli et al., 2017; Piras et al., 2011; Piras et al., 2019; Prendergast et al., 2008; Prendergast et al., 2009; Rasschaert et al., 2012; Schwaiger et al., 2012; Tîrziu et al., 2020; Zdolec et al., 2015.

Table 5
The five most common *Salmonella* serotypes in humans in the EU, 2016–2020[a].

Serotype	2020		2019		2018		2017		2016	
	No	%	No	%	No	%	No	%	No	%
Enteritidis	20,610	48.7	39,451	50.4	39,516	50.0	38,780	49.1	33,325	48.5
Typhimurium	5258	12.4	9288	11.9	10,297	13.0	10,593	13.4	9789	13.4
Monophasic Typhimurium 1,4, [5],12:i:	4697	11.1	6432	8.2	6374	8.1	6324	8.0	5697	8.4
Infantis	1040	2.5	1912	2.4	1852	2.3	1805	2.3	1658	2.4
Derby[b]	518	1.2	719	0.92	707	0.90	612	0.8	620	0.8

[a] EFSA & ECDC, 2019; 2021b.
[b] Derby was among the top-five in 2020 and 2016.

Table 6
Pork-related *Salmonella* outbreaks in Europe originating form included studies (n = 17) from the period of 2000–2020 based on PubMed publications.

Salmonella serotype	Cases	Year	Country	Source	Reference
Muenchen	198	2001	Germany	Raw pork	Buchholz et al. (2005)
Typhimurium	63	2004	Italy	Pork salami	Luzzi et al. (2007)
Ohio	60	2005	Belgium	Possibly pork	Bertrand et al. (2010)
Typhimurium	1054	2008	Denmark	Pork products	Ethelberg et al. (2008)
Goldcoast	79	2009	Italy	Pork-containing food (salami)	Scavia et al. (2013)
Typhimurium	172	2010	Denmark	Pork products	Kuhn et al. (2013)
Typhimurium	20	2010	Denmark	Pork salami	Kuhn et al. (2011)
MST	16	2011	Italy	Cooked pork products	Lettini et al. (2014)
MST	337	2011	France	Dried pork sausage	Gossner et al. (2012)
Typhimurium	22	2011	Denmark	Smoke pork tenderloin	Wójcik et al. (2012)
Typhimurium; MST; Derby	83	2011	Spain	Dried pork sausage	Arnedo-Pena et al. (2016)
Derby	145	2013	Germany	Raw pork sausage	Simon et al. (2018)
Infantis	267	2013	Germany	Raw minced pork	Schroeder et al. (2016)
MST	61	2013	Germany	Raw minced pork	Alt et al. (2015)
Muenchen	203	2013	Germany	Raw pork sausage	Schielke et al. (2017)
Muenchen	247	2014	Germany	Raw pork sausage	Schielke et al. (2017)
MST	37	2017	Greece	Pork	Mandilara et al. (2021)
MST	49	2018	Denmark	Pork sausage	Helmuth et al. (2019)

MST, monophasic *Salmonella* Typhimurium.

all *Salmonella* will be prevented. From a public health point of view, raw pork products will remain a potential source of *Salmonella*, which makes proper handling and/or cooking of such meat products essential measures to ensure food safety for the consumer.

