Foodborne pathogens on Scottish livestock farms: risks, attitudes, and potential interventions

Eleanor Watson, Clare Hamilton, Lee Innes

Contact: eleanor.watson@moredun.ac.uk

SEFARI

Scottish Government
Riaghaltas na h-Alba
gov.scot

Food Standards Scotland
foodstandards.gov.scot

Moredun

Table of Contents

Photo: Shutterstock.com

Executive Summary

This project reviews knowledge on the introduction and risk factors for foodborne pathogens (FBPs) on livestock farms and the potential interventions that may be applied to reduce the risks. FBPs are microbes, which include viruses, bacteria, and parasites, that cause illness in people through the consumption or handling of contaminated food and may occur at all stages of the food chain. FBPs may enter the farm through a variety of routes, including introduction of new animals, contaminated machinery or vehicles, contact with wildlife and through consumption of contaminated feed and water. Deciding on specific interventions to reduce the risk of FBPs will require knowledge of individual pathogen biology, transmission routes and survival in the environment along with prevalence on-farm. Once in livestock, FBPs can multiply, often in the gut of the animal and be shed in faeces so management practices to minimise animal contact with faeces and methods to treat or inactivate pathogens in faeces will help to reduce the risk of spread of FBPs. Factors to consider are types of housing, bedding, flooring surfaces, stocking density of animals and rearing animals in similar age groups. General hygiene and biosecurity practices involving mechanical cleaning and regular removal of soiled bedding material and faecal waste will help to reduce pathogen load on the farm. Quarantining new animals coming onto the farm and maintaining closed groups of livestock can help to reduce the risks associated with FBPs along with hygiene practices involving hand washing, cleaning boots and use of personal protective equipment (PPE). Some disinfectants used on-farm can help to reduce bacterial FBPs and use of heat and steam cleaning will reduce infectivity of *Cryptosporidium* oocysts that are resistant to most commonly used disinfectants. Farmyard manure should be stored in appropriate conditions prior to spreading on land to reduce the viability of any FBPs present. Environmental conditions such as moisture and temperature will influence pathogen survival, multiplication, and risk to livestock. Types of feed and feed supplements may influence shedding of FBPs in livestock. There are vaccines available against specific FBPs e.g. *Salmonella* in pigs and cattle, and *Toxoplasma* in sheep. These vaccines are used to prevent production diseases in livestock but may also provide benefit in reducing the shedding of *Salmonella* in faeces and reducing the presence of *T. gondii* cysts in meat, therefore being of additional benefit to reduce the impact of FBPs. Vaccines are also being developed for *Escherichia coli* O157 to help reduce shedding of the bacteria in cattle. Information from a survey of livestock farmers showed a strong majority of farmers said they were more likely to use vaccination as an intervention strategy if the vaccine also gave protection against a production disease in their livestock compared with a vaccine that was being used to solely provide a public health benefit. The majority of livestock farmers in the survey thought that FBPs were a problem for the industry and were interested in finding out more about the risk of these pathogens in their livestock. They also thought that public perception of the risk of FBPs in livestock was a threat to the industry.

1. Introduction

1.1 Background

Foodborne diseases are caused by microbes, which include bacteria, viruses, and parasites, that contaminate food, and these may occur at all stages of the food chain. Foodborne pathogens (FBPs) originate within livestock animals, as opposed to microbes that cause food spoilage; therefore, a reduction in FBPs within food producing animals may have significant impacts on the risk of human exposure through a reduction in consumption of contaminated meat. Furthermore, a reduction of FBPs at farm-level would also decrease risks through environmental exposure e.g. through mud or water that is contaminated by faeces, and the emergence of new strains with increased virulence or antimicrobial resistance.

To date, efforts to reduce FBPs in meat have focussed mainly on practices during animal transport, within the abattoir, through the food supply chain, and consumer handling. This study focusses on how these microbes enter the food chain at farm level, the factors that influence the presence and burden of FBPs, and what farm interventions may be put in place to mitigate these risks.

FBPs cause approximately 2.4 million cases of disease in the UK population annually and impose an annual cost to society of approximately £9.1 billion[1]. Examples of some of these pathogens include *E. coli* O157 (and other Shiga toxin-producing *E. coli* (STEC)), *Campylobacter* spp., *Salmonella, Listeria monocytogenes, Toxoplasma gondii,* and *Cryptosporidium.*

A major route of meat contamination is the transfer of contaminated faeces via the hide to the carcass during processing, so interventions that result in both reduction of pathogen prevalence and shedding, especially pre-slaughter, are likely to be effective in reducing pathogen contamination of food. In some cases, however, the pathogen is present within the meat (e.g. *Toxoplasma gondii* cysts) and decreasing prevalence for such pathogens is a more appropriate approach.

1.2 Objectives

The main aim of the project is to review current literature and evidence relating to available on-farm interventions for reducing transmission and carriage of FBPs in livestock. Specific objectives that were explored were:

- Risk factors associated with the transmission and burden of FBPs on livestock farms
- Interventions that have proven to be effective, with relevant examples referenced
- Identification of incentives and barriers to implementation of interventions in Scotland and across the UK

Note: poultry farms were out of scope for this review.

2. Methods

A review of current academic and grey literature pertaining to available on-farm interventions for reducing transmission and carriage of FBPs in ruminants was carried out. Literature was mined for risk identifications for each pathogen of interest as well as general risks, risks associated with different farm type and farming practices, and areas where interventions may be effective. A systematic approach was initially taken, using a variety of search terms including all pathogen names alongside animal species and terms such as "farm interventions" and "risks". Due to the diverse nature of the subject area additional terms were used depending on specific areas, informed by the initial systematic phase. A number of key reviews focussing on different aspects of on-farm interventions or specific pathogens were also consulted. Representative studies are described but this is a large field and this report is not a fully comprehensive review of all relevant evidence.

A farmer survey was also conducted alongside the review to capture expert opinion relating to current practices, opinion on feasibility of interventions, and views on incentives and barriers. A focus group was set up comprising a group of farmers from various regions of Scotland with different livestock businesses, mainly cattle and sheep, and one veterinarian. The focus group provided feedback and comments on the survey questions, and these were revised accordingly. The survey was then launched in November 2023 and promoted through social media, and Moredun Foundation networks and industry contacts. During the 3-week launch time, the survey was completed by 80 participants, including a group of 20 young farmers. Results of the survey are included in this document (Appendix 1) and key findings are summarised within this document (Section 3.4).

Photo: Shutterstock.com

3. Results

3.1 Risk factors associated with transmission and amplification of foodborne pathogens on farms

A wide array of factors have been identified that influence carriage and transmission of FBPs on farms and these vary greatly depending on farm type, localisation, and management practices. Some factors influence pathogens universally, and knowledge and understanding of these factors and, importantly, the risks associated with Scottish farms are crucial to the development and implementation of effective interventions. However, different pathogens react variably to stress and have distinct propensities to adapt to changing environments affecting survival, transmission, shedding, and infectivity so while an intervention may work for one pathogen, it may not work or have inverse effects on others. Risks may also have synergistic effects, e.g. high moisture content on pasture may increase the persistence of bacterial species within wildlife faeces, housing conditions may influence the quantity and type of pathogens in manure, and higher temperatures may influence pathogen multiplication in on-farm waterbodies.

As FBPs are largely found in animal intestines, they are generally spread through **faecal contamination** on farms (and during transport). Presence, quantity, and persistence of faeces on animals, pasture, and in housing and water are key risks involved in multiple farm scenarios. Also, faeces on animal hides can lead to contamination of meat as well as transmission to other animals and pose a risk to handlers. A study investigating levels of zoonotic pathogens (*E. coli, Listeria, Salmonella, Campylobacter, Cryptosporidium, Giardia*) in British livestock manure and slurry found that a significant proportion of fresh and stored waste contained at least one zoonotic pathogen[2] and some studies have shown that *Cryptosporidium, Salmonella, E. coli* and *Campylobacter* can survive in manure or slurry for up to 20 weeks[3]. Pathogen survival in soil following application of organic fertilisers should also be considered[4].

'Food we produce must be safe and seen to be safe' *

Well established links have been shown between **stress and susceptibility to disease**. Although the mechanisms underlying susceptibility to gastrointestinal pathogens are still not fully understood, impairment of gut function and integrity and/or permeability is thought to play a major role[5]. Mechanisms may involve direct effects on pathogen number, localisation, and shedding as well as indirect effects through changing the equilibrium of the microbiome more generally. Evidence relating to the carriage and transmission of specific FBPs is somewhat lacking and sometimes conflicting, and effects in livestock reservoirs are even less well studied. Some studies have shown that interaction with stress hormones such as norepinephrine can provide a fitness advantage for the pathogen[6,7]. Livestock animals can become stressed due to a variety of factors, including heat (both chronic and acute), transport, feed withdrawal, clipping, shearing, dipping, lactation, and pregnancy. Jones *et al*.[8] found that shedding of *Campylobacter* by sheep on three different farms increased during lambing. Some studies have reported higher levels of bacterial carriage by livestock during warmer temperatures[9], although the influence of temperatures on environmental survivability may also play a role, especially relating to hide contamination[10] as well as other seasonal factors. Another study suggested that shedding of *E. coli* O157 and generic *E. coli* was not affected by heat stress in feedlot cattle[11]. A comprehensive review of the relationship between FBPs and stress was carried out by Rostagno[12] outlining the various mechanisms and factors that may influence FBP risks as well as important knowledge gaps. Further understanding the role of stress will support the development of rational intervention studies. It is also important to note that legislation and regulations exist relating to animal welfare, which should also be considered when devising novel intervention strategies.

FBPs can be **spread through contact with other animals.** Transmission can occur between livestock species or animals in the same flock / herd / group but introduction from other sources, such as new livestock animals that are brought onto farm, is an important factor and should be limited through biosecurity measures and monitoring. A cross-sectional survey showed that herd size and having brought breeding females onto the farm within a year were both associated with farm-level positive status for *E. coli* O157[13]. Animal movements, either transport to slaughter or at markets, may cause cross-contamination of hides[14,15].

Wildlife species can introduce pathogens. Species such as birds, rodents and insects can carry and shed FBPs as well as acting as mechanical vectors, spreading pathogens between farms. This can occur at a local level but wildlife species with a wide geographical range can also introduce risks. Wild bird populations have been shown to harbour *Campylobacter* that can spread to livestock[16], and Synge *et al*.[17] reported that the presence of wild geese was a risk factor for shedding of *E. coli* O157 by grazing beef suckler cows on Scottish farms, although other studies found no association between presence of geese and shedding[18]. Other elements such as season and housing may be conflating factors. Within Scotland, a low prevalence of STEC O157 was found in wild deer (0.28%) although isolated strains were of a type that is associated with severe disease in humans[19]. A number of studies have also highlighted FBP risks associated with different rodent species (reviewed by Jahan *et al*.[20]) and a scoping review revealed STEC has been associated with a number of wildlife species including wild birds and rodents[21]. Environmental conditions can play an important role in the survival of bacteria in wildlife faeces. A study showed that survival of *E. coli,* and *Campylobacter jejuni* in Canada Goose faeces, shed on pasture, was dependent on temperature and faecal moisture content[22]. Factors that influence the distribution or number of wildlife species can therefore also influence these risks. This was highlighted in a study that investigated the effect of land use change on risks of human exposure to zoonotic pathogens from rats and found that rodent reservoirs were found more commonly in anthropogenically altered sites[23].

Diet can have a major influence on pathogen carriage and shedding, both directly and indirectly through influencing the microbiome. Dietary forage and crude protein levels are found to influence *E. coli* O157 and *Listeria*[24]. Jones *et al*.[8] reported that shedding of *Campylobacter* spp. was found to be lower when sheep were fed on hay and silage (during the winter months) compared with when they were grazing pasture. Pasture type and quality may play a role in FBP carriage. Grove-White *et al*.[25] found that shedding of *C. jejuni* by dairy cattle and sheep was associated with higher pasture quality and hypothesised that this was a dietary affect. *Listeria*, STEC and *Salmonella* have also been linked with poor silage quality, where silage has come into contact with contaminated soil, water or manure and it is important that this type of fodder is handled correctly for both human and animal health[26].

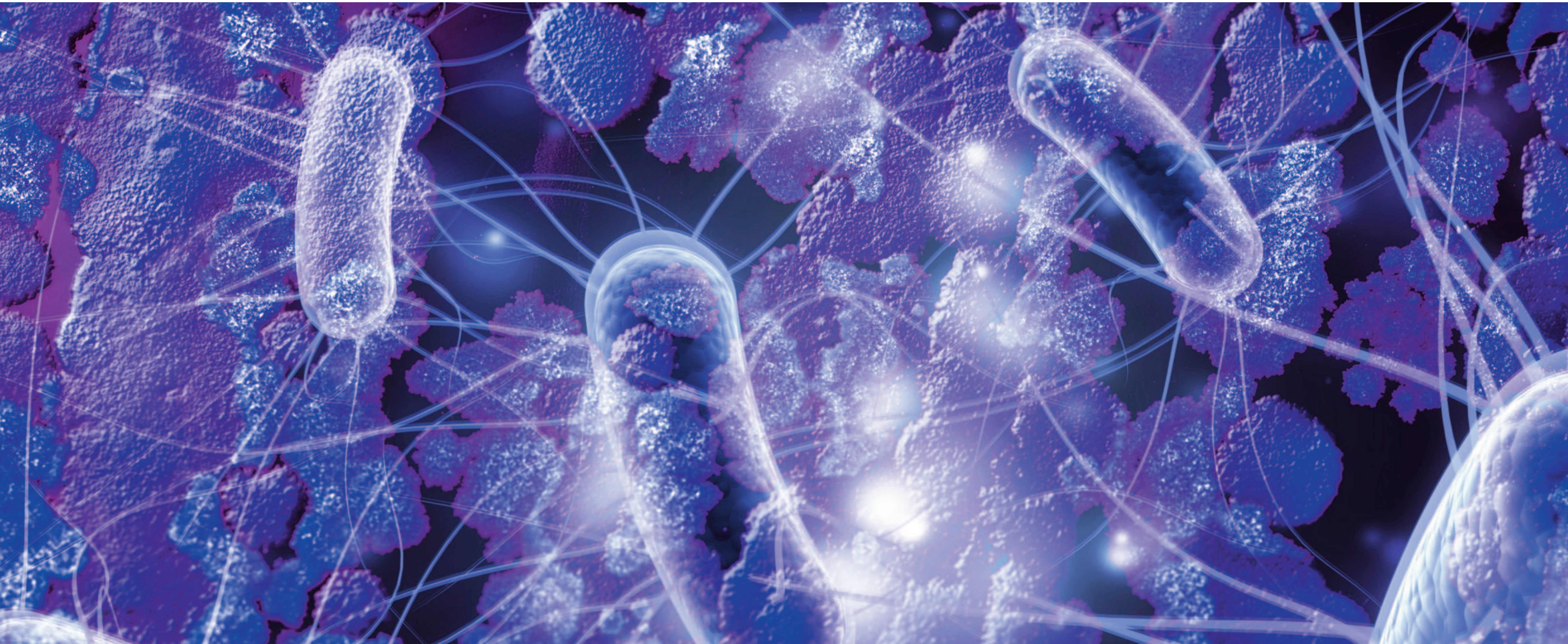
*All quotations throughout the document are taken from respondents to the survey

'They (FBP) are a problem for the food industry and we are part of that industry as primary producers'

Water is an important vehicle for pathogen dissemination on farms and sometimes harmful bacteria can multiply, particularly in warmer weather. It is important to consider waterbodies such as streams and pools on farms as well as ground water, where harmful bacteria can persist. Additionally, water troughs may also harbour bacteria. Risks with water vary for each organism. *E. coli* and *Campylobacter* spp. were both detected in a stream draining dairy pasture and different transport dynamics were observed for each organism[27]. A study of young cattle on farms in England and Wales demonstrated that drinking-water from a private water supply (wells or bore holes) significantly increased the odds of cattle shedding *Campylobacter*[28]. Water may also be a source of both *Cryptosporidium* and *Toxoplasma* oocysts as this parasite life cycle stage is very resistant in the environment and can survive for several months in water[29,30].

Seasonality can also influence risk of FBPs. Specific interventions may not be possible to address these areas directly, but their influence should be factored into the development and implementation of novel practices. **Environmental conditions** can have marked effects on the survival of FBPs on pasture, and climate effects include temperature changes as well as extreme weather events. The effects of weather variables in Canada on prevalence of *Campylobacter, E. coli* and *Salmonella* on meat products were investigated with results suggesting that seasonality played an important role in *Campylobacter* contamination of pig meat[31]. A study focussing on STEC in dairy and beef cattle found that dairy cattle were significantly more likely to shed the bacteria when temperatures were above 28.9°C[32]. Survival of *E. coli* and *Campylobacter* in sheep faeces on pastures was shown to vary according to moisture and temperature levels[33]. Other seasonal affects are **host-associated**. In one study, 5% of pigs were *Salmonella*-positive at the end of the fattening period at the farm and when examined at the slaughterhouse nearly 40% of the pigs were positive[34]. The group of pigs found to be shedding *Salmonella* in the slaughterhouse was comprised of (i) newly contaminated pigs and (ii) the initially infected pigs in which latent infection had been reactivated and (iii) pigs that were already shedding. The authors considered that half of the increase was due to new contaminations.

Photo: Shutterstock.com



FARM INTERVENTION OVERVIEW

Housing practices such as changing bedding and reducing stocking density can limit FBP spread

Cleaning and disinfection can reduce FBP transmission

Fencing can reduce FBP transmission by restricting contact between livestock herds and wildlife

Animal movement can result in FBP transmission between farms. Lowering faecal contamination of hides can reduce this

Vaccination may be used to lower carriage and shedding of FBP

Feed can influence the number of FBPs within the animal gut and in turn, shedding of FBP

FBP and other pathogens can survive in **manure**, which should be managed appropriately to reduce risk

Restricting access to **waterbodies** and courses can reduce exposure to FBP

3.2 Intervention strategies

When assessing interventions or changes in farm management practices to reduce FBPs, some studies focus on pathogens in farm environments (e.g. water, bedding) but levels in animals are not recorded (and even less so for meat), so care must be taken when interpreting results. It is important to note that while most studies focus on individual pathogens, some multi-pathogen studies reported that certain strategies decreased levels of one pathogen while increasing or having no effect on others. Some studies have limited relevance for Scotland e.g. due to differences in climate, availability of materials and farm management options. It is important to fully understand the risks associated with specific farming practices and how farm variation may influence these. Therefore, risk assessments for each scenario should be carried out where possible to evaluate the impact of each intervention. Many studies report findings that indicate no or limited impact of interventions but in this report, we largely consider evidence of where interventions were shown to be successful.

