



Review

Salmonellosis in Cattle: Sources and Risk of Infection, Control, and Prevention

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Simple Summary: Salmonellosis remains a significant public health concern, with animals such as cattle serving as potential sources of infection. The slaughter of infected animals from contaminated farms is a major contributor to human *Salmonella* infections. In this review, the various pathways are explored through which *Salmonella* enters cattle populations and strategies are examined for mitigating or controlling the disease on farms. Ultimately, a comprehensive appeal is made to all stakeholders in cattle production to actively contribute to reducing *Salmonella* infections on farms.

Abstract: Salmonellosis in humans is a public health threat and cattle are important reservoirs for the pathogen. Cattle products such as ground beef have been linked to human salmonellosis outbreaks, and some disease investigations have been traced back to infected animal herds on farms and animal markets as the origin of infection. It is now common to isolate *Salmonella* from many cattle operations as the pathogen once introduced onto a farm can establish an undesirable endemic condition among herds. It is, therefore, essential to adopt measures to mitigate or prevent the introduction and spread of zoonotic disease agents like *Salmonella* in animal populations. With this background, the potential sources and risks of *Salmonella* infection in cattle, the control of already established infection, and other preventative measures are discussed in this article. We conclude that a holistic approach involving all stakeholders in cattle production is needed to safeguard public health, eventually forestalling human salmonellosis from cattle sources. In achieving this, it will be essential to consider the farm as a critical control point in preventing the introduction of *Salmonella* into the food chain.

Keywords: salmonellosis; transmission; cattle; zoonosis; public health; control; prevention



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1. Introduction

Salmonella is a zoonotic pathogen of great concern worldwide [1], with food animals remaining significant reservoirs for human infection [2]. Although most human salmonellosis cases are linked to contaminated poultry, pork, and egg products [3], the risk of

infection from cattle and their products continues to pose a serious public health threat [4]. Reports worldwide indicate the frequent isolation of *Salmonella* from retail beef and its products [5–8], as well as from raw dairy milk and related products [9–13].

Outbreaks of salmonellosis have been repeatedly associated with the consumption of unpasteurized milk [14] and beef products [15]. In the U.S., beef accounted for an estimated 5.7–9.1% of all human foodborne salmonellosis cases between 2012 and 2019, including several outbreaks [5] often linked to ground beef consumption [16]. Similarly, in France, a prolonged outbreak of *Salmonella* Enteritidis was traced to frozen beef burgers imported from Poland [17]. In the Netherlands, a national outbreak investigation also identified contaminated raw beef as the source of infection [18].

Traceback investigations have often pointed to animal farms and markets as potential sources of infections [19,20]. For instance, a multi-drug-resistant *Salmonella* Heidelberg outbreak in the U.S. was linked to contact with dairy calves [19]. In the same country, another investigation of an outbreak involving ground beef contamination identified dairy cattle in the state of New Mexico as the source [21]. Among other livestock, during the persistent polyclonal *Salmonella* Enteritidis outbreak across 18 countries between 2016 and 2020 which was linked to contaminated chicken eggs, farms in Poland and some other packaging centers were implicated [22].

Studies globally have revealed that isolating *Salmonella* from dairy or beef cattle and their environments is common [23–25]. The persistence of *Salmonella* on cattle farms is attributed to the pathogen's ability to cycle between host and non-host environments, surviving for extended periods on various surfaces [26]. Traditionally, the beef industry has focused its efforts on interventions at the processing and packaging stages to reduce human exposure to *Salmonella* [4]. However, in recent years, there has been a shift toward understanding *Salmonella* ecology in pre-harvest cattle on farms [4]. Ongoing research aims to assess the *Salmonella* populations present in pre-harvest cattle and their environments [25,27,28], yet the pathogen's endemicity in cattle farms persists [29].

The introduction of *Salmonella* to cattle farms often occurs through infected animals, contaminated feed, and vectors such as birds and rodents [30]. Additional sources include contaminated water, other livestock, wildlife, insects, people, equipment, and vehicles [28]. Due to these multiple potential sources, the introduction of the pathogen to a new herd is frequently considered a multi-source event [23].

Given the One Health concept, which emphasizes the interconnectedness of human, animal, and environmental health [31], preventing the introduction and spread of pathogens like *Salmonella* in cattle populations is crucial for safeguarding public health and minimizing environmental contamination. In this article, the risk factors and potential sources of *Salmonella* infection in cattle farms, the factors facilitating its persistence, and possible intervention strategies are explored.

2. Common Risk Factors and Sources of *Salmonella* Infection in Cattle

2.1. Infected Newcomers and Animal Trading

Introducing new cattle into a herd has long been a significant source of *Salmonella* in cattle operations [32], making it one of the primary pathogen sources. In larger farms, the continual purchase of replacement animals or herd expansion from external sources is often essential and unavoidable for management [23]. Farmers may introduce new cattle for various reasons, such as replacing culled bulls or heifers to prevent inbreeding and maintaining herd size [33]. While some operations raise their own heifers, others continue to purchase replacements [33]. However, this practice can increase the prevalence of *Salmonella* within the herd, as it heightens the risk of introducing infected animals [23].