4. Antimicrobial resistance in the pork production chain

In recent decades, intensive farming has been frequently associated with the use of antimicrobials. Therefore, AMR is common among microorganisms isolated from food-producing animals, and transmission of these bacteria to humans *via* direct contact or ingestion of derived food products cannot be excluded (FAO et al., 2021). Initially, monitoring of AMR in *Salmonella* isolates from carcasses of fattening pigs and fresh pork was laid down by Commission Implementing Decision 2013/652/EU following Directive 2003/99/EC on the monitoring of zoonoses and zoonotic agents. Antimicrobials to be tested for resistance in *Salmonella* isolates were ampicillin, azithromycin, cefotaxime, ceftazidime, ciprofloxacin, chloramphenicol, colistin, gentamicin, meropenem, nalidixic acid, sulfamethoxazole, tetracycline, tigecycline and trimethoprim. In 2020, Commission Implementing Decision 2020/1729/EU repealed Decision 2013/652/EU, and amikacin was added to the list of antimicrobials included in AMR monitoring. As requested by EU legislation, EUCAST thresholds for resistance are to be followed (EC, 2013; 2020). *Salmonella* isolates of pork origin were found to be resistant to ampicillin, sulfamethoxazole and tetracycline, which have been widely used for years to treat infections in pigs (Lekagul et al., 2019). The average proportion of *Salmonella* isolates from pig carcasses and that were resistant to ampicillin, sulphonamides and tetracyclines was 52.7%, 52.1% and 48.9%, respectively, as reported by 26 MSs in 2018/2019 (EFSA & ECDC, 2021c). According to the categorisation of antibiotic classes for veterinary use by the European Medicines Agency, ampicillin, sulfamethoxazole and tetracycline belong to category D (Prudence) and should be used as first-line treatments, but only when medically needed (EMA, 2020).

Fluoroquinolones and 3rd and 4th generation cephalosporins are categorised as critically important antimicrobials (CIAs) (WHO, 2019) and are used as first-line treatment for invasive salmonellosis in humans. These classes are represented by ciprofloxacin and cefotaxime/ceftazidime, included in the antimicrobial panel for the monitoring of AMR in *Salmonella*. In the EU, isolates from pigs were relatively infrequent (5.8%) resistance to ciprofloxacin or to nalidixic acid (4.5%). The low proportion of nalidixic-acid resistant strains might be due to plasmid-mediated quinolone-resistance mechanisms responsible for resistance to ciprofloxacin only (Lil et al., 2013), as observed in isolates of ST, *S.* Derby and *S.* Brandenburg recovered from pig carcasses in Spain, Croatia and Italy (EFSA & ECDC, 2021c).

Resistances to other CIAs, such as azithromycin, tigecycline and 3rd generation cephalosporins (cefotaxime and ceftazidime) in *Salmonella* isolates from pig carcasses were either not detected or were observed at low proportions (<1.0%). Resistance to colistin (polymyxin E) is of concern because it is used as a last-line treatment in human infections by MDR Gram-negative bacteria (WHO, 2019). In 2018/2019, colistin resistance was found at low proportion (1.8%) in *Salmonella* isolates from pig carcasses (EFSA & ECDC, 2021c).

Another important issue is MDR, i.e., resistance to three or more antimicrobial classes (Magiorakos et al., 2012). MDR *Salmonella* serotypes, due to their resistance to antimicrobial treatments, could rapidly spread among susceptible populations. This was the case for ST phage type DT104 and its rapid global dissemination during the last three decades. ST DT104 is characterised by its resistance to ampicillin, chloramphenicol, streptomycin, sulphonamide and tetracycline (R-Type ACSSuT) along with its capacity to acquire additional resistance to other clinically important antimicrobials (Helms et al., 2005). Data from reporting MSs showed a high proportion (43.3%) of MDR *Salmonella* isolates were recovered from pig carcasses in 2018/2019. On the other hand, 34.7% of *Salmonella* isolates from pigs were completely susceptible to the abovementioned panel of antimicrobials (EFSA & ECDC, 2021c).

AMR data for the serotypes ST, MST and Derby are shown in Table 7. Resistance to ampicillin was extremely common in ST and MST, being reported in 44/49 (89.8%) and 87/89 (97.8%) isolates, respectively. Also, resistance to sulphonamides and tetracycline was extremely widespread, reaching 95.8% (23/24) and 78.7% (37/47) in ST and 95.7% (67/70) and 97.8% (89/91) in MST, respectively. In *S*. Derby isolates, a lower proportion of ampicillin resistance was reported (21.0%; 13/62), but resistance to sulphonamides (83.7%; 41/49) and tetracycline (95.2%; 59/62) was extremely common. In addition, in the European pork production chain, resistance of *Salmonella* to sulfamethoxazole and streptomycin was extremely frequent (64.5% and 81.2% of isolates, respectively). On the contrary, most of the *Salmonella* isolates were sensitive to 3rd generation cephalosporins, colistin and ciprofloxacin.