HOUSING / REARING CONDITIONS:

Housing practices for livestock can vary greatly, including the density of animals, duration, season, surfaces and flooring, frequency of bedding changes, and cleaning and disinfection options. Housing management practices must be balanced with welfare and other factors such as skid resistance and durability, and solutions should be sought that improve both hygiene and welfare whilst allowing normal patterns of behaviour.

Indoor housing has been identified as a risk factor for *Campylobacter* detection in young cattle[28], and housing animals from different sources together at various stages of production has been shown to be a significant risk of introduction and spread of *Campylobacter*[35] and *Cryptosporidium*[36]. However, pigs reared outside total confinement (e.g. free-range, or on pasture) are at increased risk of infection with *Salmonella*[37] and *Toxoplasma gondii*[38]. With a move towards more organic systems and outdoor husbandry to suit consumer demand, there may be increased risk of these infections. For housed dairy cattle, the lack of use of tie-stall or stanchion facilities has been associated with an increase in likelihood of shedding *Salmonella*[39].

A number of factors associated with housing may play a role in pathogen transmission and offer opportunities for interventions to reduce this.

Photo: Shutterstock.com

Bedding

Provision of bedding provides a more comfortable environment for housed animals and can encourage them to lie down; however, if not managed properly it can also act as a vehicle for microbial contamination. Previous work has shown that the brisket of cattle (i.e. lower chest) was found to have the highest levels of bacteria compared to rump and flank, likely because this area of the animal comes into contact with the ground when they lie down[40]. As the brisket is the site of the initial cut-line during hide removal at the abattoir, contamination of this area is associated with a higher risk of carcass contamination during processing. The addition of and/or replacement with fresh, clean, straw bedding for cattle can reduce contamination of hides prior to transport for slaughter, or whilst in lairage[41]. Studies have focussed on the influence of type of bedding material and likelihood of microbial contamination. Berry *et al.*[42] investigated carriage and shedding of *E. coli* O157:H7 by cattle housed in pens with pond ash versus pens surfaced with soil and found no differences. Other studies have demonstrated that *E. coli* O157, *Salmonella* and *Campylobacter* all have higher survival rates on straw bedding compared to concrete or metal surfaces without bedding[43]; however, the risk may be reduced if the bedding is sufficiently deep and kept clean and dry. Indeed, keeping bedding dry was shown to be an important factor in reducing shedding of *E. coli* O157 by young cattle[44].

Surfaces and structures

Often, provision of straw (or other) bedding is not feasible on a large scale, so animals are housed on concrete slatted floors. One of the main problems encountered with this flooring is the requirement for a large manure collection pit beneath the floor, which requires regular emptying. A study assessing the level of "dirtiness" of cattle housed on slatted floors demonstrated that cattle were significantly cleaner when housed on single slats compared to gang slats[45]. Brscic *et al.*[46] reported that cattle housed on rubber covered slatted flooring were dirtier than those housed on concrete slatted flooring, due to the lower drainage area of the rubber pens compared with the concrete slatted floor. However, a study in Northern Ireland found no difference in cleanliness of cattle held on rubber covered slats compared with concrete slats[47]. Given the welfare issues surrounding the housing of cattle on fully slatted flooring (e.g. higher number of atypical lying down and standing up movements), the use of rubber covered slats may offer an alternative if straw bedding is not feasible, but the latter option is preferred[48]. Studies in the United States demonstrated that the prevalence of *Salmonella* infection was lower in pigs housed on slatted flooring than in those housed on flush-gutter flooring[49,50], and in Belgium, a fully slatted floor had a protective effect compared with partially slatted floors[51].

Stocking

Stocking density is thought to be an important factor in the transmission of pathogens whether animals are kept outside or housed indoors; however, the results in research reports are varied. A study of 10 sheep farms in Canada demonstrated no significant effect of stocking density on levels of *Campylobacter*, and a marginal effect on levels of *Yersinia*, found in soil, water, and faecal samples[52]. Higher stocking density was identified as a possible risk factor for increased *Campylobacter* prevalence in dairy cattle as well as other pathogens that cause disease in young cattle, such as *Cryptosporidium*[53,54]. Significantly higher levels of *Cryptosporidium* were also found in pigs at higher stocking densities[55]. A stochastic model assessing the effect of interventions on the risk of slaughter-age cattle and sheep carrying *E. coli* O157 found that increased stocking density was associated with increased risk of shedding of the bacteria[56]. Stocking density is important when animals are housed on slatted floors as it reduces the quantity of faeces produced and ensures that as much as possible is trodden through the slats[57].

'I am interested enough to not want anything I do to jeopardise the health of my stock or the health of anyone who might buy my produce'

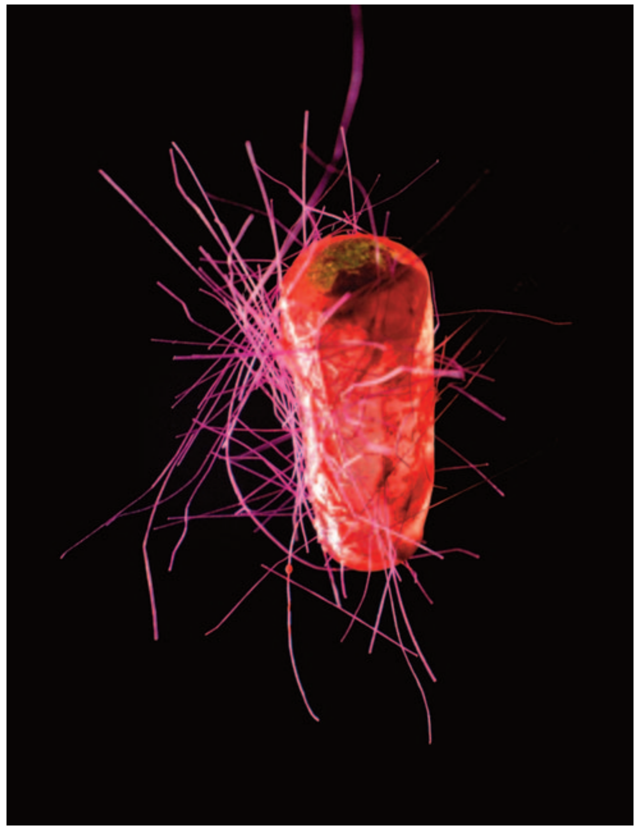


Photo: Shutterstock.com

Drinking Water

A study examining different farm practices to control *E. coli* O157 in young cattle found that emptying water troughs weekly, cleaning water troughs weekly, or raising water troughs to animal chin height did not affect shedding[44]. Furthermore, farmers commented that emptying water troughs weekly impacted on their ability to keep bedding dry. Beauvais *et al.*[58], investigated the effect of reducing water levels on automatically refilling water-troughs in feedlot cattle pens. High levels of water were hypothesised to be a risk for bacterial growth, particularly in warmer weather, but the results showed an association between lower water levels and increased prevalence of *E. coli* O157:H7 in faeces, suggesting that increasing water-trough levels may reduce shedding. When a private water source is used for drinking water, the odds of cattle shedding *Campylobacter* are significantly increased[28]; therefore, use of mains water is encouraged where possible.

Other

Other management strategies include efforts to alleviate heat stress through the use of sprinklers before milking which may have an effect on shedding of *Salmonella* and STEC[59] although Morrow *et al.*[60] reported that this approach did not affect the incidence of these pathogens in feedlot cattle. Herd size may also be a significant factor as indicated in a recent UK-based study focusing on *E. coli* O157[13]; the likelihood of carriage increased for each additional animal in the herd, although it was noted that this may be because herd size was acting as a proxy for other undefined management factors.

CLEANING, DISINFECTION, AND BIOSECURITY

General hygiene and biosecurity practices are employed on farms to varying degrees for reduction of disease transmission and pathogen control in general and these practices can also reduce environmental exposure to FBPs. Practices can relate to the animals themselves, housing, feeders, drinkers, farm workers, equipment, and vehicles. Generally, biosecurity measures that are carried out in isolation are not as effective as combined efforts. A comprehensive literature review of biosecurity and water, sanitation, and hygiene (WASH) interventions was carried out by Pinto Jimenez *et al.*[61] that focussed on animal agricultural settings and reducing infection burden as well as antibiotic use and antibiotic resistance. Interventions aiming to reduce microbial load in animals involved chemical disinfection, manure management / composting, acidification of drinking water, and improved air quality. Whilst many studies reported positive effects of the chosen intervention on reduced microbial load (particularly cleaning and disinfection), others also reported mixed effects or no effect at all for the same intervention. Over 65% of interventions aiming to reduce infections in animals or humans, which involved a combination of changing a farm personnel's hygiene practices with other measures, reported positive effects. However, many studies did not measure long term adherence to the introduced intervention. When this was assessed, the simplicity and feasibility of the intervention influenced adherence by the farmer. The authors also concluded that interventions incurring high costs or involving significant changes were less common, and their effectiveness could be undermined by reduced application if the increased costs of implementing the intervention co-occurred with a perceived lack of reward.

Mechanical **cleaning** can be used to remove contaminated material such as faeces, bedding and unused feed. A study focussing on Enterobacteriaceae, which could include *Salmonella* and STEC, on pig farms in Ireland indicated that cleaning and disinfection may be effective in decreasing bacterial load on floors although this was not observed for feeders and in some farms the bacterial counts on feeders were higher after cleaning[62]. A study focussing on interventions on Norwegian dairy farms suggested that major cleansing of barns was associated with lower contamination of milk by STEC[63]. Methods that involve power washing should be carried out with caution to limit the risk of pathogen transmission through aerosols and spread of contaminated material, especially to areas such as feeders.

An array of **disinfectants** are used on farms and there are some reports of individual disinfectants and inactivation of FBPs. Martelli *et al.*[64] showed that cleaning pig finisher buildings on 10 farms with a glutaraldehyde and quaternary ammonium compound disinfectant at Defra (Department for Environment, Food and Rural Affairs) General Orders concentration was more effective at reducing *Salmonella* than protocols that did not include disinfection. One study focussing on total aerobic counts for Enterobacteriaceae in pig pens investigated efficacy of scraping, soaking with or without detergent, pressure washing, disinfection, and natural drying and found effects varied according to surface and bacterial target[65]. Significant reduction of bacterial counts was observed after soaking metal and concrete (but not stock board) with Blast-Off detergent (Biolink Ltd) and disinfection with Virkon® S (Lanxess) on concrete and stock board but not metal.

A number of studies have focussed on **disinfection of drinking water** to reduce pathogen carriage, with varying degrees of success. Argüello *et al.*[66] investigated the effects of the addition of organic acids (a mixture of lactic, formic, propionic, and acetic) in drinking water and feed on the prevalence of *Salmonella* in finishing pigs. A reduction in seroprevalence and shedding in some groups was observed in this small study although, other studies have not shown similar effects for organic acids[67] and other factors may be important, including concentration, water consumption, age, duration, and contamination levels. Zhao *et al.*[68] investigated the efficacy of chlorine, ozone, disinfectant combinations, and competing *E. coli* in drinking water for cattle. Results showed that competing *E. coli* had minimal effects on reducing *E. coli* O157 populations but chemical combinations containing acidic calcium sulfate were highly effective, although the reduction in burden within cattle was not tested. Limitations for these treatments are costs and unpleasant odours.

'Pathogens can lead to illness that can have an effect on efficiency and profitability'

Biosecurity based around **mixing of animals** is another management practice that may reduce spread of FBPs between individuals and groups. Measures include not bringing new animals onto the farm, limiting contact with other animals, maintaining closed groups, and limiting access to shared water sources. Ellis-Iversen *et al.*[44] identified that keeping closed groups of animals was potentially an effective measure to limit *E. coli* O157 on farms and indicated maintaining animals in the same group may also be important. Keeping animals in the same group has also been identified as a cost-effective intervention as no investment in infrastructure is required[69].

Farm workers, visitors, and their vehicles can also introduce and spread FBPs on farms and therefore biosecurity measures relating to human activities are also important. While there are few studies demonstrating the efficacy of these measures in controlling FBPs on farms, many studies have shown the importance of farm worker biosecurity in reduction of animal diseases, and it is likely that these practices will also reduce FBPs. Practices include correct hand washing procedures and use of personal protective equipment (PPE) in certain scenarios, which should be handled and disposed of appropriately. When cleaning items such as boots, care should be taken to avoid splash risk.

Some studies have focussed on multiple approaches and general biosecurity. Ellis-Iversen *et al.*[44] carried out a randomised controlled trial focussing on multiple practices for control of *E. coli* O157. Results indicated that maintaining clean environments e.g. by keeping bedding dry, cleaning pens before animals are housed, and emptying and cleaning water troughs weekly was effective and that introduction of *E. coli* O157 into herds could be avoided by using biosecurity measures such as use of boot dip and overcoats. Measures were recorded in "packages", so the efficacy of individual measures was difficult to ascertain.

MANAGEMENT OF ORGANIC FERTILISERS

Organic fertilisers are used to provide nutrients and support growth of crops and pasture. They are naturally produced, deriving from plant or animal material and include animal manure, bone meal, compost, dried plant material, human waste, and other components such as used bedding. With increasing demands on agricultural land and the movement of management practices towards net zero targets, the use of manure and organic fertilisers are an attractive option to support a circular economy, providing nutrients for crops and pasture from waste. The success of such a sustainable approach relies on the safe use of manures and many studies have focussed on the survival of pathogens within manure and organic fertilisers. Survival in contaminated matrices and the soil where it is applied is also a major factor and will vary greatly between farm environments[4]. If pathogens remain viable, they may be spread to livestock and crops through leachates from the manure heap, surface run-off, or contamination of water on farmland. Manure handling varies considerably on farms, including animal source, animal housing (indoor or in yards), feed, inclusion of bedding and/or waste feed, location of heap, and use as manure or slurry. Storage of manure also varies greatly. Moisture content, carbon:nitrogen ratios, pH, interactions with other microbes and temperature of manure heaps can vary, affecting pathogen survival.

Manure management guidelines are in place to reduce contamination of crops[70] and the majority of studies investigating FBP risks related to manure, focus on fresh produce rather than impact on livestock carriage and shedding. In Scotland, if farmers are in nitrate vulnerable zones (areas designated at risk of agricultural nitrate pollution for conservation purposes), they must comply with certain rules including keeping accurate farm records, providing adequate storage for livestock manures and slurries, comply with spreading controls and prepare a risk assessment and a fertiliser and manure management plan[71].

Factors that have been considered for intervention strategies include timing of application, time between spreading and grazing, heap turning, and diet modifications to reduce shedding. Risks also vary with the type of organic fertiliser; Nicholson *et al.*[72] reported that *E. coli* O157*, Salmonella, Listeria* and *Campylobacter* survived for longer in slurries and dirty water than in solid manure heaps and Gunn *et al.*[18] reported that cattle were more at risk of shedding *E. coli* O157 if they grazed on farmland where slurry had been spread rather than manure.

'In my experience most of the general public thinks their food comes from and is produced by the supermarket and they do not associate food production with livestock'

Manure should be stored long enough and at the right conditions to ensure that pathogens are inactivated. There are a number of studies that report survival of pathogens in different manure types and conditions. Franz *et al.*[73] found that to reduce the risk of contaminating lettuce with *E. coli* O157 on farms in the Netherlands, a minimum storage time of 30 days and a delay of 60 days between application of fertiliser and planting was required. Heating pig manure to 42°C or 52°C killed *Campylobacter coli* within a few hours[74]. Some studies have focussed on interventions to enhance deactivation of pathogens. Coverings can improve the efficiency of heat treatment by increasing temperatures. Shepherd *et al.*[75] showed that the use of coverings for compost heaps, which consisted of manure, sawdust, waste feed, old straw and fresh straw, increased surface temperatures and rapidly reduced survival of *E. coli* O157 when compared with compost heaps that were covered with fresh straw or left un-covered. Other approaches have focussed on additives to reduce the survival of pathogens. Ravva *et al.*[76] showed that neem tree (*Azadirachta indica*) materials and extracts reduced the survival of *E. coli* O157 in dairy manure. Shepherd *et al.*[77] monitored inactivation of *E. coli* O157 within sample bags placed in manure heaps and reported that the bacterium survived at the surface for up to 4 months, indicating that heap turning may be a practical approach to inactivating *E. coli* O157 within manure heaps.

Hutchison *et al.*[78] showed that length of time before livestock wastes are incorporated into agricultural soil after application influences the presence of viable foodborne bacteria (*Salmonella, Listeria, Campylobacter* spp. and *E. coli* O157). Inactivation was significantly more rapid when wastes were left on the soil surface, which may offer a cost-effective intervention measure.

ANIMAL MOVEMENT

Microbial contamination of animal carcasses can occur in abattoirs, with one of the main sources of contamination being from animal hides during processing and dressing. Despite there being guidelines and legislation for producing clean animals for slaughter[79], it can often be a difficult task for farmers, particularly as cleanliness of animals and their hides can be dependent on many factors, including weather, housing conditions, type of feed, and transport time to slaughter. Most research has focused on cross-contamination of cattle hides by *E. coli* O157. A study of Scottish cattle found that animals transported to the abattoir by a commercial transporter, rather than the farmer, were five times more likely to have *E. coli* O157 contamination on their hides[80]. A follow-up study following cattle from farm to the abattoir found that the likelihood of hide contamination was higher when groups of animals from different farms were transported together and when a commercial transporter was used[14]. The hides of over half of the cattle tested in the study were positive for *E. coli* O157, but 84% of the positive hides were contaminated with a subtype that had not been detected in any animal on the finishing unit, suggesting that contamination had occurred once the animals had left the farm of origin. Indeed, mixing animals from different farms results in dirtier animals arriving at slaughter as unfamiliar animals tend to defecate more and rub against each other[79].

Therefore, encouraging farmers to transport their own (clean) animals to slaughter could be a possible intervention to reduce hide contamination; however, this may not always be feasible. Transportation time to the abattoir can also influence dirtiness and contamination of hides, with cattle transported for long distances (> 160 km) being twice as likely, to be positive for *E. coli* O157 than those transported a shorter distance[81]. Other studies have shown that the prevalence of *Salmonella* in pigs significantly increases when the time of transport to the abattoir is longer than two hours, and a transport and lairage time of 2-6 h can double the number of animals shedding *Salmonella*[82]. Finishing diets can impact on the cleanliness of animals during transportation to the abattoir, with cereal-based diets leading to smaller amounts of dry faeces compared to diets of young grass, silage, and roots which result in larger quantities of wet faeces, potentially causing more hide contamination[57]. Hide contamination is associated with pathogen carriage, as a study of sheep at slaughter demonstrated the mean $\log_{10}$ total viable counts of Enterobacteriaceae at shoulder and abdomen carcass swab sampling sites increased with increasing dirtiness of the animals[57]. Clipping of animal fleeces or hides to remove faecal contamination can be carried out prior to transportation to market or the abattoir, or at the abattoir prior to slaughter. Although clipping may help to improve cleanliness of animals it can be stressful for the animal and may result in injury to both the handler and the animal.

