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A critical review on risk evaluation and hazardous management in carcass burial

Long-term risk assessment and risk management approach for livestock burial sites after biosecurity management period.

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Summary

Carcass disposal from livestock disease outbreaks or on-farm, routine mortalities present a number of challenges. Proper management of carcasses can no longer be addressed as an incidental occurrence, as they represent a persistent pathway of infectious agricultural wastes with potential to harm the environment. The long-term management of carcass disposal sites is essential irrespective of the cause of mortality. Critically this ensures eradication of disease and environmental protection from a range of biological and chemical hazards. Strategies for large-scale carcass disposal require preparation and coordinated, proactive planning in advance of emergencies to meet environmental protection guidelines and maximize the efficiency of response.

Carcass disposal methods include burial, incineration, composting, alkaline hydrolysis, lactic acid fermentation and anaerobic digestion. Burial techniques include trench burial, landfill, and notably mass burial as one of the most common methods of disposal. However, there are concerns about possible impacts to the environment and subsequent risk to human health regardless of the initial logistical and economic advantages.

This review provides an overview of our current understanding of the potential threats of carcass burial and possible management options. The environmental implications of terminating burials is discussed as is the role of biochar and phytoremediation which can contribute to the management of burials. These examples are considered in the case study context of Korea where long-term considerations remain a priority. The outcome of the review is structured to provide information to decision-makers that is of value when equipping themselves with comprehensive guidelines for the sustained management of carcass burials. Finally, recommendations that address future research needs are outlined.

Outline

1. Introduction

Regular mortality of animals is an expected consequence of intensive livestock farming. Farm animals are threatened easily by exotic disease outbreak, pandemics such as foot and mouth disease (FMD), avian influenza (AI) and transmissible spongiform encephalopathy (TSE), i.e. a group of progressive prion disease conditions that affect the brain and nervous system of animals and humans. These TSEs are also known as bovine spongiform encephalopathy (BSE) or mad cow in cattle, or chronic wasting disease in deer and elk. Large scale catastrophic mortality events can occur from disease outbreaks or natural disaster. In the case of a disease outbreak, animals within a certain area are culled and require safe disposal that is practical and economically prudent (SAF, 2005).

Several methods including burial, incineration, rendering, composting, anaerobic digestion, and alkaline hydrolysis are available options for carcass disposal (Engel et. al., 2004; SAF, 2005). Each method has advantages and disadvantages for large scale mortality events (Table 1). When dealing with carcass disposal from disease outbreaks factors such as; the vectors of disease transmission, public health and environmental impact must be considered.

Burial has been shown throughout history to be one of the most practiced methods for disposal. This is well established for on-farm mortalities in many countries including South Korea. Burial refers to the disposal of animal carcasses through the excavation of a trench or ditch and covering them with the backfill soil (NABC, 2004). The process relies on containment of the pathogens for a duration long enough to ensure inactivation before the potential migration of pathogens or toxins to nearby surface and groundwater sources (Gwyther et al., 2011). Cost and regulatory restrictions on other disposal methods results in this often being considered as the preferred method for disposal of carcasses. Alternatives such as rendering and incineration of livestock carcasses frequently prove to be prohibitive in these contexts (CFR, 2010). Disposal of carcasses through burial provides an inexpensive, quickly prepared and high capacity solution for the removal of infective materials particularly where catastrophic mortality is underway from a disease outbreak (de Klerk, 2002; McClaskey, 2014; Scudamore, 2002). In addition, on-site burial has the advantage of controlling airborne livestock diseases such as foot-and-mouth disease and avian influenza where removal to alternative sites may increase these risks.

