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Review

Food safety incidents in the red meat industry: A review of foodborne disease outbreaks linked to the consumption of red meat and its products, 1991 to 2021

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ABSTRACT

Red meat is a significant source of human nutrition, and the red meat industry contributes to the economy of nations. Nonetheless, there is a widespread global concern about public health issues posed by severe food safety incidents within the red meat industry. Most of these incidents are associated with foodborne disease outbreaks that impact individual consumers, food businesses and society. This study adopts a systematic search and review approach to identify three decades of published investigation reports of global foodborne disease outbreaks linked with the consumption of red meat and products made from them. The review aims to evaluate the critical features of these outbreak incidents to get insight into their contributing factors and root causes. In particular, this review discusses the transmission setting (origin of pathogenic agents), the food vehicles mostly incriminated, the causative pathogens (bacteria, viruses, and parasites) causing the most illnesses, and the most commonly reported contributing factors to the outbreaks. This information can help researchers and food business operators (FBOs) inform future risk assessment studies and support risk management activities in developing risk-mitigating strategies for the industry. Findings from this study suggest that implementing food safety management strategies which include adequate control measures at all stages of the food chain, from farm to fork, is imperative in preventing outbreak incidents. Of equal importance is the need for enhanced and sustained public education about the risk of foodborne illnesses associated with meat and its products whilst discouraging the consumption of raw meat products, especially by high-risk groups.

1. Introduction

1.1. Background

Food safety incidents within the red meat industry pose a severe threat to public health as they continue to be a widespread concern globally (Shang and Tonsor, 2017). These could be in the form of food contamination, which predominantly occurs during processing, distribution, retail, or catering (FSA, 2020), and could potentially lead to foodborne disease outbreak(s) from where these incidents are identified.

Food safety incidents could potentially lead to a food product being withdrawn or recalled and enforcement action taken at the implicated food establishment(s) following investigation and intelligence information from responsible authorities (Robertson et al., 2016). A single food safety incident, such as a foodborne disease outbreak, can have very grievous consequences, with losses of lives and businesses (Hussain and Dawson, 2013). Most of the serious food safety issues resulting in consumer health problems and costly product withdrawals and recalls from the food supply chain of potentially contaminated meat products are associated with microbial hazards, especially bacterial pathogens (Sofos, 2008). Although various foods can serve as sources of foodborne illness, the literature suggests that meat and meat products are important sources of human infections (Nørrung et al., 2009). Several studies on outbreak investigations have reported red meat, such as beef, pork and products derived from them, as the culprit (Bélanger et al., 2015; Bryan, 1980; Jeffer et al., 2021; Omer et al., 2018).

For example, The US Department of Agriculture's Food Safety and Inspection Service (FSIS) investigated foodborne illness outbreaks associated with its regulated products – meat and poultry – from 2007 through 2012. From the investigation, 163 outbreaks were identified, associated with 4132 illnesses, 772 hospitalisations, and 19 deaths. Further, the report revealed that 105 outbreaks were linked to raw beef

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products sold commercially (Robertson et al., 2016). Similarly, the Centres for Disease Control and Prevention (CDC) reports that an estimated 48 million people get sick, 128,000 hospitalisations, and 3000 deaths occur every year nationwide in the USA from foodborne illnesses, most of which are related to the consumption of meat and meat products (CDC, 2011).

In 2012, Alberta Health Services, Canada, reported an *Escherichia coli* O157:H7 infection outbreak linked to the consumption of needle-tenderised beef steaks produced with beef from a meat plant in Alberta and purchased at a store in Edmonton, Alberta (Helmuth et al., 2019). Consequently, a staggering 4000 tons of beef products were recalled to control the outbreak, thus, making it the largest beef recall in Canadian history (Helmuth et al., 2019).

Another study reports that about 1060 people had become ill, and 216 died, between 2017 and 2018, in the largest recorded *Listeria monocytogenes* ST6 outbreak linked to the consumption of processed meat products from one of the largest food companies in South Africa - Tiger Brands. This food safety incident's impact was catastrophic, resulting in a significant reduction in consumer confidence in South Africa (Smith et al., 2019).

The aftermath of these incidents has a broader socio-economic impact beyond affected consumers. The financial costs to the food industry and state economy also can be substantial, particularly when product recalls, trade restrictions, litigations, and lost market share result from large-scale outbreaks (Limon et al., 2020). This fact was corroborated by another study that concludes that the estimated cost of food safety incidents for the economy of the United States is around $7 billion per year derived from consumer notifications, removal of food from shelves, and payment of damages as a result of lawsuits (Hussain and Dawson, 2013).

It is noteworthy that not all food safety incidents result in disease outbreaks. However, the key is that there have to be concerns or risks about the food product's safety that may require intervention to protect consumers' interests. These concerns could be actual, potential, or perceived risks of illness associated with consuming food (FSANZ, 2021). For example, a meat slaughter and cutting establishment in the North of the UK was prosecuted and handed fines and costs totalling £266,000. The prosecution was occasioned by an incident in the plant where the Food Standard Agency (FSA) identified failings by the food business operator (FBO) to ensure the removal of specified parts of the animals, required by law, referred to as "Specified Risk Material (SRM)" (FSA, 2019).

In a similar event, another meat processing plant based in the Midlands in the UK was prosecuted and fined over £250,000. The food safety incident, in this case, involved the FBO removing meat that the FSA previously detained on suspicion of risk of contamination with the potential of the meat being injurious to health (FSA, 2019).

Given the severe consequences of food safety incidents associated with red meat and its impact on individuals, businesses and the wider society, it is imperative to get insight into the contributing factors and root causes of these incidents to aid in developing risk-mitigating strategies and countermeasures. However, this study focuses on foodborne disease outbreaks, although many diffuse foodborne diseases also exist. Thus, this study was conducted as a comprehensive review of published investigation reports and officially reported global foodborne disease outbreak incidents linked with the consumption of red meat and its products to evaluate the critical features and associated consequences of these outbreak incidents in the red meat industry.

The review highlights the food vehicles and related animal species mostly incriminated in the outbreaks, the foodborne pathogens (bacteria, viruses, and parasites) causing the most illnesses and identifies contributing factors to these outbreaks. Furthermore, this review strives to help researchers and FBOs, through this information, to inform future risk assessment studies and support risk management activities to prevent future outbreaks and protects public health and enhance food safety.

2. Materials and method

2.1. General approach

This study adopted a "systematic search and review" methodology to search peer-reviewed literature from four journal databases (Ebsco-Food Science Source, Google Scholar, PubMed, and Web of Science) to identify and summarise published reports of global outbreaks of foodborne disease linked to the consumption of red meat and their products, from 1991 to 2021. Two official websites, the Centers for Disease Control and Prevention and the European Centers for Disease Control and Prevention websites were reviewed. A total of 24,995 foodborne disease outbreaks related to different foods presented in summary reports from 1991 to 2020 were screened from these sites to identify 1628 outbreaks linked to red meat and its products. On the other hand, to extract data from the journal article databases, a review protocol was created outlining the search strategy, screening, selection criteria, and data extraction process.

2.1.1. Search strategy

A six-step measure adopted from Rasmussen University Learning & Library Services (2018) was applied to achieve this:

2.1.1.1. Extraction of the main ideas – identification of keywords. Firstly, the search string was started by identifying the concepts and keywords central to the title or review statement: Food Safety Incidents, Red Meat, and Consumption were the key concepts of focus.

2.1.1.1.1. Creation of a search menu. Brainstorming a list of synonyms and related words to the key concepts was undertaken and subsequently added to the corresponding concepts row to create a search menu:

Concept 1: Food Safety Incident (Outbreak, foodborne disease, foodborne illness).

Concept 2: Red Meat (Beef; beef product, meat product, ham, burger, beef carcase, pork product, cattle, sheep, bovine).

Concept 3: Consumption (Intake; eat, ate, linked, associated).

