The environmental and biosecurity characteristics of livestock carcass disposal methods: A review

Journal Item

The environmental and biosecurity characteristics of livestock carcass disposal methods: A review

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ABSTRACT

Livestock mortalities represent a major waste stream within agriculture. Many different methods are used throughout the world to dispose of these mortalities; however within the European Union (EU) disposal options are limited by stringent legislation. The legal disposal options currently available to EU farmers (primarily rendering and incineration) are frequently negatively perceived on both practical and economic grounds. In this review, we assess the potential environment impacts and biosecurity risks associated with each of the main options used for disposal of livestock mortalities in the world and critically evaluate the justification for current EU regulations. Overall, we conclude that while current legislation intends to minimise the potential for on-farm pollution and the spread of infectious diseases (e.g. Transmissible Spongiform Encephalopathies, bacterial pathogens), alternative technologies (e.g. bioreduction, anaerobic digestion) may provide a more cost-effective, practical and biosecure mechanism for carcass disposal as well as having a lower environmental footprint. Further social, environmental and economic research is therefore warranted to assess the holistic benefits of alternative approaches for carcass disposal in Europe, with an aim to provide policy-makers with robust knowledge to make informed decisions on future legislation.

Keywords

Animal disease; composting; greenhouse gases; prions; viruses; zoonoses.

1. Introduction

Routine mortality of animals is an inevitable consequence of livestock farming systems. With a global livestock population of approximately 1.9×10^{10} birds and 2.31×10^{8} mammals (FAO, 2007), farming systems generate a significant volume of mortalities that need to be disposed of safely, practically and economically. Throughout history, the most widely utilised methods for disposal of on-farm mortalities has probably been burial and to a lesser extent, burning. However, implementation of the European Union (EU) Animal By-Product Regulations (1774/2002) (Anon, 2002) forbids these practices within the EU and limits the disposal routes to incineration (either on or off-farm), rendering, high temperature / pressure alkaline hydrolysis, disposal at maggot farms or through licensed waste collectors (Anon, 2002). The prohibition within the regulations was founded on the perceived risk of pathogens and infective agents entering the animal feed chain due to their incomplete destruction during burial and burning of mortalities (Anon, 2002). Particular concern relates to the safe management of prions responsible for Transmissible Spongiform Encephalopathy (TSE) (Anon, 2002). However, carcass disposal is also perceived to be synonymous with pollution, such as the increased concentrations of soluble nitrogen in soil and groundwater due to burial (Ritter & Chirnside, 1995), odour issues or the fear of dioxins and furans being released into the air as a result of incomplete or uncontrolled combustion (Scudamore et al., 2002). It is therefore essential that disposal methods can eliminate or contain these risks. However, practices such as burial are still widely utilised outside of the EU (Anon, 2007). The different interpretation of the threats and/or risks posed by each disposal option raises questions about the quality of the evidence-base upon which legal decisions have been made. There is therefore a need to critically assess the biosecurity and pollution merits and drawbacks of the different disposal options currently available to farmers.

The following review outlines the major routine disposal routes used throughout the world and the biosecurity and environmental credentials of each. It also highlights areas where, due to a lack of peer-reviewed science, regulations have been obliged to make assumptions about the risks associated with particular disposal methods; particularly in the context of EU regulations. An analysis of the economic viability of each option is discussed briefly but a full economic analysis is beyond the scope of this review due to the lack of sufficient data and a fundamental difference in the respective cost of each method in different countries.

2. Current methods for disposal of livestock mortalities

2.1. Burial

The traditional methods of on-farm burial of livestock mortalities include burial in graves, trenches, or in open-bottomed containers referred to as mortality or disposal pits (CAST, 2008a; Freedman & Fleming, 2003). Livestock burial has been banned in the EU due to fears that infectious agents may inadvertently enter both the human food and animal feed chains or lead to environmental pollution (Anon, 2002). Outside of the EU, some concern has been raised that improper burial may lead to contamination of ground and surface water with pathogens and the chemical products of decomposition (NABC, 2004). However, no studies could be found that reported any serious environmental impact from routine disposal via burial. Indeed, Ritter and Chirnside (1995) concluded that the pollution from burial pits was similar to that of domestic septic tanks and could be controlled with legislation synonymous with on-site wastewater treatment regulation.

Many of the assumptions about the environmental impact of the burial of fallen (dead) stock have been made following mass-burial at incidences of high mortality. However, it is unlikely that the findings of such studies provide an accurate representation of the typical risks posed by routine burial of on-farm mortalities. For instance, weekly disposal of dead animals from an American turkey farm typically equates to approximately 2,000 kg (CAST, 2008a), whereas Glanville (2000) evaluated the environmental impact of burying 28,000 kg of turkeys in two pits following a barn ventilation failure. Similarly, numbers of dead sheep from a typical European farm will be significantly less than those generated following mass-disease outbreaks. During the UK Foot and Mouth Disease (FMD) outbreak in 2001, approximately 61,000 tonnes of carcasses were disposed of at four mass burial sites (Anderson, 2002). It is inevitable that such mass burial would pose considerably greater environmental and biosecurity risk than burial of routine mortalities and hence extrapolation of the results from studying such extreme events may be erroneous. Indeed, Vinten et al. (2008) concluded that the concentrations of *E. coli* and *Cryptosporidium* in ground and surface water were affected to a greater extent by excretion from live animals than they were from the burial of a small number of carcasses. The risk posed by routine burial should therefore be balanced against other widespread agricultural practices (e.g. farm waste land-spreading) so that the threat is realistically evaluated in relative terms.

In addition to the potential introduction and subsequent survival of pathogenic bacteria in soil and water arising from carcass burial, concern has also arisen that burial may lead to propagation of pathogens and subsequent pollution of groundwater and drinking water. Many factors affect the movement of pathogens through soil to groundwater, including soil type, permeability, water table depth and rainfall (Beal et al., 2005). However, adsorption, filtration and predation by natural microbial populations significantly reduce the amount of pathogens that eventually reach underlying groundwaters (Beal et al., 2005). Within an aquifer, there are also many factors that govern the inactivation of the pathogens, e.g. pH, water flow rate and substrate grain size (John & Rose, 2005). Taking all these factors into account, it is plausible that the numbers of pathogens reaching any drinking water source due to routine burial are likely to be low; particularly if boreholes and wells are deep, thereby increasing the time taken by pathogens to reach the underlying aquifer and thus the likelihood of their demise before reaching the water. In support of this, Myers et al. (1999) reported low concentrations of coliforms and *Salmonella* in observation wells surrounding disposal pits, concluding that bacteria did not move more than 30 m laterally in groundwater. Similarly, in a survey of poultry disposal pits, Ritter and Chirnside (1995) found the average concentrations of faecal coliforms and faecal streptococci in water samples to be relatively low (24 CFU 100 ml^{-1} and 3 CFU 100 ml^{-1}, respectively); with many samples testing negative. Indeed, no studies have been reported in the literature linking the burial of animal carcasses to detrimental effects on either human or animal health, although burial of humans within a water table has led to incidences of contaminated groundwater (Bastianon et al., 2000). Furthermore, the addition of hydrated lime ($Ca(OH)_2$) to the base of burial pits has been shown to effectively reduce the survival of pathogens and the possibility for off-site pathogen transfer (Sanchez et al., 2008). The use of a chemical barrier to minimise risk is supported by Avery et al. (2009) who found no viable *E. coli* O157 cells in contaminated abattoir waste treated with lime applied at a rate of 10 g of CaO lime l^{-1} waste. Applying lime both during the construction and subsequent operation of burial sites may impede the growth of all micro-organisms and hence slow the process of decomposition. However, in the context of improving biosecurity, it is a simple and cost-effective procedure that would be accessible to many farmers; justifying the case for further research to enable the scientific basis of current legislation to be critically evaluated.