Photo: Pixabay.com

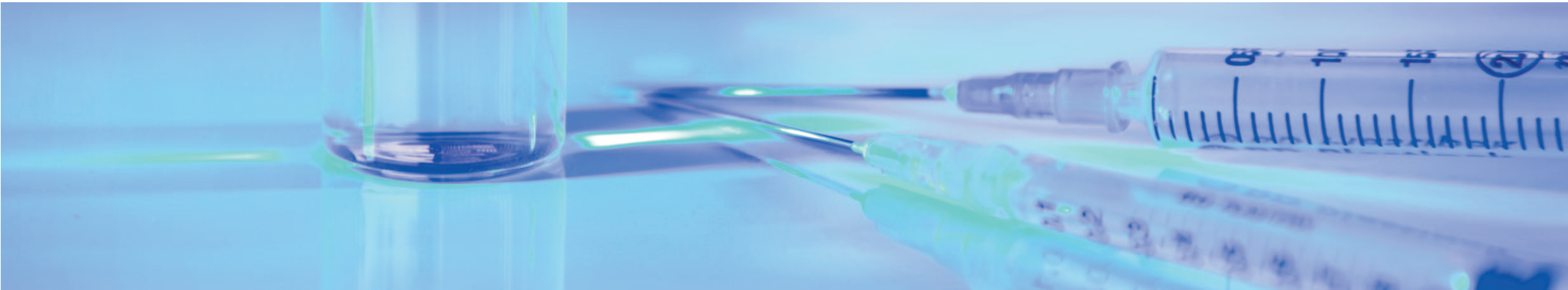
Vaccines are an important tool in combatting human and animal diseases, and their use in livestock has been explored as an on-farm intervention strategy to reduce the carriage of pathogens that cause foodborne illness. Cattle are a major reservoir of *E. coli* O157, and much research has focused on the effect of vaccination on reduction of faecal shedding of the pathogen, particularly in North America where there are commercial vaccines available (incorporating antigens from Type III secreted proteins or siderophore receptor and porin (SRP) proteins). This topic has been reviewed extensively elsewhere[83-85], but studies have shown that vaccinated cattle shed significantly less *E. coli* O157 in their faeces and for a shorter duration of time than non-vaccinated cattle, in natural exposure trials. Although natural exposure trials do not allow for measurement of the bacterial load the vaccinated animals were "challenged" with, they represent real field conditions and are therefore more representative than experimental challenge trials[84]. Despite *E. coli* O157 vaccines being commercially available in the USA and Canada, uptake by farmers is reported to be low, which is likely due to the cost involved, and the lack of observed benefit to their animals as most cattle do not develop clinical disease (see Section 3.3 below). However, vaccination of cattle has been predicted to reduce the number of human cases of *E. coli* by 85% thus highlighting the need to further explore this intervention strategy, particularly in super-shedding cattle which contribute significantly to human cases[86].

Approximately one in three foodborne disease outbreaks in the EU in 2018 were caused by *Salmonella*. Although the majority of cases are caused by *Salmonella* Enteritidis which is associated with poultry, the second most commonly isolated serovar is *Salmonella* Typhimurium which is found in all farmed livestock, particularly pigs[87]. A recent farm-to-fork quantitative microbiological risk assessment for *Salmonella* in pigs in Europe, demonstrated that a large proportion of human risk for infection derives from pigs shedding high concentrations of *Salmonella* in their faeces, and that interventions should focus on measures which can reduce this[88]. Indeed, a similar study estimated that a reduction in prevalence of *S.* Typhimurium in slaughter-age pigs by 50% would reduce the number of human *S.* Typhimurium cases attributable to pig meat by a similar percentage[89]. Given the reports of antimicrobial resistance in some strains of *Salmonella*, vaccination is potentially a more attractive and sustainable option for controlling this pathogen. Commercial vaccines are available for use in pigs and cattle (as well as poultry), and in the UK Salmoporc (CEVA) is licensed for use in pigs to protect against *Salmonella* Typhimurium, and Bovilis® Bovivac® S (MSD) is licensed for use in cattle (mostly dairy cattle) to protect against *Salmonella* Dublin and *Salmonella* Typhimurium. There are a number of studies assessing the use of vaccination as a means of reducing shedding of *Salmonella*[90,91] and carcass contamination at slaughter, thus highlighting the potential of this intervention as a means of controlling foodborne infection. In a study by the Animal and Plant Health Agency (APHA), which trialled three intervention strategies in the control of *Salmonella* in outdoor reared pigs in the UK, vaccination of sows on eight different farms with a live attenuated vaccine resulted in a significant reduction in *Salmonella* prevalence compared to control farms where vaccination was not used[92]. However, there was variation in shedding reduction between the study farms and the authors concluded that vaccination may prove to be a useful intervention to reduce *Salmonella* when used in conjunction with other strategies. In a systematic review of the literature to evaluate the efficacy of vaccination to reduce *Salmonella* prevalence in market-weight finisher pigs, it was concluded that, overall, vaccination is associated with reduced *Salmonella* prevalence in pigs at or near slaughter age[93]. However, there was huge variability in the way the studies included in the review were conducted meaning the authors conducted a qualitative analysis, rather than a pooled data analysis, and suggest this may have influenced the outcome of their review. Overall, vaccines that target the types of *Salmonella* that cause disease in pigs and are also a food safety risk in humans are commercially available and although they have a positive effect and appear to reduce shedding, more robust studies would be required to fully determine their role as an on-farm intervention to reduce foodborne salmonellosis.

'If I can improve my knowledge of foodborne pathogens , I believe I can improve my business'

Foodborne transmission of *T. gondii* is thought to be attributable to 40-60% of clinical cases of toxoplasmosis[94], and consumption of undercooked infected meat has been reported as a significant risk factor for human infection in a number of studies, including in the UK[95].

Currently, there is one vaccine available (Toxovax®) for the protection of congenital toxoplasmosis in sheep, which is licensed for use in the UK, Ireland, France, and New Zealand. The strain used in the vaccine (S48) is "incomplete" and can no longer differentiate into bradyzoites and form tissue cysts, thus making it an attractive option to reduce foodborne transmission of *T. gondii*. Studies have shown that vaccination of pigs[96] and lambs[97] with Toxovax® prior to an oral challenge with oocysts results in a significantly lower burden of cysts in their tissues, demonstrating the potential of vaccination to lead to the production of safer meat. Farmers are less likely to vaccinate their animals solely for the benefit of public health (see Section 3.3); however, in situations where there is an obvious benefit to their animals it may be a more attractive option. For example, where the vaccine protects against abortion. This is well known in sheep, but recently *T. gondii* has been associated with abortions in farmed red deer in New Zealand[98]. With the planned expansion of the farmed deer sector in Scotland[99], and the reported higher incidence of *T. gondii* in venison[100], vaccination may offer a double benefit to farmers – improving fertility of the hinds and making the meat safer for human consumption. *Campylobacter jejuni* and *Campylobacter fetus* can also cause sheep abortion and although there is currently no vaccine against *Campylobacter* available in the UK, Campyvax 4 (MSD Animal Health) is used in New Zealand and can be imported into the UK using the special imports scheme. This vaccine induces immunity against *Campylobacter jejuni* and *Campylobacter fetus* and therefore may reduce risks related to human campylobacteriosis. There is limited data in this area however and further studies are required to determine whether it may have a role as an on-farm intervention to reduce the impact of FBPs.



FEED AND FEEDING SYSTEMS

The addition of chemical or biological treatments to feed and water, as well as altering types of feed, offers an opportunity to reduce intestinal carriage of pathogens by livestock destined for the food chain. Probiotic microbial cultures, such as lactobacilli and bifidobacteria, are often fed to livestock as a means of increasing production efficiency, but they may also have an added benefit of reducing FBP shedding by competing for nutrients or attachment sites in the gut, or by production of antimicrobial compounds. Many studies have investigated the addition of probiotic cultures to feed and although results are not always consistent, there is potential for some probiotics to reduce *Salmonella* shedding in pigs[101], *E. coli* O157:H7 shedding in lambs[102], and *E. coli* O157:H7 and *Salmonella* shedding in cattle[103]. In a systematic review of the literature and meta-analysis to assess the efficacy of direct-fed microbials (DFM) on *E. coli* O157 shedding in beef cattle, it was shown that cattle administered DFM during the pre-harvest stage of production shed significantly lower levels of *E. coli* O157 compared to animals fed a placebo or no treatment[104]. The use of acidified feed (for example, supplemented with lactic acid and/or formic acid) has been shown to reduce carriage of *Salmonella* in market-age pigs[105], as growth and survival of the bacteria is significantly reduced in an acidic environment. However, a systematic review of feed practices and *Salmonella* prevalence in finisher pigs showed that only four out of 14 studies demonstrated a reduction in *Salmonella* prevalence and shedding when fed acidified feed[106]. De Busser *et al.*[107] found no significant reduction in *Salmonella* shedding in finisher pigs fed acidified drinking water for 14 days prior to slaughter.

Different feed types have also been shown to have an effect on carriage of FBPs. In a study focussing on the effect of different feed types on *Salmonella* seroprevalence in finisher pigs, it was reported that a diet of wheat meal reduced seroprevalence by 66% compared to pigs fed heat-treated wheat pellets[108]. Barley was found to be a protective factor against *Salmonella* in pigs in a study in the UK[109]. Many studies have investigated the effects of diet on *E. coli* O157 shedding in ruminants with variable results. Sheep fed hay prior to experimental challenge with *E. coli* O157:H7 were shown to shed significantly higher levels of *E. coli* and for a longer duration than sheep fed corn and pelleted alfalfa[110]. In contrast to this, cattle fed on hay have been demonstrated to have 100-fold lower levels of *E. coli* in their gut compared to cattle fed corn / soybean meal[111]. Furthermore, *E. coli* recovered from the faeces of hay-fed animals had reduced acid resistance than those cultured from faeces of grain-fed cattle. Hay has also been recommended as a diet to feed cattle prior to transportation to slaughter, as it was found to result in drier faeces and cleaner hides compared to those cattle kept at pasture[112], and also led to lower levels of *E. coli* in the faeces compared to fasted animals[113]. However, a study in the UK demonstrated that cattle fed hay were 3 times more likely to shed *Campylobacter* than those not fed hay[28]. A study in the UK also demonstrated that livestock fed on cereal solids (processed grains) shed significantly higher levels of *Cryptosporidium* and *Listeria* in their faeces, and livestock fed primarily on grass shed significantly lower levels of *E. coli* O157 and *Salmonella*. However, levels of *Campylobacter* were higher in grass-fed livestock[55].

'Although people working with livestock must develop strong immunity, this is not necessarily the case for people unused to a farm environment'

It is possible for animal feeds to become contaminated with pathogens during the production process and act as a vehicle for transmission to livestock on farms[114,115]. It is well documented that contaminated feed can be a source of *E. coli* O157 and Salmonella for livestock[115-117]. Although the commercial production of animal feed is regulated, it is important that farmers only purchase feed from approved suppliers or manufacturers who operate high hygiene standards. Correct and hygienic storage of feed is important to reduce contamination by wildlife, rodents, or farm cats. Covering feed storage bins to prevent access to cats and reduce contamination with *T. gondii* oocysts (shed in cat faeces) resulted in a significant reduction in *T. gondii* seroprevalence in finisher pigs in the Netherlands[118].

'What affect would there be if pathogens (FBP) were found in my livestock?'

FENCING AND OTHER TYPES OF WILDLIFE CONTROL

Appropriate fencing is an option for farmers to limit contact with animals on neighbouring farms. Ensuring fencing is repaired when needed and erecting double fencing at farm boundaries to prevent nose-to-nose transmission can limit spread of livestock diseases as well as FBPs. This may be an option that can be employed by farmers to limit spread of FBPs that also brings benefits in terms of animal health. Double fencing with a minimum gap of three metres is recommended for diseases such as bovine viral diarrhoea as part of the Scottish eradication scheme[119]. Fencing has also been used successfully to restrict access to deer and limit the transmission of ticks to livestock. The use of deer fencing may have associated conservation issues and therefore might not be appropriate in all locations[120]. Fencing also enables restriction of access to watercourses (see pages 22-23).

Rodents can be controlled through the use of snap traps and bait boxes and by using rodenticide products. Control of rodents over a four-month period on an organic pig farm was associated with a significant decrease in *Toxoplasma* seropositivity[121].

WATER MANAGEMENT

Pathogens can be spread via water courses and can persist and proliferate in water bodies, water troughs, and ground water on-farm. Treatment of water troughs with chemicals can reduce *E. coli* O157 in cattle[68]. The source of drinking water may influence pathogen carriage. A study in England reported that 10 out of 12 dairy herds that drank water from rivers and streams shed *Campylobacter* while herds that drank tap water were culture-negative[122]. Private water supplies have been associated with increased shedding of *Campylobacter* in young cattle[28]. Kay *et al.*[123] noted that due to high rates of faecal indicator organism (FIO) die-off during storage of farmyard manure and slurry, these wastes are likely to pose a much smaller microbial pollution risk than fresh faeces voided on pastures, especially where grazing livestock have unrestricted access to watercourses. In a more recent study, the same authors investigated the use of streambank fencing as an intervention to reduce FIO fluxes to watercourses from grazed pastures and found that cattle spend a disproportionate amount of time in watercourses that are not fenced. Where total exclusion is in place (through fencing) there is a 1-2 $\log_{10}$ reduction in *E. coli* and intestinal enterococci along the stream reach[124]. Fencing of watercourses, along with grazing management, also led to a reduction in *Cryptosporidium* detection in catchments supplying a public water supply[125].

'As far as I know, public perception of the risks is not currently a threat to the farming industry but it could become one if incidences of food borne diseases were to increase'

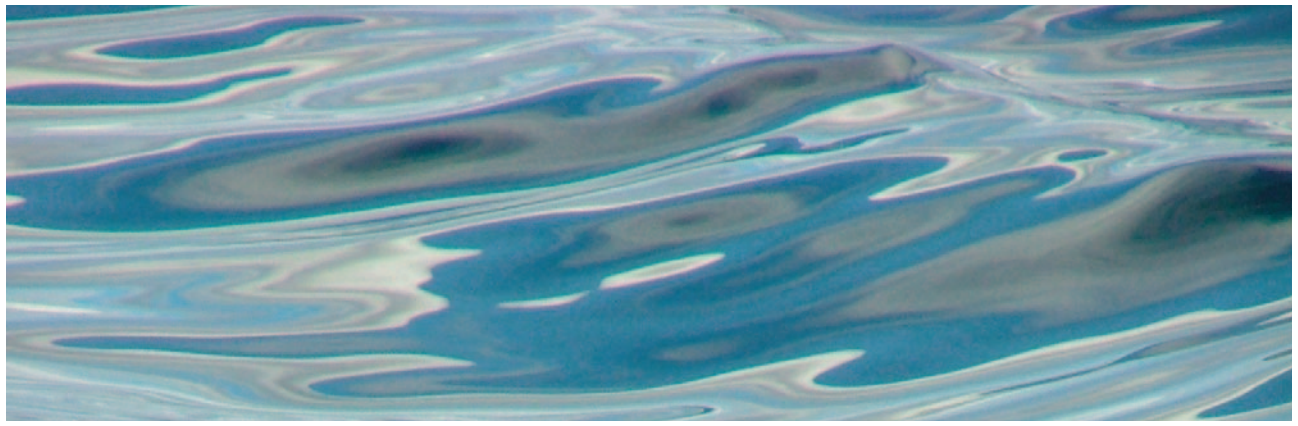


Photo: Pixabay.com

Interventions have been applied to protect the quality of water catchments from zoonotic *Cryptosporidium* parasites. A large outbreak of cryptosporidiosis that occurred in Scotland in 2000 was associated with drinking water supplied from Loch Katrine where the catchment area surrounding the loch had a large sheep and cattle population. Livestock were removed from the area by the water authorities as a precaution and a rapid gravity filtration system was introduced, which successfully reduced the *Cryptosporidium* oocysts from the finished water[126]. A further international example of interventions on farms to protect water quality involved health authorities working together with farmers to protect water catchments in one of the largest water supply systems in the USA. This catchment provided over 9 million people in the New York City area with 4.5 billion litres of water daily from a single source of unfiltered water. Farmers in the Catskills area of New York State had intensified livestock production, leading to increased pollution from faeces and manure getting into the watershed[127]. The New York City authorities worked with the farmers to set up a whole farm planning system to customise pollution control on each farm to maximise effectiveness and minimise cost[128]. By continuing to work effectively with the farmers, the New York City authorities were able to protect the environment in the water catchment area and avoid the multi-billion-dollar cost of filtering the water supply, illustrating very well how a managed environment will produce good quality water.

FUTURE STRATEGIES

Other approaches which are currently in development may also represent successful on-farm interventions. This includes the development of **new innovations** such as the application of antibacterial coatings that are used in materials, for example implants and sewer and water pipes. Kerek *et al.*[129] showed that modified titanium dioxide (TiO_2), a photocatalytic material, was effective in inactivating *E. coli.* A number of studies have focussed on the administration of **bacteriophages**, also known as phage therapy, which has emerged as a potential alternative to treatment with antibiotics. A review of the use of bacteriophages for control of FBPs was carried out by Bumanang *et al.*[130] and highlights potential points for application as well as shortcomings and strategies for improvement. Interventions related to a reduction in bacterial biofilm formation may also play a role in reducing risks associated with FBPs on farms[131]. Alternative approaches include the use of dung beetles as a method of biological control. The presence of dung beetles on organic farms has been shown to reduce the transmission of *E. coli* O157 from pig faeces to broccoli plants by fly vectors[132]. A number of studies have focussed on successful interventions for poultry and although their efficacy for livestock has not been assessed, these interventions may also have applications on livestock farms. These include practices related to hygiene and biosecurity[61] as well as alternative approaches such as competitive exclusion[133].

3.3 Identification of incentives and barriers to implementation of interventions in Scotland and across the UK

Implementation of farm interventions is dependent on a number of factors, and practices that are effective, cost efficient and simple to deploy are more likely to be successful. Barriers including cost, time, complexity, lack of buy-in from farmers, legislative restrictions, conflicting advice and other impacts on farm management will reduce the likelihood of implementation. Interventions that offer added value to farmers such as increased health and productivity of livestock more generally, accreditation schemes that improve routes to retailers and provision of financial options, may incentivise uptake on farms. Economic barriers are likely to have a major impact on uptake; for example, a cost-benefit analysis of *Salmonella*-control strategies in pigs reared in the United Kingdom demonstrated that the cost of implementation outweighed the financial benefits related to human health and pig productivity[134].