Several search strings were created by linking concepts and synonyms with the Boolean logic operator. For example, ((“outbreak”) AND (“consumption” OR “link*” OR “associated”) AND (“meat” OR “beef” OR “ham” OR “goat” OR “sheep” OR “pork” OR “cow” OR “boar”) NOT (“poultry” OR “fish” OR “vegetable”)); ((“foodborne disease”) AND (“consumption” OR “link*” OR “associated”) AND (“meat” OR “beef” OR “ham” OR “goat” OR “sheep” OR “pork” OR “cow” OR “boar”) NOT (“poultry” OR “fish” OR “vegetable”)); ((“outbreak”) AND (“consumption” OR “link*” OR “associated”) AND (“meat” OR “beef” OR “ham” OR “goat” OR “sheep” OR “pork” OR “cow” OR “boar”) NOT (“poultry” OR “fish” OR “vegetable”)); ((“foodborne illness*”) AND (“consumption” OR “link*” OR “associated”) AND (“meat” OR “beef” OR “ham” OR “goat” OR “sheep” OR “pork” OR “cow” OR “boar”) NOT (“poultry” OR “fish” OR “vegetable”)).

The following filters/limiters were also applied to the databases:

- Full text included
- Abstract included
- Scholarly (peer-reviewed) journals
- Publication date: Between 1991 and 2021

The searches resulted in 349 hits for Ebsco-Food Science Source, 90 for Google Scholar, 618 for PubMed, and 775 for Web of Science. Journal articles retrieved by the search string were then exported from the databases and imported into Endnote X9 citation management software, where duplicate publications were identified and removed using the “find duplicates” function.

2.1.2. Relevance screening

After duplicate removal, the selected articles were exported from Endnote X9 citation management software and imported into Rayyan systematic review software to facilitate screening.

The titles were first reviewed in the screening process to check if selected articles were appropriate, and then all abstracts were screened for relevance. The initial screening of the title and abstract was based upon one key question: "Does the abstract investigate foodborne outbreak(s) associated with the consumption of red meat and products made from them?". Full texts of the relevant articles were further screened to satisfy the inclusion and exclusion criteria (Table 1).

2.1.3. Data extraction process

Data extraction was conducted on all selected articles that satisfied the predefined inclusion and exclusion criteria. The outbreak details were entered into a Microsoft Excel 2013 spreadsheet for review before data analysis. Data fields of interest extracted from the selected articles (data set) for further analysis include the following: The year the outbreak incident occurred; the country where it happened; the setting or place associated with the outbreak; the causative pathogen (aetiology); incriminated meat types and their products; the number of cases (people ill); the number of hospitalisations; deaths; cases/patients with Haemolytic Uraemic Syndromes (HUS); contributory factors.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed in reporting the methods and results of this review (Fig. 1). However, the researchers did not conduct a meta-analysis as the study's focus was to summarise critical features of foodborne disease outbreaks. Meta-analysis is mainly conducted on randomised controlled trials (RCTs) or intervention studies (EFSA, 2010; Uetani et al., 2009).

3. Results

Table 2 presents key features of the review of journal databases and official websites. In contrast, Table 3 shows the descriptive summary and citation list of each investigated outbreak reported in selected journal articles from the databases. The data sources from the official sites were summary reports without details of specific incidents (CDC, 2022a; ECDC, 2022a, 2022b).

3.1. Transmission setting

Table 4 presents the classification of transmission settings associated with foodborne disease outbreaks reported in the scientific literature. Of the 101 outbreak incidents, most were linked to meat processing establishments, 42(42.4 %), followed by household settings, 25(24.9 %), which resulted in 67.4 % of the total outbreaks reported. The remaining 32.7 % of the outbreak incidents occurred in the other reported five categories of establishments.

Table 1
Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Language: English	Language: Any language other than English.
Product: The outbreak must be linked to the consumption of red meat and its products.	Product: The outbreak was linked to the consumption of poultry, fish, vegetable (s) or products other than red meat and its products.
Study type: Full outbreak investigation with detailed information such as source, food vehicle, aetiology etc. - Adequately described outbreaks of foodborne illnesses.	Study type: Summary studies that lacked sufficient details on individual outbreaks.
Outcome: 2 or more confirmed cases of illness.	Outcome: Single case of illness.

N/B: The outcome is necessary to satisfy the definition of an outbreak, i.e., an incident in which two or more persons experience a similar illness after exposure to a common source.

3.2. Food vehicles

Table 5 presents the proportion of reported outbreaks, illnesses, hospitalisation, and deaths associated with the different meat types/species. Beef and pork were reported as the type/species of red meat most frequently associated with outbreaks, with beef (1077 or 62.35 %) coming first, followed by pork (555 or 32.1 %). This was followed by mixed species of meat (33 or 1.9 %).

Overall, the consumption of beef meat and its products resulted in more illnesses (23,907 or 57.7 %), hospitalisations (5324 or 49.8 %), and deaths (4792 or 47.6 %) than the consumption of pork meat and its products. The consumption of pork meat resulted in 14,977 or 36.1 % illnesses, 4886 or 45.7 % hospitalisations, and 4727 or 47.7 % deaths.

Nevertheless, the ratio beef:pork in number of outbreaks is around 2:1, and this lowers to around 1.5:1 for number of cases, and almost 1:1 for hospitalizations and deaths. Thus, pork appears to cause more cases and more severe disease within an average outbreak.

Table 6 presents a classification of the different food vehicles (products) derived from the different red meat types/species.

3.3. Etiologic agents (foodborne pathogens)

Shown in Table 7 is the proportion of reported outbreaks, illnesses, hospitalisations, and deaths associated with the eighteen foodborne pathogens identified. Most of the outbreaks were reported to be caused by *Salmonella* (469 or 27.1 %), followed by *E. coli* (414 or 23.9 %) and then *Clostridium* (294 or 17 %.). In the same vein, *Salmonella* was associated with more illnesses or outbreak cases (13,469 or 32.5 %), hospitalisations (4349 or 40.7 %) and deaths (3826 or 38 %) than all the other pathogens. This was followed by *E. coli* and *Clostridium*.

Table 8 reveals that *Clostridium* is more associated with beef and its product (209 or 71.1 %) followed by pork (80 or 27.2 %). *E. coli* is also more associated with beef (380 or 91.9 %), followed by pork (12 or 27.2 %), and *Salmonella* is also more associated with beef (244 or 52.5 %).

3.4. Contributing factors

The factors that were contributory to the outbreaks are based on findings from the investigation reports from the scientific literature, as summary data from the official government websites did not give details of individual incidents or causes and hence were not used in the identification of contributory factors. Thus, the findings revealed that most of the outbreak incidents were associated with "Temperature abuse" 71/101(70.3 %), followed by contamination 49/101(48.5 %). The third was "cross-contamination", 40/101(39.6 %) but also, at least one contributory factor was associated with each foodborne disease outbreak.

4. Discussion

With a systematic search and review methodology, this study identified the contributing factors and critical features of foodborne disease outbreak incidents published in technical journals and official websites associated with the consumption of red meat and products made from them. Most of the elements have been identified in previous studies to cause foodborne disease outbreaks linked to other foods that are not red meat. However, to the best of the researchers' knowledge, this study is the first to undertake a comprehensive review of foodborne disease outbreaks associated with the consumption of red meat and its products from a global standpoint.