Despite the seemingly low incidence of drinking water contamination with enteric pathogens arising due to burial of carcasses, some infectious material such as anthrax spores or prions can reside within the soil after carcass decomposition (Brown, 1998; Johnson et al., 2006, 2007; Nechitaylo et al., 2010). This may lead to animals inadvertently ingesting contaminated soil and the infectious agents and hence may lead to development of neurodegenerative disease (e.g. BSE or scrapie) in the case of prions (Johnson et al., 2007), or the reintroduction of anthrax (Sharp & Roberts, 2006). While such events pose real risks, measures can be implemented to reduce the risk of prion transmission and propagation arising through burial of carcasses. Primarily, animals suspected of dying from neurodegenerative disease or anthrax should be automatically sent for incineration or rendering following examination by a veterinary practitioner. Burial sites could also be located away from livestock fields and at sufficient depth so that the potential for transfer of infectious agents back to the surface (e.g. through earthworm activity (Nechitaylo et al., 2010; Williams et al., 2006)) is very low. Indeed, burial of carcasses at depth may stimulate prion-degrading enzyme production by indigenous microbial populations, thus further reducing any threat (Rapp et al., 2006). The use of soil additives incorporating prion degrading proteases or microbes known to degrade prions could also stimulate prion degradation and is a potential area for future research. Risk assessments undertaken in 1997 after the UK BSE crisis concluded that the leachate from the landfills used to dispose of BSE-infected cattle was not likely to cause a significant risk to local inhabitants (Spouge & Comer, 1997). However, burial at depth may induce hypoxic conditions, particularly in soils with very high moisture content (e.g. when waterlogged) (Killham, 1994; Pounder, 1995). This may impede microbial degradation and ultimately sustain infectivity and thus pose a biosecurity threat if pits are inadvertently exposed at a later date. Nevertheless, the associated probability of TSE transmission through burial of carcasses in Europe is clearly reduced given that the number of livestock infected with prions has decreased dramatically over the last decade (DEFRA, 2008a).

In the UK, groundwater vulnerability maps were used during the 2001 FMD outbreak to locate suitable mass-burial sites (Anderson, 2002) and are currently used to locate suitable human cemetery sites (EA, 2004). A similar risk assessment method could be employed to reduce the risk of contamination to groundwater from routine livestock burial using additional datasets, including locations of boreholes and wells, topography, and land-use. Such methods could identify potential on-farm burial sites that minimise the risk of environmental pollution whilst proving to offer a viable and practical option for farmers to dispose of on-farm mortalities. In summary, more evidence is needed to definitively test the environmental impact of burial of routine mortalities.

2.2. Burning

On-farm burning of livestock mortalities on pyres is commonly used as a disposal method in many countries. Burning on pyres has also been used extensively in many disease outbreaks such as the 2001 FMD outbreak in the UK (Scudamore et al., 2002), and the 2004/2005 outbreak of anthrax in Uganda (Wafula et al., 2008). Despite the potential for pollution to occur from the mass-burning that occurred during the FMD outbreak, evidence of groundwater contamination from ash burial was minor, soil contamination from pyres was found to be negligible, and air emissions from pyres did not significantly affect air quality beyond the immediate vicinity (EA, 2001). Furthermore, studies indicated that the spread of FMD virus via smoke plumes was very unlikely (Champion et al., 2002). Biosecurity concerns therefore principally reside with the fate of TSEs, as open-air combustion is not likely to be as complete or reach as high a temperature as incineration, increasing the risk of TSEs remaining infectious (EC SSC, 2003a) (see Section 2.3). However, studies by Brown et al. (2004) suggest that the potential for the airborne or bottom ash transfer of TSEs from animal carcasses is highly unlikely. Further, complete combustion can be successfully achieved when sufficient labour, air and fuel is provided (Animal Health Australia, 2007).

Possible human health risks associated with on-farm burning (apart from physical burns and direct smoke inhalation) include the emission of dioxins from incomplete carcass combustion. Dioxins and furans are carcinogens and can negatively affect human reproduction, development and immune systems (Rier, 2008). Dioxins released from pyres during the 2001 FMD outbreak were estimated to be between 7 and 73% of total annual UK dioxin emissions (EA, 2001), yet there were no significant dioxin concentration increases in products destined for the food chain at that period (Rose et al., 2005). Although the environmental impact of burning was shown to be minimal, considerable social concerns were expressed regarding odour, unsightliness, etc. (Anderson, 2002; EA, 2001);

so much so it resulted in the abolishment of pyre burning as a viable disposal option (Scudamore et al., 2002). Nevertheless, such conclusions were drawn following mass-burning at over 950 sites (EA, 2001) and it is unclear whether burning of routine on-farm mortalities would raise such concerns or pose any environmental risk if performed effectively. Indeed, there is little evidence to legitimately deny or endorse the use of on-farm burning for routine disposal and more scientific analyses of pyres should be instigated to test common conceptions (e.g. increased dioxin levels and groundwater contamination), especially as disposal on pyres could potentially be used again should another disease outbreak occur (Anon, 2002). Such work should be supported by social studies to elucidate the fears and possible misconceptions associated with livestock burning so that effective communication of risk can occur.

2.3. Incineration

Incineration is the process where animal carcasses or by-products are burnt at high temperatures (≥ 850 °C) to produce an inorganic ash (Anon, 2002; NABC, 2004). The process is expected to destroy all infective agents (NABC, 2004). Ash typically represents 1 to 5% of initial carcass volume (Chen et al., 2003, 2004), though this will vary with the incinerator type, process, fuel and animal species. In EU countries, ash resulting from specified risk material (SRM) (e.g. the spinal cord and brain) is subsequently sent to designated landfill sites (in accordance to the ABPR), as is the recommendation in other countries such as the USA (NABC, 2004).