The implications of our findings are that AMR in *Salmonella* of porcine origin is a crucial issue, especially for those serotypes that are responsible for most of the pork-related human cases of salmonellosis, such as ST and MST.

5. *Salmonella* eradication and control programmes in European countries

EFSA's scientific opinion on a quantitative microbiological risk assessment of *Salmonella* in slaughter and breeder pigs pointed out that the control of *Salmonella* in pigs in the EU is a reasonable objective, and the EU *Salmonella* control strategy in pigs should be continuously evaluated to identify possible improvements (EFSA, 2010).

In the EU, the control of *Salmonella* in the pork production chain is based on several legislative documents.

- Commission Regulation (EU) No 217/2014 of March 7, 2014 amending Regulation (EC) No 2073/2005 as regards *Salmonella* in pig carcasses;
- Directive 2003/99/EC on the monitoring of zoonoses and zoonotic agents;
- Regulation (EC) No. 2160/2003 on the control of *Salmonella* and other specified food-borne zoonotic agents;
- Regulation (EC) No. 2073/2005 on microbiological criteria for foodstuffs.

Of these, Directive 2003/99/EC defines *Salmonella* as a zoonotic agent to be included in the mandatory annual monitoring system where "monitoring" means a system of collecting, analysing and disseminating data on the occurrence of zoonoses and zoonotic agents. Regulation (EC) No 2160/2003 covers the set-up of national *Salmonella* control programmes (NSCPs) for the poultry population as well as for breeding and slaughter pigs to reduce the prevalence of serotypes with public health significance. In the EU the implementation of NSCPs has been set up in a harmonised way for certain poultry species, but not for pigs. For this reason, according to EFSA (2021a), data on *Salmonella* in food, animals and feed (other than those collected for poultry) are not equally monitored because requirements for sampling strategies, sampling methods, analytical tests or reporting are not harmonised among European countries, as extensively reported by Correia-Gomes et al. (2021).

To date, based on *Salmonella* control programmes in the pork production chain, European countries can be divided into three categories: (a) countries that have eradication programmes in place (Sweden, Finland and Norway); (b) countries that have applied *Salmonella* surveillance and control programmes in place to apply a reduction strategy (Denmark, Germany, the Netherlands, Belgium, Ireland, Estonia and the United Kingdom) and; (c) countries that have not yet implemented any *Salmonella* programme at herd level but conform solely to the updated process hygiene criterion on *Salmonella* in pig carcasses. This criterion allows a maximum of three positive carcasses out of 50, as laid down in Regulation EC No 2073/2005 with amendments. Examples of selected group (a) and (b) countries are given to highlight the most important differences between *Salmonella* eradication and control programmes.

First, eradication programmes can be implemented if the *Salmonella*

Table 7
Antimicrobial resistance of *Salmonella* Typhimurium (ST), monophasic *S*. Typhimurium (MST) and *Salmonella* Derby in the European pork production chain originating from included studies (n = 8) from the period of 2000–2020[a].