Animals already infected with *Salmonella* may appear healthy but can still shed the pathogen in their feces [34]. Fecal samples from cattle herds may test positive for *Salmonella* even 14 months after the initial exposure [35]. Although clinically infected animals tend to shed *Salmonella* at higher rates than asymptomatic ones, both can continue shedding the pathogen for extended periods [36,37]. It is estimated that approximately 10^2 to 10^7 colony-forming units (CFUs) of *Salmonella* can be shed per gram of cattle feces [20]. Studies have indicated that certain *Salmonella* serovars, such as *Salmonella* Typhimurium, can persist in large dairy herds for about 3.5 years and in calf units for up to 2 years [38]. Conversely, serovars like *Salmonella* Dublin can lead to persistently infected cattle that exhibit no clinical signs [39]. The absence of obvious symptoms, such as diarrhea, in apparently healthy yet infected cattle increases the risk of introducing them into uninfected herds. A study on *Salmonella* Dublin in a Danish dairy production system revealed that, on average, a single infected calf could infect two others when introduced into a fully susceptible population [40].

Animal trading has long been a crucial factor in understanding the epidemiology of salmonellosis in cattle [41]. Simply put, it involves a production farm and a dealer who purchases and sells calves to multiple rearing farms [41]. The buying and selling of animals create opportunities for pathogen transmission, such as *Salmonella*, as the commingling of animals at sale sites facilitates fecal–oral infection cycles [42–44]. Some researchers have even described animal markets as “hubs” for pathogen transmission [45]. A recent multistate salmonellosis outbreak, caused by a multidrug-resistant *Salmonella* Heidelberg strain, was traced to a livestock market where male dairy calves were auctioned [19]. Essentially, cattle trading forms a network of animal holdings and premises connected through multiple animal movements [46]. These movements, particularly between agricultural premises, contribute significantly to the spread of infectious agents and are regarded as a critical epidemiological factor in several livestock diseases [47].

2.2. Fomites

2.2.1. People, Contaminated Instruments, and Equipment

Despite the growing number of reports highlighting the potential transmission of infections from humans to animals, these occurrences have not been comprehensively explored, and the extent of human contributions to disease outbreaks in affected animal populations remains insufficiently examined [31,48,49].

In the case of salmonellosis in cattle, human movement in and out of farm premises plays a significant role in mechanically transmitting the pathogen among herds [38,45]. Animal traders, such as specialized veal producers, are a prime example of this risk group, as they frequently purchase and raise calves from multiple dairy herds [50]. Although their primary role is to transport purchased animals to slaughterhouses, their interactions with animals from different herds particularly during farm visits can facilitate the spread of pathogens from infected to uninfected flocks [45].

Additionally, the employment of farm workers presents a potential risk for pathogen transmission. Many of these individuals may work on multiple farms while managing their own livestock, inadvertently serving as vectors for disease spread, particularly in the absence of stringent biosecurity measures [45].

Veterinary health facilities also serve as common hotspots for nosocomial infections, including pathogens such as *Salmonella* spp. [51]. These facilities can become hubs for fomites, especially in the absence of stringent hygiene standards. Common fomites in veterinary clinics from which pathogens have been isolated include burdizzos, doorknobs, drawer handles, fridge handles, hoof cutters, ice chests, kidney bowls, mobile phones, muzzles, pens, record books, surgical instruments, surgical tables, switches, and vials, all

of which can play a crucial role in the spread of infectious agents [52]. Animal workers who do not use examination gloves or change into new examination gloves for each animal are highly likely to cause cross-contamination [53,54]. This is typically seen during rectal maneuvers among large herds, usually for pregnancy confirmation or artificial insemination procedures.

2.2.2. Farm Equipment and Vehicles

The sharing of equipment among farmers poses a significant risk for the spread of *Salmonella* among herds within a common geographic area [33,44,45]. Tractors, trailers, and wagons are the most commonly shared equipment, followed by harvesting and plowing machinery, as well as muck vehicles [45]. Farmers frequently borrow tractors from one another for tasks such as waste handling and feeding [45]. Additionally, animal chutes used for restraint are also commonly shared. The use of shared vehicles and equipment increases the likelihood of pathogen transmission, as they may already be contaminated from previous use. Some researchers have proposed targeted interventions for trailers to reduce *Salmonella* infections in calves [55], including thorough washing and disinfection of vehicles after use.

2.3. Feed

Animal feed is one of the many potential sources of *Salmonella* infection in animals [26]. Increasing evidence suggests that *Salmonella* can spread from feed to food-producing animals [56]. Cattle feed, in particular, not only serves as a potential source of *Salmonella* transmission but also harbors other significant pathogens, such as *Escherichia coli* O157:H7 [57]. Several studies have reported the isolation of *Salmonella* from cattle feed, with some demonstrating its potential transmission to cattle through feed, as summarized in Table 1.