The principal concern with incineration of carcasses relates to gaseous emissions; however, small-capacity incinerators in some EU states have been deemed to be exempt from local air pollution controls as emissions of key pollutants represent ≤ 0.2% of the total air emissions (AEA Technology, 2002). Further reductions in harmful emissions may also occur after adoption of optimum techniques as introduced with the ABPR (e.g. use of afterburners).

Polycyclic Aromatic Hydrocarbon (PAH) emissions from two animal waste incinerators have been measured and directly compared with those from medical waste incinerators. Mean concentration of PAHs in the flue gas were greater in the animal incinerators than the medical waste incinerator, which was attributed to higher chamber retention times in the medical waste facility (Chen et al., 2003). In a further study, metal concentrations in the flue gas were found to be higher in the animal carcass incinerators than the medical incinerators (Chen et al., 2004). As neither of the two animal waste facilities met the ABPR (1774/2002) standards of heating to 850 °C for at least two seconds (Anon, 2002), yet the medical waste facility did, this suggests that current EU standards should reduce emissions from on-farm incinerators if operated correctly. However, more evidence is needed to elucidate the gaseous emissions arising from incineration of carcasses, especially under scenarios where the technology may not be working under optimal conditions..

Other health concerns arising from incineration include the release of dioxins and furans from flue gas and fly ash. There is a risk that dioxins and furans from incomplete combustion can settle in areas around carcass incinerators and could enter the food chain through grazing animals or through human consumption of contaminated crops. However, afterburners fitted to incinerators can dramatically reduce the risk of noxious emissions release and numerous studies on different types of incinerators have found that dioxin and furan emission levels are rarely higher than ambient concentrations (Mari et al., 2008; Nadal et al., 2008; Yan et al., 2008). Furthermore, concentrations of dioxins and furans decrease significantly with increasing distance from incinerators (Yan et al., 2008) and the siting of on-farm incinerators is regulated within the EU (e.g. so as not to be within the immediate vicinity of livestock (Anon, 2002)). Indeed, it is thought that dioxins and furans from small animal incinerators account for only 0.07% of total UK dioxin emissions (AEA Technology, 2002). In theory, land-spreading of the generated ash as a soil improver may increase the risk of dioxins and furans entering the food chain via bioaccumulation. However, it is likely that this would pose an extremely low risk given the low concentrations released by small animal incinerators. With regards to human health, a study of large-scale municipal solid waste incinerators indicated elevated dioxin levels in operators who worked with bottom ash (Liu et al., 2008). However, further work is needed to elucidate if such effects occur from small-scale facilities.

There has been some debate previously about the effectiveness of incinerating TSE-infected carcasses and SRM (NABC, 2004). However, it is generally accepted that incineration destroys prion proteins more effectively than other methods of livestock disposal (with the possible exception of alkaline hydrolysis; (NABC, 2004)). Concerns have been raised about the levels of TSE remaining in the fly ash and slag generated, hence the requirement to land-fill all ash potentially infected with TSEs in the EU. Risk assessments have shown that there is less than a 1 in 1×10^9 chance of the most exposed individual being infected with BSE via ingestion of ash following incineration and that the degree of infectivity of ash generated from incineration of BSE-infected meat and bone meal would be negligible (Spouge & Comer, 1997). The main risk to humans is attributed to the contamination of groundwater supplies from leaking sewerage pipes containing washwater from spillages of TSE-infected material at the incinerator (Spouge & Comer, 1997). In reality, the probability of this happening is extremely low, particularly if effluent is treated on-site. From a human and animal health perspective, the high temperature of incineration also completely destroys zoonotic and animal pathogens, including resilient spore-forming bacteria such as *Bacillus anthracis* (anthrax) (NABC, 2004). Land-spreading of ash from incineration of pigs and poultry is permitted in the UK, although under increasingly stringent regulation (DEFRA, 2008b). Whilst land-spreading of ash derived from carcass incineration can potentially cause environmental damage (e.g. through heavy metal pollution (Chen et al., 2004)), a search of the literature failed to find any evidence which justifies the introduction of more stringent regulation. If such regulations become unworkable, it may result in the unnecessary land-filling of material that could be used in the fertiliser industry as a potential soil improver (Paisley & Hostrup-Pedersen, 2005).

One of the main perceived risks related to off-farm incineration is the transportation of dead livestock between farms. In Europe, centralised collection services exist for livestock mortalities where licensed operators collect carcasses and subsequently transfer the animals for incineration (or rendering) as necessary. It is inevitable that the vehicles may cover significant distances between farms whilst they are laden with carcasses from diseased animals and this has raised significant concerns within the livestock industry (Kirby et al., 2010). Such concerns appear to be justified as it was found that transporting animals between premises facilitated the spread of the FMD virus in the UK (Anderson, 2002; Scudamore et al., 2002); whilst transport of carcasses could propagate other serious animal diseases such as avian influenza (Pollard et al., 2008) and BSE (Spouge & Comer, 1997). The lag time between the death of a diseased animal and its collection may also pose a hazard if carcasses are not stored securely. It should be remembered that the risk of propagating disease via transporting carcasses between farms may be reduced given that some infective agents (e.g. viruses) survive only on live animals. Further, such risks may be reduced via employing good biosecurity practices such as disinfection of collection vehicles and protective clothing between sites; and by having sealed containers which livestock or vermin cannot access and which fluids cannot escape (Pollard et al., 2008). However, it is unlikely that such practices are always performed by all farmers and contracted operators, especially given the number of operators needed to run a national collection service. It is clear that further studies are needed to elucidate the risks of disease propagation through transport of carcasses both within and between farms.

Studies are required to directly compare the environmental footprint of incineration against other carcass disposal options via a life-cycle assessment (LCA) approach. Incineration of carcasses is likely to generate greenhouse gas (GHG) emissions due to the energy-intensive nature of the process and the relatively high water content of carcasses. The limited number of central incinerators also necessitates long-distance transportation of fallen stock, although this may be balanced against greater efficiency when larger waste volumes are incinerated. There may therefore be an argument that due to biosecurity and environmental concerns, incineration should take place on-farm. Nevertheless, outside of the EU, on-farm incineration is not subject to the same monitoring regimes as commercial high-capacity sites and therefore may not be as stringently regulated as those in the EU.

2.4. Rendering

Rendering entails crushing carcasses and animal by-products into particles of a uniform size, heating the particles and then separating out the fat, proteinaceous material and water into, where possible, useful products including meat and bone meal and tallow (CAST, 2008a; Kalbasi-Ashtari et al., 2008; Woodgate & van der Veen, 2004). In the EU, mammalian meat and bone meal must now be land-filled, incinerated or used as a fuel source (Anon, 2002); although reductions in TSE levels may lead to it being reinstated as an additive for animal feed (Anon, 2010). Tallow from rendering can be used in, amongst other things, soaps, washing powders, as lipids in the chemical industry and cosmetics (Kalbasi-Ashtari et al., 2008; NABC, 2004). It may also be burnt for energy production and due to its high fat content a considerable amount of energy may be recovered which would otherwise be lost; thus reducing the net environmental footprint of the process (Woodgate & van der Veen, 2004). As with incineration, rendering has a high energy demand but if tallow is recovered for subsequent energy production then the net GHG emissions are likely to be low.