Strategies that also reduce animal diseases may be much more attractive to farmers. Some FBPs, including *Toxoplasma gondii, Campylobacter* and *Salmonella* can cause ovine abortion and reducing the presence of these pathogens on farms may also lower the incidence of abortions in sheep. A number of correlations have been observed between other animal diseases and carriage of FBPs. For example, infection with *Fasciola hepatica* (liver fluke) in cattle is associated with increased susceptibility to *Salmonella*[135] and may be associated with increased shedding of *E. coli* O157[136]. Furthermore, evidence exists that some interventions such as vaccination for animal diseases can also reduce FBP carriage e.g. a reduction in the seroprevalence for *Salmonella* in swine herds was observed following administration of the Enterisol® Ileitis vaccination for *Lawsonia intracellularis*, a causative agent of intestinal disease in pigs[137].

A study carried out by Ellis-Iverson *et al.*[138] focusing on perceptions, circumstances and motivators for implementation of zoonotic control programmes in English and Welsh cattle farmers indicated that the majority of farmers enrolled in the study acknowledged a social responsibility for food safety, and highlighted advice from veterinarians as a motivating factor as well as consumer confidence. These results suggest that farmers are already well-engaged but require support to enable and empower them to implement new practices, and education was highlighted as a key factor in implementation of interventions. Other factors influencing uptake of interventions that were identified in this study include perceived futility of adopting practices unless these are adopted at a national level, financial pressures from supermarkets and retailers, lack of support from the government, lack of branding and control of imported products, differences in opinion on where responsibility lies for food safety and lack of belief in self-efficacy.

Education has been identified as a major obstacle in adoption of practices, and this will be paramount to improve understanding of the problem and incentivise buy-in, as well as ensuring that interventions are implemented correctly. It may be appropriate for education to be centralised, possibly at the government level to ensure confidence, and materials should be available in different formats and disseminated through different routes, to maximise reach and cater for the diversity of farmers and their preferred means of accessing information.

Farmer-led participatory approaches may offer opportunities to explore and address incentives and barriers more fully as well as provide farmers with opportunities to contribute through their own expertise and experience in farm management practices. A study carried out by Morgans *et al.*[139] highlighted the benefits of this approach in changing practices around antimicrobial use on UK farms and demonstrated the value of engaging farmers in a public health initiative at an early stage.

Photo: Shutterstock.com

3.4 Survey of livestock farmers

A survey of livestock farmers was conducted to capture expert opinion relating to current practices, opinion on feasibility of interventions concerning FBPs on-farm, and attitudes to incentives and barriers to changing farm practices. A focus group was set up comprising livestock farmers (sheep and cattle) from different geographical regions of Scotland along with one veterinarian. This group provided feedback and comments on the survey questions and the length of the survey was revised accordingly. The survey was launched on the 20th of November 2023 and closed on the 12th of December 2023 and was promoted through social media, the Moredun Foundation and other farming industry networks.

The survey was completed by 80 participants with the majority, 70% (56/80), from Scotland. The respondents came from a wide range of locations across Scotland including: Orkney, Shetland, Highland, Ross-shire, Caithness, Moray, Banffshire, Aberdeenshire, Perthshire, Fife, Angus, Renfrewshire, Lanarkshire, East Lothian, Borders, and Dumfriesshire. The respondents were all involved in livestock farming with 76-79% in sheep and/or beef, and 40% of respondents also with a component of arable.

The majority of respondents had heard of the main FBPs covered in the survey; 99% (77/78) had heard of *E. coli* (O157 and other STECs) but respondents were less aware of *Cryptosporidium* (78%; 61/78) and *Campylobacter* (76%; 59/78). Most respondents (59%; 46/78) understood that some of these pathogens may also cause production diseases in livestock and may be spread through faeces or on raw meat. Seventy-one percent (71%; 55/77) of respondents thought that FBPs are a problem for the industry but only 24% (18/76) felt that FBPs were a problem for their own business. Encouragingly, 92% (70/76) of respondents were interested in finding out more about FBPs in their livestock and just over half of those surveyed (51%; 39/76) thought that the public perception of the risk of foodborne diseases in livestock were a threat to the industry.

Most respondents (88%; 64/73) were a member of one or more farm assurance schemes, with the majority being a member of the QMS Assurance Scheme (67%; 49/73), as well as others such as Red Tractor (29%; 21/73) and Scottish Quality Crops (14%; 10/73).

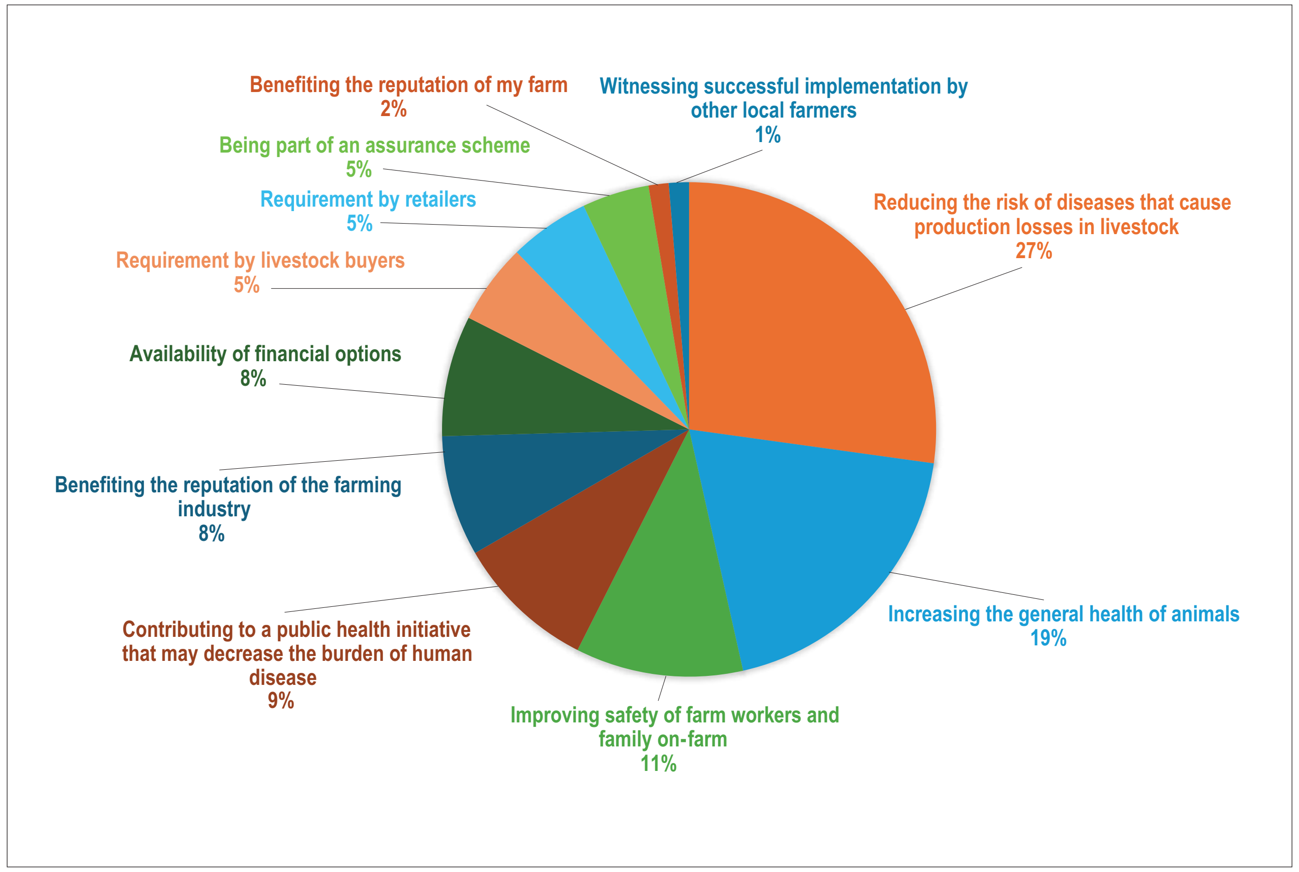
There was a strong majority view, 93% (70/75), that farmers would be much more likely to vaccinate their animals if the vaccine also afforded protection against a production disease in livestock, whereas only 45% (34/76) of respondents said they would consider vaccinating livestock solely for a public health benefit. The top three incentives for farmers to consider using vaccination as an intervention method to protect against FBPs were: to increase the value of their animals (72%); if there were financial options to cover the costs (62%); and if the vaccine could be administered along with other flock management practices (54%).

'Being an extensive system and through regular contact with our vet we don't perceive there to be an issue (with FBP)'

Eighty-seven percent (87%; 67/77) of the respondents use farmyard manure and or slurry as a fertiliser on their farm and only very few (1.8%; 1/57) use human sewage or sludge pellets. The majority of respondents would replace soiled bedding and remove farmyard manure from livestock pens weekly or more frequently. Those who do not, cite the reasons as being too time-consuming, too expensive, and not practical for other reasons. Although 52% (40/77) of respondents already clean feeding troughs on a weekly basis or more frequently, only 36% (28/77) currently clean water troughs at least once a week. Time was identified as a barrier for cleaning both feed and water troughs although this was also identified as being not practical for other reasons. Forty-one percent (41%; 30/74) of respondents currently have double fencing and cost was an important factor in respondents deciding whether to erect additional fencing as a biosecurity measure.

Figure 1

*Farmer responses in relation to the question **"What would you consider to be the top 3 drivers / incentives for implementing new farm practices to reduce foodborne pathogens on farm?"** Farmers could choose up to 3 possible answers, and percentages represent the proportion of a specific answer amongst all answers chosen. Percentages have been rounded to the nearest whole number. For information on the number of farmers choosing each intervention, see Appendix 1 (Qu.24).*

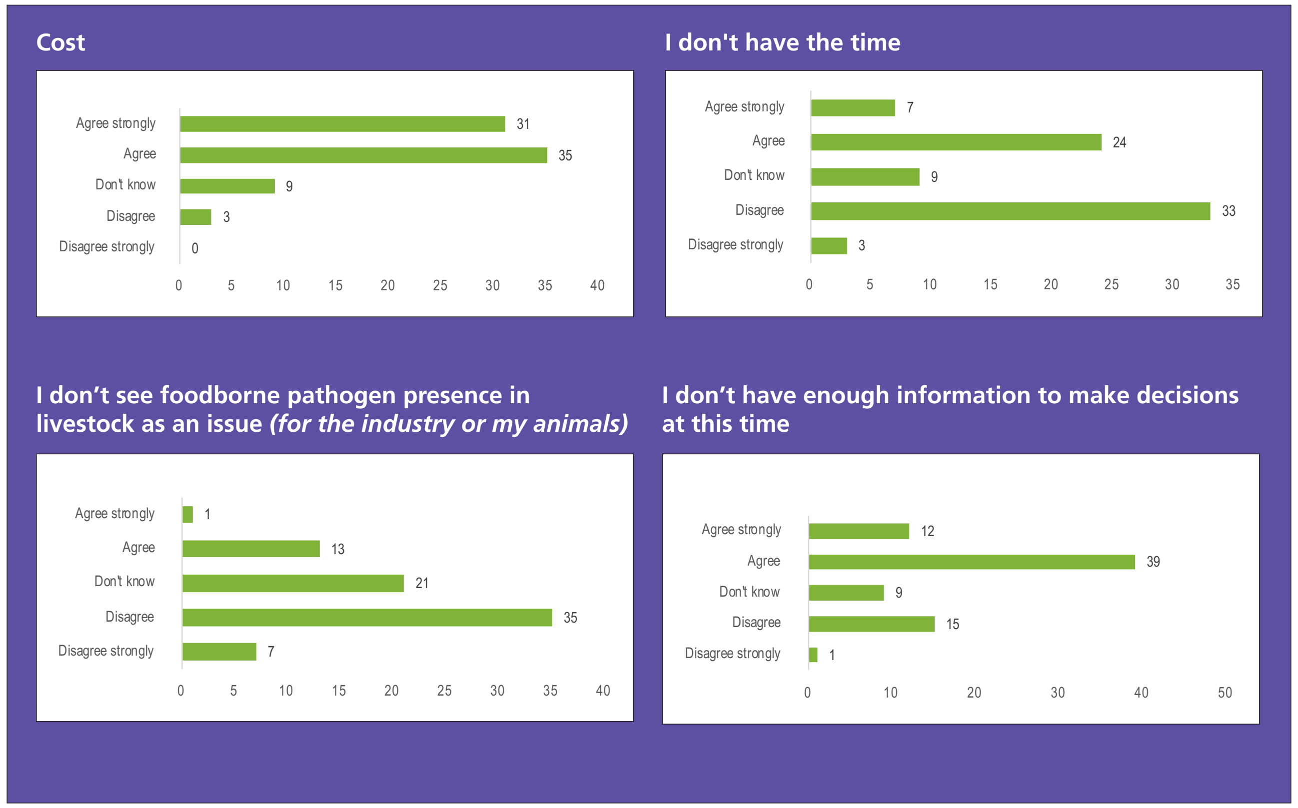


The top three incentives for farmers to implement farm practices to reduce FBPs on farm were: reducing the risk of diseases that cause production issues in livestock, increasing the general health of animals, and improving safety of farm workers and family on farm (Figure1). Cost and lack of information were seen as barriers to implementing new farm practices to reduce FBPs, an observation that has been reported in other studies[61] (Figure 2). Local vets were identified as the main source from which respondents currently receive general infection control guidance.

'It is important to keep stock healthy and minimize risk to consumers, after all I too am a consumer and have no desire to eat contaminated food'

Figure 2

Farmer responses in relation to the question ***"What would prevent you from implementing new farm practices to reduce foodborne pathogens?"***



4. Other Considerations

There are a number of additional considerations related to development and implementation of management practices that are relevant only to specific farming systems. Pathogen-specific considerations may also be important e.g. for *Campylobacter,* proximity of livestock to poultry and use of chicken manure, and for *Toxoplasma,* the presence of cats on-farm. Additionally, the influence of other animal diseases and the treatments for those diseases may also influence shedding and dissemination. It may therefore be more appropriate to apply interventions that are tailored to specific farms and farming practices rather than recommend blanket approaches. It is also important to consider the application of **pathogen monitoring** on-farm and how this may be used to inform when interventions might be required. Alongside this, improved diagnostics for related animal diseases such as ovine abortion caused by FBPs such as *Campylobacter* and *Toxoplasma,* and calf scour caused by *Cryptosporidium,* can also play important roles in understanding spread and impact of certain FBPs on farms, especially when this may result in increased uptake of interventions with multiple benefits to both farmers and public health.

Climate change is a key factor that may have a major influence on the distribution and burden of FBPs within farmed environments. Changes relating to global temperatures and seasonality, rainfall levels, and extreme weather events may influence the survival and proliferation of pathogens in the environment as well as impacting on host factors that influence disease susceptibility. Animal behaviour may also be an influencing factor, including patterns of wildlife migration and distribution of vectors, and this may result in changes in transmission risks. Many of these challenges are outlined in reviews carried out by Hellberg and Chu[140] and Cavicchioli *et al.*[141]

Changes in legislation and the implementation of novel initiatives may influence farm practices and also provide opportunities to consolidate efforts related to both animal and public health. For example, the Animal Health and Welfare Pathway[142] (involving both Defra and the Scottish Government through the Agriculture Reform Implementation Oversight Board) may offer opportunities for farmers to reduce disease burden that also impacts on carriage of FBPs.
The implementation of eradication schemes may provide indirect benefits. Equally, changes to requirements and legislation that are driven by Brexit through agricultural reform or through initiatives related to net zero targets[143] may limit or influence implementation of interventions. Examples of changes may relate to manure management, regulations around the use and importation of feed additives as well as sustainable and innovative practices. In some cases, changes or lifting of restrictions may result in unforeseen risks associated with FBPs. Horizon scanning would help mitigate this and highlight emerging issues. Engagement with animal health organisations and consortia such as EPIC, the Scottish Government's Centre of Expertise on Animal Disease Outbreaks, may be beneficial, where lessons learned relating to uptake of practices, effective biosecurity, and identification of farm risk factors may be applied in the successful implementation of interventions to reduce the impact of FBPs.

Finally, although not the focus of this study, the spread and emergence of antimicrobial resistance is an issue that should be considered in parallel with challenges related to FBPs. Many factors that influence risks associated with FBPs also impact on resistant bacteria (e.g. effects of climate change, nutritional effects on the microbiome, faecal oral transmission routes, survival in manure) and interventions may therefore offer **One Health solutions** for both challenges. Drivers for implementation are also linked and this may be an important consideration when developing initiatives to support farmers. Studies that focus on changing practices related to antimicrobial use on UK farms may provide insights into uptake of practices to reduce the impact of FBPs.

5. Conclusions

- Understanding the main routes of entry, carriage, multiplication and further spread of FBPs on livestock farms will help to determine the most effective interventions to apply to reduce the impact of FBPs at the farm level.
- Knowledge of the prevalence of particular FBPs on-farm would be helpful in prioritising specific interventions to achieve optimal impact in reducing the risk of FBPs on farm.
- As many of the FBPs are shed in faeces, sampling eDNA (environmental DNA) from wastewater coming from the farm may give insight into the presence and quantity of specific pathogens. Wastewater surveillance has been used to successfully monitor for specific pathogens such as SARS-Cov-2 during the Covid-19 pandemic[144].
- Applying biosecurity measures involving new animals being introduced to the farm, use of fencing to keep out wildlife and contact with other animals, regular cleaning of animal accommodation, stocking density and not mixing age groups of animals will help to minimise risk of amplification and spread of FBPs.
- Vaccination may be an effective intervention to help reduce the spread and transmission of FBPs. Some vaccines are available that reduce livestock production diseases caused by pathogens (which are also a cause of foodborne diseases) so these may offer an option for FBP control. Although, this would require validation studies that focus on reduction of pathogen shedding as well as data on duration of immunity.
- In a survey of livestock farmers there was interest in finding out more about FBPs in livestock and an understanding of the threat of FBPs to the industry.
- Farmers were much more likely to vaccinate their livestock against a production disease of animals than if there was only a public health benefit.
- The cost of implementing interventions and lack of information on the risks posed by FBPs were seen as barriers to implementing new farm practices or interventions to reduce FBPs.
- Different farmers have different motivators, and this should be acknowledged when devising intervention strategies.
- A review of the literature showed several interventions that could be applied on-farm to reduce the risk of FBPs but there is a lack of compelling evidence to support any singular intervention that demonstrates significant efficacy in reducing the occurrence and burden of specific FBPs.
- There will be a lot of variation between farms on the relative risk of FBPs and each farm would require a risk assessment with different interventions being prioritised.
- Engagement in biosecurity and hygiene practices of farm workers and visitors would also bring benefits in reducing disease burden.
- There are a number of potential novel interventions in development, such as phage therapy, and progress in these areas should be monitored.