A notable example of feed-related *Salmonella* infection among other livestock is the 2009 *Salmonella* Tennessee outbreak in Finland, which affected pigs and hens and was traced back to contamination in a feed mill production line [58]. In countries like Sweden, where *Salmonella* is well controlled or absent in food-producing animals, contaminated feed is considered a major route of infection for farm animals [58]. A single batch of contaminated feed from a commercial mill can be distributed to multiple farms, potentially leading to widespread infection [59].

It has long been recognized that *Salmonella* can colonize the cooling systems used for processing pellet or mash feed in animal feed mills, contaminating ingredient intake pits, and out-loading gantries [60]. Additionally, *Salmonella* present in feed components may survive processing and subsequently infect food-producing animals [59]. For instance, the pathogen can persist in both the dry raw materials used for poultry feed production and in the final dry feed for extended periods [58].

Table 1. Some reported *Salmonella* serovars isolated from cattle feed and ingredients.

Isolation Source	Serotype Involved	Reference
Dry beef cattle feed	Agona Anatum Barranquilla Cerro Cubana Give Infantis Kentucky Lexington Liverpool Mbandaka Meleagridis Montevideo Muenster Orion var. 15+, 34+ (Thomasville) Senftenberg Soerenga Typhimurium var. O 5- (Copenhagen)	[61]
Medicated beef cattle feed	Cerro Cubana Infantis Lexington var. O 15+ (Manila) Liverpool Mbandaka Montevideo Newport Tennessee Typhimurium var. O 5- (Copenhagen)	[61]
Dairy cattle feed	42:z ₄ ,z ₂₃ Agona Alachua Barranquilla Havana Kentucky Livingstone Mbandaka Meleagridis Rissen Senftenberg	[61]
Cattle feed ingredients	Typhimurium ** Mbandaka Cerro Braenderup Meleagridis	[57]
Feed mill	Menhaden	[62]
Cattle feed	Infantis **	[63]
Animal feed ingredients	Senftenberg Enteritidis Gallinarum Saintpaul Lexington	[64]
Animal feed	Mbandaka	[65]

** : Feed and cattle *Salmonella* isolates were genetically the same or closely related.

2.4. Non-Production Animals and Production Animals

2.4.1. Wildlife, Rodents, Birds, and Flies

Consumer demands and animal welfare policies have driven the transition of animal production industries from intensive to more extensive farming systems [66,67]. Extensive farming systems follow a natural or semi-natural approach to raising animals [68], providing them with ample space to exercise and engage in natural behaviors such as grazing in open areas like pastures, meadows, and mountains [69,70]. While these practices contribute

to improving meat quality [71], they also increase the potential for interactions between farm animals and wildlife. Various wildlife species have been identified as reservoirs of *Salmonella*, raising concerns about the transmission of infectious agents to free-ranging domestic food animals [2,72,73]. Rodents, wild birds (e.g., wild geese, sparrows, and waterfowl), reptiles, wild boars, and rabbits have all been implicated in transmitting *Salmonella* to farm animals [37,38,74–78]. Cattle, for instance, may ingest contaminated fecal droppings from these animals while grazing in open fields.

In addition, wild birds can contaminate stored animal feed with their droppings, particularly in cases of inadequate feed storage [74,75]. An investigation into a salmonellosis outbreak in a cattle herd linked the disease to haylage contamination by blackbirds, starlings, and geese [79]. The presence of wild geese around cattle and their feed was significant in establishing clinical salmonellosis within the herd [79]. Molecular studies have identified genetically identical *Salmonella* serovars in both wildlife and cattle (Table 2), suggesting transmission between the two. Public health concerns are rising due to the epidemiological significance of salmonellosis in wildlife [78], as many wildlife species such as rodents, reptiles, and amphibians can carry *Salmonella* asymptotically [80].

Flies and other insects have also been identified as vectors of *Salmonella* transmission [81], especially those feeding on cattle manure. In some cases, these flies have contributed to the spread of antibiotic-resistant *Salmonella* on farms [20]. Common flies that may facilitate transmission include horse flies, house flies, horn flies, face flies, stable flies, and deer flies [33].

2.4.2. Pets Animals, Herding Animals, and Stray Animals

Fecal shedding of *Salmonella* among pet animals, including dogs and cats, has been well-documented even in asymptomatic cases [82–85]. Some farmers keep these companion animals on-site [74], posing a risk of feed contamination if infected pets have access to storage areas [58]. A study in Denmark found *Salmonella* in dogs and cats living near infected cattle herds [86].

In some regions, herding dogs are commonly used to manage livestock such as sheep, goats, and cattle [87]. The Old English Sheepdog, for example, was originally bred for herding purposes [88]. However, if these herding animals are infected with *Salmonella*, they can shed the bacteria in their feces, potentially infecting the herd. A recent study in Southern Bavaria found that some herding dogs were shedding the cattle-adapted serovar *Salmonella* Dublin [89].

Stray animals, which include unowned, homeless, free-roaming, or abandoned dogs and cats, are frequently found near livestock breeding sites and contribute to the spread of *Salmonella* among farm animals [90,91]. They can introduce pathogens into the environment through fecal shedding, amplifying the spread of infection. Due to inadequate care and treatment, sick stray animals often remain untreated, leading to persistent environmental contamination with pathogens such as *Salmonella* [92].