The main environmental concerns associated with rendering relate to gas and odour emissions. Odours may be generated from the raw material, during processing and from the resulting waste effluents (DEFRA, 2008c). Emissions must be prevented, reduced or treated, preferably in that order, using best available technologies (DEFRA, 2008c). In a review of rendering systems, Kalbasi-Ashtari et al. (2008) report that 90% of odours can be removed using cold water washing with further emission reductions achieved using afterburners, scrubbers or biofilters. With regards to effluents generated at rendering plants, suspended solids, oils and greases must be regulated to prevent the release of effluents with high biological and chemical oxygen demand into watercourses. Pollutants can be reduced simply by water use or recycling and reusing, or by treatment on or off-site at conventional sewage treatment works (DEFRA, 2008c).

A hygiene standard of 133 °C /20 min /300 kPa or equivalent is required by the EU for the rendering of high-risk material, including livestock carcasses, to inactivate agents such as TSEs. As there is no guarantee that the rendering process completely destroys the prions responsible for TSE infections (EC SSC, 1999), SRM must currently be incinerated after rendering (Anon, 2002). Seidel et al. (2006) have shown, however, that alternative strategies to terminal incineration are possible with minimal risk, suggesting that current EU legislation is too constraining, particularly for pork and poultry where there is no evidence of naturally occurring TSEs (EC SSC, 1999). NABC (2004) reports that rendering sufficiently destroys most pathogens but recontamination can occur, particularly with *Salmonella*, during handling, storage and transportation of the final product. However, this can occur with most common municipal and animal waste streams (e.g. compost or digestate) and can be considered to be of low risk if effective handling and storage procedures are in place.

Although the negative issues of biosecurity for carcass collection and transport for rendering are similar to those discussed previously for centralised incineration, it does represent a well established method of livestock disposal for those with access to a central collection service (Tables 1 and 2; Woodgate & van der Veen, 2004). However, commercial rendering facilities are becoming increasingly scarce due to economic pressures on the industry (Anderson, 2002; CAST, 2008b; Kalbasi-Ashtari et al., 2008; Stanford & Sexton, 2006). Traditionally, farmers have been paid to have their livestock mortalities rendered as the revenue from rendering products outweighed the cost of the process, but the inability of the process to completely destroy TSEs has led to the reduction in saleable products, resulting in the introduction of fees (Stanford & Sexton, 2006). Nevertheless, rendering is still a preferred option for disposing of diseased animals in the EU and is likely to continue to be so, preferably in combination with incineration and a pathogen monitoring regime (Anon, 2002; Pollard et al., 2008).

2.5. Composting

Outside of the EU, aerobic composting is widely used to dispose of livestock mortalities. Composting is a simple technique that can be undertaken on-farm using windrow and bin composting (NABC, 2004), or at dedicated facilities using enclosed windrows or in-vessel techniques (DEFRA, 2008d). Typically, the process involves the layering of carcasses between strata of carbon-rich substrate such as straw, sawdust or rice hulks with a final covering of carbon-rich substrate over the entire pile (NABC, 2004). Larger carcasses are typically placed in single layers while poultry can be multi-layered; and the compost piles are subsequently aerated or turned (NABC, 2004). Depending on carcass weights, the waste material may decompose at rates as high as 1–2 kg day^{-1} (Kalbasi et al., 2005) into a useful product that can be used as a soil amendment. The process essentially occurs in two phases – a primary, thermophilic phase (temperatures up to 70 °C generated for a number of weeks) and a secondary, mesophilic phase (typically 30–40 °C) for a number of months (Kalbasi et al., 2005).

When an impermeable base is not used, small-scale composting of mortalities has been shown to contaminate the underlying soil due to the loss of leachate with a high ionic strength from the compost piles (Glanville et al., 2006); and is likely to be exacerbated under periods of high rainfall. To minimise the risk of pollution (i.e. leaching and runoff), composting should be undertaken on an impervious base (e.g. hard standing or plastic liner) and a bulking agent utilised to absorb excess liquids produced from the decomposing bodies (e.g. sawdust; NABC, 2004). The risk can be further reduced by undertaking the composting indoors or under gas-permeable covers to prevent rain ingress into the compost piles (Sivakumar et al., 2008). This precaution should also prevent run-off and leaching of nutrients as well as reducing ammonia emissions. In terms of gaseous emissions, odour levels from the composting of carcasses are considered to be low in comparison to manure-related facilities (Glanville et al., 2006); and whilst composting carcasses may also lead to GHG emissions, it is unknown whether these emissions are any greater than those released through natural decomposition (Xu et al., 2007).

The temperatures generated during the thermophilic phase of carcass or meat waste composting has been shown to effectively reduce numbers of bacteria, viruses, protozoa and helminths (Glanville et al., 2006; Ligocka and Paluszak, 2008; Wilkinson, 2007). However, some bacteria, particularly *Salmonella*, can re-colonise the compost when temperatures are reduced near the end of the composting process or if the pile has not been adequately aerated or turned (NABC, 2004; Wilkinson, 2007). It is also possible that opportunistic pathogens may colonise the compost pile if insufficient temperatures are reached (Sanabria-Leon, 2006). In a trial where road-killed deer were composted in a static pile, Schwarz et al. (2008) found that numbers of bacterial indicator species were reduced to near zero after twelve months, but they recommend that a cautious approach be taken and the compost used in areas with limited public contact (e.g. along roads) to further negate any risks. Studies have shown that the avian influenza virus can be deactivated at ambient temperatures (15–20 °C) in less than a week, or after 15 minutes when mixed with chicken manure at 56 °C (Lu et al., 2002); temperatures easily achieved in composting piles. Further, a recent study by Guan et al. (2009) showed that composting rapidly eliminates avian influenza and Newcastle Disease viruses in chicken carcasses. A risk-based review of disposal options for avian influenza by Pollard et al. (2008) placed in-vessel composting on the preferred list of disposal methods on the grounds of exposure assessment. Glanville et al. (2006) showed that a 45 to 60 cm layer of clean material covering cattle carcasses was enough to prevent the compost piles containing vaccine strains of avian encephalomyelitis and Newcastle Disease virus from infecting sentinel birds. When the surface of the compost piles was contaminated with the strains, six out of the twenty two sentinel birds showed positive serum antibody tests, stressing that clean material must be used to cover the composting piles. There is little information regarding the fate of prions or spore forming bacteria such as *Bacillus anthracis* during carcass composting, thus preventing it from becoming considered as an EU-compliant disposal route. However, Huang et al. (2007) found some initially promising evidence in their study with scrapie-infected sheep, with prion removal in one experiment and prion reduction (but not destruction) in the second.