Photo: Shutterstock.com

6. Recommendations

- Improved methods and pipelines for pathogen monitoring will support identification of pathogen risks on individual farms as well as the means to determine efficacy of interventions.
- More evidence is required on the efficacy of interventions on Scottish farms. Methods should be devised to measure the impact of applying interventions and these may have to focus on specific pathogens.
- Education is key and the provision of trusted resources and knowledge brokers with consistent messaging is necessary. This should relate to specific issues and risks around FBPs, background information to improve understanding of pathogen survival and transmission as well as guidance in implementing certain interventions.
- Engagement of farmers about the benefits of tackling FBPs on-farm could initially focus on those that also cause production diseases as farmers are already incentivised to take action in controlling these pathogens.
- Cost analyses for interventions (individually and in combination) should be carried out to support decision making around adoption of new practices.
- Continued consultation with farmers is recommended as this will support the identification of interventions and management practices which are practical and effective, and farmer-led initiatives may offer additional benefits.

Photo: Shutterstock.com

Acknowledgements

We would like to thank Dr David Bartley and Dr Lynsey Melville for their helpful advice in conducting the survey of livestock farmers. We are also very grateful to our farmer focus group who provided us with feedback and suggestions on the questions for the survey.

This work was jointly funded by Food Standards Scotland (FSS) and Rural & Environment Science & Analytical Services Division (RESAS) Scottish Government.

Disclaimer: The content of this report does not reflect the official opinion of the Scottish Government. Responsibility for the information and views expressed therein lies entirely with the author(s).

This project was commissioned in 2024.

References

1 Daniel, N., Casadevall, N., Sun, P., Sugden, D. & Aldin, V. The Burden of Foodborne Disease in the UK 2018. (https://www.food.gov.uk/, 2020).

2 Hutchison, M. L., Walters, L. D., Avery, S. M., Synge, B. A. & Moore, A. Levels of zoonotic agents in British livestock manures. *Lett Appl Microbiol* **39**, 207-214, doi:10.1111/j.1472-765X.2004.01564.x (2004).

3 Hutchison, M. L., Walters, L. D., Moore, A. & Avery, S. M. Declines of zoonotic agents in liquid livestock wastes stored in batches on-farm. *J Appl Microbiol* **99**, 58-65, doi:10.1111/j.1365-2672.2005.02585.x (2005).

4 Black, Z. *et al*. The Fate of Foodborne Pathogens in Manure Treated Soil. *Front Microbiol* **12**, 781357, doi:10.3389/fmicb.2021.781357 (2021).

5 Gonzalez-Rivas, P. A. et al. Effects of heat stress on animal physiology, metabolism, and meat quality: A review. *Meat Sci* **162**, 108025, doi:10.1016/j.meatsci.2019.108025 (2020).

6 Bansal, T. *et al*. Differential effects of epinephrine, norepinephrine, and indole on *Escherichia coli* O157:H7 chemotaxis, colonization, and gene expression. *Infect Immun* **75**, 4597-4607, doi:10.1128/IAI.00630-07 (2007).

7 Cogan, T. A. *et al*. Norepinephrine increases the pathogenic potential of *Campylobacter jejuni*. *Gut* **56**, 1060-1065, doi:10.1136/gut.2006.114926 (2007).

8 Jones, K., Howard, S. & Wallace, J. S. Intermittent shedding of thermophilic *Campylobacters* by sheep at pasture. *J Appl Microbiol* **86**, 531-536, doi:10.1046/j.1365-2672.1999.00702.x (1999).

9 Renter, D. G. *et al*. Detection and determinants of *Escherichia coli* O157:H7 in Alberta feedlot pens immediately prior to slaughter. *Can J Vet Res* **72**, 217-227 (2008).

10 Barkocy-Gallagher, G. A. *et al*. Seasonal prevalence of Shiga toxin-producing *Escherichia coli*, including O157:H7 and non-O157 serotypes, and *Salmonella* in commercial beef processing plants. *J Food Prot* **66**, 1978-1986, doi:10.4315/0362-028x-66.11.1978 (2003).

11 Brown-Brandl, T. M., Berry, E. D., Wells, J. E., Arthur, T. M. & Nienaber, J. A. Impacts of individual animal response to heat and handling stresses on *Escherichia coli* and *E. coli* O157:H7 fecal shedding by feedlot cattle. *Foodborne Pathog Dis* **6**, 855-864, doi:10.1089/fpd.2008.0222 (2009).

12 Rostagno, M. H. Can stress in farm animals increase food safety risk? Foodborne *Pathog Dis* **6**, 767-776, doi:10.1089/fpd.2009.0315 (2009).

13 Henry, M. K. *et al*. The British *E. coli* O157 in cattle study (BECS): factors associated with the occurrence of *E. coli* O157 from contemporaneous cross-sectional surveys. *BMC Vet Res* **15**, 444, doi:10.1186/s12917-019-2188-y (2019).

14 Mather, A. E. *et al*. Factors associated with cross-contamination of hides of Scottish cattle by *Escherichia coli* O157. *Appl Environ Microbiol* **74**, 6313-6319, doi:10.1128/AEM.00770-08 (2008).

15 Liu, W. C. *et al*. Metapopulation dynamics of *Escherichia coli* O157 in cattle: an exploratory model. *J R Soc Interface* **4**, 917-924, doi:10.1098/rsif.2007.0219 (2007).

16 Sanad, Y. M., Closs, G., Jr., Kumar, A., LeJeune, J. T. & Rajashekara, G. Molecular epidemiology and public health relevance of *Campylobacter* isolated from dairy cattle and European starlings in Ohio, USA. *Foodborne Pathog Dis* **10**, 229-236, doi:10.1089/fpd.2012.1293 (2013).

17 Synge, B. A. *et al*. Factors influencing the shedding of verocytotoxin-producing *Escherichia coli* O157 by beef suckler cows. *Epidemiol Infect* **130**, 301-312, doi:10.1017/s0950268802008208 (2003).

18 Gunn, G. J. *et al*. An investigation of factors associated with the prevalence of verocytotoxin producing *Escherichia coli* O157 shedding in Scottish beef cattle. *Vet J* **174**, 554-564, doi:10.1016/j.tvjl.2007.08.024 (2007).

19 Fitzgerald, S. F. *et al*. Prevalence of Shiga Toxin-Producing *Escherichia coli* O157 in Wild Scottish Deer with High Human Pathogenic Potential. *Animals (Basel)* **13**, doi:10.3390/ani13172795 (2023).

20 Jahan, N. A., Lindsey, L. L. & Larsen, P. A. The Role of Peridomestic Rodents as Reservoirs for Zoonotic Foodborne Pathogens. *Vector Borne Zoonotic Dis* **21**, 133-148, doi:10.1089/vbz.2020.2640 (2021).

21 Espinosa, L., Gray, A., Duffy, G., Fanning, S. & McMahon, B. J. A scoping review on the prevalence of Shiga-toxigenic *Escherichia coli* in wild animal species. *Zoonoses Public Health 65*, 911-920, doi:10.1111/zph.12508 (2018).

22 Moriarty, E. M., Weaver, L., Sinton, L. W. & Gilpin, B. Survival of *Escherichia coli*, enterococci and *Campylobacter jejuni* in Canada goose faeces on pasture. *Zoonoses Public Health* **59**, 490-497, doi:10.1111/zph.12014 (2012).

23 Mendoza, H., Rubio, A. V., García-Peña, G. E., Suzán, G. & Simonetti, J. A. Does land-use change increase the abundance of zoonotic reservoirs? Rodents say yes. *European Journal of Wildlife Research* **66**, doi:10.1007/s10344-019-1344-9 (2019).

24 Biswas, S. *et al*. Impacts of dietary forage and crude protein levels on the shedding of *Escherichia coli* O157:H7 and *Listeria* in dairy cattle feces. *Livestock Science* **194**, 17-22, doi:10.1016/j.livsci.2016.10.011 (2016).

25 Grove-White, D. H., Leatherbarrow, A. J., Cripps, P. J., Diggle, P. J. & French, N. P. Temporal and farm-management-associated variation in the faecal-pat prevalence of *Campylobacter jejuni* in ruminants. *Epidemiol Infect* **138**, 549-558, doi:10.1017/S0950268809991051 (2010).

26 Queiroz, O. C. M., Ogunade, I. M., Weinberg, Z. & Adesogan, A. T. Silage review: Foodborne pathogens in silage and their mitigation by silage additives. *J Dairy Sci* **101**, 4132-4142, doi:10.3168/jds.2017-13901 (2018).

27 Stott, R. *et al*. Differential behaviour of *Escherichia coli* and *Campylobacter* spp. in a stream draining dairy pasture. *J Water Health* **9**, 59-69, doi:10.2166/wh.2010.061 (2011).

28 Ellis-Iversen, J., Pritchard, G. C., Wooldridge, M. & Nielen, M. Risk factors for *Campylobacter jejuni* and *Campylobacter coli* in young cattle on English and Welsh farms. *Prev Vet Med* **88**, 42-48, doi:10.1016/j.prevetmed.2008.07.002 (2009).

29 Innes, E. A., Chalmers, R. M., Wells, B. & Pawlowic, M. C. A One Health Approach to Tackle Cryptosporidiosis. *Trends Parasitol* **36**, 290-303, doi:10.1016/j.pt.2019.12.016 (2020).

30 López Ureña, N. M. *et al*. Contamination of Soil, Water, Fresh Produce, and Bivalve Mollusks with *Toxoplasma gondii* Oocysts: A Systematic Review. *Microorganisms* **10**, doi:10.3390/microorganisms10030517 (2022).

31 Smith, B. A., Meadows, S., Meyers, R., Parmley, E. J. & Fazil, A. Seasonality and zoonotic foodborne pathogens in Canada: relationships between climate and *Campylobacter, E. coli* and *Salmonella* in meat products. *Epidemiol Infect* **147**, e190, doi:10.1017/s0950268819000797 (2019).

32 Venegas-Vargas, C. *et al*. Factors Associated with Shiga Toxin-Producing *Escherichia coli* Shedding by Dairy and Beef Cattle. *Appl Environ Microbiol* **82**, 5049-5056, doi:10.1128/AEM.00829-16 (2016).

33 Moriarty, E. M., Mackenzie, M. L., Karki, N. & Sinton, L. W. Survival of *Escherichia coli*, Enterococci, and *Campylobacter* spp. in sheep feces on pastures. *Appl Environ Microbiol* **77**, 1797-1803, doi:10.1128/AEM.01329-10 (2011).

34 Berends, B. R., Urlings, H. A., Snijders, J. M. & Van Knapen, F. Identification and quantification of risk factors in animal management and transport regarding *Salmonella* spp. in pigs. *Int J Food Microbiol* **30**, 37-53, doi:10.1016/0168-1605(96)00990-7 (1996).

35 Collins, J. D. & Wall, P. G. Food safety and animal production systems: controlling zoonoses at farm level. *Rev Sci Tech* **23**, 685-700, doi:10.20506/rst.23.2.1510 (2004).

36 Thomson, S. *et al*. Bovine cryptosporidiosis: impact, host-parasite interaction and control strategies. *Vet Res* **48**, 42, doi:10.1186/s13567-017-0447-0 (2017).

37 van der Wolf, P. J. *et al*. *Salmonella* seroprevalence at the population and herd level in pigs in The Netherlands. *Vet Microbiol* **80**, 171-184, doi:10.1016/s0378-1135(00)00387-4 (2001).

38 van der Giessen, J., Fonville, M., Bouwknegt, M., Langelaar, M. & Vollema, A. Seroprevalence of *Trichinella spiralis* and *Toxoplasma gondii* in pigs from different housing systems in The Netherlands. *Vet Parasitol* **148**, 371-374, doi:10.1016/j.vetpar.2007.06.009 (2007).

39 Fossler, C. P. *et al*. Herd-level factors associated with isolation of *Salmonella* in a multi-state study of conventional and organic dairy farms I. *Salmonella* shedding in cows. *Prev Vet Med* **70**, 257-277, doi:10.1016/j.prevetmed.2005.04.003 (2005).

40 Reid, C. A., Small, A., Avery, S. M. & Buncic, S. Presence of food-borne pathogens on cattle hides. *Food Control* **13**, 411-415, doi:https://doi.org/10.1016/S0956-7135(01)00050-0 (2002).

41 Adam, K. & Brulisauer, F. The application of food safety interventions in primary production of beef and lamb: a review. *Int J Food Microbiol* **141 Suppl 1**, S43-52, doi:10.1016/j.ijfoodmicro.2009.12.020 (2010).

42 Berry, E. D. *et al*. Soil versus Pond Ash Surfacing of Feedlot Pens: Occurrence of *Escherichia coli* O157:H7 in Cattle and Persistence in Manure. *J Food Prot* **73**, 1269-1277, doi:10.4315/0362-028x-73.7.1269 (2010).

43 Small, A., Reid, C. A. & Buncic, S. Conditions in lairages at abattoirs for ruminants in southwest England and in vitro survival of *Escherichia coli* O157, *Salmonella Kedougou*, and *Campylobacter jejuni* on lairage-related substrates. *J Food Prot* **66**, 1570-1575, doi:10.4315/0362-028x-66.9.1570 (2003).

44 Ellis-Iversen, J. *et al*. Farm practices to control *E. coli* O157 in young cattle - a randomised controlled trial. *Vet Res* **39**, 3, doi:10.1051/vetres:2007041 (2008).

45 Fallon, R. J. & Lenehan, J. J. Factors Affecting the Cleanliness of Cattle Housed in Buildings wiith Concrete Slatted Floors. (Teagasc, 2002).

46 Brscic, M. *et al*. Synthetic rubber surface as an alternative to concrete to improve welfare and performance of finishing beef cattle reared on fully slatted flooring. *Animal* **9**, 1386-1392, doi:https://doi.org/10.1017/S1751731115000592 (2015).

47 Lowe, D. E., Lively, F. O. & Gordon, A. W. The effect of diet and covering fully slatted concrete floors with rubber strips on the intake, performance and cleanliness of dairy-origin bulls. *Animal* **13**, 2092-2100, doi:https://doi.org/10.1017/S1751731119000272 (2019).

48 Absmanner, E., Rouha-Mülleder, C., Scharl, T., Leisch, F. & Troxler, J. Effects of different housing systems on the behaviour of beef bulls—An on-farm assessment on Austrian farms. *Applied Animal Behaviour Science* **118**, 12-19, doi:https://doi.org/10.1016/j.applanim.2009.02.009 (2009).

49 Davies, P. R. *et al*. Prevalence of *Salmonella* in finishing swine raised in different production systems in North Carolina, USA. *Epidemiol Infect* **119**, 237-244, doi:10.1017/s095026889700784x (1997).

50 Davies, P. R. *et al*. Risk of shedding *Salmonella* organisms by market-age hogs in a barn with open-flush gutters. *J Am Vet Med Assoc* **210**, 386-389 (1997).

51 Nollet, N. *et al*. Risk factors for the herd-level bacteriologic prevalence of *Salmonella* in Belgian slaughter pigs. *Prev Vet Med* **65**, 63-75, doi:10.1016/j.prevetmed.2004.06.009 (2004).

52 Sutherland, S. J., Gray, J. T., Menzies, P. I., Hook, S. E. & Millman, S. T. Transmission of foodborne zoonotic pathogens to riparian areas by grazing sheep. *Can J Vet Res* **73**, 125-131 (2009).

53 Grout, L., Marshall, J., Hales, S., Baker, M. G. & French, N. Dairy Cattle Density and Temporal Patterns of Human Campylobacteriosis and Cryptosporidiosis in New Zealand. *Ecohealth* **19**, 273-289, doi:10.1007/s10393-022-01593-9 (2022).

54 Bailey, G. D. *et al*. A study of the foodborne pathogens: *Campylobacter, Listeria* and *Yersinia*, in faeces from slaughter-age cattle and sheep in Australia. *Commun Dis Intell Q Rep* **27**, 249-257 (2003).

55 Hutchison, M. L., Walters, L. D., Avery, S. M., Munro, F. & Moore, A. Analyses of livestock production, waste storage, and pathogen levels and prevalences in farm manures. *Appl Environ Microbiol* **71**, 1231-1236, doi:10.1128/aem.71.3.1231-1236.2005 (2005).

56 Stacey, K. F., Parsons, D. J., Christiansen, K. H. & Burton, C. H. Assessing the effect of interventions on the risk of cattle and sheep carrying *Escherichia coli* O157:H7 to the abattoir using a stochastic model. *Preventive Veterinary Medicine* **79**, 32-45, doi:https://doi.org/10.1016/j.prevetmed.2006.11.007 (2007).

57 FSA. Red Meat Safety & Clean Livestock. (Food Standards Agency, 2002).

58 Beauvais, W. *et al*. The prevalence of *Escherichia coli* O157:H7 fecal shedding in feedlot pens is affected by the water-to-cattle ratio: A randomized controlled trial. *PLoS One* **13**, e0192149, doi:10.1371/journal.pone.0192149 (2018).

59 Edrington, T. S. *et al*. Influence of sprinklers, used to alleviate heat stress, on faecal shedding of *E. coli* O157:H7 and *Salmonella* and antimicrobial susceptibility of *Salmonella* and *Enterococcus* in lactating dairy cattle. *Lett Appl Microbiol* **48**, 738-743, doi:10.1111/j.1472-765X.2009.02603.x (2009).

60 Morrow, J. L. *et al*. Effect of water sprinkling on incidence of zoonotic pathogens in feedlot cattle. *J Anim Sci* **83**, 1959-1966, doi:10.2527/2005.8381959x (2005).

61 Pinto Jimenez, C. E. *et al*. Biosecurity and water, sanitation, and hygiene (WASH) interventions in animal agricultural settings for reducing infection burden, antibiotic use, and antibiotic resistance: a One Health systematic review. *Lancet Planet Health* **7**, e418-e434, doi:10.1016/S2542-5196(23)00049-9 (2023).

62 Mannion, C., Leonard, F. C., Lynch, P. B. & Egan, J. Efficacy of cleaning and disinfection on pig farms in Ireland. *Vet Rec* **161**, 371-375, doi:10.1136/vr.161.11.371 (2007).

63 Jaakkonen, A. *et al*. Longitudinal Study of Shiga Toxin-Producing *Escherichia coli* and *Campylobacter jejuni* on Finnish Dairy Farms and in Raw Milk. *Appl Environ Microbiol* **85**, doi:10.1128/AEM.02910-18 (2019).