Available data revealed that the 1729 outbreaks identified over the 30-year period under review resulted in 41,438 illnesses (outbreak cases), 10,691 hospitalisations, and 10,063 deaths. This indicates that about 5 outbreaks, 115 illnesses, 30 hospitalisations and 28 deaths

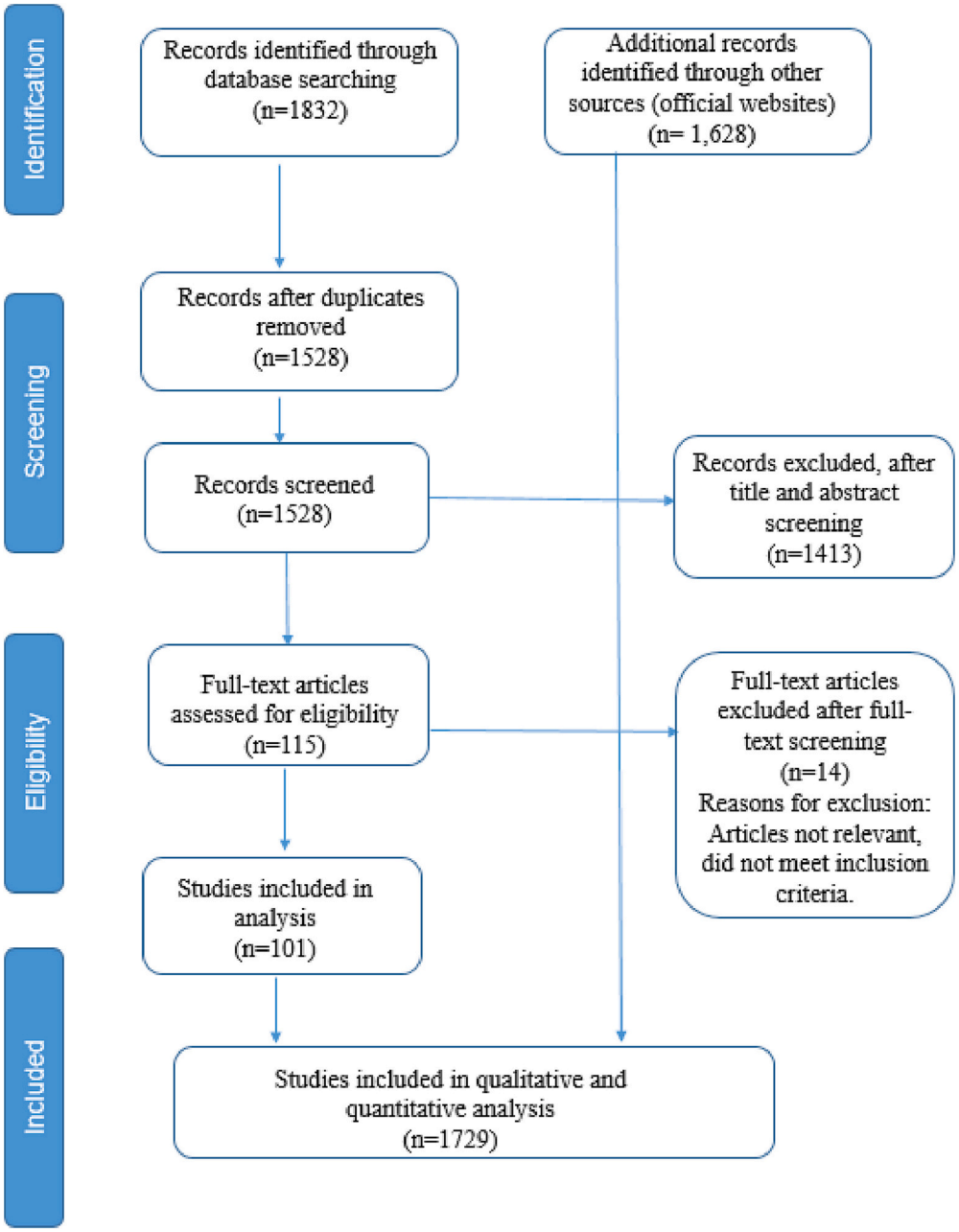

Fig. 1. PRISMA flow chart detailing article screening and selection through the systematic search and review process.

Table 2
Summary of key features of the outbreaks reported over three decades.

Key features	Database	Official site	Total
Outbreaks	101	1628	1729
Illnesses (outbreak cases)	6800	34,638	41,438
Hospitalisations	909	9782	10,691
Deaths	254	9809	10,063
Cases with HUS	91		
Minimum median age	2 yrs		
Maximum median age	89 yrs		

occurred each month. These figures are of course indicative as it could have been more, probably due to underreporting. The reported median age of outbreak cases ranged from 2 yrs to 89 yrs, indicating that there is no age limit for contracting foodborne illness.

4.1. Transmission setting or origin of infective agent (pathogens)

The place or setting where meat and its products were contaminated, pathogens survived and proliferated differed in each outbreak. These settings are categorised in Table 4. Reports highlight how meat and its product are either mishandled or mistreated in the cause of processing and or preparation, thus, resulting in an outbreak incident.

The findings of this study revealed that most of the reported outbreaks were linked to meat processing establishments followed by household settings. This reflects the potential risk posed by meat processing establishments. The peculiarity of the nature of operations within meat slaughter and processing establishments is no doubt a factor. Poor environmental hygiene, GMP, and bio-security measures within meat abattoirs are significant risk factors (Butt et al., 2021).

The most significant risk to meat safety within meat establishments is the presence of enteropathogenic bacteria capable of causing disease in the intestines or gastrointestinal tract of food-producing animals, which

Table 3
Descriptive summary and citation list of each investigated outbreak report.

Year	Location	Setting	Etiologic agent	Food incriminated	Type of meat	Contributory factors	No. of cases	Median age	Hospitalisation	Deaths	HUS cases	Recall	Reference
1993	Switzerland	Food manufacturing establishment	*Salmonella* Braenderup	Meat pies	Beef	Contamination; Poor GMP; Poor hygiene practices; Cross-contamination.	156	32	6	0	NA.	No	Urfer et al. (2000)
1995	Australia	Church dinner	*Salmonella Typhimurium*	Roast pork meat	Pork	Temperature abuse; Cross-contamination	22	22	1	0	NA.	No	Delpech et al., 1998
1998	Canada	Church Supper	*Trichinella*	Bear Burger	Bear	Temperature abuse	8	NA	0	0	NA.	No	Nelson et al., 2003
1999	USA	Restaurant	*E. coli* O157:H7	Beef Tacos	Beef	Temperature abuse	13	12	5	0	3	No	Jay et al. (2004)
1999	USA	Meat processing establishment	*L. monocytogenes*	Fankfurters and deli meats	Pork	Contamination; Temperature abuse	108	NA	0	14	0	Yes	Mead et al. (2006)
2001	Denmark	Household setting	*Trichinella*	Walrus and Polar bear meat	Bear	Contamination; Temperature abuse	6	NA	0	0	0	No	Møller et al. (2005)
2001	Spain	Meat slaughter/ cutting establishment	*Trichinella*	Domestic pig meat	Pork	Contamination; Temperature abuse	26	NA	0	0	0	No	Cortés-Blanco et al. (2002)
2001	Slovakia	Household setting	*Trichinella spiralis*	Pork meat	Pork	Contamination; Poor Hygiene practices; Temperature abuse	23	34.4	6	0	o	No	Reiterova et al. (2007)
2001	Germany	Meat processing establishment	*Salmonella* Muenchen	Pork meat	Pork	Contamination; Poor hygiene practices; Temperature abuse	198	NA	NA	NA	NA	No	Buchholz et al. (2005)
2001	Germany	Meat processing establishment	*Salmonella* Goldcoast	Fermented Sausage	Pork	Poor GMP; Cross-contamination.	44	54	NA.	NA	NA	No	Bremer et al. (2004)
2001	USA	Restaurant	*Salmonella* Uganda	Roast pork meat	Pork	Poor hygiene practices; Cross-contamination	24	NA.	NA	NA	NA	No	Jones et al. (2004)
2002	Canada	Household setting	*Trichinella*	Bear meat	Bear	Contamination; Temperature abuse	71	42	5	0	0	No	Schellenberg et al., 2003
2002	USA	Meat cutting establishment	*E. coli* O157:H7	Beef burger	Beef	Contamination; Cross-contamination; Poor hygiene practices; Temperature control.	9	14	3	0	3	Yes	Vogt and Dippold (2005)
2002	Sweden	Meat processing establishment	*E. coli* O157:H7	Fermented Sausage	Beef	Poor GMP; Temperature abuse	39	14	NA	NA	12	No	Sartz et al. (2008)
2002	USA	Meat processing establishment	*E. coli* O157:H7	Ground beef	Beef	Contamination; Temperature abuse	18	15	7	0	5	Yes	CDC (2002)
2003	New Zealand	Household setting	*Campylobacter jejuni*	Pre-cooked cocktail sausages	Pork	Temperature abuse; Cross-contamination	3	NA	0	0	0	No	Graham et al. (2005)
2003	USA	Meat processing establishment	*Salmonella Typhimurium*	Ground beef	Beef	Cross-contamination; temperature abuse	58	49	11	0	0	No	Dechet et al. (2006)
2003	USA	School potluck lunch	*Salmonella Typhimurium*	Ground beef	Beef	Poor food hygiene practice; Cross-contamination; Temperature abuse.	47	8	2	0	0	No	McLaughlin et al. (2006)
2004	Italy	Household setting	*Salmonella Typhimurium*	Corallina Salami	Pork	Cross-contamination; Poor hygiene practice	63	7.5	NA	NA	NA	No	Luzzi et al., 2007
2004	Belgium	Meat cutting establishment	Hepatitis A Virus (HAV)	Raw beef	Beef	Cross-contamination; Poor hygiene practice; Temperature abuse.	269	36.6	0	0	0	No	Robesyn et al. (2009)
2004	Italy	Household setting	*E. coli* O157	Dry fermented Salami	Pork	Contamination	3	29	2	0	0	No	Conedera et al. (2007)
2004	Italy	Meat processing establishment	*E. coli* O157	Salami	Pork	Contamination	2	60	2	0	0	No	Conedera et al. (2007)
2005	The Netherlands	Mobile food caterers	*Salmonella Typhimurium*	Filet américain (Steak tartare)	Beef	Temperature abuse	56	NA	0	0	NA.	No	Kivi et al. (2007)
2005	France	Food manufacturing establishment	*E. coli* O157:H7	Beef burger	Beef	Poor hygiene practices; Cross-contamination; Temperature abuse.	69	5	17	0	17	Yes	King et al. (2009)