In the foreseeable future, in-vessel composting of routine mortalities, particularly on pig and poultry farms where there is no evidence linking to TSE infection (EC SSC, 1999) could provide a practical, cost-effective and low-risk method of carcass disposal. The use of Geographical Information Systems and Groundwater Vulnerability maps to locate ideal composting sites, along with good composting practices (e.g. using clean and fresh carbon substrate) in tandem with stringent regulation to restrict subsequent land-spreading to specific soil types, a pathogen monitoring regime and a maximum mass of carcasses to be disposed, would further decrease perceived risks. Biosecurity can be improved again by composting in fenced, contained areas (Xu et al., 2009). In summary, although mortality composting is not currently allowed in the EU, there seems to be no scientific evidence to suggest that compost derived from pig and poultry carcasses should be subject to any greater legislative restrictions than compost derived from municipal food waste.

2.6. Anaerobic digestion

Anaerobic digestion (also termed biodigestion) of dead livestock is not permitted within current EU legislation without prior treatment of the carcass, e.g. rendering (Anon, 2002); however the technique is increasingly utilised in other countries. Anaerobic digestion involves the degradation of organic material under anaerobic conditions to produce methane (biogas), which can be utilised as a fuel source (Ward et al., 2008). Other end products include liquid and solid fertilisers (digestate). Digesters can vary in size and technology according to needs and location (Owen et al., 2005). On-farm systems can be as simple as a plastic-covered trench covered with a pipe leading to a storage tank as used in some developing countries (Owen et al., 2005) or large commercial technical plants available for treating large waste volumes (CAST, 2008b). Anaerobic digestion of carcasses can take place at psychrophilic (<20 °C), mesophilic (20 to 45 °C) and thermophilic (45 to 60 °C) temperatures (Cantrell et al., 2008) for different durations. The time–temperature combination affects the physico-chemical conditions within the system and hence the survival of pathogenic agents. Although seemingly one of the most promising technologies to deal with livestock mortalities, biodigestion of carcasses currently remains markedly understudied and most available information relates to the disposal of manure and slurry wastes from farms. However, increasing interest in the disposal of dead livestock is generating research, particularly into the potential of co-digesting of carcasses with other farmyard waste such as manure or slurry. For example, Masse et al. (2008) investigated the addition of ground swine carcasses to swine manure slurry using psychrophilic anaerobic digestion and found no reduction in efficiency.

In the UK, ongoing work seeks to determine the reduction of *Enterococcus faecalis*, *Salmonella senftenberg* and porcine parvovirus in pig carcasses during co-digestion with livestock slurries (Kirby; personal communication). There are some studies on anaerobic digestion of wastewater biosolids and swine manure that have reported varying levels of success at pathogen removal. For instance, Viau and Peccia (2009) found mesophilic anaerobic digestion combined with composting of wastewater biosolids failed to eradicate *Legionella pneumophila* in half of digestate samples. Likewise, Côté et al. (2006) found that although *Salmonella*, *Cryptosporidium* and *Giardia* were removed during anaerobic digestion, indigenous faecal indicators such as total coliforms had persisted in just over half of samples, although at significantly reduced levels. Nevertheless, there is a plethora of evidence that shows anaerobic digestion can eliminate a range of pathogenic viruses and bacteria from a range of waste matrices (Sahlström et al., 2003, 2008; Viau and Peccia, 2009; Ward et al., 2008). Further, it is also common to include a secondary heat treatment process (e.g. composting or pasteurisation) and a minimum storage period at the end of the process for the digestate as additional measures to inactivate pathogenic organisms (Sahlström, 2003). Grinding waste to smaller particle sizes prior to anaerobic digestion has also been shown to improve sterilisation as it increases the surface area subject to treatment, whilst also increases the rate of subsequent carcass breakdown (Paavola et al., 2006).

TSEs are not destroyed at the operational temperatures of anaerobic digestion (Brown et al., 2000) and have been shown to remain intact through biodigestion of biosolids (Hinckley et al., 2008). Therefore, if infected carcasses are anaerobically digested, digestate potentially contaminated with TSEs can remain in the bottom of the digester (Adkin et al., 2010; Hinckley et al., 2008; NABC, 2004). It is therefore important that techniques are found to remove prions by heat-treating the resulting waste post-digestion as per the EU regulations (Anon, 2002; DEFRA, 2008d). As with composting though, concerns regarding persistence of prions during anaerobic digestion are somewhat irrelevant in terms of pigs and poultry. In environmental terms, anaerobic digestion is evidently the optimal method of carcass disposal as it yields a low-carbon source of power from a waste product. However, if additional treatment of carcasses (e.g. secondary heat treatment) is needed to satisfy biosecurity concerns, this may decrease its environmental credentials.

The initial capital costs, the difficulty in optimising the process in a one-stage reactor and at thermophilic temperatures (Chen and Huang, 2006) may prove to be inhibitory to the uptake of anaerobic digestion as a method of on-farm disposal of livestock mortalities. However, the ability for anaerobic digestion to produce bio-energy makes this an important livestock disposal option given current climate change concerns. Indeed, in the event that existing digesters can be adapted to degrade carcasses mixed with slurry or manure, this method of livestock disposal could prove to be both environmentally sound and economically appealing given the increasing financial incentives for production of bio-energy.

2.7. Alkaline hydrolysis

Alkaline hydrolysis was developed in the 1990s and is hence a relatively new technology. It uses sodium hydroxide or potassium hydroxide to catalyse the hydrolysis of biological material (e.g. carcasses) into a sterile aqueous solution consisting of peptides, amino acids, sugars, and soaps (Kaye et al., 1998; NABC, 2004; Shafer et al., 2000, 2001). Carcasses are placed in a steel alloy container to which the alkali is added in either solid or solution form, the concentration of which depends on the weight of the carcass material. The container is then sealed and the process run at 150 °C for up to six hours and at high pressure in order to significantly accelerate the process (EC SSC, 2003b; Kalambura et al., 2008).

Whilst it is reported that there are few gaseous emissions and associated odour problems from alkaline hydrolysis, the effluent is highly alkaline and very rich in nutrients which could pose a problem when discharging the effluent to wastewater treatment systems (NABC, 2004). Indeed, effluent is not currently allowed to be discharged to sewers in the EU without prior treatment so as to prevent the solidification of hydrolysate (EC SSC, 2003b). However, the process has been used with poultry carcasses to produce a fertiliser which can be land-spread (CAST, 2008a). Indeed, recent studies have highlighted the use of the product of alkaline hydrolysis as a highly valuable and effective fertiliser with soil neutralising properties (Gousterova et al., 2008; Kalambura et al., 2008). Alkaline digestion (i.e. alkaline hydrolysis without heating) can also be used as a preservative and the resulting poultry meal has been used as a feed seemingly without detrimental effect (CAST, 2008a); however, in the EU, feeding animals with protein from the same species is prohibited (Anon, 2002).