The major challenges associated with the disposal of catastrophically high numbers of mortalities are directly associated with managing the logistics and resources needed to cull and dispose of high volumes of carcasses, then managing and mitigating potential environmental impacts. These two phenomena are not mutually exclusive as the pressure for disposing of carcasses quickly has an influence on both the site selection and process of disposal (Joung et al., 2013; Mesmer, 2011; Scudamore, 2002). For example during the FMD and AI outbreaks of 2010 in Korea, the requirement to cull and dispose of animal carcasses within a short time scale caused a high percentage of burial pits to be constructed without full consideration of the environmental and biosecurity protocols necessary (Mesmer, 2011; Ok et al., 2015). In some instances, the unacceptable process of burying livestock alive due to the shortage of euthanisation chemicals and man-power resulted in complete destruction of the bottom and sideliners of the burial pits from hoof punctures (Kim and Pramanik, 2015). These instances, in association with regional weather patterns of high temperature followed by intense rainfall during the monsoon season raised concerns about the potential contamination of both groundwater and surface-waters due to leachate infiltration from poorly constructed burial pits (Mesmer, 2011; Kim and Pramanik, 2015). Some of these concerns were confirmed in several studies where soil, surface and groundwater contamination by nitrogen (N) compounds, pathogens, antibiotics and chlorine (Cl) from cleaning, were observed from carcass disposal directly through land burial (Pratt, 2009; Joung et al. 2013; Kim and Kim, 2013; Yuan et al., 2013). Public, animal and environmental health in the surrounding regions in several of these studies are at increased risk and thus need careful monitoring to minimise current and future risks. This review considers these risks and looks at potential threats to the environment, public health from carcass burials and then looks at the management of these threats with the result of deriving more effective burial management plans.

2. Potential hazards related to carcass burial

Disposal by burial has historically been the most common method used by producers to dispose of livestock mortalities. Although animal carcasses are buried beneath the soil surface, i.e. no longer visible, they remain potential sources of danger to the environment. The hazards associated with carcass burial are not limited and have been identified to cause several potential threats including nutrient, pathogen, antibiotics and other chemical transmission to the environment.

2.1 Nutrient pollution

Nutrient pollution is one of the most widespread, costly and challenging environmental problems associated with agricultural systems and intensive livestock operations, with major constituents consisting of excess nitrogen (N) and phosphorus (P) in the soil, water and air (USEPA, 1995). Although, N and P support the growth of algae and plants, excess nutrients in the system may cause serious environmental and human health issues. Excess nutrients in surface water may cause fast growth of aquatic plants and algae resulting in eutrophication. Although N generally is not a problem with adults, excessive amounts (> 10 mg N L-1 of Nitrate) in drinking water may cause low oxygen levels in the blood of young infants or young livestock, a potentially fatal condition (Spalding and Exner, 1993; USEPA, 1995). Generally, P is not considered harmful in drinking water; however, it can cause detrimental effects to the environment when in excess. Currently there is no standard for phosphorus content in drinking water, but the concentrations exceeding 0.5 μg L-1 can cause carcinogenic effects from a lifetime of exposure (Pratt, 2009).

Carcass leachate contains significant nutrients concentrations including N (mainly ammonium-N) and P ($H_2PO_4^-$) (Yuan et al., 2013; Table 2). These burials can be a major source of nutrients as pollutants in surface water and groundwater (GW). In most cases a proportion of leachate produced during the decomposition of animal carcasses in burial pits is retained in the adjacent soil. Some leachate may transport to nearby surface water bodies and or to GW depending on subsurface conditions including the amount of leachate produced, soil type, GW level, etc. The carcass soil may then act as a further, secondary source of nutrients that contaminates the water if nutrients leach to the GW and or are washed out to surface water during precipitation. Ammonium-N that is largely present in leachate can be oxidized to nitrate-N by autotrophic and heterotrophic bacteria in the presence of oxygen and organic carbon, respectively. The conversion of ammonium-N to nitrate-N is of greatest concern in the transport of N from burial sites into GW due to its potentially high mobility in GW (Pratt, 2009).

Several studies report significantly high concentrations of ammonium and nitrate-N in burial pit soil, surrounding surface water (SW) and shallow GW. For example, Ritter and Chirnside (1995) observe high concentrations of ammonia (366 mg N L^{-1}) and nitrate-N (77.6 mg N L^{-1}) in GW collected from wells adjacent to poultry burial pits. Glanville (2000) also reports similar observations with ammonia-N concentration in GW samples (403 mg N L^{-1}) collected from monitoring wells installed within 1 m of turkey and swine carcass burial pits. Myers et al. (1999) report concentrations of nitrate-N (39.7 mg N L^{-1}) as higher than that of ammonia-N (0.2 mg N L^{-1}) in GW samples collected near well-drained poultry mortality pits.