2.4.3. Other Livestock Animals

In farming systems where various livestock species, such as cattle, poultry, sheep, goats, and pigs, are reared together, farmers may adopt a multi-species grazing system on the same land, which can be a more sustainable farming approach [93]. However, this practice increases the risk of inter-species pathogen transmission through the fecal–oral route. Like other livestock, sheep and goats can serve as reservoirs of *Salmonella*, potentially shedding the pathogen in their feces [91]. The evidence of genetically related *Salmonella* strains isolated from cattle and other livestock, indicating inter-species transmission, is presented in Table 2.

Table 2. Studies showing evidence of possible inter-specie infection of *Salmonella* between cattle and other production and non-production animals.

Animal Type	Specie	Serovar	Comparative Methodology	Reference
Wildlife	Raccoons Crows	Braenderup, Dublin, Montevideo, 4, [5], 12:i:-	PFGE	[94]
Wildlife	Hedgehog	Muenster	PFGE	[95]
Wildlife	Wild boar	Meleagridis, Anatum	PFGE	[96]
Production Animal	Chicken	Enteritidis	ERIC-PCR	[97]
Production Animal	Pig	Typhimurium	PFGE	[98]

PFGE: pulse field gel electrophoresis; ERIC-PCR: enterobacterial repetitive intergenic consensus–polymerase chain reaction.

2.5. Herd Size

Studies have reported an association between large herd size, *Salmonella* infection, and fecal shedding in cattle herds [32,99]. Large herd size is considered a key risk factor for the persistent presence of *Salmonella* on farms [36]. Unfortunately, it is challenging for large herds to transition from a positive to a negative infection status [100]. Several factors contribute to the increased risk of *Salmonella* infection in large herds, including a higher likelihood of purchasing cattle from external sources, increased herd density that facilitates transmission, stress due to overcrowding, and difficulties in implementing effective interventions [99].

For instance, free-stall housing, which is commonly used in large herds, poses significant challenges in controlling manure-transmitted pathogens like *Salmonella*. The unrestricted movement of animals in free-stall barns allows direct contact with fecal matter, leading to further contamination of shared feed and water sources [99]. Additionally, it has been observed that larger operations are more likely to move cattle to grazing areas without defined borders, which increases the risk of pathogen spread [33]. Even when borders are in place, nose-to-nose contact across farm boundaries can facilitate the transmission of pathogens between neighboring farms [45].

Furthermore, intensive husbandry systems are not always a reliable solution, as they can create environments conducive to *Salmonella* shedding. Exposure to pathogen-laden manure in such systems can perpetuate chronic infections within the herd [101,102].

2.6. Communal Pastures and Grazing

The most cost-effective way to feed cattle is by grazing them on pasture, making cattle a popular choice for utilizing pasture lands [33]. Grazing becomes even more efficient and manageable when multiple animals share communal pastures. These communal grazing areas have sometimes been used to temporarily hold cattle before they are transported to other locations [103]. In some regions, pasturing cattle on alpine meadows is a cherished tradition [89], and it is a common practice for farmers to take their animals to shared pastures, particularly during the summer grazing period [104].

However, communal grazing exposes cattle to cross-infection [89]. On pastures, *Salmonella* Dublin can survive in feces for at least 119 days and remain viable in surface water for approximately 87 days, facilitating the rapid spread of the pathogen among animals [89]. Studies have also shown that *Salmonella* can persist in cattle fecal pats, especially when moisture levels remain around 80% [105].

In some regions, the practice of agistment where farmers pay to graze their livestock on communal pastures alongside other animals such as sheep is common. Although sheep do not typically transmit many cattle diseases, *Salmonella* Dublin and certain viruses can spread between the two species [45]. The shedding of *Salmonella* during these periods can result in extensive environmental contamination, increasing the risk of within-herd transmission and unintentional spread to other herds [99].

Additionally, ponds, rivers, cisterns, and streams are commonly used as drinking water sources for cattle during grazing. For example, many cattle operations in the U.S. rely on ponds for drinking water [33]. However, these water sources can harbor foodborne pathogens such as *Salmonella* [106], making them potential hotspots for infection [79].

2.7. Animal Waste Handling as Slurry and Manure

Salmonella can persist in manure and slurries for extended periods, even when processed and used as organic fertilizers [107], which are often applied to grazing fields. Consequently, spreading slurry containing *Salmonella* and other pathogens can facilitate the transmission of disease to farm premises, ultimately infecting animals [108]. A study of U.S. dairy herds found that farms with at least one antibiotic-resistant isolate were more likely to use composted or dried manure for bedding [109]. Similarly, a study conducted in New South Wales, Australia, reported that manure from an old dairy farm had been applied to the pasture of a new dairy farm a few months before a salmonellosis outbreak occurred [38]. Manure from older dairy farms is likely to harbor several pathogens, including *Salmonella* [110,111], which can survive for several weeks in dry environments and several months in wet environments [80]. Further investigations revealed that in addition to slurry application, the pasture on the new farm was irrigated with water from an effluent pond contaminated with runoff from washings of the old dairy farm [38]. The authors concluded that the improper use of manure and effluent as fertilizer likely contributed to the introduction and persistence of *Salmonella* Typhimurium in the herd [38]. Additionally, some cattle owners spread poultry manure on adjacent properties, an activity that has also been identified as a potential source of *Salmonella* infection in cattle [75].