64 Martelli, F. *et al*. Evaluation of an enhanced cleaning and disinfection protocol in *Salmonella* contaminated pig holdings in the United Kingdom. *PLoS One* **12**, e0178897, doi:10.1371/journal.pone.0178897 (2017).

65 Hancox, L. R., Le Bon, M., Dodd, C. E. & Mellits, K. H. Inclusion of detergent in a cleaning regime and effect on microbial load in livestock housing. *Vet Rec* **173**, 167, doi:10.1136/vr.101392 (2013).

66 Argüello, H. *et al*. in *International Conference on the Epidemiology and Control of Biological, Chemical and Physical Hazards in Pigs and Pork.*

67 De Ridder, L. *et al*. Evaluation of three intervention strategies to reduce the transmission of *Salmonella* Typhimurium in pigs. *Vet J* **197**, 613-618, doi:10.1016/j.tvjl.2013.03.026 (2013).

68 Zhao, T. *et al*. Inactivation of enterohemorrhagic *Escherichia coli* in rumen content- or feces-contaminated drinking water for cattle. *Appl Environ Microbiol* **72**, 3268-3273, doi:10.1128/aem.72.5.3268-3273.2006 (2006).

69 Lyons, N. A., Smith, R. P. & Rushton, J. Cost-effectiveness of farm interventions for reducing the prevalence of VTEC O157 on UK dairy farms. *Epidemiol Infect* **141**, 1905-1919, doi:10.1017/S0950268812002403 (2013).

70 FSA. Managing Farm Manures for Food Safety: Guidelines for growers to reduce the risks of microbiological contamination of ready-to-eat crops. (https://www.food.gov.uk/business-guidance/managing-farm-manures-for-food-safety Food Standards Agency, 2009).

71 Scottish Government Consultation (https://www.gov.scot/publications/delivering-scotlands-river-basin-management-plans-silage-slurry-anaerobic-digestate-improving-storage-application/, 2021).

72 Nicholson, F. A., Groves, S. J. & Chambers, B. J. Pathogen survival during livestock manure storage and following land application. *Bioresour Technol* **96**, 135-143, doi:10.1016/j.biortech.2004.02.030 (2005).

73 Franz, E., Semenov, A. V. & van Bruggen, A. H. Modelling the contamination of lettuce with Escherichia coli O157:H7 from manure-amended soil and the effect of intervention strategies. *J Appl Microbiol* **105**, 1569-1584, doi:10.1111/j.1365-2672.2008.03915.x (2008).

74 Bui, X. T., Wolff, A., Madsen, M. & Bang, D. D. Fate and Survival of *Campylobacter coli* in Swine Manure at Various Temperatures. *Front Microbiol* **2**, 262, doi:10.3389/fmicb.2011.00262 (2011).

75 Shepherd, M. W., Jr., Kim, J., Jiang, X., Doyle, M. P. & Erickson, M. C. Evaluation of physical coverings used to control *Escherichia coli* O157:H7 at the compost heap surface. *Appl Environ Microbiol* **77**, 5044-5049, doi:10.1128/aem.02940-10 (2011).

76 Ravva, S. V. & Korn, A. Effect of Neem *(Azadirachta indica)* on the Survival of *Escherichia coli* O157:H7 in Dairy Manure. *Int J Environ Res Public Health* **12**, 7794-7803, doi:10.3390/ijerph120707794 (2015).

77 Shepherd, M. W., Jr., Liang, P., Jiang, X., Doyle, M. P. & Erickson, M. C. Fate of *Escherichia coli* O157:H7 during on-farm dairy manure-based composting. *J Food Prot* **70**, 2708-2716, doi:10.4315/0362-028x-70.12.2708 (2007).

78 Hutchison, M. L., Walters, L. D., Moore, A., Crookes, K. M. & Avery, S. M. Effect of length of time before incorporation on survival of pathogenic bacteria present in livestock wastes applied to agricultural soil. *Appl Environ Microbiol* **70**, 5111-5118, doi:10.1128/AEM.70.9.5111-5118.2004 (2004).

79 FSA. *Cleaner Cattle and Sheep*, https://www.food.gov.uk/business-guidance/cleaner-cattle-and-sheep (2024).

80 Mather, A. E. *et al*. Risk factors for hide contamination of Scottish cattle at slaughter with *Escherichia coli* O157. *Preventive Veterinary Medicine* **80**, 257-270, doi:https://doi.org/10.1016/j.prevetmed.2007.02.011 (2007).

81 Dewell, G. A. *et al*. Impact of transportation and lairage on hide contamination with *Escherichia coli* O157 in finished beef cattle. *J Food Prot* **71**, 1114-1118, doi:10.4315/0362-028x-71.6.1114 (2008).

82 Massacci, F. R. *et al*. Transport to the Slaughterhouse Affects the *Salmonella* Shedding and Modifies the Fecal Microbiota of Finishing Pigs. *Animals (Basel)* **10**, doi:10.3390/ani10040676 (2020).

83 Doyle, M. P. & Erickson, M. C. Opportunities for mitigating pathogen contamination during on-farm food production. *Int J Food Microbiol* **152**, 54-74, doi:10.1016/j.ijfoodmicro.2011.02.037 (2012).

84 Snedeker, K. G., Campbell, M. & Sargeant, J. M. A systematic review of vaccinations to reduce the shedding of *Escherichia coli* O157 in the faeces of domestic ruminants. *Zoonoses Public Health* **59**, 126-138, doi:10.1111/j.1863-2378.2011.01426.x (2012).

85 Saeedi, P. *et al*. A review on strategies for decreasing *E. coli* O157:H7 risk in animals. *Microb Pathog* **103**, 186-195, doi:10.1016/j.micpath.2017.01.001 (2017).

86 Matthews, L. *et al*. Predicting the public health benefit of vaccinating cattle against *Escherichia coli* O157. *Proc Natl Acad Sci U S A* **110**, 16265-16270, doi:10.1073/pnas.1304978110 (2013).

87 Hill, A. A., Snary, E. L., Arnold, M. E., Alban, L. & Cook, A. J. Dynamics of *Salmonella* transmission on a British pig grower-finisher farm: a stochastic model. *Epidemiol Infect* **136**, 320-333, doi:10.1017/s0950268807008485 (2008).

88 Snary, E. L. *et al*. A Quantitative Microbiological Risk Assessment for *Salmonella* in Pigs for the European Union. *Risk Anal* **36**, 437-449, doi:10.1111/risa.12586 (2016).

89 Hill, A. *et al*. A 'farm-to-consumption'risk assessment for *Salmonella* Typhimurium in pigs. *Weybridge: Department of Risk Research, Veterinary Laboratories Agency* (2003).

90 Moura, E. *et al*. *Salmonella* Bacterin Vaccination Decreases Shedding and Colonization of *Salmonella* Typhimurium in Pigs. *Microorganisms* **9**, doi:10.3390/microorganisms9061163 (2021).

91 Husa, J. A., Edler, R. A., Walter, D. H., Holck, J. T. & Saltzman, R. J. A comparison of the safety, cross-protection, and serologic response associated with two commercial oral *Salmonella* vaccines in swine. *J Swine Health Prod.* **17**, 11 (2009).

92 Smith, R. in *APHA Science Blog: Bringing home the bacon* (2018).

93 Denagamage, T. N., O'Connor, A. M., Sargeant, J. M., Rajić, A. & McKean, J. D. Efficacy of vaccination to reduce *Salmonella* prevalence in live and slaughtered swine: a systematic review of literature from 1979 to 2007. *Foodborne Pathog Dis* **4**, 539-549, doi:10.1089/fpd.2007.0013 (2007).

94 EFSA. EFSA Panel on Biological Hazards: Scientific Opinion on the public health risks associated with food-borne parasites. *EFSA Journal* **16**, doi: https://doi.org/10.2903/j.efsa.2018.5495 (2018).

95 Said, B. *et al*. Risk factors for acute toxoplasmosis in England and Wales. *Epidemiol Infect* **145**, 23-29, doi:10.1017/s0950268816002235 (2017).

96 Burrells, A. *et al*. Vaccination of pigs with the S48 strain of *Toxoplasma gondii*-safer meat for human consumption. *Vet Res* **46**, 47, doi:10.1186/s13567-015-0177-0 (2015).

97 Katzer, F. *et al*. Immunization of lambs with the S48 strain of *Toxoplasma gondii* reduces tissue cyst burden following oral challenge with a complete strain of the parasite. *Vet Parasitol* **205**, 46-56, doi:10.1016/j.vetpar.2014.07.003 (2014).

98 Patel, K. K. *et al*. Investigation of *Toxoplasma gondii* and association with early pregnancy and abortion rates in New Zealand farmed red deer (*Cervus elaphus*). *Parasitol Res* **118**, 2065-2077, doi:10.1007/s00436-019-06355-1 (2019).

99 Scotland Food and Drink. Beyond the Glen: A Strategy for the Scottish Venison Sector to 2030. (https://foodanddrink.scot/helping-business/other-resources/publications/beyond-the-glen-a-strategy-for-the-scottish-venison-sector-to-2030/, 2018).

100 Plaza, J. *et al*. Detection of *Toxoplasma gondii* in retail meat samples in Scotland. *Food Waterborne Parasitol* **20**, e00086, doi:10.1016/j.fawpar.2020.e00086 (2020).

101 Casey, P. G. *et al*. A five-strain probiotic combination reduces pathogen shedding and alleviates disease signs in pigs challenged with *Salmonella enterica* Serovar Typhimurium. *Appl Environ Microbiol* **73**, 1858-1863, doi:10.1128/AEM.01840-06 (2007).

102 Lema, M., Williams, L. & Rao, D. R. Reduction of fecal shedding of enterohemorrhagic *Escherichia coli* O157:H7 in lambs by feeding microbial feed supplement. *Small Rumin Res* **39**, 31-39, doi:10.1016/s0921-4488(00)00168-1 (2001).

103 Stephens, T. P., Loneragan, G. H., Karunasena, E. & Brashears, M. M. Reduction of *Escherichia coli* O157 and *Salmonella* in feces and on hides of feedlot cattle using various doses of a direct-fed microbial. *J Food Prot* **70**, 2386-2391, doi:10.4315/0362-028x-70.10.2386 (2007).

104 Wisener, L. V., Sargeant, J. M., O'Connor, A. M., Faires, M. C. & Glass-Kaastra, S. K. The use of direct-fed microbials to reduce shedding of *Escherichia coli* O157 in beef cattle: a systematic review and meta-analysis. *Zoonoses Public Health* **62**, 75-89, doi:10.1111/zph.12112 (2015).

105 Creus, E., Pérez, J. F., Peralta, B., Baucells, F. & Mateu, E. Effect of acidified feed on the prevalence of *Salmonella* in market-age pigs. *Zoonoses Public Health* **54**, 314-319, doi:10.1111/j.1863-2378.2007.01069.x (2007).

106 O'Connor, A. M., Denagamage, T., Sargeant, J. M., Rajić, A. & McKean, J. Feeding management practices and feed characteristics associated with *Salmonella* prevalence in live and slaughtered market-weight finisher swine: A systematic review and summation of evidence from 1950 to 2005. *Preventive Veterinary Medicine* **87**, 213-228, doi:https://doi.org/10.1016/j.prevetmed.2008.06.017 (2008).

107 De Busser, E. V. *et al*. Effect of organic acids in drinking water during the last 2 weeks prior to slaughter on *Salmonella* shedding by slaughter pigs and contamination of carcasses. *Zoonoses Public Health* **56**, 129-136, doi:10.1111/j.1863-2378.2008.01172.x (2009).

108 Hansen, C., Bach Knudsen, K., Jensen, B. & Kjærsgaard, H. in *International Conference on the Epidemiology and Control of Biological, Chemical and Physical Hazards in Pigs and Pork.*

109 Smith, R. P., Clough, H. E. & Cook, A. J. Analysis of meat juice ELISA results and questionnaire data to investigate farm-level risk factors for *Salmonella* infection in UK pigs. *Zoonoses Public Health* **57** Suppl 1, 39-48, doi:10.1111/j.1863-2378.2010.01362.x (2010).

110 Kudva, I. T., Hunt, C. W., Williams, C. J., Nance, U. M. & Hovde, C. J. Evaluation of dietary influences on *Escherichia coli* O157:H7 shedding by sheep. *Appl Environ Microbiol* **63**, 3878-3886, doi:10.1128/aem.63.10.3878-3886.1997 (1997).

111 Diez-Gonzalez, F., Callaway, T. R., Kizoulis, M. G. & Russell, J. B. Grain feeding and the dissemination of acid-resistant *Escherichia coli* from cattle. *Science* **281**, 1666-1668, doi:10.1126/science.281.5383.1666 (1998).

112 Gregory, N. G., Jacobson, L. H., Nagle, T. A., Muirhead, R. W. & Leroux, G. J. Effect of preslaughter feeding system on weight loss, gut bacteria, and the physico–chemical properties of digesta in cattle. *New Zealand Journal of Agricultural Research* **43**, 351-361, doi:10.1080/00288233.2000.9513434 (2000).

113 Jacobson, L. H. *et al*. Effect of feeding pasture-finished cattle different conserved forages on *Escherichia coli* in the rumen and faeces. *Meat Sci* **62**, 93-106, doi:10.1016/s0309-1740(01)00233-9 (2002).

114 Maciorowski, K. G., Herrera, P., Jones, F. T., Pillai, S. D. & Ricke, S. C. Effects on poultry and livestock of feed contamination with bacteria and fungi. *Animal Feed Science and Technology* **133**, 109-136, doi:https://doi.org/10.1016/j.anifeedsci.2006.08.006 (2007).

115 Crump, J. A., Griffin, P. M. & Angulo, F. J. Bacterial contamination of animal feed and its relationship to human foodborne illness. *Clin Infect Dis* **35**, 859-865, doi:10.1086/342885 (2002).

116 Davies, P. R., Scott Hurd, H., Funk, J. A., Fedorka-Cray, P. J. & Jones, F. T. The role of contaminated feed in the epidemiology and control of *Salmonella* enterica in pork production. *Foodborne Pathog Dis* **1**, 202-215, doi:10.1089/fpd.2004.1.202 (2004).

117 Davis, M. A. *et al*. Feedstuffs as a vehicle of cattle exposure to *Escherichia coli* O157:H7 and *Salmonella* enterica. *Veterinary Microbiology* **95**, 199-210, doi:https://doi.org/10.1016/S0378-1135(03)00159-7 (2003).

118 Eppink, D. M. *et al*. Effectiveness and costs of interventions to reduce the within-farm *Toxoplasma gondii* seroprevalence on pig farms in the Netherlands. *Porcine Health Manag* **7**, 44, doi:10.1186/s40813-021-00223-0 (2021).

119 Government, S. (Scottish Government, https://www.gov.scot/publications/bovine-viral-diarrhoea-bvd/, 2019).

120 Baines, D. & Summers, R. W. Assessment of Bird Collisions with Deer Fences in Scottish Forests. *Journal of Applied Ecology* **34**, 941-948, doi:10.2307/2405284 (1997).

121 Kijlstra, A. *et al*. The role of rodents and shrews in the transmission of *Toxoplasma gondii* to pigs. *Vet Parasitol* **156**, 183-190, doi:10.1016/j.vetpar.2008.05.030 (2008).

122 Humphrey, T. J. & Beckett, P. *Campylobacter jejuni* in dairy cows and raw milk. *Epidemiol Infect* **98**, 263-269, doi:10.1017/s0950268800062014 (1987).

123 Kay, D. *et al*. in *Animal Waste, Water Quality and Human Health: WHO - Emerging Issues in Water and Infectious Disease series* (eds A. Dufour, J. Bartrum, R. Bos, & V. Gannon) 195-255 (IWA Publishing, 2012).

124 Kay, D., Crowther, J., Stapleton, C. M. & Wyer, M. D. Faecal indicator organism inputs to watercourses from streamside pastures grazed by cattle: Before and after implementation of streambank fencing. *Water Res* **143**, 229-239, doi:10.1016/j.watres.2018.06.046 (2018).

125 Wells, B. *et al*. Prevalence, species identification and genotyping *Cryptosporidium* from livestock and deer in a catchment in the Cairngorms with a history of a contaminated public water supply. *Parasites & Vectors* **8**, 66, doi:10.1186/s13071-015-0684-x (2015).

126 Pollock, K. G., Young, D., Robertson, C., Ahmed, S. & Ramsay, C. N. Reduction in cryptosporidiosis associated with introduction of enhanced filtration of drinking water at Loch Katrine, Scotland. *Epidemiol Infect* **142**, 56-62, doi:10.1017/s0950268813000678 (2014).

127 Starkey, S. R., White, M. E. & Mohammed, H. O. *Cryptosporidium* and dairy cattle in the Catskill/Delaware watershed: a quantitative risk assessment. *Risk Anal* **27**, 1469-1485, doi:10.1111/j.1539-6924.2007.00982.x (2007).

128 Appleton, A. F. How New York City used an ecosystem services strategy carried out through an urban-rural partnership to preserve the pristine quality of its drinking water and save billions of dollars and What lessons it teaches about using ecosystem services. (Virginia Tech Sustainable Agriculture and Natural Resource Management Knowledgebase, 2002).

129 Kerek, A. *et al*. Photoreactive Coating Material as an Effective and Durable Antimicrobial Composite in Reducing Bacterial Load on Surfaces in Livestock. *Biomedicines* **10**, doi:10.3390/biomedicines10092312 (2022).

130 Bumunang, E. W. *et al*. Bacteriophages for the Targeted Control of Foodborne Pathogens. *Foods* **12**, doi:10.3390/foods12142734 (2023).

131 Butucel, E. *et al*. Farm Biosecurity Measures and Interventions with an Impact on Bacterial Biofilms. *Agriculture* **12**, 1251 (2022).

132 Jones, M. S. *et al*. Organic farms conserve a dung beetle species capable of disrupting fly vectors of foodborne pathogens. *Biological Control* **137**, doi:10.1016/j.biocontrol.2019.104020 (2019).

133 Szott, V., Reichelt, B., Friese, A. & Roesler, U. A Complex Competitive Exclusion Culture Reduces *Campylobacter jejuni* Colonization in Broiler Chickens at Slaughter Age In Vivo. *Vet Sci* **9**, doi:10.3390/vetsci9040181 (2022).

134 Gavin, C. *et al*. A cost-benefit assessment of *Salmonella*-control strategies in pigs reared in the United Kingdom. *Preventive Veterinary Medicine* **160**, 54-62, doi:https://doi.org/10.1016/j.prevetmed.2018.09.022 (2018).

135 Aitken, M. M., Hughes, D. L., Jones, P. W., Hall, G. A. & Smith, G. S. Immunological responses of fluke-infected and fluke-free cattle to *Salmonella* Dublin and other antigens. *Res Vet Sci* **27**, 306-312 (1979).