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Table 3 (*continued*)

Year	Location	Setting	Etiologic agent	Food incriminated	Type of meat	Contributory factors	No. of cases	Median age	Hospitalisation	Deaths	HUS cases	Recall	Reference
2005	France	Meat slaughter/ cutting establishment	*Salmonella* Manhattan	Cooked pork; minced beef	Mixed species	Contamination; Cross-contamination; Poor hygiene practices.	69	NA	3	0	NA.	No	Noël et al. (2006)
2005	The Netherlands	Household setting	*E. coli* O157:H7	Steak tartare	Beef	Temperature abuse	33	24	7	0	0	No	Doorduyn et al. (2006)
2005	Australia	Household setting	*Salmonella Typhimurium*	Lamb Liver	Lamb	Cross-contamination; Temperature abuse	31	23	0	0	0	No	Hess et al. (2008)
2005	Belgium	Meat slaughter establishment	*Salmonella* Ohio	Raw minced pork	Pork	Poor GMP; Poor hygiene practices; Cross-contamination	60	50	0	0	0	No	Bertrand et al. (2010)
2005	USA	Meat processing establishment	Norovirus	Delicatessen meat	Beef	Poor hygiene practices; Poor GMP; Cross-contamination.	57	NA	NA	0	0	No	Malek et al. (2009)
2005	Denmark	Restaurant	*Salmonella Typhimurium*	Carpaccio (thinly sliced raw fillet of beef)	Beef	Contamination; Temperature abuse	32	NA	11	0	0	Yes	Ethelberg et al. (2007)
2006	Norway	Slaughter/cutting establishment	*E. coli* O103	Cured mutton sausage	Mutton	Poor GMP; Cross-contamination; Poor hygiene; Contamination.	17	NA	14	1	10	No	Schimmer et al. (2008)
2006	Norway	Household setting	*Yersinia enterocolitica*	RTE-Brawn	Pork	Contamination	11	44	4	2	0	No	Grahek-Ogden et al. (2007)
2006	Germany	Meat processing establishment	*L. monocytogenes*	RTE-Scalded pork	Pork	Cross-contamination; Poor hygiene practices.	16	NA	2	0	0	No	Winter et al. (2009)
2007	USA	Chain store butchery	*Salmonella* Newport	Ground beef	Beef	Contamination; Cross-contamination; Poor hygiene practices; Temperature control.	42	41	17	0	0	No	Schneider et al. (2011)
2007	USA	Meat processing establishment	*Salmonella Typhimurium*	RTE Frozen Pot Pies	Beef	Contamination; Temperature abuse	401	20	128	0	0	Yes	CDC (2008)
2007	Denmark	Meat processing establishment	*E. coli* O26:H11	Organic fermented beef sausage	Beef	Poor hygiene practices; Cross-contamination.	20	2	0	0	0	Yes	Ethelberg et al. (2009)
2008	Denmark, Norway and Sweden	Meat slaughter/ cutting establishment	*Salmonella Typhimurium*	Danish pork meat meals, sausages etc.	Pork	Cross-contamination	37	54	0	4	NA.	No	Bruun et al., 2009
2008	Australia	Wine tavern	*L monocytogenes*	Jellied pork	Pork	Cross-contamination; temperature abuse	13	62	4	0	0	No	Pichler et al., 2009
2008	The Netherlands	Household setting	*E. coli* O157:H7	Steak tartare	Beef	Temperature abuse	20	41	7	0	0	No	Jager et al. (2009)
2008	USA	Meat slaughter establishment	*E. coli* O157 (STEC O157)	Ground beef	Beef	Contamination; Poor GMP; Poor hygiene practices; Temperature abuse	99	21	19	0	1	Yes	CDC (2010)
2009	Italy and Hungary	Restaurant	*Salmonella* Goldcoast	Salami Sandwich	Pork	Cross-contamination	79	50	17	2	NA.	No	Scavia et al., 2013
2009	The Netherlands	Household setting	*Salmonella Typhimurium*	Steak tartare	Beef	Temperature abuse	23	17	8	1	0	No	Whelan et al. (2010)
2009	Denmark	Mobile food caterers	*L. monocytogenes*	Beef meat	Beef	Temperature abuse	8	78	0	2	0	No	Smith et al. (2011)
2009	France	Hotel	*Trichinella*	Smoked warthog meat	Warthog	Contamination; Temperature abuse	3	NA	0	0		No	Dupouy-Camet et al. (2009)
2010	France	School Canteen	*Salmonella Typhimurium*	Beef burger	Beef	Contamination; Temperature abuse	554	NA	31	0	0	Yes	Raguenaud et al. (2012)
2010	The Netherlands	Household setting	*Salmonella Typhimurium*	Ossenworst-Raw beef Sausage	Beef	Temperature abuse	90	NA	45	0	0	No	Friesema et al. (2012)
2010	France	Meat processing establishment	*Salmonella Typhimurium*	Dried pork sausage	Pork	Cross-contamination	110	89	20	0	0	Yes	Bone et al. (2010)
2010	USA	School grounds	*E. coli* O157:H7	Venison product	Deer	Temperature abuse	29	NA	2	0	0	No	Rounds et al. (2012)

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Table 3 (*continued*)