The aerosolized transmission of *Salmonella* in livestock is also possible [112,113]. Certain farm practices, such as using flush water systems to wash manure, can facilitate the airborne spread of the pathogen [32]. An early experimental study demonstrated that *Salmonella* Typhimurium could survive in the air long enough to pose a significant airborne transmission hazard [114]. Inhalation of *Salmonella* Typhimurium by mice caused disease and death, with doses as low as 150 CFU proving infectious [114]. This finding suggests that airborne transmission should be considered a potential route of infection for *Salmonella* Typhimurium in cattle, particularly in calves [114]. Experimental inoculation of calves with approximately 10^4 to 10^6 CFU of *Salmonella* Typhimurium via ‘mouth and nose only’ or ‘whole body’ aerosol exposure successfully induced infection [114].

2.8. Abortions and Live Births

Abortions can occur in cattle infected with *Salmonella* [36], with aborted tissues and fluids serving as potential sources of infection for other herds. Abortion due to *Salmonella* infection typically occurs during the last trimester [23,115]. However, certain serovars, such as *Salmonella* Dublin, can induce abortion at any stage of pregnancy and may present as the only clinical sign [116,117]. A study investigating abortion in dairy cattle identified *Salmonella* Brandenburg in placental tissues [115], indicating that cattle exposed to such aborted materials can become infected with *Salmonella* [118].

Additionally, evidence has suggested that vertical transmission from the dam to the fetus is possible, with viable calves potentially being born already infected without fecal–

oral exposure [119]. Vertical transmission of *Salmonella* has been documented not only in cattle but also in poultry [51].

Clinical signs observed in *Salmonella*-infected pregnant cows may include intermittent loose stools, acute post-abortion pyrexia, and reduced feed intake [115]. Although the bacterium is rarely shed directly in the milk of infected dams, serovars such as *Salmonella* Dublin have a higher likelihood of shedding compared to other serovars [30].

2.9. Cattle Shows

A United States Department of Agriculture (USDA) report highlighted instances where some farmers transported their cattle to events such as shows, fairs, and rodeos [33]. Following these events, some farmers reintegrate their animals into their herds without implementing any quarantine measures [33]. Such practices present potential pathways for disease introduction, as the animals come into contact with numerous humans and other animals during these gatherings. Additionally, during such events, animals from different locations may be housed in the same confined spaces or share common feed and water sources, facilitating the potential transmission of pathogens. These events can also induce significant stress in the animals [120], and stress in any form can contribute to the shedding of pathogens.

3. Prevention and Control

Upon confirmation of *Salmonella* infection in cattle, a series of comprehensive investigations and control measures must be promptly implemented, taking into account all possible sources of infection [23]. It is essential to identify and map out all potentially exposed and infected premises to ensure the rigorous implementation of control measures [103]. Morbidity, mortality, and production losses in newly infected or persistently infected herds are significant concerns [121]. Regardless of the serovar involved, similar control measures can be applied, though specific challenges arise with the host-adapted serovar *Salmonella* Dublin [23]. The following sections discuss preventative and control measures to mitigate *Salmonella* in cattle herds, beginning with biosecurity.

3.1. Biosecurity

The OIE (2015) defines biosecurity as “a set of management and physical measures designed to reduce the risk of introduction, establishment and spread of animal diseases, infections or infestations to, from and within an animal population” [122]. Simply put, biosecurity encompasses any practices or systems aimed at preventing the spread of pathogens to susceptible or naïve farm animals and their environment [123]. For cattle farmers, this involves implementing management systems and practices that prevent herd infections [124]. There is no single universal approach to biosecurity; instead, various tools are available to control infections, which can be tailored to the specific needs and objectives of each herd [125]. The primary goal of biosecurity measures is to prevent disease introduction to naïve herds, with other aspects serving as contingency plans in case prevention efforts fail [122]. However, achieving this goal in modern cattle farming is challenging due to various operational constraints, necessitating collaborative efforts among stakeholders to address these challenges [126]. The preventative measures discussed here outline key biosecurity strategies to prevent or control *Salmonella* on cattle farms.

3.2. Interventions Aimed at Farm Animals and Their Environment

Strategies to reduce cattle exposure to *Salmonella* while enhancing their disease resistance are crucial for preventing and controlling the pathogen [30]. However, despite their effectiveness, these strategies can be demanding and, in some cases, impractical, especially

in large herds. Nevertheless, where feasible, farmers can combine human resources and mechanization to optimize disease prevention and control on their farms.

A key approach is maintaining a strict hygienic environment through periodic disinfection and thorough cleaning of the premises. Additionally, herd owners must assess the risk of introducing new livestock from infected herds. Therefore, maintaining a high level of external biosecurity is essential [100]. Ideally, farmers should source cattle from *Salmonella*-free herds or ensure all new animals undergo serological testing before integration.