Data in research literature on soil and surface water nutrient pollution concentrations from burial pits are rare. Therefore, further investigations need to be carried out in this field to understand better the environmental impacts of carcass burial. However, it can be predicted that mass burial pits have the potential to cause significant impact on nutrient loading in localized soils (McDonald et al., 2014) as well as surface water bodies located near burial pits. Chowdhury et al. (2016) reports significantly high concentrations of N in carcass burial soil which is likely to be a secondary source of contamination. Further, Flory et al. (2015) report leachate leaking from burial pits to nearby creeks in Korea.

2.2 Pathogenic agents

A range of pathogenic microorganisms may be present in leachate produced from decomposing carcasses including foot and mouth virus, E. *Coli*, campylobacter, salmonella, *Leptospira* and water born protozoa such as *Cryptosporidium* and *Giardia* (Dolan and Koppel, 2005). Traditionally it is thought that pathogens are destroyed or deactivated in the soil during decomposition in soil. However, recent evidence indicates that some pathogenic agents/microorganisms from decomposing carcasses may survive for long periods of time. Moreover, they can be transported in leachate to groundwater and surface waters and thus threaten water quality. For instance faecal coliforms, *E. Coli* and *Salmonella spp.* were detected in groundwater samples collected from nearby burial pits (Joung et al., 2013; Myers et al., 1999). Kim and Kim (2012) and Ritter and Chirnside (1995) also report similar microbial contamination of groundwater around livestock mortality burial sites. Whilst risks remain low for the majority of the burial sites, evidence from these studies show that pathogenic agents in drinking water are a matter of public concern. It is known that infectious materials including anthrax spores and prions can exist within soils for long periods after carcass decomposition (Nechitaylo et al., 2010; Gwyther et al., 2011). This risks reintroduction of anthrax or the development of neurodegenerative disease, e.g. TSE or scrapie in the case of prions, if contaminated soil incorporating such infectious agents are ingested by animals (Sharp and Roberts, 2006; Johnson et al., 2007).

2.3 Veterinary drugs

In the process of animal production and care antibiotics are widely used agents in veterinary medicine. Veterinary drugs including antibiotics/antimicrobial compounds, anti-parasitic drugs, antifungals, hormones and growth promoters are all used (Bartikova et al., 2016). The effects of antibiotics in the environment are important as they can lead to antibiotic resistance with the possible consequences of reductions in effectiveness of treatment options for both animals and humans (Kim et al., 2011; Regassa et al., 2016). Antibiotics drugs are commonly used in animal production for the treatment and prevention of bacterial infection. Veterinary antibiotics (VAs) are applied as drugs or feed additives to treat or prevent livestock animal infections. VAs can also be used as growth promoters to improve feed efficiency and weight gain for increased food, meat and or milk production (Bartikova et al., 2016; Du and Liu, 2012). Whilst the use of antibiotics for growth promotion as feed additives in livestock production was banned in the European Union in 1998, large amounts of antibiotics are still used in the sector worldwide (Du and Liu, 2012). The most frequently used VA includes tetracyclines, sulphonamides, beta-lactams and macrolides (Bartikova et al., 2016; Grave et al., 2010).