Year	Location	Setting	Etiologic agent	Food incriminated	Type of meat	Contributory factors	No. of cases	Median age	Hospitalisation	Deaths	HUS cases	Recall	Reference
2011	France	Meat processing establishment	*E. coli* O157	Frozen beef burger	Beef	Poor hygiene practices; Cross-contamination; Temperature abuse.	18	3	18	0	18	No	King et al. (2014)
2011	USA	Household setting	*Trichinella*	Wild boar meat - Game	Wild Boar	Contamination; Temperature abuse; Poor food safety practice.	6	NA	1	0	0	No	Holzbauer et al. (2014)
2011	Canada	Catering Event	*E. coli* O157:H7	Pork roast	Pork	Contamination; Temperature abuse.	29	31	7	0	0	No	Trotz-Williams et al. (2012)
2011	France	Meat processing establishment	*Salmonella Typhimurium*	Pork sausage	Pork	Poor GMP; Cross-contamination	337	10	0	0	0	Yes	Gossner et al. (2012)
2011	India	Community gathering	*Trichinella*	Roast pork meat	Pork	Temperature abuse	54	NA	0	1	0	No	Sharma et al. (2014)
2011	Denmark	Retail chain (supermarket)	*Salmonella Typhimurium*	RTE meat-Smoked pork tenderloin	Pork	Contamination	22	NA.	NA	NA	NA	Yes	Wójcik et al. (2012)
2012	Norway	Hotel	*Clostridium perfringens*	Beef stew	Beef	Temperature abuse	43	16	0	0	NA.	No	Wahl et al., 2013
2012	England	Food manufacturing establishment	*L. monocytogenes*	Pork pie	Pork	Cross-contamination; Poor hygiene practices; Temperature control.	14	NA	0	0	0	Yes	Awofisayo-okuyelu et al. (2016)
2012	Vietnam	Household setting	*Trichinella*	Raw pork meat	Pork	Contamination; Temperature abuse	24		6	0	0	No	Van de et al. (2012)
2012	Canada	Slaughter/ processing establishment	*E. coli* O157:H7	Ground beef	Beef	Poor GMP; Cross-contamination; Contamination.	18	31	6	0	0	Yes	Currie et al. (2019)
2012	New Zealand	Meat processing establishment	*L. monocytogenes*	RTE meat	Mixed species	Contamination	4	NA	NA	2	NA	No	Rivas et al. (2019)
2012	Serbia	Funeral reception	*Trichinella*	Smoked pork	Pork	Temperature abuse	13	NA	8	0	0	No	Popović-Dragonjić and Kocić (2018)
2012	Belgium	Meat slaughter establishment	*E. coli* O157:H7	Steak tartare	Beef	Contamination; Poor Hygiene practices; Temperature abuse	24	31	15	0	5	No	Braeye et al. (2014)
2013	Scotland	Food manufacturing establishment	*L. monocytogenes*	Steak pie	Beef	Cross-contamination; Poor hygiene; Bad manufacturing practices	3	87	3	0	0	No	Okpo et al., 2015
2013	USA	Meat slaughter/ cutting establishment	*E. coli* O157:H7	Beef burger	Beef	Poor hygiene practices; Poor GMP; Cross-contamination; Temperature abuse.	24	25	8	0	NA.	No	Torso et al. (2015)
2013	France	Wedding event	Hepatitis E Virus (HEV)	Spit-Roasted Piglet	Pork	Contamination; Temperature abuse	17	45	2	0	0	No	Guillois et al. (2016)
2013	Germany	Meat processing establishment	*Trichinella*	Wild boar meat - Game	Wild Boar	Contamination; Poor GMP	21	52	0	0	0	No	Faber et al. (2015).
2013	Germany	Meat cutting establishment	*Salmonella Typhimurium*	Pork sausage, Minced pork	Pork	Contamination; Cross-contamination; Temperature abuse; Poor hygiene practices	61	57	36	0	0	No	Alt et al. (2015)
2013	China	Restaurant	*Clostridium botulinum*	Smoked Pork ribs	Pork	Contamination; Temperature abuse; Poor food safety practices.	12	NA	7	0	0	Yes	Feng et al. (2015)
2013	Germany	Slaughter establishment	*Salmonella* Infantis	Raw minced pork	Pork	Contamination; Poor GMP; Poor hygiene practices; Temperature abuse	267	56	85	0	0	No	Schroeder et al. (2016)
2014	France	Meat processing establishment	*Salmonella Enteritidis*	frozen beef burger	Beef	Contamination; Temperature abuse	45	9	0	0	NA.	Yes	Jones et al. (2016)
2014	Belgium	Restaurant	*Trichinella*	Wild boar meat	Wild Boar	Contamination; Temperature abuse	16	37	10	0	0	Yes	Messiaen et al. (2016)

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Table 3 (*continued*)

Year	Location	Setting	Etiologic agent	Food incriminated	Type of meat	Contributory factors	No. of cases	Median age	Hospitalisation	Deaths	HUS cases	Recall	Reference
2014	Germany	Pig Farm	*Salmonella* Muenchen	Raw pork products, sausages and spreads.	Pork	Poor hygiene practices	247	56	0	0	0	No	Schielke et al. (2017)
2014	Sweden	Meat processing establishment	*L. monocytogenes*	Cold cut ham	Pork	Cross-contamination; Poor hygiene practices	51	77	0	0	0	Yes	Dahl et al. (2017)
2014	Germany	Meat processing establishment	*L. monocytogenes*	RTE Sausage	Pork	Poor GMP; Poor hygiene practices; Cross-contamination	39	73	25	18	0	Yes	Lachmann et al. (2021)
2015	Italy	Food manufacturing establishment	*L. monocytogenes*	Hog head cheese (Processed pork)	Pork	Cross-contamination; Poor hygiene practice	35	75	24	4	0	Yes	Duranti et al., 2018
2015	Spain	Household setting	Hepatitis E Virus (HEV)	Wild boar meat	Wild Boar	Contamination; Temperature abuse	8	NA	0	0	0	No	Rivero-Juarez et al. (2017)
2015	France	Meat slaughter/ cutting establishment	*Trichinella*	Figatelli (pork sausages)	Pork	Contamination; Cross-contamination; Poor hygiene practices.	3	NA	1	0	0	No	Ruetsch et al. (2016)
2015	Scotland	Slaughter/cutting establishment	*E. coli* O157:H7	Venison	Deer	Cross-contamination; Temperature abuse	12	41	0	0	0	No	Smith-Palmer et al. (2018)
2015	England	Meat processing establishment	*E. coli* O157	RTE meat	Mixed species	Cross-contamination; Poor hygiene practices; Temperature control.	15	38	10	0	7	No	Wilson et al. (2018)
2015	USA	Meat slaughter/ cutting establishment	*Salmonella* Infantis	Roaster pork meat	Pork	Contamination; Cross-contamination; Poor GMP; Poor hygiene practices; Temperature control.	192	35	30	0	0	Yes	Kawakami et al. (2019)
2015	The Netherlands	Meat processing establishment	*Salmonella Typhimurium*	Filet américain (raw beef spread)	Beef	Contamination; Temperature abuse	45	21	29	0	0	No	Freidl et al. (2018)
2016	Italy	School Canteen	*L. monocytogenes*	Cooked beef ham	Beef	Cross-contamination; Temperature abuse	162	NA	5	0	0	No	Maurella et al. (2018)
2016	The Netherlands	Meat processing establishment	*Salmonella* Bovismorbificans	Ham	Pork	Contamination	54	65	15	0	0	Yes	Brandwagt et al. (2018)
2016	Japan	Restaurant	*Trichinella T9*	Bear meat meal	Bear	Contamination; Temperature abuse; Poor food safety practice.	21	19	0	0	0	No	Tada et al. (2018)
2016	Serbia	Household setting	*Trichinella britovi*	Wild boar Ham and sausages	Wild Boar	Contamination; Temperature abuse	114	NA	19	0	0	No	Dmitric et al. (2018)
2016	Italy	Household setting	*Trichinella*	Boar meat sausage	Wild Boar	Contamination; Temperature abuse	5	NA	1	0	0	No	Turiac et al. (2017)
2016	Switzerland	Meat processing establishment	*L. monocytogenes*	Meat Pate	Beef	Cross-contamination; Poor GMP; Poor hygiene practices; Temperature abuse	7	84.8	0	0	0	Yes	Althaus et al. (2017)
2016	India	Household setting	*Aeromonas hydrophila*	Carcase meat	Beef	Contamination; Temperature abuse	33	NA.	NA	NA	NA	No	Tsheten et al. (2016)
2016	Japan	Household setting	*E. coli* O157:H7	Raw minced meat cutlets	Mixed species	Temperature abuse	61	31	24	0	4	Yes	Furukawa et al. (2018)
2016	Canada	Household setting	*Trichinella*	Jerky (dried bear meat)	Bear	Temperature abuse	10	NA	0	0	0	No	Dalcin et al. (2017)
2017	England	Household setting	*E. coli* O157:H7	Frozen beef burger	Beef	Temperature abuse	12	16	8	0	4	Yes	Byrne et al. (2020)
2017	Uganda	Meat slaughter/ cutting establishment	*Anthrax*	Beef meat	Beef	Poor GMP; Poor hygiene practices; Contamination; Temperature abuse	61	NA	0	0	0	No	Nakanwagi et al. (2020)
2017	South Africa	Meat processing establishment	*L monocytogenes*	RTE meat - Polony sausage	Mixed species	Poor GMP; Poor hygiene practices; Contamination; Cross-contamination.	937	NA	2	197	NA	Yes	Thomas et al. (2020)