Serotype		No. of resistant isolates/Total No. of isolates													
		AMP	CTX	CAZ	CIP	COL	ENR	GEN	NAL	SUL	STR	SMX	SXT	TET	TMP
ST	Farm (n = 0)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Slaughter (n = 37)	36/37	0/37	0/13	0/37	0/35	0/12	0/37	0/37	13/13	19/37	14/23	0/12	26/36	5/25
	Retail (n = 12)	8/12	0/12	0/12	0/12	0/1	0/1	0/12	0/11	10/11	12/12	ND	0/1	11/11	8/11
	Total (n = 49)	44/49	0/49	0/25	0/49	0/36	0/13	0/49	0/48	23/24	31/49	14/23	0/13	37/47	13/36
MST	Farm (n = 43)	41/41	ND	ND	ND	ND	ND	16/43	27/43	42/43	43/43	ND	0/43	43/43	ND
	Slaughter (n = 48)	46/48	1/35	0/13	4/27	0/13	11/34	3/48	ND	25/27	47/48	ND	23/48	46/48	ND
	Retail (n = 0)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Total (n = 91)	87/89	1/35	0/13	4/27	0/13	11/34	19/91	27/43	67/70	90/91	–	23/91	89/91	–
Derby	Farm (n = 0)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Slaughter (n = 61)	13/61	0/43	0/30	3/56	0/29	0/26	3/61	3/61	40/48	42/61	6/8	2/44	58/61	8/17
	Retail (n = 1)	0/1	0/1	0/1	0/1	ND	ND	0/1	0/1	1/1	1/1	ND	ND	1/1	0/1
	Total (n = 62)	13/62	0/44	0/31	3/57	0/29	0/26	3/62	3/62	41/49	43/62	6/8	2/44	59/62	8/18
	Total (n = 202)	144/200	2/128	0/69	7/133	0/78	11/73	22/202	30/153	131/143	164/202	20/31	25/148	185/200	21/54

AMP, Ampicillin; CTX, Cefotaxime; CAZ, Ceftazidime;; CIP, Ciprofloxacin; COL, Colistin; ENR, Enrofloxacin; GEN, Gentamicin; NAL, Nalidixic acid; SUL, Sulphonamide; STR, Streptomycin; SMX, Sulfamethoxazole; SXT, Sulfamethoxazole-trimethoprim; TET, Tetracycline; TMP, Trimethoprim.
ND, not done.
[a] Bonardi et al., 2013; Bonardi et al., 2016; Cota et al., 2019; Fernandes et al., 2016; Piras et al., 2011; Prendergast et al., 2008; Prendergast et al., 2009; Schwaiger et al., 2012.

prevalence in the pig population is very low, as has been the case in Sweden, Finland and Norway (EFSA, 2009) for more than 30 years. As an example, in Sweden, the eradication programme starts with surveillance of breeding herds, which are tested annually and should be free of *Salmonella* in faeces. In positive farms, animal movement is forbidden and partial depopulation is enforced, together with feed testing, manure management, cleaning and disinfection. In addition, the *Salmonella* control programme for pig feed production appears to be crucial for protecting the pig herds. Typically *Salmonella* feed control programmes include monitoring of the raw materials, heat treatment of the feed and monitoring of critical control points in the feed plant on the clean side after processing. Finding *Salmonella* on the clean side mandates mitigation actions, e.g., reprocessing before the feed is permitted to be fed to pigs (Wierup & Häggblom, 2010). At slaughter, surveillance includes *Salmonella* testing of lymph nodes and carcasses, withdrawal of contaminated products and environmental testing (Sundström et al., 2014). In 2020, Sweden reported only three *Salmonella*-positive pig carcasses out of 6757 official samples (0.04%), thus confirming a prevalence close to negligible. In 2020, Finland and Norway reported no positive results in 6197 carcasses (0.0%) and one positive carcasses of 3010 (0.03%), respectively (EFSA and ECDC, 2021b).