136 Howell, A. K. *et al*. Co-infection with *Fasciola hepatica* may increase the risk of *Escherichia coli* O157 shedding in British cattle destined for the food chain. *Prev Vet Med* **150**, 70-76, doi:10.1016/j.prevetmed.2017.12.007 (2018).

137 Meschede, J., Holtrup, S., Deitmer, R., Mesu, A. P. & Kraft, C. Reduction of *Salmonella* prevalence at slaughter in *Lawsonia intracellularis* co-infected swine herds by Enterisol® Ileitis vaccination. *Heliyon* **7**, e06714, doi:10.1016/j.heliyon.2021.e06714 (2021).

138 Ellis-Iversen, J. *et al*. Perceptions, circumstances and motivators that influence implementation of zoonotic control programs on cattle farms. *Prev Vet Med* **93**, 276-285, doi:10.1016/j.prevetmed.2009.11.005 (2010).

139 Morgans, L. C. *et al*. A participatory, farmer-led approach to changing practices around antimicrobial use on UK farms. *J Dairy Sci* **104**, 2212-2230, doi:10.3168/jds.2020-18874 (2021).

140 Hellberg, R. S. & Chu, E. Effects of climate change on the persistence and dispersal of foodborne bacterial pathogens in the outdoor environment: A review. *Crit Rev Microbiol* **42**, 548-572, doi:10.3109/1040841X.2014.972335 (2016).

141 Cavicchioli, R. *et al*. Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology* **17**, 569-586, doi:10.1038/s41579-019-0222-5 (2019).

142 DEFRA. Animal Health and Welfare Pathway: Policy Paper (https://www.gov.uk/government/publications/animal-health-and-welfare-pathway/animal-health-and-welfare-pathway, 2023).

143 Scottish Government Climate Change Policy. https://www.gov.scot/policies/climate-change/, 2019).

144 Diamond, M. B. *et al*. Wastewater surveillance of pathogens can inform public health responses. *Nat Med* **28**, 1992-1995, doi:10.1038/s41591-022-01940-x (2022).

Glossary

Anthropogenic: relating to, or resulting from, the influence of humans on nature

Bacteriophage: a virus that can infect and replicate inside bacteria. Also known as a phage

Biosecurity: the prevention of disease-causing agents entering or leaving a place where they can pose a risk to farm animals, other animals, humans, or the safety and quality of a food product

Circular Economy: a model of resource production and consumption in any economy that involves reusing, repairing, refurbishing, recycling, sharing, or leasing existing materials and products for as long as possible

Drinkers: equipment used to deliver and hold liquids for animals

eDNA: environmental DNA. It can be collected / isolated from a variety of environmental samples, including soil, water, snow, or air

Farmyard Manure: material often used as a fertiliser, composed of waste products, faeces and urine produced by farm livestock

Feeders: equipment used to deliver and hold feed for animals

Horizon scanning: examination of potential threats (e.g. emerging disease) using early detection techniques

Lairage: a holding area for livestock at market or prior to slaughter

Mechanical vector: an agent that can transmit disease by transporting the infectious pathogen on their feet or mouth parts from contaminated material (e.g. faeces) to another animal or human (or food and water). Examples include insects such as flies, but also animals such as migratory birds or rodents

Microbe: an organism of microscopic size which may exist in a single-celled form or as a colony of cells (e.g. bacteria, protozoa, fungi, algae, amoeba). Also called a microorganism

Microbiome: a community of microbes / microorganisms (and their genes) that inhabit a particular environment such as the gut

One Health: An integrated, multisectoral, transdisciplinary approach that recognises the connections between the health of humans, animals, and the environment

Organic Fertiliser: Naturally produced materials, derived from plants or animals, and including animal manure, bone meal, compost, dried plant material, human waste, and other components such as used bedding. They are used to provide nutrients and support growth of crops and pasture

Pathogen: an organism that causes disease. Pathogens include bacteria, viruses, parasites, and fungi

Reservoir: a host or environment that harbours a pathogen and serves as a source of the infectious agent that can be transmitted to other hosts

Seropositive: giving a positive result in a blood test indicating that the animal / person has been exposed to or infected with a pathogen and has produced specific antibodies against it

Shedding: expelling microorganisms (usually bacteria) from the body, for example in faeces

Stanchion: an upright metal or wooden bar through which a cow puts its head to keep it restrained. The bars can be adjusted to allow some movement

Zoonosis: an infectious disease that is transmitted from animals to humans

Abbreviations

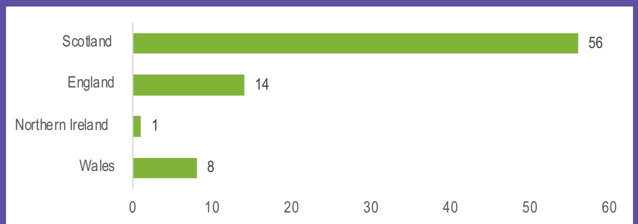
APHA: Animal and Plant Health Agency
DFM: Direct Fed Microbials
EU: European Union
FBP: Foodborne pathogens
FIO: Faecal Indicator Organism
PPE: Personal protective equipment
SRP: Siderophore receptor and porin
STEC: Shiga toxin-producing *Escherichia coli*
WASH: Water, sanitation, and hygiene

Appendix 1: Farm Inverventions Survey Results

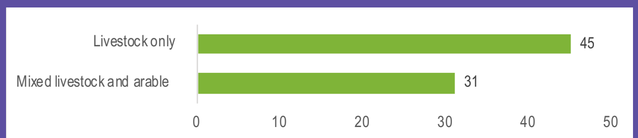
A survey of livestock farmers was conducted to capture expert opinion relating to current practices, opinion on feasibility of interventions concerning FBPs on-farm, and attitudes towards incentives and barriers to changing farm practices. A focus group was set up comprising livestock farmers (sheep and cattle) from different geographical regions of Scotland along with one veterinarian. This group provided feedback and comments on the survey questions and the length of the survey was revised accordingly. The survey was launched on the 20th of November 2023 and closed on the 12th of December 2023 and was promoted through social media, the Moredun Foundation and other farming industry networks. The survey was completed by 80 participants, including a group of 20 young farmers. 70% (56/80) of respondents came from Scotland and included a wide range of locations such as Orkney, Shetland, Highland, Ross-shire, Caithness, Moray, Banffshire, Aberdeenshire, Perthshire, Fife, Angus, Renfrewshire, Lanarkshire, East Lothian, Borders, and Dumfriesshire. The length of time that respondents have been farming ranged from 3 years to over 65 years, with some farmers specifying that they had grown up on farms and have been involved in farming since they were children. The size of farms also varied greatly, from holdings with less than 40 animals to over 14,000 animals.

For all results presented below, the numbers at the end of each bar indicate the number of respondents who selected that answer. Please note, not all respondents answered every question.

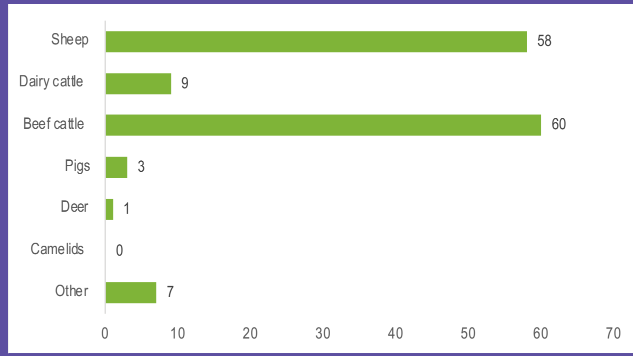
1. What country do you live in?



2. Type of farm



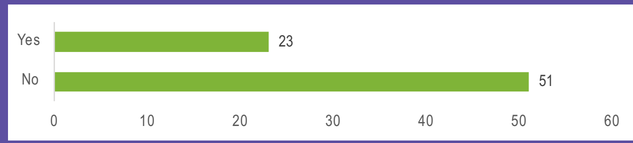
3. What animals do you keep on your farm?



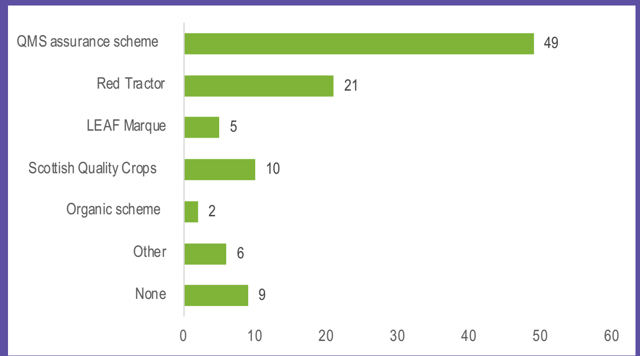
If you selected Other, please specify:

Chickens; Horses (2); Goats (2); Hens; Pony; Seasonal turkeys

4. Are poultry also present on your farm *(e.g. kept as pets, or for eggs)*?



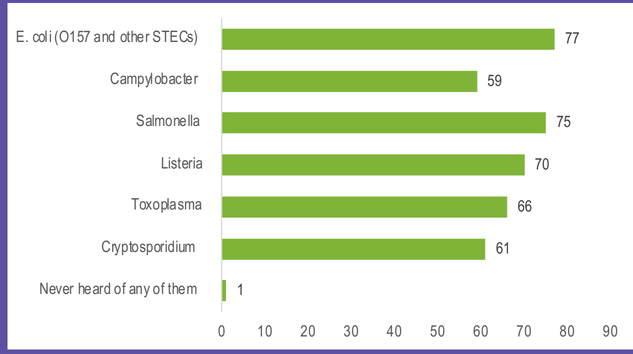
5. Are you a member of any farm assurance schemes?



If you selected Other, please specify:

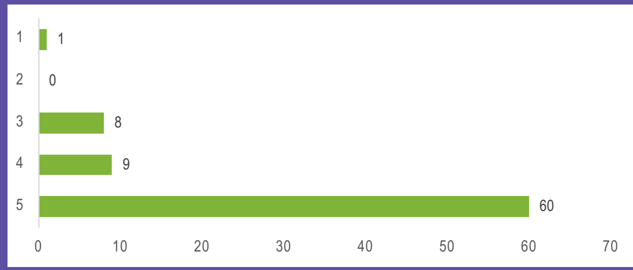
FAWL (4); Combinable Crops; Fresh Produce; Lindon Foods; FQAS NI; Pasture for life

6. Are you aware of the following microbes as foodborne pathogens?

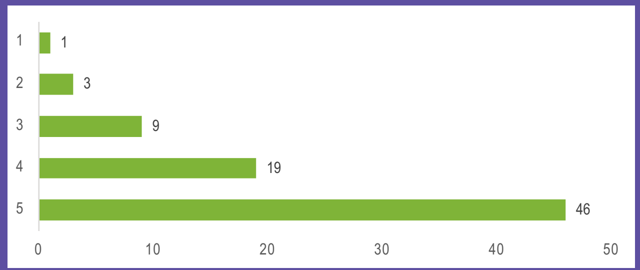


7. How aware are you of the following? *(1 is unaware, 5 is very aware)*

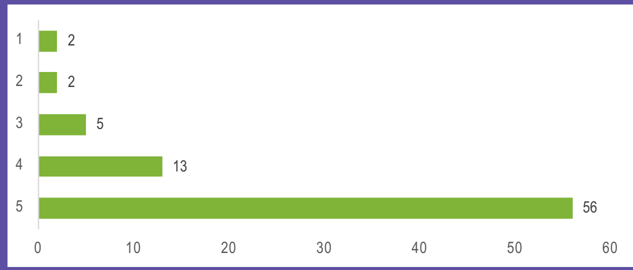
a. People and animals can be infected with foodborne pathogens through exposure to contaminated water, food, or soil



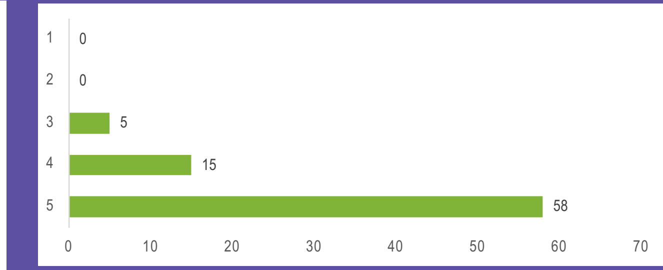
b. Foodborne pathogens are often carried by livestock without the animal showing any signs of disease



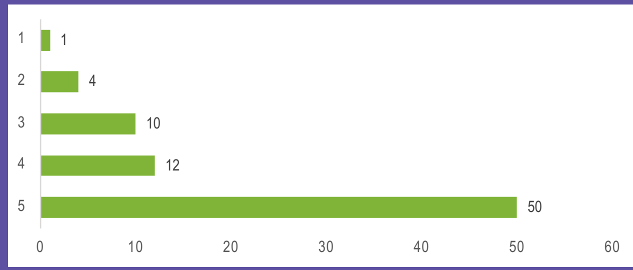
c. Some foodborne pathogens can also cause disease in animals *(e.g. sheep abortion)*



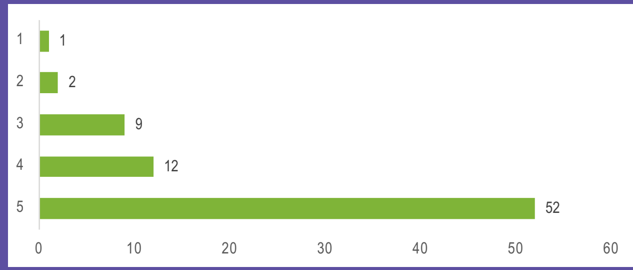
d. Foodborne pathogens can be shed into the environment in faeces



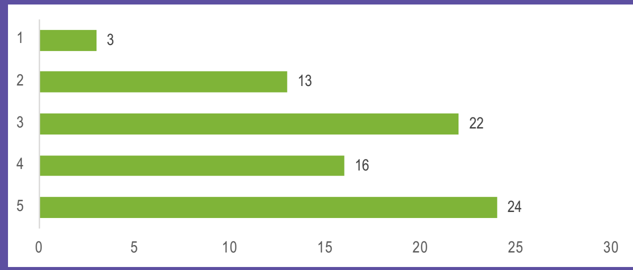
e. Water can become contaminated by animal faeces which can spread foodborne pathogens to crops / salad / vegetables



f. Foodborne pathogens can be present on raw meat



f. Foodborne pathogens don't need to multiply on or in food to cause disease in humans



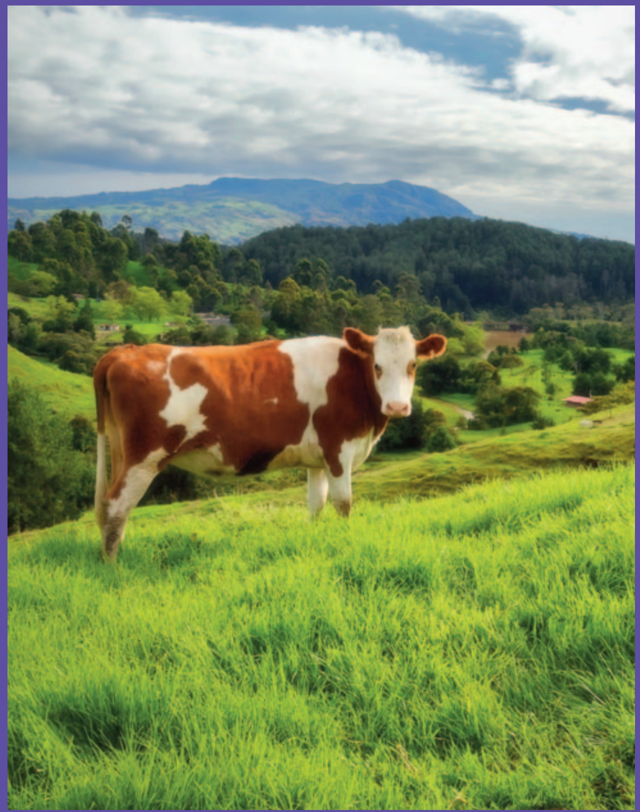
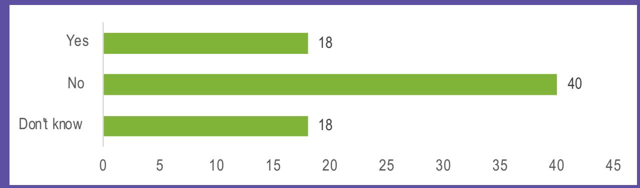


Photo: Unsplash.com

9. Are foodborne pathogens a problem for your business?

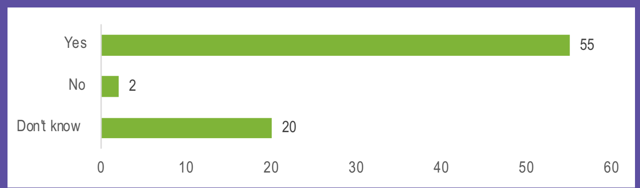


Reason for answer:

A selection of representative answers is given below.

- "All under control"
- "Can cause illness - lack of staff"
- "Cost of loss in business"
- "Have a farm shop"
- "Have had no direct feedback that they are but they probably could become one at any point"
- "Haven't had a problem"
- "Milk is always tested then processed"
- "Not aware of it being a problem"
- "Not obviously so, but could be sub clinical"
- "Unknown presence of pathogens"

8. Are foodborne pathogens a problem for the farming industry?

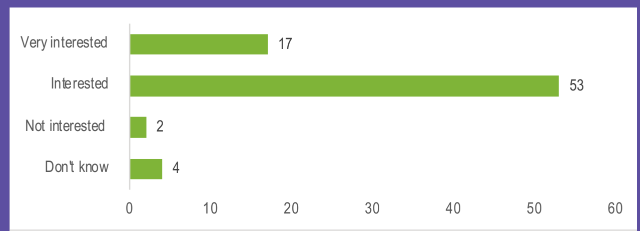


Reason for answer:

A selection of representative answers is given below.

- "A common transfer route"
- "Any bacteria which cause health or disease risks are a problem"
- "Consumer confidence is knocked which can lead to poor farm gate prices"
- "Financial loss and damaging public perceptions"
- "Food we produce must be safe and be seen to be safe"
- "Having an issue with abortion can have a financial impact on the business"
- "I don't know the incidence of when this is a problem to have an opinion"
- "I have not been made aware of an issue in the farming press"
- "Never impacted our meat as far as I'm aware"
- "Relative to other issues not big problem at moment"
- "Sometimes hard to know they are there"
- "They are a problem for the food industry, and we are part of that industry as primary producers"
- "We have a responsibility to produce safe food"

10. How interested are you in foodborne pathogens in your livestock?

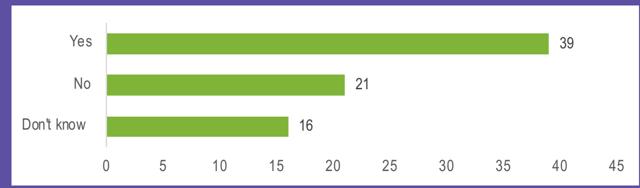


Reason for answer:

A selection of representative answers is given below.