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Table 3 (*continued*)

Year	Location	Setting	Etiologic agent	Food incriminated	Type of meat	Contributory factors	No. of cases	Median age	Hospitalisation	Deaths	HUS cases	Recall	Reference
2017	USA	Retreat	*Toxoplasma gondii*	Venison - grilled	Deer	Temperature abuse	11	51	0	0	0	No	Schumacher et al. (2021)
2017	USA	House party	*Trichinella*	Raw boar meat	Wild boar	Temperature abuse	36	NA	0	0	0	No	Heaton et al. (2018)
2018	Denmark	Household setting	*Salmonella Typhimurium*	Medister sausage (Raw Danish pork sausage).	Pork	Cross-contamination; temperature abuse	49	66	0	0		No	Helmuth et al., 2019
2018	USA	Meat slaughter/ cutting establishment	*Salmonella* Newport	Beef meat	Beef	Contamination; Poor GMP; Poor hygiene practices; Temperature abuse	255	36	60	2	0	No	Plumb et al. (2019)
2018	Canada	Hunting Retreat	*Toxoplasma gondii*	Venison	Deer	Temperature abuse	6	NA	1	0	0	No	Gaulin et al. (2020)
2019	The Netherlands	Food manufacturing establishment	*L. monocytogenes*	RTE meat products	Mixed species	Cross-contamination; Poor hygiene practices.	21	78	21	3	o	Yes	ECDC-EFSA (2019)
2019	China	Household setting	*Clostridium botulinum*	Vacuum-packed Ham	Pork	Temperature abuse	4	55	4	1	0	No	Min et al. (2021)
2019	The Netherlands	Household setting	*E. coli* O157	Steak tartare	Beef	Temperature abuse	20	41	7	0	0	No	Greenland et al. (2009)
2019	UK.	Retail chain (supermarket)	*E. coli* O157:H7	Raw minced beef	Beef	Contamination; Temperature abuse	13	19	5	0	2	No	Butt et al. (2021)

Table 4
Classification of reported transmission settings associated with foodborne disease outbreak.

Transmission setting	Category
Meat cutting plant, pig farm, red meat abattoir, meat slaughterhouse, fresh meat processing establishment, game meat cutting plant, slaughter/co-located cutting plant, slaughter establishment, retail chain butcher, privately owned meat butchery, local meat butcher store.	Meat processing establishment
Food manufacturing establishment	Food manufacturing establishment
Church supper, church dinner, school canteen, school grounds, school potluck lunch	Institutional establishment
Hotel, restaurant, mobile food caterers, hospital catering	Foodservice establishment
Chain store butchery, retail chain (supermarket)	Retail chain supermarket
Home, house, house party	Household setting (HHS)
Wedding events; catering events; wine tavern; hunting retreats; funeral receptions; community gatherings; family retreats.	Others (OTR)

Table 5
The proportion of outbreaks, illnesses, hospitalisations, and deaths associated with the different meat-types.

Meat species	Outbreak	Illness	Hosp.	Death
	No.	No.	No.	No.
Bear	21	202	30	25
Beef	1077	23,907	5324	4792
Bison	3	76	49	31
Buffalo	2	15	3	3
Deer	4	58	3	0
Goat	6	85	27	27
Lamb	17	261	116	118
Mixed species	33	1620	197	328
Mutton	1	17	14	1
Pork	555	14,977	4886	4727
Warthog	1	3	0	0
Wild Boar	9	217	42	11
Total	**1729**	**41,438**	**10,691**	**10,063**

Table 6
Classification of incriminated food vehicles associated with foodborne disease outbreak incidents.

Incriminated food (meat products) vehicle	Category
Bear Burger, Bear meat, Beef burger, Beef meat, Boar meat sausage, Carcase meat, Carpaccio (thinly sliced raw fillet of beef), Domestic pig meat, Filet américain (raw beef spread), Ground beef, Lamb Liver, Medister sausage (Raw Danish pork sausage), minced beef, Minced pork, Ossenworst-Raw beef Sausage, Pork meat, Pork sausage, Raw beef, Raw boar meat. Raw minced beef, Raw minced pork, Raw pork meat, Roaster pork meat, sausages and spreads, Steak tartare, Venison, Walrus and Polar bear meat, Wild boar Ham and sausages, Wild boar meat	Freshly processed meat products (FPM)
Corallina Salami, cured mutton sausage, Delicatessen meat, Dried pork sausage, Dry fermented Salami, Fermented Sausage, Figatelli (pork sausages), Frankfurters and deli meats, Jerky (dried bear meat) Meat Pate, Organic fermented beef sausage, RTE-Brawn, RTE-meat products, RTE-Polony sausage, RTE-Scalded pork, RTE-Smoked pork tenderloin, Salami Sandwich, Smoked pork	Ready-to-eat meat products (RTEM)
Beef stew, Beef Tacos, Cold cut ham, cooked beef ham, Frozen Pot Pies, Grilled venison, Hog head cheese (processed Pork), Jellied pork, Meat pies, Pork pie, Pork roast, Pre-cooked cocktail sausages, Roast pork meat, Smoked pork ribs, smoked warthog meat, Spit-Roasted Piglet, Steak pie, vacuum-packed ham	Cooked meat/meal products (CMM)

Table 7
The proportion of outbreaks, illnesses, hospitalisation, and deaths caused by etiologic agents.

etiologic agent	Outbreak	Illnesses	Hospitals	Deaths
	No	No	No	No
Aeromonas hydrophila	1	33	0	0
Anthrax	1	61	0	0
Bacillus cereus	51	692	279	279
Campylobacter jejuni	15	261	44	42
Clostridium	294	11,071	2762	2843
E. coli	414	4953	1092	791
Enterobacter	2	30	0	0
Hepatitis E Virus	1	269	0	0
Hepatitis E Virus	2	25	2	240
Listeria monocytogenes	120	3106	627	530
Norovirus	144	3067	429	442
Salmonella	469	13,469	4349	3826
Sapovirus	1	22	22	22
Shigella	7	173	0	0
Staphylococcus	134	3048	652	662
Toxoplasma gondii	2	17	1	0
Trichenella	55	953	426	382
Yersinia	16	188	6	4
Total	**1729**	**41,438**	**10,691**	**10,063**

renders them symptomless carriers of foodborne diseases among livestock presented for slaughter (Lianou et al., 2017). For instance, some meat-borne pathogens (such as *Salmonella*, *Campylobacter*, *E. coli* O157: H7, and *Yersinia*) live in the intestine of animals that frequently and easily contaminate meat (DeWaal et al., 2006). Some of these pathogens are found on the skins of animals, potentially causing cross-contamination of meat and the environment (Antic et al., 2021). In addition to the skin, the gastrointestinal and respiratory tracts, urine, and milk duct are other vital sources of infection (Nel et al., 2004).