The combination of high pH (typically *ca.* 14) and a period of sustained elevated pressure and temperature facilitate highly effective eradication of infective agents from carcasses and animal wastes. For instance, both Kaye et al. (1998) and Neyens et al. (2003) showed that alkaline hydrolysis resulted in the near total eradication of pathogenic microorganisms; whilst the former study and more recently Murphy et al. (2009) also proved the effectiveness of alkaline hydrolysis in destroying prions. The EC SSC (2003b) approved this method for the treatment of TSE-infected material provided that the risk of TSE infectivity was excluded from residues. Alkaline hydrolysis is also one of the preferred options of disposal of poultry infected with Avian Influenza H5N1 (Pollard et al., 2008).

Given its effectiveness in eliminating both pathogens and prions from animal by-products, the growth seen in the popularity of alkaline hydrolysis for carcass disposal is of no surprise. Further, recent papers state that it compares favourably in economic terms to other disposal methods for animal by-products (Gousterova et al., 2008; Kalambura et al., 2008); which is especially true for centralised, large-scale or intensive livestock production systems. It is therefore likely that alkaline hydrolysis will increasingly be at the forefront of methods used to dispose of livestock carcasses both within and outside of the EU.

3. The future of livestock mortality disposal

3.1. Novel disposal methods

Novel methods of livestock disposal are briefly summarised in Table 3. These have not been discussed thoroughly in the text as they are currently unlikely to be economically viable for most farmers or considered to be environmentally safe and biosecure for the foreseeable future. Further work will be needed on these aspects if they are to be developed and utilised on a commercial scale and more importantly if they are to gain legislative acceptance.

3.2. Carcass storage and bioreduction methods

In addition to the different methods of carcass disposal, there are several potential options that allow carcasses to be stored safely on-site prior to disposal via one of the approved routes previously discussed. The main advantage of storing carcasses is that farmers can wait until it is economically viable and convenient to organise their disposal, and in some cases the volume of livestock can be decreased therefore reducing disposal costs. A summary of storage methods is provided (Table 4), although the two most likely to be appealing and practical for farmers, bioreduction and freezer storage, are discussed briefly here.

Bioreduction is a method which simultaneously permits storage and reduction in the volume of carcasses and relies on internal enteric microorganisms and enzymes to drive decomposition. Briefly, carcass material is placed in a watertight vessel, where the contents are heated (to 40 ± 2 °C) and actively aerated with a pump. In contrast to in-vessel composting or anaerobic digestion, the process relies on an aqueous environment to promote microbial degradation of organic material. To facilitate this, vessels are two thirds filled with water prior to carcass addition. During storage, the putrescible carcass material liquefies, facilitating liquid phase disposal; and a reduction in volume occurs due to evaporation through an air vent (Williams et al., 2009). Heating encourages microbial replication, whilst regular aeration facilitates eradication of zoonotic gut pathogens due to them predominantly being facultative anaerobes. Work on bioreduction so far has focussed on sheep mortalities, but anaerobic bioreduction has been studied on pig and rabbit farms in Spain (Gutiérrez et al., 2003; Lobera et al., 2007a, 2007b). It is analogous to aerobic bioreduction but without a direct input of air, but differs to anaerobic digestion as the system is not fully sealed since the aim is not to produce (or capture) methane for bio-energy production. Although the technology is in its infancy and has not yet been studied with larger carcasses such as cattle or horses, early results for bioreduction are promising. Both the aerobic and anaerobic bioreduction systems have been shown to be highly effective with regards to the rate of carcass breakdown (Lobera et al., 2007a, 2007b; Williams et al., 2009). Once full, the liquid portion of the vessels is emptied via vacuum suction and is subsequently incinerated or rendered. However, as the volume of waste is considerably reduced, it must only be disposed of intermittently; which may reduce the environmental footprint associated with carcass disposal and also alleviate biosecurity concerns associated with collecting vehicles frequently accessing different livestock holdings (Kirby et al., 2010; Williams et al., 2009).

Bioreduction may cause some biosecurity concern, especially in the form of bioaerosols due to the active aeration of the contents. However, both aerobic and anaerobic bioreduction systems appear to reduce survival of enteric bacteria potentially present in livestock; including *Salmonellae*, *E. coli* and *E. coli* O157 (Gutiérrez et al., 2003; Williams et al., 2009), *Clostridium* (Lobera et al., 2007a, 2007b) and *Campylobacter* (Williams et al., 2009). Further work is needed to determine the survival of bacterial pathogens and viruses when the bioreduction system is not managed under optimal conditions (e.g. when the air and heat input is switched off).

The potential for TSEs to persist within a bioreduction system and the risk of subsequent propagation was recently evaluated in a systematic review (Adkin et al., 2010). It was concluded that microbial processes and enzymatic breakdown of proteins (proteolysis) was likely to lead to the degradation of TSEs. However, prions have been shown to be resistant to proteases and the mesophilic temperatures within the vessels are not sufficiently high to deactivate the protein (Brown et al., 2000). As a result, it is possible that a proportion of prions would adhere to the solid component of the waste material and settle to the bottom of the vessel, where they could remain in a potentially infective state (Adkin et al., 2010). Nevertheless, the assessment concluded that the risk of TSE agents being dissipated through the chimney via gaseous emissions were likely be negligible (a 1 in 1×10^{12} probability over a one year period), and their exit via aerosols through the opening hatch during operational procedures was only of slightly greater concern (Adkin et al., 2010). The findings of the review by Adkin et al. (2010) will soon be validated through *in-vitro* models to deduce the fate of prions in bioreduction systems in order to better inform future risk assessments.

In the event that prion and pathogen destruction within the liquor is proved, it is possible that alternative methods of disposal can be utilised for the liquor such as treatment via lime stabilisation (Avery et al., 2009) or co-composting followed by land-spreading in suitable areas. This may reduce biosecurity fears due to the containment of the entire process on-farm and would also include the added benefit of closing the nutrient cycle.

Since there is no evidence linking either poultry or pigs to TSE infection (EC SSC, 1999), the resulting waste from bioreduction of such carcasses may certainly be suitable for land-spreading if further work substantiates that the liquid waste produced poses limited biosecurity and environmental threat. If mismanaged (e.g. if anaerobic conditions are allowed to develop), odour can be an issue of concern during bioreduction (Williams et al., 2009). However, ongoing trials have shown that odour may be alleviated through the use of a woodchip biofilter (Williams et al. unpublished). Future studies are needed to elucidate the temporal changes in microbial communities during bioreduction and optimisation of enzymatic degradation processes in order to improve the process and facilitate legislative approval.