- "Always keen for a better understanding"
- "Continuous CPD"
- "If I can improve my knowledge of these, I believe I can improve my business"
- "Interested enough to not want anything I do to jeopardise the health of my - stock or the health of anyone who may buy my produce"
- "Is there anything needing to be done to cure, prevent. Learn for myself and educate others"
- "Not a huge worry as long as food prepared correctly, and animals managed well"
- "Risks should always be assessed"
- "Safer for family and workers"
- "What affect would there be if pathogens were found in my livestock?"
- "Would like to know more about how pathogens can be spread"

11. In your view, is the public perception of the risks of foodborne diseases in livestock a threat to the farming industry?

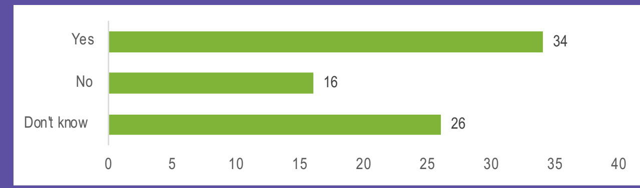


Reason for answer:

A selection of representative answers is given below.

- "A disease outbreak would cause very bad publicity"
- "Any opportunity for the media to create a negative story is bad for the industry"
- "I do not think the public is aware of the potential for pathogens in food - they expect the retailer to supply non-pathogenic food"
- "Because of misinformation particularly on social media"
- "Could be, education about it needs to be carefully delivered to the public"
- "If press elevate a story, the public are easily scared, unable to process relative risk"
- "It can be a threat if their lack of proper understanding affects their judgement and behaviour"
- "Potential bad publicity from illness or deaths"
- "The salmonella in eggs issue many years ago shows the potential risk"
- "There is a lot of negative press surrounding the industry irrespective of the issue or the full facts"
- "They don't know it is a risk, they perceive meat as being safe to eat"

12. Would you consider vaccinating your livestock against foodborne pathogens solely for the benefit of public health?



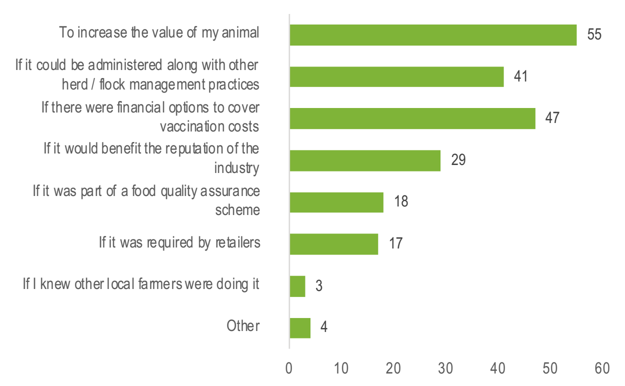
Reason for answer:

A selection of representative answers is given below.

- "Already doing so"
- "Better to have hygienic practices than introduce further vaccines"
- "Cost - risk and efficacy"
- "Cost benefit too small and ill-defined benefit to consumers"
- "Depends if pathogen present on farm"
- "Depends on the pathogen, risk and on price, and how easy one can mitigate in other ways"
- "If it was a requirement to sell the livestock into the food chain, then yes"
- "If it was an issue and not expensive"
- "If there was a public health benefit then it would have to be considered"
- "Important to keep stock healthy and minimise the risk to consumers - after all, I too am a consumer and have no desire to eat contaminated foodstuffs"
- "Moral responsibility"
- "Not unless incentivised"
- "There would need to be a benefit to animal health or some sort of money incentive"
- "To ensure our product is safe for the consumers"
- "Welfare of the livestock to be considered. Extra handling. Jagging"

Photo: Unsplash.com

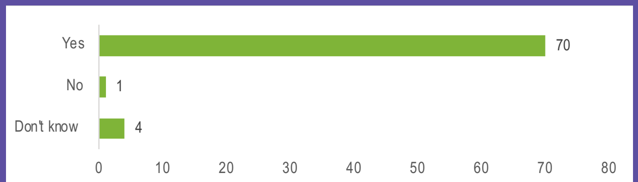
13. What 3 factors are most likely to incentivise you to use a vaccine against foodborne pathogens?



If you selected Other, please specify:

Respondents also identified protection of farm workers and improving animal health as additional incentives.

14. Would you consider vaccinating your livestock against foodborne pathogens if it would benefit both your animals and public health? *(There are some foodborne pathogens (microbes) that cause production diseases in livestock (e.g. abortion in sheep) and can also cause diseases in people)*

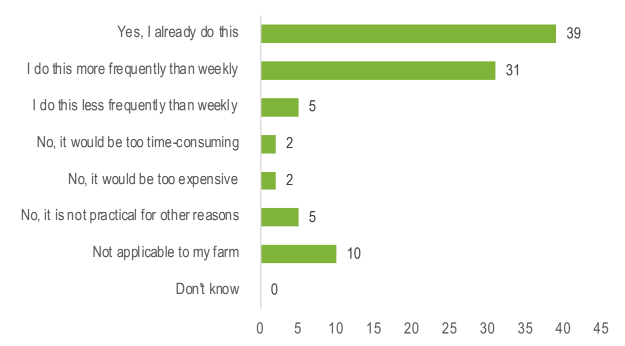


Reason for answer:

A selection of representative answers is given below.

- "Abortion is a great worry of mine"
- "Animal welfare and consumer confidence"
- "Business improvement & reputation"
- "Dual benefit - worth my time!"
- "I certainly would consider it if there were constant local outbreaks, but I wouldn't do it without it being in my area"
- "If it helps the economics of the business"
- "No brainer to do something that benefits my animals"
- "Win win"

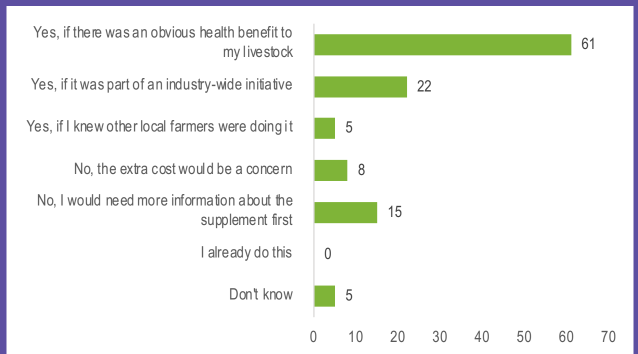
15. During periods when livestock are housed, do you replace soiled bedding, add fresh bedding, or remove farmyard manure / slurry from pens on a weekly basis? *(tick all that apply)*



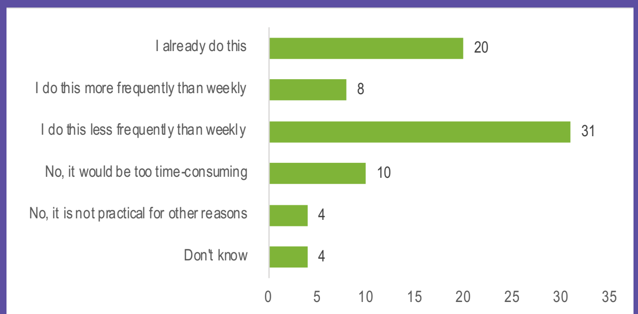
If you do this but less frequently than weekly, how often?

Some respondents specified that they changed bedding frequently but cleaned the pens on a less frequent basis, and other respondents indicated that they varied their activities depending on factors such as level of muck, type of bedding and other conditions.

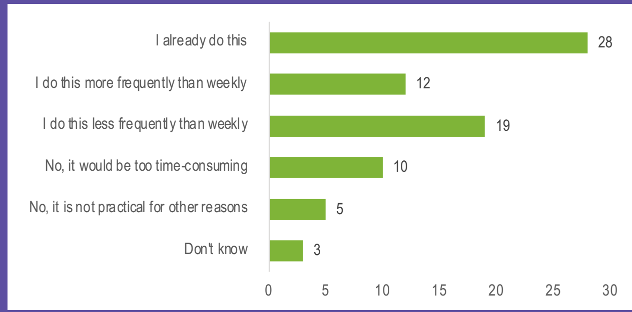
16. If a supplement could be incorporated into feed to reduce the presence of foodborne pathogens would you use it? *(tick all that apply)*



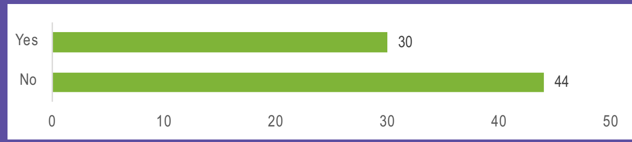
17. Would you consider cleaning water troughs on a weekly basis?



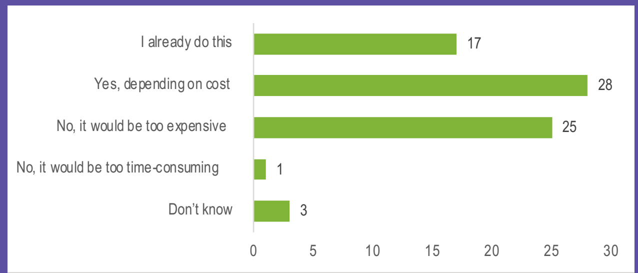
18. Would you consider cleaning feeding troughs on a weekly basis?



19. Do you have double fencing in place?



20. Would you consider erecting additional fencing to reduce the chances of pathogen spread from other livestock (e.g. neighbouring farm) or wildlife (e.g. deer), or to limit contamination of water courses?

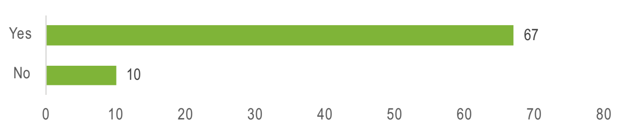


Additional comments:

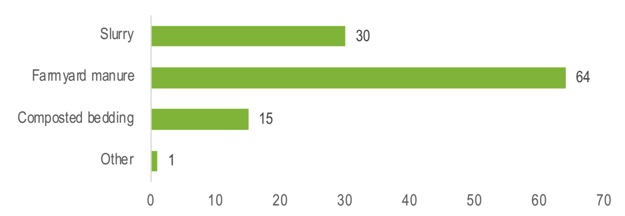
A selection of representative comments is given below.

- "Around isolation fields for purchased stock"
- "Burns are double fenced"
- "Deer are a problem, but the cost of fencing them out is prohibitive"
- "Not practical on a hill farm, with open boundaries"
- "We work on seasonal rented ground so could be different from one month to the next so very difficult to control"

21. Do you use farmyard manure / slurry as a fertiliser on your farm?



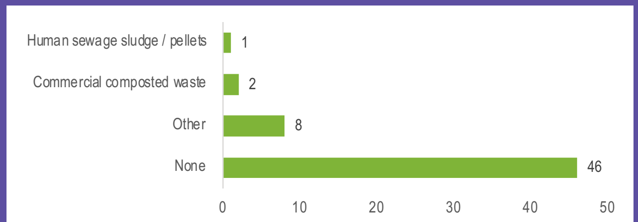
If yes, what type of manure do you use? (tick all that apply)



If you selected Other, please specify:

One respondent mentioned hen layer manure.

22. Do you use other land dressings?



If you selected Other, please specify:

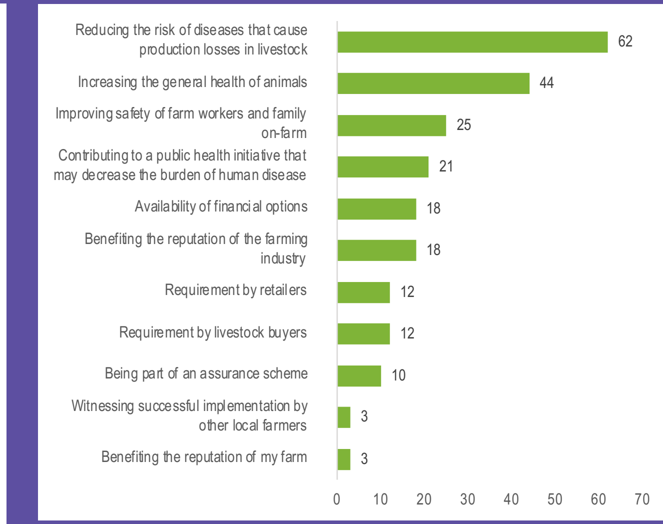
Other land dressings identified by respondents included bagged NPK fertiliser, basalt rock, digestate (3), lime (2), fibrophos, and sheep dip following procedures.

23. Are there other management practices that you think would reduce the transmission of foodborne pathogens on farm?

A selection of representative answers is given below.

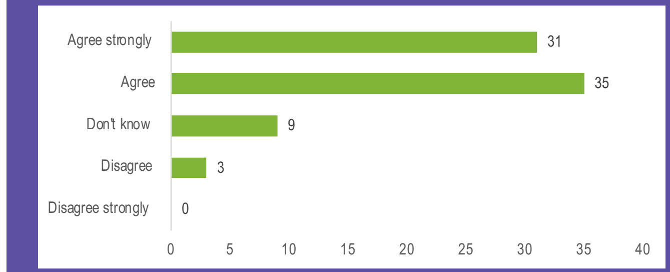
- "Any form of mob grazing. Rest and recover is the most important thing on the farm"
- "Better hygiene - pens, water, colostrum and washing in between plus hand washing facilities"
- "Calves individually housed and good ventilation"
- "Cleaning of livestock trailers"
- "Good biosecurity so you do not buy in any more pathogens. Keep livestock out of buildings and feed stores"
- "Further development of vaccines. Identifying genetic resistance and modifying genes accordingly"
- "Improve hygiene of calving and lambing pens"
- "Keeping livestock out of water courses"
- "Keeping a closed herd and a closed flock"
- "Keeping food storage clean"
- "Maintaining a healthy herd or flock"
- "Minimising unnecessary direct contact with stock by folks who have no real need to be near them"
- "More education"
- "Not being overstocked, using lime in straw bedding, clean livestock heading to abattoir"
- "Outwinter livestock when possible"
- "Overgrazing of paddocks in a regenerative grazing system is likely to increase the spread of pathogens within a group of livestock"
- "Prompt identification of sick animals and investigate if there are concerns e.g. abortions"
- "Right to roam poses a risk"
- "Rotational grazing where possible and the use of clean pastures"
- "Seagulls can carry Salmonella if forage at waste tips"
- "Spread slurry on arable crops only"
- "The physical layout of the farm; Transport over areas limited where unnecessary"
- "Treating water troughs and animal bedding with beneficial bacteria"
- "Controlling vermin"
- "Well ventilated sheds"

24. What would you consider to be the top 3 drivers / incentives for implementing new farm practices to reduce foodborne pathogens on farm?

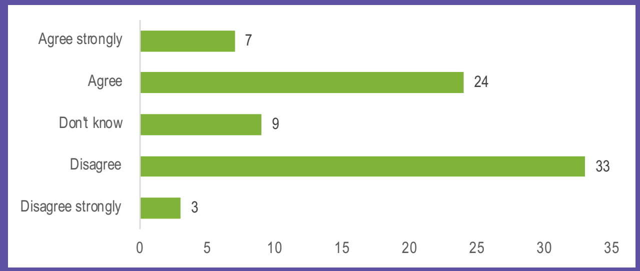


25. What would prevent you from implementing new farm practices to reduce foodborne pathogens?

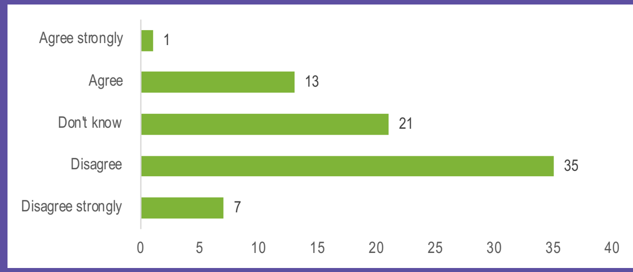
a. Cost



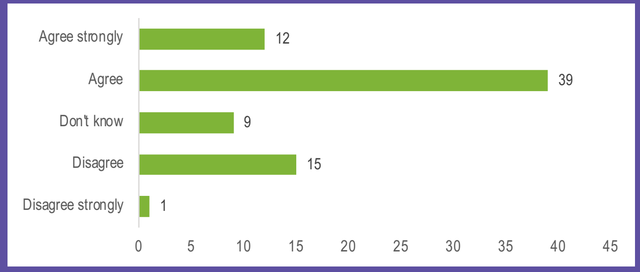
b. I don't have the time



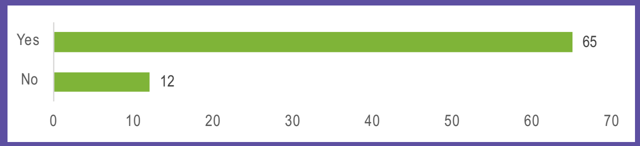
c. I don't see foodborne pathogen presence in livestock as an issue *(for the industry or my animals)*



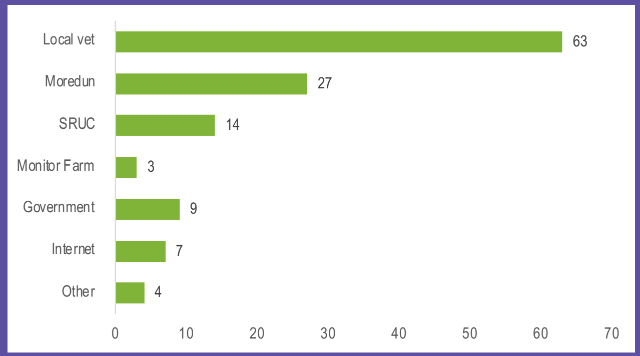
d. I don't have enough information to make decisions at this time



26. Do you currently receive guidance on infection control on your farm?



If Yes, where from? *(tick all that apply)*



If you selected Other, please specify:

Other sources of information included the Premium Cattle Health Scheme, a Registered Animal Medicines Advisor or Suitably Qualified Person (2), Scottish Agricultural College Consulting, feed supplier and ruminant nutritionist.

If you access information on the internet, which websites do you visit?

Other websites visited included the farming press, National Sheep Association, breeding companies, National Animal Disease Information Service, Scottish Government, The Farming Forum, National Office of Animal Health, and other relevant animal health sites.