Contamination of meat can also occur during processing at abattoirs, particularly during evisceration, where gut contents are likely to contaminate exposed meat if incorrect techniques are applied (noted from the researcher's professional experience). However, the literature reveals that carcase contamination during beef slaughter and processing mostly occurs during dehiding and skinning (Antic et al., 2021; Kennedy et al., 2014; McEvoy et al., 2000) and preventing cross-contamination from the hide surface to the carcass is very challenging due to the nature of the hide removal process (McEvoy et al., 2000). Other potential sources of contamination during the dressing of meat carcases include the knives, hands and clothing of workers, processing equipment such as saws, boning tables, conveyors, and water used to wash carcases (Govender et al., 2013). Therefore, it is vital to observe a minimum standard of sanitation and personal hygiene to minimise contamination.

4.2. Food vehicles most incriminated in the outbreaks

For clarity and simplicity, the various types of meats and their products implicated as vehicles of foodborne disease were classified into three broad categories (Table 6). These include freshly processed meat, ready-to-eat meat and cooked meat/meal products (CMM).

Freshly processed meat products are primarily raw meat that requires further processing, in most cases, before consumption. For instance, some freshly processed meat products, such as steak tartar and beef burger, were consumed raw or undercooked, i.e., cooked "medium-rare" (Kivi et al., 2007).

The different ways these foods are processed or prepared can affect how they are contaminated or influence the survival and proliferation of pathogens (Bryan et al., 1997).

Regarding the species or type of meat, the data reveals that beef (1077 or 62.35 %) and pork (555 or 32.1 %) were most frequently associated with outbreaks (Table 5). Thus, beef and pork meat and their products were the most incriminated food vehicles reported during the 30-year period under review. This is partly connected to beef and pork

Table 8
Proportion of etiologic agent associated with meat type/species.

Etiologic agent	Bear	Beef	Bison	Buffalo	Deer	Goat	Lamb	Mixed	Mutton	Pork	Warthog	Wild Boar
	No	No	No	No	No	No	No	No	No	No	No	No
Aeromonas hydrophila	0	1	0	0	0	0	0	0	0	0	0	0
Anthrax	0	1	0	0	0	0	0	0	0	0	0	0
Bacillus cereus	0	36	0	0	0	0	0	0	0	4	0	0
Campylobacter jejuni	0	8	0	0	0	0	0	15	0	6	0	0
Clostridium	0	209	0	0	0	1	0	4	0	80	0	0
E. coli	0	380	3	1	2	1	9	5	1	12	0	0
Enterobacter	0	2	0	0	0	0	0	0	0	0	0	0
Hepatitis A Virus	1	0	0	0	0	0	0	0	0	0	0	0
Hepatitis E Virus	0	0	0	0	0	0	0	0	0	1	0	1
Listeria monocytogenes	0	62	0	0	0	0	0	6	0	50	0	0
Norovirus	0	86	0	0	0	0	0	3	0	58	0	0
Salmonella	0	244	0	0	0	1	8	6	0	207	0	0
Sapovirus	0	0	0	0	0	0	0	0	0	1	0	0
Shigella	0	7	0	0	0	0	0	0	0	6	0	0
Staphylococcus	0	40	0	0	0	0	0	4	0	91	0	0
Toxoplasma gondii	0	0	0	0	2	0	0	0	0	0	0	0
Trichenella	18	0	0	0	0	0	0	0	0	21	1	8
Yersinia	0	0	0	0	0	0	0	0	0	15	0	0

being the most consumed species of red meat globally. According to the FAO (2019), pork is the most widely eaten meat in the world (36 %), followed by poultry (33 %), beef (24 %), and goats/sheep (5 %).

The consumption of beef meat and its products showed to have resulted in more illnesses or outbreak cases (23,907 or 57.7 %), and hospitalisations (5324 or 49.8 %) than the consumption of pork meat and its products.

4.3. Foodborne pathogens (bacteria, viruses, and parasites) causing the most illnesses

Of the eighteen foodborne pathogens identified, *Salmonella*, *E. coli*, and *Clostridium* were reported as the three most common causes of foodborne outbreaks linked to the consumption of red meat and its products, respectively (Table 7).

4.3.1. Etiologic agent vs meat type

Findings in this study regarding etiologic agents associated with meat types/species reveal that specific pathogens are more associated with specific meat types and their products (Table 8). For instance, it was revealed that *Clostridium* was more associated with beef and its product (71.1 %), followed by pork (27.2 %); *E. coli* was also more associated with beef (91.9 %) followed by pork (12 or 27.2 %) and *Salmonella* was also more associated with beef (52.45 %) followed by pork (44.4 %). This knowledge can inform risk management decisions. More so, specific interventions directed at these food categories and their associated pathogens would help prevent or reduce the frequency of foodborne illness outbreaks.

4.3.2. Salmonella

In this analysis, *Salmonella* caused most (469 or 27.1 %) of the outbreaks, with consequent illnesses or outbreak cases of 13,469 or 32.5 %, 4349 or 40.7 % hospitalisations and 3826 or 38 % deaths. In many countries, food poisoning outbreaks caused by *Salmonella* in meat and its products are commonly reported, and *Salmonella* is considered one of the foodborne pathogens of great concern (Plumb et al., 2019). A previous study on an overview of foodborne outbreaks in Canada for 16 years highlighted the importance of *Salmonella* as an etiologic agent of enteric illness as it was the most common pathogen and caused 40.3 % of the outbreaks (Bélanger et al., 2015).

Salmonella is a bacterium that can cause an illness or a zoonotic disease called salmonellosis in humans. In the EU, over 91,000 salmonellosis cases are reported each year (EFSA, 2022). Food-source animals sometimes become infected, or their skin or feet become contaminated on farms. The salmonellae are conveyed to processing plants in or on these animals, usually in faecal material on their feet. These organisms can spread to carcases or cuts of meat during processing. In most cases, when raw or inadequately cooked, these products allow salmonellae to survive and cause foodborne disease outbreaks (Bryan, 1980).

Salmonellosis may result in severe illness; however, the spread of the disease can be controlled by hygienic slaughtering practices and thorough cooking and refrigeration of meat and its products (Braeye et al., 2014).

4.3.3. E. coli

The second-highest number of outbreaks (414), was attributed to *E. coli*, resulting in 4953 illnesses, 1092 hospitalisations and 791 deaths. Like *Salmonella*, *E. coli* is a naturally occurring bacteria commonly found in the gastrointestinal tract of animals, especially cattle (Wahl et al., 2013; Brusa et al., 2022). Most *E. coli* strains are harmless, although Shiga toxin-producing *E. coli* (STEC), the strain most commonly reported in this study, can cause severe and life-threatening foodborne diseases such as haemolytic uraemic syndrome (HUS), thrombocytopenia, renal failure, and occasionally death, especially in children and the elderly (Bélanger et al., 2015; WHO, 2022).

This study shows that 100 % of all the outbreak cases with HUS reported from the scientific literature reviewed were associated with *E. coli* infection, which corroborates relevant literature. For instance, a study conducted by Feitz et al. (2021) reveals that Shiga toxin-producing *E. coli* bacteria infection was implicated to have caused 90 % of childhood haemolytic uraemic syndrome (HUS) cases.

Most of the outbreak investigation reports suggest that *E. coli* infection transmission to consumers occurs through the consumption of raw or undercooked meat (such as minced or ground beef burgers) that had already been contaminated during slaughter and processing in meat processing plants (Duranti et al., 2018). Faecal contamination of carcase meat and cross-contamination from carcases to the hands of operators, equipment, tools and the abattoir environment and from them to other carcases are also risk factors (Costa et al., 2020; Dickson and Acuff, 2017). Thus, good manufacturing/hygiene practices in meat processing establishments should help prevent beef product contamination (Buncic et al., 2014). As STEC is heat-sensitive and destroyed by thorough cooking, meat preparation at home should adhere to basic food safety practices such as “cook thoroughly”.