Freezing of mortalities retards the rate of decomposition by lowering the core temperature of the carcasses (NABC, 2004). Depending on the volumes of mortalities, facilities can be as simple as using chest freezers or loading carcasses into cold storage until disposal is required (NABC, 2004). As with bioreduction, its appeal arises due to the reduced frequency for off-farm transportation of small volumes of carcasses and hence improved levels of biosecurity. In contrast to bioreduction however, the volume of waste does not decrease during freezer storage and therefore it is only likely to be suitable for farms that generate small quantities of mortalities (e.g. <50 kg per day (Blake, 2004)). Freezing is probably most applicable to poultry (Blake, 2004) and pig (CAST, 2008b) enterprises; however, it has also been used effectively to store larger species as a contingency prior to disposal during disease outbreaks such as FMD and BSE (de Klerk, 2002; NABC, 2004). Nevertheless, little is mentioned in the literature regarding on-farm freezing of carcasses and animal by-products which probably relates to the potential for considerable running costs, and the ABPR (1774/2002) only mentions it in the context of Category 3 intermediate plants that may temporarily store animal by-products by freezing into blocks prior to disposal.

The cold storage of carcasses is not meant to destroy pathogens and infective agents but rather to prevent their proliferation and reduce further carcass decay whilst storing for bulk disposal (CAST, 2008b). Prions are known to remain viable after freezing for considerable lengths of time (Stamp, 1967). Zoonotic pathogens such as *Campylobacter* (Maziero and de Oliveira, 2010; Sandberg et al., 2005), *Salmonella* (Escartin et al., 2000) and *E. coli* O157 (Dykes, 2000) have been detected in frozen raw meat, whilst *Cryptosporidium* have been isolated from cattle faeces after periods of freezing (Olson et al., 1999). However, all studies reported a significant decrease in numbers of these organisms following the freezing period. Indeed, freezing is used as a pre-treatment method for reducing *Campylobacter* sp. in broiler chickens (Georgsson et al., 2006, Loretz et al., 2010, Rosenquist et al., 2009). For non-ruminant carcasses where TSEs are not of concern, freezer storage prior to ultimate disposal may therefore actually yield unexplored benefits in terms of biosecurity.

Environmental costs are inevitable when a constant use of electricity is required, as there is for freezing. However, energy-efficient freezers are increasingly available and the potential GHG savings made by reducing the transport of carcasses may compensate for this energy expenditure. As with bioreduction, a detailed life-cycle assessment for a number of case-study farm scenarios is needed to identify the potential cost-benefits to the environment. Another environmental factor related to freezing is the potential for spills to occur when loading carcasses into cold storage containers (NABC, 2004). Effective handling areas and the ability to sanitize such facilities must therefore be implemented if freezing is to be a successful on-farm method of pre-disposal storage.

4. Conclusions

There are many disposal options for dead livestock currently in use throughout the world; however, the knowledge that TSEs and some pathogens may not be completely destroyed may limit their utility in the wake of changing legislation (e.g. the amended EU Animal By-Products Regulation (1069/2009) which comes into effect in March 2011). On-farm disposal methods are favoured by the farming community due to the perceived environmental, practical, economical and biosecurity benefits, therefore processes such as composting and anaerobic digestion have found favour in countries such as the USA and Canada. Under the ABPR in the EU, these options are not deemed safe; however, the legal alternatives are not favoured by the farming community leading to widespread non-compliance and potentially greater environmental risk (due to illegal dumping, etc. (Kirby et al., 2010)). There is therefore a real need for new methods to be developed and validated and the legislation reconsidered following submission of new evidence. From this perspective, bioreduction and freezing seems to be promising on-farm storage methods for livestock mortalities, limiting the need for off-farm transport thus reducing associated biosecurity risks.

While the implementation of highly precautionary, risk-averse mortality disposal systems is admirable in many ways, similar risk assessments and legislation do not apply to other components of the livestock sector which may pose a similar or even greater risk to human health or environmental contamination (e.g. spreading of animal waste, animal access to watercourses, public access to grazing land). It is important therefore that mortality disposal systems are based on a realistic and proportionate level of acceptable risk in comparison to other components of the food chain, rather than the current zero-risk approach. It is clear that more evidence is needed on each disposal and storage method in order to make substantiated risk assessments, e.g. the effects of spreading carcass ash on crops or the potential of leachate from burial to contaminate ground or surface water. This review has initiated this process by applying a simple five-star award system to each livestock disposal and storage method (Table 3 and Table 4, respectively) in order to rudimentarily classify various biosecurity and environmental factors based on current scientific evidence. Methods in need of greater research have also been highlighted where there is either limited or no existing published literature. Further research into the economic impacts of dead livestock disposal is necessary for legislators to appreciate the cost implications on the livestock sector, whilst life-cycle assessments are needed to help provide more environmentally sustainable disposal solutions.

Acknowledgements

We are grateful to BPEX Ltd. who funded the PhD programme that led to this review, and to the Welsh Assembly Government and Hybu Cig Cymru – Meat Promotion Wales for further support.

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Table 1. Grading of the socio-economic and biosecurity aspects of methods used throughout the world for disposal of routine livestock mortalities; assuming best practice.

Method	Socio-economic aspects			Human health	Biosecurity aspects					
	Process speed	Relative cost	Practicality (for the farmer)	Dioxins/ furans	Pathogen contamination of: Air (bioaerosols)	Pathogen contamination of: Soil and vegetation	Pathogen contamination of: Water	Land-spreading of waste produced	Transport of animals off-farm	Prion destruction
Burial	***	*****	****	*****	****	***	MRN	N/A	*****	*
Burning	****	****	***	**	MRN	MRN	MRN	MRN	*****	***
Incineration (on-farm) [a]	*****	**	***	****	***** [b]	*****[b]	***** [b]	MRN	*****	*****
Incineration (large central facility)	*****	**	*****	***	***** [b]	***** [b]	***** [b]	MRN	*	*****
Rendering	*****	***	*****	MRN	*****	N/A	MRN	N/A	*	****
Composting [c]	**	****	***	MRN	***	***	MRN	MRN	*****	***
Anaerobic digestion	**	*** [d]	***	MRN	****	***	***	MRN	*****	**
Alkaline hydrolysis	****	** [e]	***	MRN	*****	*****	*****	*****	*****	*****

*	Very poor
**	Poor
***	Moderate
****	Good
*****	Very good
MRN	More research needed
N/A	Not applicable

[a] Assumes conformation to ABPR (1774/2002) specifications e.g. use of afterburners
[b] Omits handling and storing phase of carcasses pre-incineration which may constitute potential biosecurity risks (Section 2.3)
[c] Assumes unlined static pile with no forced aeration
[d] Benefits from methane production (biogas for energy production) not considered

[e] Unlikely to be suitable for small farms; although increasingly cost-effective with increasing farm size

Table 2. Grading of the environmental impacts of methods used throughout the world for disposal of routine livestock mortalities; assuming best practice.