Whenever possible, maintaining a closed herd is recommended [30]. Stressors such as introducing new animals, overcrowding, and inadequate transition space and time should be minimized or avoided [37]. If acquiring new animals is unavoidable, introducing younger cattle is preferable, as they pose a lower risk of carrying *Salmonella* compared to adults [127]. This is because adult cattle have a higher likelihood of testing positive for *Salmonella* [34]. Nevertheless, regardless of where the animal is obtained, the quarantining and vaccination of new arrivals will remain important to reduce the chances of introducing *Salmonella* into a herd [128,129]. However, vaccinations are not a substitute for good management practices [37], as the efficiencies of current vaccines for cattle are still evaluated for improvement [130,131]. just like in other livestock such as poultry [132] and pigs [133].

While larger herd sizes are linked to challenges in *Salmonella* control, reducing herd size is neither a practical nor an economically viable solution [75]. Instead, farmers should focus on implementing management systems that minimize herd exposure to potential infection sources. For instance, using flooring systems that allow manure to fall into a collection trench can improve hygiene and reduce the risk of fecal–oral disease transmission. Additionally, the periodic testing and culling of infected animals should be carried out [30].

To manage sick animals effectively, particularly in large dairies where the number of cases can be overwhelming, farmers should avoid housing sick, maternity, and recovering animals together for convenience's sake [23].

Newborn and milk-fed calves require special attention as they are highly susceptible to *Salmonella* infection [116]. Before calving, cattle that test positive for *Salmonella* must be housed separately from those testing negative [37]. Maintaining high hygienic standards in calving and calf housing environments is essential. Furthermore, all newborns should be fed colostrum or milk exclusively from *Salmonella*-negative cattle [37]. In endemic situations where these standards are difficult to meet, heat treatment of colostrum and pasteurization of milk may be beneficial [116].

Providing pre-weaned calves with medicated milk replacers can further lower their risk of *Salmonella* infection and shedding [75]. Preventing contact between adult cattle and calves, along with implementing an all-in, all-out system in calf and heifer-raising facilities, can significantly reduce *Salmonella* transmission from infected cattle to young calves [37].

Although no evidence currently exists of *Salmonella* transmission to cattle through contaminated semen, a recent study reported the isolation of a multi-drug-resistant strain of *Salmonella* Dublin from the cryopreserved semen of a 17-month-old Holstein bull at a stud facility in the Midwest U.S. [134]. The pathogen was also cultured from various postmortem samples of the euthanized bull, including urine, bile, feces, prostate, seminal vesicles, preputial mucosa, colon, and small intestine [134]. Notably, the antimicrobial resistance pattern of the isolates from the cryopreserved semen was identical to that of the postmortem samples [134].

Therefore, farmers are advised to ensure that bulls brought onto their farms for mating purposes are free from *Salmonella* infection. Moreover, achieving completely sterile semen during breeding is virtually impossible, as microorganisms are naturally present in every ejaculate [135]. Nevertheless, bulls designated for semen production for artificial

insemination should be housed in strictly regulated semen collection centers that adhere to specific protocols. These protocols include regular clinical examinations, pathogen assessments of semen, and routine testing for various diseases, all of which must be conducted and approved by qualified veterinary authorities [135].

However, testing the total volume of the millions of semen doses collected worldwide is both impractical and unsafe. The most reliable and effective approach is to ensure that all bulls used for semen production are pathogen-free. In doing so, it can be reasonably presumed that the semen from these bulls is also pathogen-free [135].

Minimizing fecal contamination of feedstuffs, feeding surfaces, water troughs, and equipment is crucial [37]. In areas where open grazing is practiced, cattle should be restricted from grazing on slurry-treated pastures for at least a month after application [38]. Proper drainage and leveling of water-collecting areas on farms and pastures are essential [37], as stagnant water may attract birds and other animals that could use it as a drinking source.

As previously mentioned, cleaning and disinfecting the farm environment is vital; however, this task can be daunting, particularly in large dairy herds [23]. Removing all visible debris is a critical step in the cleaning and decontamination process, as even the most effective disinfectants may have limited impact in environments containing organic matter such as feces and bedding material [23]. Cleaning helps eliminate most microorganisms, allowing disinfectants to effectively eradicate the remaining microbes. This method is particularly effective in controlling pathogens transmitted via the fecal–oral route, such as *Salmonella* [23].

However, pressure washing is not recommended for cleaning animal pens and farm premises, as it can aerosolize pathogens and facilitate their spread [23,29]. Additionally, power washing is ineffective in removing microbial biofilms; therefore, the use of handheld foamers to apply alkaline detergents and acid rinses is advised where applicable [23]. Concrete pads should be disinfected after cleaning and exposed to sunlight for several days [29] as *Salmonella* is susceptible to most disinfectants and ultraviolet radiation [101].

Special attention should be given to cleaning livestock trailers, maternity and calf pens, feeding equipment, and other areas prone to *Salmonella* contamination [23]. The routine cleaning and disinfection of vehicles and animal market premises are also recommended as essential measures for salmonellosis control [136]. Additionally, veterinarians and farm personnel should frequently clean and disinfect all instruments to reduce the risk of infection spread [52].