Resulting risks from this treatment is that animal carcass burial sites potentially contain antibiotics that were once used in animal production. It is increasingly likely that antibiotics will be evident in the soil from animal carcasses. The presence of antibiotics in carcass leachate and adjacent soils (Kim and Kim, 2012; Yuan et al., 2013) can be a potential threat to GW quality as there is a significant risk of transport of the antibiotics to GW. For example, the study by Furtula et al. (2012) has detected VAs in surrounding environments including soil and GW. Kim and Kim (2012) also report antibiotics detected in GW from the wells located near burial pits, i.e. within 10 m. Moreover, VAs can be taken up by plants which potentially lead to secondary exposure to humans through vegetative consumption (Bartikova et al., 2016). For instance, VAs were observed in plant tissue grown in soil mixed with sulfamethazine (Rajapaksha et al., 2014). Therefore, carcass burial sites are a potential source of antibiotics that present a risk of transmission to the public and animal sector if these sites are used for cultivation without proper management. Whilst the amount of antibiotics consumed through the food chain may be very low (0.1-1.2 ppm), i.e. below the toxic level. Ingestion of antibiotics in foods in minute amounts can be considered potentially unsafe due to likely long-term, chronic toxicity (Bartikova et al., 2016; Boxall et al., 2003; Regassa et al., 2016). These chronic impacts require further long-term investigation.

2.4 Other contaminants/chemicals

Carcass leachate contains several other hazardous elements which can be transported to the surrounding environment including chlorine (Cl), sodium (Na). For example, Cl (109 mg L^{-1}) and total dissolved solids (1,527 mg L^{-1}) were detected in GW adjacent to poultry carcass burial pits (Glanville, 2000). Knight and Dent (1995) also found increasing concentrations of Cl and Na in groundwater near recent graves when compared to background waters. Delgado et al. (2014) reported high Cl and Na concentrations in excavated carcass soil used for cultivation in Korea. These high amounts of Na and Cl in soil can lead to increases in soil salinity (Knight and Dent, 1995) and thus soil productivity may decrease. Excess Cl in water may result in adverse health impacts such as weakness and coma when ingested. Excess concentrations of Na in the human body are also known to cause high blood pressure, renal failure and death. Symptoms of Na poisoning include increased sensitivity, twitching, tremors, oedema and stupor (Pratt, 2009).

The production of volatile organic compounds during carcass decomposition in burial pits is also possible. These VOCs include a wide group of organic compounds, including sulphur-containing compounds, nitrogen-containing compounds, alcohols, phenols, ketones, esters, volatile fatty acids, and terpenes (Pagans et al., 2006). In a composting system with swine carcass and plant materials, Akdeniz et al. (2010) detected 43 VOCs including dimethyl disulfide, dimethyl trisulfide, and pyrimidine. They also confirmed that these three VOCs were only found to be produced by decaying swine carcass and not from decaying plant materials. It is also assumed that some greenhouse gas (GHG) emissions will be produced during carcass decomposition, though little is known about GHG emissions from carcass burial. However, increasing GHG (CO_2, CH_4, N_2O) emissions in a composting system with livestock/cattle mortalities (Xu et al., 2007) supports this assumption.

3. Factors influencing the direct hazards related to carcass burial

Direct hazards of burials often indicate groundwater contamination due to leaked leachate and therefore focus on an individual site. The factors affecting the leachate generation are pit location, shape, size, and species buried and lining materials used in the pit.

3.1 Hydrogeophysical properties of burial sites/Location of pit

Hydro-geophysical properties of burial sites such as soil texture, permeability, slope and water table are all factors influencing contaminant transport to the surrounding environment. Sandy textured and highly permeable soils increase the leachate percolation rate and thus enhance vulnerability of GW contamination from carcass burial (Dolan and Koppel, 2005). Freedman and Fleming (2003) report that the potential for GW contamination is high from the burial pits which are located in sandy soils with high seasonal GW tables. Yuan et al. (2013) report that site topography affects leachate production and transport. They observed the lowest amount of leachate produced in the pit at the highest elevation, with all other pits located down slope thereby increasing runoff over the surface of the pits located down slope. Kaown et al (2015) monitored microbiological properties of two hydrogeologically different burial sites (flat area and mountain slope) and observed GW contamination from the carcass burial site located on the sloped area.

3.2 Placement depth of carcass

It is recommended that carcasses should be placed under the soil in a pit with a minimum earth cover of 0.6-1.9 m (Freedman and Fleming, 2003). They also suggest maintaining a minimum distance of 1.0-1.5 m from the pit to the bottom of the GW table. However, increasing the burial depth as well as carcass placement depth may induce hypoxic conditions, particularly in waterlogged soils (Killham, 1994). This can obstruct microbial decay of prions, which leads to prolonged infectivity and thus creating a biosecurity threat if pits are inadvertently exposed at a later date (Gwyther et al., 2011).