Method	**Environmental impacts**					
	Odour	Greenhouse gas emission	Pollution and contamination of:			Land-spreading of waste produced
			Air	Soil and vegetation	Water	
Burial	***	****	*****	**	***	N/A
Burning	*	MRN	MRN	MRN	MRN	MRN
Incineration (on-farm) [a]	****	**	**** [b]	**** [b]	**** [b]	MRN
Incineration (large central facility)	*****	**	*** [b]	*** [b]	**** [b]	MRN
Rendering	***	****	MRN	*****	***	MRN
Composting (unlined)	****	****	MRN	***	MRN	****
Anaerobic digestion	****	*****	*****	MRN	MRN	****
Alkaline hydrolysis	***	MRN	MRN	****	***	***

*	Very poor
**	Poor
***	Moderate
****	Good
*****	Very good
MRN	More research needed
N/A	Not applicable

[a] Assumes conformation to ABPR (1774/2002) specifications e.g. use of afterburners

[b] Omits handling and storing phase of carcasses pre-incineration which may constitute potential environmental risks (Section 2.3)

Table 3. The environmental, health and biosecurity aspects of alternative methods for disposal of routine* and large numbers+ of livestock mortalities.

Method	Environmental and health aspects	Biosecurity aspects	References
Hydrolysis+ Indirect steam application to a bioreactor where the material is treated at 180°C/40'/12 bar.	Produces a biofuel.	Not deemed suitable for TSE-infected material.	EC SSC (2003a) Cantrell et al. (2008)
Gasification+ Uses high temperature combustion in excess oxygen to oxidise organic matter.	Production of NO_2, SO_2 & CO gases, VOCs, PAHs, dioxins and furans and particulate matter including ash. Less air emissions released than standard incineration.	Not deemed suitable for TSE-infected material. Preferred option in the disposal of Avian Influenza Virus H5N1.	Hetland and Lynum (2001) EC SSC (2003a) Cantrell et al. (2008) Pollard et al. (2008) CAST (2008a)
Thermal depolymerisation+ Uses high heat and pressure to convert organic matter into a biofuel.	Produces re-useable combustible gas and a biofuel. Waste minerals to be used as fertiliser.	Expected to destroy prions and pathogens as the process destroys organic matter at the molecular level. Carcasses pre-processed on-farm and transported in sealed containers, improving biosecurity.	NABC (2004)
Plasma arc process+ High heat torch used to vitrify or gasify material into a reduced volume solid.	Remaining solids can be land-filled or used as gravel, moulded into bricks or used as concrete aggregate. Methane produced contributes to global warming if not captured.	Expected to destroy prions and pathogens. Carcasses pre-processed on-farm and transported in sealed containers, improving biosecurity.	Hetland and Lynum (2001) NABC (2004)
Ocean disposal*+ Dumping of carcasses beyond territorial limits.	Additional nutrient loading at dumping sites. Would need to prevent floating debris. More research needed.	Potential spread of parasites and pathogens, although likely to be diluted and have limited survival.	NABC (2004)
Napalm*+ Use of fast-burning napalm to replace burning pyres.	Burning would produce emissions to air, ash and contamination of soil and groundwater. Health issue when using and handling napalm.	Expected to destroy pathogens although no conclusive information currently available.	NABC (2004)
Pyrolysis+ Use of electromagnetic waves to heat organic material – not yet tested on carcasses.	Reported to reduce emissions and hydrocarbons; low energy requirements. Only small amounts of waste produced.	Expected to destroy TSEs and pathogens, although no conclusive information currently available.	Hetland and Lynum (2001) NABC (2004) Cantrell et al. (2008)

Natural exposure* Use of natural processes and predators to remove carcasses.	Many potential environmental and health implications. Only an option in scarcely populated areas.	Potential spread of parasites and pathogens.	Anon (2007) Stanford and Sexton (2006)
Extrusion+ Use of friction to grind and 'cook' poultry carcasses. Moisture removal and the addition of a dry ingredient turns waste carcass into feed.	Unknown. Possibly harmful if process is unregulated and contaminated feed is fed to livestock animals.	No information on TSEs; though elimination of pathogens. Possibly harmful if process is unregulated and contaminated feed is fed to livestock animals.	Blake (2004)

Table 4. The environmental, health and biosecurity aspects of alternative methods for storage of both routine* and large numbers+ of livestock mortalities.

Method	Environmental and health aspects	Biosecurity aspects	References
Bioreduction* Carcasses stored in a vessel containing water, where the contents are heated and aerated. Used for volume reduction prior to disposal	Stored in watertight containers therefore no environmental impact from leakage or seepage expected. GHG emissions being investigated.	Reduced number of on-farm collections. Bioaerosol generation and pathogen survival being investigated.	Williams et al. (2009)
Freezing*+ Storage of carcasses on-farm and transported in a refrigerated unit in larger quantities.	Stored in sealed containers so little environmental impact. Energy consumption needs to be balanced against transport savings made.	Pathogen eradication unlikely; however carcasses can be stored in sealed units to reduce chance of propagation.	NABC (2004) Blake (2004) CAST (2008a)
Lactic acid fermentation+ 'Pickling' of animal carcasses when inoculated with *Lactobacillus acidophilus* and a carbon source in an anaerobic environment at ~30°C. Carcasses must be ground first.	Fermentation may not complete if putrefaction is allowed to start before carcasses are fermented. If the rendered material is turned into feed then it may contain toxic amines. Process is sealed so little environmental threat expected.	Low pH (optimum 4.5) and heat treatment (~30°C) should deactivate most pathogens. Rendering should complete the process. No information on TSE persistence.	NABC (2004) Blake (2004) CAST (2008a)
Grinding & storing*+ Grinding of carcasses and storage in chemicals (e.g. inorganic acid) or heat-treatment in sealed units.	Storage in sealed containers should have little environmental impact unless preservative is spilt [a].	Grinding speeds up decomposition therefore waste needs quick disposal, unless preserved. Grinding may improve subsequent eradication of pathogens; however may constitute a risk at times of disease outbreaks (e.g. avian influenza).	Lo et al. (1993) NABC (2004) CAST (2008a) CAST (2008b) Cai et al. (1995)
Yeast fermentation+ Similar to lactic acid fermentation. Ground carcasses added to an agitated tank with a Carbon source and yeast inoculant. Kept at *ca.* 26-29°C.	Unknown.	Some pathogens shown to recover 12 h and 48 h post-inoculation.	Blake (2004)

[a] Author's opinion