4.3.4. Clostridium

Clostridium was the third most reported pathogen incriminated in this study, following *E. coli*, however the findings reveal it caused more

illnesses (11071), hospitalisations (2762) and deaths (2843) than *E. coli*. *Clostridium perfringens* are spore-forming bacteria that can survive heat, dryness, and other environmental conditions. *C. perfringens* bacteria are one of the most common causes of food poisoning, with an estimated nearly 1 million foodborne illnesses caused by the bacterium every year in the United States (CDC, 2022b).

Chicken, turkey and red meat (such as beef and pork) are specific foods commonly associated with *C. perfringens* outbreaks. This is especially when they are cooked in large batches and held at unsafe temperatures, which occurs predominantly in settings like schools, hospitals, factories and catering establishments (Bennet et al., 2013).

On the other hand, *Clostridium botulinum* is a bacterium that causes botulism. The bacterium produces heat-resistant endospores which are very resistant to a number of environmental stresses, such as heat and high acid (CDC, 2013). Although the bacteria and spores alone do not cause disease, their production of botulinum toxin renders them pathogenic (Feng et al., 2015).

Foodborne botulism results from the ingestion of preformed botulinum toxin in food. The toxin can be found in food that has not been properly cooked, processed, handled, or canned and is often present in canned food, such as vegetables, meat, and seafood products (CDC, 2013).

4.4. Most reported contributing factors to the outbreaks

Several factors contributed to meat contamination and the survival or proliferation of the etiologic agents in the meat and its products. These factors contributed to the outbreaks' causation and were identified and classified as: contamination, cross-contamination, poor "GMP", poor hygiene practice, temperature abuse, and poor food safety practice. At least one contributory factor was associated with each foodborne disease outbreak. The most reported contributing factor was "Temperature abuse". This result suggests that temperature control is a critical factor in preventing outbreaks.

The findings indicate that it may take more than one contributing factor to cause an outbreak and that all contributing factors may not occur in one establishment. For instance, contamination might have happened in a different setting (e.g., meat processing establishment, food service establishment, retail chain store, etc.), and mishandling that allowed survival or proliferation (e.g., temperature abuse; cross-contamination) might have occurred in another setting in an outbreak incident.

Some of the reported factors that have contributed to outbreaks classed as "temperature abuse" include improper cooling, insufficient temperature or time during cooking, improper hot holding and insufficient temperature or time during reheating of food.

Besides the temperature abuse, contamination was reported at different stages of the production and preparation of meat and its products. Poor standards of hygiene (environment and personal), poor GMP and cross-contamination in meat processing establishments have contributed to and influenced the occurrence of foodborne outbreak incidents. Others were mishandling or mistreatment of meat coupled with a disregard for suitable hygienic measures and a lack of food safety awareness and training of food handlers. These factors contributed to pathogens coming into contact with food and, in some cases, enabling the survival and multiplication of pathogens to cause foodborne disease outbreak incidents.

5. Strengths and limitations

A key strength of this study is its contributions and novelty in undertaking a comprehensive review of factors associated with the consumption of red meat and its products from a global standpoint. This type of review combines the strengths of a critical review with an exhaustive systematic search process which can provide a much more complete picture of the prevalence of the research problem in question (Grant and Booth, 2009). The search was conducted following an organised plan or stipulated set of clearly defined objectives and reproducible methods. Literature reveals several types of systematic reviews that adhere to various guidelines on conducting a review to help standardise them and improve their quality (Kitchenham, 2004; Needleman, 2002).

One crucial aspect that cuts across these guidelines is, assessing the methodological quality of the included studies or considering the validity of the individual studies (Ahn and Kang, 2018; EFSA, 2010; Kitchenham, 2004; Needleman, 2002). However, this review did not undertake a quality assessment of selected outbreak reports as part of the inclusion/exclusion criteria partly because this review does not adhere to a specific systematic review guideline.

Nevertheless, the researchers retrieved the outbreak reports included in this study from peer-reviewed literature, which implies that the journal articles have gone through an evaluation process in which journal editors and other expert scholars critically assessed the quality and validity of the research methodology and procedures. The Peer-review process ensures that the research quality and the findings' validity are high. Besides, the review of official websites ensures data credibility given that government websites provide accurate records of foodborne disease outbreaks.

However, the findings of this study have some limitations. First, reporting and publication bias may have resulted in under-reporting foodborne disease outbreaks in the literature, given that large outbreaks are more likely to be investigated and published. Since the terminology used to describe outbreaks report investigations differed by report, it is possible that outbreak investigation reports that did not explicitly mention the keywords used in the search strings could have been missed in the database searches. However, the robust search strategy adopted for this study was aimed to minimise the number of potentially missed outbreak reports.

Another consideration is that because the search strategy, by design, did not include searches beyond bibliographic databases, such as exploring the grey literature, it might have missed some vital outbreak reports in the grey literature. Further, as English language was one of the inclusion criteria in this study, publications in other languages other than English language might have been missed as well.

6. Conclusion

With a systematic search and transparent review methodology, this review identifies outbreak investigation reports of global foodborne disease associated with red meat consumption for three decades, from 1991 through 2021. The study provided a comprehensive account of the features of the reported outbreaks under review. Eighteen pathogens (of which *Salmonella* was the most reported) were identified from these outbreaks to have caused 1729 outbreaks, 41,438 illnesses, 10,691 hospitalisations, and 10,063 deaths. Besides, these outbreak incidents were reported to have led to product recalls/withdrawals, which are costly to food establishments due to downtime. Beyond affected consumers, these outbreak incidents negatively impact the socio-economy of businesses and countries. It is noteworthy that many of the foodborne diseases reported are diffuse cases. For instance, outbreaks generated due to contamination originating at meat processing establishments have been reported to result in widespread contamination through the supply chain and affected a potentially much greater number of people across geographically distributed locations with a massive public health impact.

Given that a combination of factors can contribute to the same outbreak, preventing outbreak incidents requires approaches or control measures at all stages of the food chain. Thus, implementing robust food safety management strategies from agricultural production on the farm to processing, manufacturing, and preparing foods in all establishments - commercial, institutional and household establishments – is imperative.

Findings from this study have important implications for improving

food safety programmes, setting priorities based on preventive intervention for future outbreaks, and strengthening food safety policies, including risk assessment, especially in the red meat industry. Besides, the data can inform decisions at places and operations where regulations need to be established and enforced and indicate educational and training needs.

Suffice it to say that since the findings indicate meat processing establishments are chiefly implicated as the transmission setting or origin of pathogens, abattoirs have a significant role to play in measures toward the reduction of outbreak incidents in general. However, a shared responsibility of all stakeholders within the food chain: from farm to fork, i.e., farmers, processors, distributors, retailers, caterers, and consumers, all have their part to minimise the risks of food safety incidents.

In a nutshell, to prevent outbreak incidents and tackle food safety challenges faced by the meat industry, the findings of this review highlight the need for a high meat-producing standard which includes maintaining adequate hygiene standards and process controls during the slaughter and processing of animals. The need for adequate information, training and supervision of meat production/handling operatives in safe food handling practices to prevent cross-contamination and proliferation of foodborne pathogens is of equal importance.

The findings also point to the need for enhanced and sustained public education about the risk of foodborne illnesses associated with meat and its products whilst discouraging the consumption of raw meat products, especially by high-risk groups.

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CRediT authorship contribution statement

DW and BO: Conceptualisation of the overarching research goals and aims.

DW and BO: Design of the data search method.

DW: Data Collation and data presentation.

DW and BO: Data analysis and data interpretation.

DW: Preparation and writing of the initial draft.

DW and BO: Structuring of manuscript and critically reviewing the contents.

BO: Supervision; oversight and leadership responsibility for the research activity planning and execution.

BO: Approval to submit the manuscript for publication.

All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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