3.3 Carcass volume

During decomposition, significant amounts of leachate are produced from a large volume of carcass, i.e. generally the liquid:solid ratio is 70:30). Excess leachate after adsorption by surrounding soils can be percolated into the GW system. Due to ion adsorption and contaminant loading, impacted burial pit soils may act as a secondary source of contaminants and leaching.

Therefore, the negative impacts of carcass burial on the environment are likely to be increased with increasing carcass volume/weight in pit.

3.4 Carcass type

Contaminant loading in the leachate produced from carcass decomposition varies between species. For example, Pratt (2009) analysed leachate chemistry produced from poultry, swine and bovine mortalities. The highest N concentration was found in bovine leachate with the lowest from poultry leachate. However, in case of Cl content, the results were opposite to the N content. Therefore, the carcass type is likely to play a significant role in determining contaminant mass loading to the environment and thus the impact to which the subsurface will be exposed.

3.5 Lining material

Unlined carcass burial pits and trenches exuding leachate present a greater risk of soil and GW contamination, especially those sites located in sandy soils. Lining materials such as synthetic liners or compacted clay liner systems in carcass burial trenches and pits can reduce GW contamination significantly by impeding the ingress of leachate. Lining material installation in burial pits acts as a barrier for vertical movement of the leachate and is helpful to control flow (Pratt, 2009; Kim and Pramanik, 2015). In lined systems leachate can be pumped for treatment before discharge and thus water contamination via carcass burial can be controlled more effectively (Albano et al., 2011). However, it is more important to assess the extent to which the amount of leachate affects groundwater quality in the watershed, i.e. the likely impact from the volume and concentration of leachate produced from a burial site.

4. Management of hazards related to carcass burials

It is clear that impacts from carcass burials are directly relevant to environment conditions. Leachate can cause direct deterioration of the local ecosystem with land use in the vicinity of burials becoming increasingly vulnerable to environmental and health impacts from inadequate site planning and poor process management. General waste management schemes of reduction-recycling-disposal are not applicable to carcass disposal due to time and land constraints as well as the need for biosecurity. Therefore, research to date largely focuses on understanding leachate characteristics and the properties of individual burial sites to minimise the impact of other burials. Many contingency and investment management schemes emphasise environmentally responsible approaches. In cases even where disasters have not occurred, it is logical to develop a waste management system to sustain safe disposal and thus minimise environmental impacts.

4.1 Management options for direct hazard of leachate

Leachate produced during carcass decomposition is a complex mixture of compounds regarded as a polluting agent if it leaks from the burial pits. Once released it can be expensive and difficult to manage, therefore precautionary measures including selection of a suitable location, designing the pit volume, and using lining material must be taken into account before burying carcasses.

4.1.1 Location/site selection

Site selection for carcass burial whether on-farm or off-farm, requires a careful examination and evaluation of all of the factors/parameters with the potentially to adversely effects the environment. Ideally, burial sites should be identified and planned prior to an incident or outbreak. This reduces the risk of sub-standard site selection from time pressure during an incident (Dolan and Koppel, 2005). Databases exist in many countries worldwide that provide guidance on site selection criteria plus guidance on environmental protection (MOK, 2010; CAST, 2008; Dolan and Koppel, 2005; The animal by-products regulations-Scotland, 2003). Summarizing this guidance the following key aspects should be considered for evaluation of characteristics during the selection of sites to minimize negative impacts of carcass burials:

(i) Geology:

Suitable geology in site selection assists in ensuring biosecurity and containment of leachate and pathogens in the long term. Screening naturally occurring geological conditions provide an assessment of protection against ground and surface water pollution risks. Site soils that provide natural attenuation include those with a capability to adsorb chemical components from the leachate (Fig. 1) This can reduce concentrations via ion exchange within the soil particles. For example, in anaerobic environments most ammonium is retained by via ion exchange with cations already present in the soil, i.e. Mg and Ca (Pratt, 2009; Kim et al., 2016). Whilst ion exchange helps manage the release of ammonia, it is relevant to note that an increased concentration of those ions it replaced will be evident at the front of the leachate plume, e.g. Na, K, Ca, Mg and others. In general, sites with a high clay content are more likely to have lower permeability than those with sand or more coarse material. Reducing permeability extends the time taken for leachate to reach potential water sources. The same is true for locations in highly fractured or unconsolidated material, or shallow sites close to bedrock. These locations will have high permeability and need to be assessed for these risks. The following geological conditions should be considered in the selection of a carcass burial site:

- Areas of low permeability ($\leq 1 \times 10^{-7}$ cm sec^{-1}) is recommended.
- Underlying soil must be clay textured otherwise a synthetic liner must be used
- Regions with highly soluble rocks, i.e. limestone and high secondary permeability, i.e. basalt, highly fractured greywacke should be avoided.
- Areas subject to instability, i.e. active geological faults, steep slopes, embankments of rivers, lakes, oceans should be avoided.

(ii) Hydrogeology: A suitable hydrogeological location is important to protect surface and groundwater resources and an understanding of the possible fate and rate of discharge of contaminants that may enter surface and groundwater systems. The following hydrogeological conditions should be taken into account during disposal site selection:

- Under no circumstances should the burial site be located in or near watercourses. In doing so, there is a serious risk of the spread of disease to livestock on neighbouring farms as well as threatening the water body as well as risks to public health. Regulations in many jurisdictions require routine, on-farm burial sites to be more than 250 m, 50 m and 10 m away from any well used for drinking water, watercourse and field drain, respectively (The animal by-products regulations-Scotland, 2003). However, sites identified for mass burial should be located at least 1000 m from any well, and 200 m away from any watercourse.
- Flood-prone areas with high GW levels and shallow aquifers should be avoided.
- Any identified crack or drains in land should be removed or permanently sealed.

(iii) Topography:

The topography of a burial site can expedite or diminish the potential for adverse effects on the environment from leachate, odour, noise and sight lines to neighbouring properties. An assessment of the potential site should include an evaluation of existing topographical features and candidate sites should be screened in order to minimize the negative impacts topography could impart. Flat land is preferred over sloped land for mass burial sites, as drainage gradients should be slower. However, areas with modest slopes may allow for easier storm water and leachate control and could be the only available option at the time.

(iv) Access and Traffic:

The conditions of roadways and disposal site access traffic to the site should to be considered during site selection for mass carcass burial. It should be confirmed that all roads and bridges on the access route to the disposal site can accommodate heavy vehicles, large oversized loads and traffic congestion as well as be constructed of pavement or concrete to minimize dust, issues with mud during heavy rain and the ability to easily cleanse in the event of accidental leachate release. Residential areas should be avoided in routes to disposal locations. Time of queuing should be minimized or eliminated completely for all disposal traffic.

4.1.2 Pit type, volume and depth

The recommended shapes for the burial pits are trapezoidal and rectangular (Fig. 2). The length of the pit is measured from the cross-sectional area of the pit geometry. Guidelines for the land area required for burial of livestock carcasses are provided by a number of sources. Table 3 shows a summary of these guidelines for trench burial. According to information in Table 3, guidelines for the required excavation volume or land area differ regionally. For instance, in the USA, USDA (2001) estimates the volume of 0.92 m^3 or 1.2 yd^3 to accommodate a mature bovine carcass whereas this value was 1.53 m^3 or 2 yd^3 in AU and NZ estimated by Agriculture and Resource Management Council of Australia and New Zealand (Nutsch and Spire, 2004). Variations in the dimension of burial pits depends on differences in the natural attenuation of soils, site hydrogeology and stability. However, the suggested ratio of pit volume to carcass volume is typically 4:1 for up to two layers of large animals and 2:1 for up to three layers of medium or small-sized animals (Mukhtar, 2012). Carcasses should be buried deep enough to prevent intrusion from carnivorous animals. However, to prevent groundwater contamination, geological conditions will determine the depth of carcass placement. The minimum distance from the water table is a separation of 1 meter; in less secure geological settings this distance should be greater (MOE, 2010).