3.3. Farm Workers and Other People

Biosecurity measures must be enforced for both employees and visitors. These measures may include washing hands with soap and warm water before and after visiting the animal herd, as well as changing clothes before and after each visit. Employees and individuals who regularly work on the farm must strictly adhere to biosecurity protocols when handling different groups of animals [30]. Visitors should be directed to a designated parking area that is located away from vehicles and equipment that have access to the animals. This precaution helps minimize the risk of disease introduction from external sources. For cases involving sick animals, it is recommended to assign dedicated personnel to handle them exclusively [23]. Additionally, water baths with disinfectants should be strategically placed at key locations on the farm premises, and boot covers must be provided for both workers and visitors while on site.

3.4. Wildlife and Flies

It is crucial to consider rodents and wildlife when implementing biosecurity measures to control *Salmonella*, as they can act as reservoirs of infection and contaminate animal feed with pathogens [33,58]. To prevent cattle from accessing pond water, other water bodies, and feeding areas shared with birds and wildlife, such as waterfowl, these areas should be fenced off or drained using appropriate channels in the case of water bodies [37]. Rodent control can be achieved through biological methods, such as using cats, or chemical methods, including baits and traps [33].

For effective fly control on farms, both topical and oral treatments, as well as treated ear tags, can be utilized. Additionally, environmental control measures such as fly sprays, foggers, traps, and fly tape should be incorporated into fly management programs. Biological control methods, such as introducing predator wasps to disrupt the fly life cycle and prevent their maturation, can also be employed [33].

Proper feed storage is essential to prevent access by wildlife and potential contamination [137]. Finally, appropriate farm fencing should be installed where necessary to deter wildlife that may serve as disease vectors.

3.5. Animal Feed

The World Organization for Animal Health (OIE), recognizing the critical role of animal feed quality in both human and animal health, has dedicated a chapter in the Terrestrial Animal Health Code to “The control of hazards of animal health and public health importance in animal feed.” This effort is further supported by guidelines from the Codex Alimentarius Commission (CAC) on the “Application of risk assessment for feed” and the “Risk analysis of foodborne antimicrobial resistance” [59].

In as much as during feed preparation, pelleting (which is heat processing), chemical additions, or both help in destroying *Salmonella* that may be present in the feed [26], in addition, every stage of the feed processing chain must be routinely monitored to prevent potential *Salmonella* contamination [137]. In Sweden, a *Salmonella* control program based on the Hazard Analysis Critical Control Points (HACCPs) principles was implemented in 1991 [56]. According to this program, if *Salmonella* is detected before heat treatment, the contaminated section of the production line undergoes thorough cleaning and disinfection. If *Salmonella* is found after heat treatment, the entire feed mill must be cleaned and disinfected, and production can only resume once environmental sampling results are negative [56].

Certain plant essential oils have also been identified as effective in reducing *Salmonella* growth [138]. Incorporating such chemical and biological compounds with antibiotic properties can significantly lower bacterial loads in animal feed. For instance, adding probiotics and modifying feed structure such as increasing feed particle size has been shown to reduce the intestinal load of *Salmonella* in pig herds, thereby decreasing fecal shedding [139]. Further studies are needed to evaluate the impact of similar modifications in pelleted cattle feed.

Additionally, methods such as radiation treatment and the inclusion of organic acids have been identified as effective measures to ensure feed safety [137]. Nonetheless, it is essential to protect all feed ingredients from contamination by wild birds and rodents, while feed transport vehicles should be regularly cleaned and sanitized [26].

3.6. Vehicles, Equipment, and Animal Movements

It is essential to clean and disinfect all equipment between use [30]. Farmers should avoid using the same equipment for both manure handling and feed distribution [23]. Additionally, they must ensure that feed delivery vehicles do not pass through manure

or manure-scraping lanes [37]. Vehicles should also be designed for easy cleaning [136]. Currently, no federal regulations in the U.S. mandate the cleaning of trailers between cattle loads. This challenge may be further exacerbated by the lack of trailer washing facilities in the region, making regular cleaning and disinfection difficult [55]. Nevertheless, farmers should adopt the practice of routinely cleaning their animal transport vehicles while public health authorities consider implementing regulations to enhance animal transport hygiene.

3.7. National Control Programs

National control programs in some countries have successfully prevented and eradicated many diseases [140]. For instance, Sweden has implemented an effective yet costly *Salmonella* control program, which has limited the number of cattle farms infected with *Salmonella* each year. This program restricts the movement of all infected herds until they are confirmed free of infection, with farmers receiving government compensation for any losses incurred. Additionally, the program treats all *Salmonella* serovars as undesirable due to their zoonotic potential [74].

Livestock disease control programs have largely relied on restricting animal movements between farms and through high-risk areas. This approach is particularly effective given the complexities of trade networks in animal production [122]. Recently, advancements in technology and infrastructure for tracking livestock movements have gained significant attention, as they provide valuable insights into the potential spread of infections within source populations [141].