Since most European countries have a non-negligible prevalence of *Salmonella* in pig herds, eradication cannot easily be the selected option. In those countries, risk-reduction surveillance and control programmes could be successfully developed. In Denmark, for example, the *Salmonella* control programme was initially based on testing of meat samples, which began in 1993 (Alban et al., 2012). Next, serology testing at herd level was initiated in breeding multiplier and finishing herds (Alban et al., 2012; Bager & Halgaard, 2002). Later, it was understood that all efforts undertaken pre-harvest could be wasted if there was not sufficient focus on hygiene during slaughter and cooling (Alban & Stärk, 2005). Moreover, *Salmonella* control at slaughter would be more cost-effective than at the herd level, where surveillance is still maintained (Alban et al., 2012). Meat-juice samples taken from finisher pigs are used for identifying herds with a high risk for *Salmonella.* A weighted prevalence for each herd is calculated monthly, based on detection of the quantitative amounts of *Salmonella* antibodies in meat-juice from carcasses. Hereby, all finisher herds are allocated one of three levels: Level 1 (no or few reactors, corresponding to a weighted prevalence <40%), Level 2 (higher proportion of reactors; 40–65% positives) or Level 3 (>65% positives, which is considered unacceptable). Level 1 farms need no intervention, while Level 2 and Level 3 farms incur penalties that act as an incentive to reduce *Salmonella* prevalences in their herds (Alban et al., 2012). At the slaughter level, there is a constant and strict focus on hygiene. In abattoirs, five carcasses are swabbed on four predilection sites, each covering 100 cm^2. These five swabs are analysed as one pooled sample while correcting for the loss of sensitivity (Alban et al., 2012). The results are evaluated by the individual plant in two rolling windows, one including 11 days of slaughter, the other including the last 12 months. If predefined limits are exceeded, actions must be taken at the plant. In 2020, the prevalence of *Salmonella*-positive pig carcasses in Danish abattoirs was 0.90% (95% CI: 0.73–1.1) (EFSA and ECDC, 2021b). This low prevalenceIt confirmed the effectiveness of the control programme, which targeted a prevalence of 1% and includes strict hygiene measures during slaughter and meat processing.

A different *Salmonella* control programme based on target serotypes was implemented in Estonia. Control measures at farm/herd level are applied if any *Salmonella* serotype is detected, but restrictions are applied only when target *Salmonella* serotypes are detected. The Estonian NSCP covers farms, abattoirs and meat-cutting plants. At the farm level, approximately 1/5 of the pig herds are examined annually according to a risk-based approach. Among annually selected herds, microbiological testing of pooled faecal samples from each batch of fattening pigs and individual faecal samples collected in breeding herds are tested for *Salmonella*. Restrictions at the farm level are imposed only when the specified *Salmonella* serotypes are detected, which are listed in Regulation no. 72 on rules of eradication of salmonellosis (Riigi Teataja, 2021). These serotypes were selected based on their importance for human health and due to them being the main salmonellosis agents in pigs. The sampling scheme ensures herds with a *Salmonella* infection prevalence of 20% will be detected with 95% confidence. The economic aspects of the Estonian *Salmonella* control programme have not been thoroughly analysed. However, Estonia reported only five positive carcasses of 1538 (0.33%) in 2020 (EFSA and ECDC, 2021b).

Apart from the NSCP being used to reduce *Salmonella* prevalence at farm/herd level, countries that apply NSCPs for categorisation of farms can include this data in the food chain information (FCI). The data are then used by risk managers to plan logistic slaughter by slaughtering the pigs from high-risk herds last, while farmers use them to implement *Salmonella*-reducing measures (e.g. optimising biosecurity, intensifying rodent control, using *Salmonella*-free feed, acidifying feed and/or drinking water, vaccinating sows and piglets) (QS, 2022).

Data from some countries with no NSCPs showed higher prevalences of *Salmonella* on pig carcasses. As reported by EFSA and ECDC (2021b), this was the case in Spain (14.3% from official samples; 6.5% from FBOs' own-check samples).

The experience obtained by the Danish programme could be used to develop and implement control programmes and risk-mitigating measures in all European countries for reducing (not eradicating) *Salmonella* prevalence in the pork production chain (Alban et al., 2012). *Salmonella* contamination of carcasses is a key parameter in food safety and, therefore, is used to measure the effectiveness of process hygiene of the abattoirs. Since a limited prevalence of *Salmonella* in pigs might be sufficient to contaminate the production line at the abattoir, actions need to be implemented also at the harvest and post-harvest stages, otherwise any action taken pre-harvest might be wasted (Alban et al., 2005). It is essential to focus on high hygiene standards during slaughter and cooling to reduce the occurrence of cross-contamination, which has an impact on prevalences of all *Salmonella* serotypes in pork (Alban & Stärk, 2005). Also EFSA's scientific opinion (EFSA, 2010) states that reduction by two logs of *Salmonella* numbers on contaminated carcasses would result in more than a 90% reduction in the number of human salmonellosis cases attributable to pig meat consumption.