4.1.3 Lining material

Interior boundary conditions of burial pits vary regionally. In geologically secure locations, pit construction can be as simple as excavation, filling and capping. In locations where the geology hinders protection of water resources, burial pits should be constructed in a manner that prohibits leachate movement out of the pit and protects surrounding groundwater resources.

Parameters determined by geotechnical site testing should be performed at each potential site location to determine requirements for pit lining. This defines whether an impermeable barrier such as a geo-synthetic liner or constructed compacted clay liner should be used. In the event of using synthetic liners the material must be compatible with the material at the pit boundary as well as be resistant to weathering and puncturing. Albano et al. (2011) recommend the use of synthetic liners with a minimum thickness of 12 mm; and compacted clay liners constructed with a minimum thickness of 150 mm with a hydraulic conductivity of no greater than 1 x 10^{-7} cm sec-1.

Chemical treatment during pit construction and loading is debated in a research texts. Hydrated lime has been used in the base of burial pits both with and without clay mineral mixes. The addition of lime ($Ca(OH)_2$) is known to be effective in reducing the survival of pathogens and thus the risk of transfer off-site (Sanchez et al., 2008). Using lime as a chemical barrier to minimize biological risks is supported by Avery et al. (2009) who report no viable *E. coli* in contaminated abattoir waste when treated with lime at a rate of 10 g of CaO lime L^{-1} waste. Adding lime to carcass material incurs a risk of delay in degradation due to impact on the microbial communities associated with decomposition (Nutsch and Spire, 2004).

Porous clays such as biochar (BC) or zeolite can also be used as lining materials in burial pits. Experimental evidence using BC or zeolite as a lining material is scarce, though it is argued that porous substances can be effective tools due to their high adsorption capacity (Ahmad et al., 2014; Chowdhury et al., 2016). However, it is necessary to maximise the leachate absorbed in the lining materials. Therefore, before using porous substances as lining materials, basic calculations to determine the volume of porous substance needed must relate to the carcass loading for the specific site.

4.1.4 Engineered constructed pit/mass burial/landfilling

Carcasses from the farms which are unsuitable for land based disposal require disposal at suitable landfills or mass burial facility away from the farm. Mass burial is used for carcass large volumes collected from multiple farms. Generally, a mass burial site should be engineered to incorporate systems and controls to collect, treat and dispose of leachate and gas produced during the decomposition of buried carcasses as shown in Fig. 3 (Fig. 3). During the 2001 outbreak of FMD in the UK, a total of seven mass burial sites were constructed to bury about

1.3 million (about 20% of the total 6 million) carcasses (NAO, 2002). During the 2010/2011 outbreak of FMD/AI in Korea, more than four thousand mass burial sites were constructed to prevent the rapid spread of virus (Kim amd Kim, 2013; Kim and Pramanik, 2015). All the locations were selected after rapid assessment. Limited planning with, in most cases no input from surrounding communities was possible due to time constraints of the emergency (Kim and Pramanik, 2015). In general, risk assessments, groundwater authorizations and planning consents were performed. However, little assessment of the site properties were undertaken. Most pits took less than a week to bring into operation and thus this was a hugely controversial issue. The potential advantages of the mass burial method can be drawn when appropriate planning and site evaluation are conducted prior to the onset of an emergency. Nutsch and Spire (2004) and MOE (2010) provide a detailed discussion of the technical aspects of the mass burial sites used in the UK and Korea , respectively.

Landfill sites bury carcasses in engineered, sealed containment areas. Similar to mass burial sites the key features of a typical landfill design include composite liners, leachate containment systems and gas collection systems. The difference between landfills and engineered carcass disposal sites is that landfills are comprised of ‘cell’ sections where wastes/carcasses are loaded, whereas in general mass carcass disposal sites contain a single section for placement. Landfills typically use impermeable lining materials to impede the flow of liquids, thus allowing leachate to be collected and removed from the site for treatment and safe disposal (Nutsch and Spire, 2004). A comprehensive overview of the design and operation of landfills is outlined by O’Leary and Walsh (2002). Whilst more expansive than mass burial and not widely used for carcass, landfill can be an environmentally friendly way for carcass disposal in a timely fashion on a bio-secure logistics route.