A notable example of such stringent control measures is Denmark's *Salmonella* Dublin program, aimed at eradicating *Salmonella* Dublin from the national cattle population [122]. The program mandates that all cattle movements between herds be recorded in the Central Husbandry Registry (CHR), which is closely integrated with the Danish Cattle Database (DCDB) and managed by SEGES, Denmark's leading agricultural consultancy service. These movement records are rigorously monitored for errors to ensure compliance with the European Union's cross-compliance standards and regulations [122].

Many governments now mandate the registration of livestock movements in centralized national databases, which facilitate swift access to data during infection investigations. Countries such as the United Kingdom, Argentina, and all European Union member states have adopted this approach [47]. However, others such as the United States currently lack a comprehensive system for tracing and identifying individual animals, their holdings, or livestock shipments, despite previous efforts [47]. The 2018 CattleTrace initiative, however, presents a valuable opportunity to enhance livestock disease control and prevention in the country by enabling the rapid tracing of infected animals [47]. Furthermore, the recently developed U.S. Animal Movement Model (USAMM) shows promise in predicting the size and spatial distribution of cattle shipments [47]. Ensuring traceability from farms to processing facilities and ultimately to consumers is crucial, especially during outbreak investigations [21].

Aside from control programs focused on animal movement, other national initiatives have implemented routine mandatory surveillance exercises, often tailored to achieve specific national objectives [142]. For instance, in the Netherlands, national control programs target six endemic cattle diseases, including salmonellosis, and are designed to address prevailing conditions such as the high exportation of dairy products [142]. As part of this strategy, periodic surveillance through bulk-milk testing for antibodies in dairy cattle has been established as a national control measure [142].

Similarly, the Canadian Integrated Program for Antimicrobial Resistance Surveillance (CIPARS) undertakes both active and passive surveillance of *Salmonella* in beef and dairy

cattle, among other responsibilities [143]. These surveillance activities can be extended to breeding centers and animal feed mills to ensure compliance with hygienic standards.

While recognizing the importance of continuous on-farm surveillance and monitoring of animal movement, national efforts should also promote broader stakeholder collaboration at various levels of cattle production. Regulations and policies, to be enforced through national instruments such as laws and bylaws, will ensure that all stakeholders involved in this critical industry contribute to minimizing the presence of *Salmonella* in cattle production.

4. Conclusions

In this article, common sources and risks of *Salmonella* infection in cattle herds (Figure 1) are reviewed and summarized and interventions are explored to reduce cattle exposure to the pathogen and contain existing infections within herds. Addressing *Salmonella* in cattle production requires a coordinated approach involving all stakeholders, including animal industries (such as feed producers and breeding stations), individuals (such as veterinarians, farmers, and animal traders), government regulatory authorities, and the public. A comprehensive approach is essential due to the numerous potential sources of *Salmonella* introduction to cattle herds. Given the ongoing threat *Salmonella* poses to public health, it is crucial to strengthen surveillance and control measures, particularly on animal farms where food animals are raised.

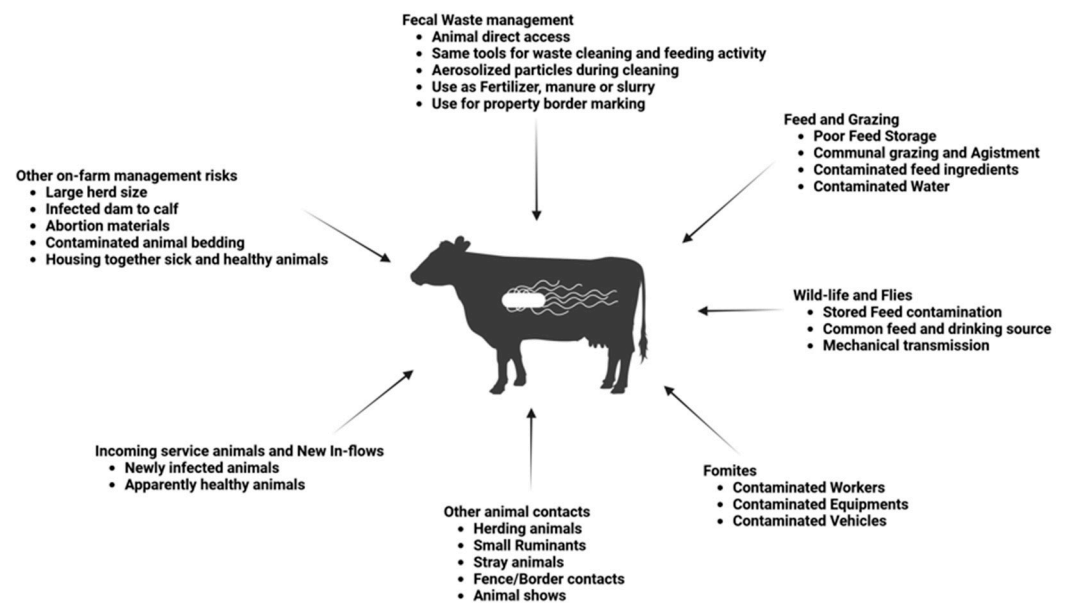


Figure 1. Sources and risk of *Salmonella* exposure to cattle.

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