6. Future trends and recommendations in *salmonella* control

Salmonella was assessed as a high-risk hazard within the revision of pig meat inspection (EFSA, 2011a). In 2014, the work by EFSA led to a tightening of the *Salmonella* process criterion for pig carcasses from previously allowing five out of 50 positives to only allowing three out of 50 (Regulation (EU) 217/2014). Nevertheless, pork remains a major risk for this hazard despite the strengthening of the microbiological criterion and controls in some European countries (EFSA & ECDC, 2021b). It is expected that *Salmonella* will continue to present a risk for pork consumers in the future and that pork will continue to be among the main sources of human salmonellosis.

Therefore, to tackle *Salmonella* as well as other important pork borne hazards (such as *Yersinia enterocolitica*), a holistic form of controls is needed. This could be assured through the development and introduction of a risk-based meat safety assurance system (RB-MSAS) that is longitudinally integrated and focused on these priority hazards with an aim of overall risk reduction (Blagojevic et al., 2021). A generic framework of the system has been presented by EFSA (2011a). The RB-MSAS's main elements include risk categorisations of the farms and abattoirs, FCI and hazard-specific harmonised epidemiological indicators (HEIs) (EFSA, 2011b). HEIs serve to help risk categorisations and to meet the targets in chilled pig carcasses. The system is planned to be coordinated by risk managers in charge of balancing preventive and reactive control measures to achieve the targets set by the authorities. For example, if *Salmonella* is highly prevalent on a farm or group of farms, the focus will be on pre-harvest interventions; this will apply, in particular, if the number of farms involved is not too large. If *Salmonella* is prevalent on dressed carcasses, harvest-level interventions will be applied. However, to decrease the *Salmonella* prevalence in pork most efficiently, fit-for-purpose pre-harvest, harvest and post-harvest measures will be implemented (Alban & Stärk, 2005). The robust monitoring system is a prerequisite for RB-MSAS to properly function and to enable assessment of its efficacy.

RB-MSAS is still in its development or early implementation phase in Europe, with significant differences in control measures applied among the countries (Antunovic et al., 2021). Some challenges in RB-MSAS's full development and implementation have already been experienced, e.g., an inadequate FCI system that still fails to make use of the HEIs (Bonardi et al., 2021). RB-MSAS provides an opportunity to further improve and, to a certain extent, harmonise monitoring and surveillance systems that are already in place in some European countries, so future *Salmonella* controls are expected to lie within this new meat safety system.

7. Conclusions

For many years, ST, MST and *S.* Derby have been reported as the most prevalent *Salmonella* serotypes in the pork production chain in Europe, with an increasing trend concerning MST. There are relatively big differences in the prevalence of *Salmonella* in the pig chain between European countries, with the tendency of lower *Salmonella* prevalences in countries that apply *Salmonella* control programmes. This noticeable trend is demonstrative of the importance and usefulness of the *Salmonella* control measures in the pork production chain for the overall reduction of human salmonellosis cases in Europe. More effective *Salmonella* control programmes at pre-harvest (including control in feed), harvest and post-harvest levels of the pork production chain are needed. In countries with a high prevalence of *Salmonella* in pigs, measures both at harvest and post-harvest levels are crucial for reducing the incidence of this zoonotic disease in humans. In conclusion, there is need for *Salmonella* surveillance and control programmes in all European countries. In our opinion, in the pork production chain, a strategy using combinations of several complementing control measures that are fit-for-purpose and adapted to local epidemiological situations can deliver acceptable consumer protection.

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Declarations of interest

L.A. works for an organisation that gives advice to farmers and meat producing industries.

Author contribution

M.R.: conceptualisation, writing and revision; S.B.: writing and general supervision; M.M.: conceptualisation, data processing and writing; L.A.: data, writing and supervision; E.G.-N.: data and writing; M.V.-P.: data and writing; I.V.: data, writing and revision; T.E. data and writing; L.L.L. data and revision; B.B.: writing, general supervision and leading of the project.

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