Site boundary security such as fencing, entrance gateways, vermin/pest control etc. should be implemented on both landfill and mass burial sites to protect the infrastructure from disturbance and individuals from harm. In the case of carcass disposal sites involving transmissible disease agents such TSE/BSE, additional biosecurity measures are needed to prevent secondary disease transmission. Nutsch and Spire (2004) and Delgado et al. (2015) provide further details about biosecurity.

4.2 Management and remediation options for the long-term hazards of the burials

Monitoring the impacts of leachate due to leaking around the burial sites is important following burial. Once leachate leaks, remediation can be a costly and long process time depending on the amount lost, its concentration and site characteristics. Thus the following measurements demonstrating contamination from the post management plan; groundwater monitoring, pumping and treatment of groundwater, PRB, phytoremediation and reopening the burials may be necessary.

4.2.1 Leachate collection and disposal

Whenever possible in cases such as mass burial or landfilling of livestock carcasses, the leachate produced during the decomposition process should be collected and disinfected before being safely discharged. Collected leachate should go through proper examination procedures prior to discharge to check for potential contaminants including pathogens, nutrients and antibiotics. Treatment of the leachate before discharge to land or waterways, should be performed by engineered waste water facilities or livestock manure treatment facilities to minimize the negative impacts of the leachate on the surrounding environment (Kim and Pramanik, 2015).

4.2.2 Groundwater monitoring for leachate pollution

Burial sites are constructed to minimize the negative impacts of carcass burial on the environment including groundwater quality. Proper monitoring of potential leachate impacts due to leaking/leaching in and around burial sites should be part of the post management plan for carcass disposal sites (Kim and Pramanik, 2015). The leachate pollution index (LPI: a quantitative tool to assess the leachate pollution potential of various landfill sites in a given geographical area) proposed by Kumar and Alappat (2003) can be used to determine the groundwater pollution trend from a particular burial site over time. LPI can be helpful to determine whether a burial site requires immediate action for remediation in order to prevent a severe pollution incident. However, the identification and quantification of the limiting number of groundwater quality parameters (i.e., chloride, ammonia-nitrogen, nitrate-nitrogen, and total coliform only) are the major players of the LPI for its successful application (Umar et al., 2010). These four parameters may not be able to differentiate between sources of pollution (i.e., manure application and carcass leachate) as livestock manure applied to the land may contribute these same nutrients to the soil and water nearby. Therefore, more appropriate quality parameters of groundwater collected from the monitoring wells of burial sites should be considered in order to differentiate between the sources of pollution. Some important quality parameters such as biomarker, microbiological approach and antibiotics can be included to overcome the drawbacks of LPI application (Kim and Pramanik, 2015).

The duration and frequency of pollution monitoring should be sufficient enough to capture complete decomposition of the buried carcasses as well as within a sufficient timeframe for the assessment of subsurface transport timelines. According to the guidelines in Korea (MOE, 2010), groundwater quality monitoring is scheduled once per quarter in the first year and twice per year in the next three consecutive years after burial. However, the duration of the groundwater quality monitoring can be increased as mass burial sites could continue to produce leachate for as long as 20 years (Nutsch and Spire, 2004; UKEA, 2001). Moreover, monitoring should be done more frequently (i.e., monthly) if Cl and ammonium-N are detected concurrently in samples (Kim and Pramanik, 2015).

4.2.3 Active remediation of contaminated groundwater

Pumping and treatment of groundwater

Pumping and treatment is a costly but common method to remove a wide range of contaminants including industrial solvents, metals, and fuel oil that are dissolved in groundwater. In this method, contaminated groundwater is pumped from wells to an above-ground treatment system in which contaminants are removed. ‘Pump and treat’ systems are also useful to treat contaminated plume produced from leaked burial sites. Pumping helps keep contaminants away from drinking water wells, wetlands, streams and other natural resources.

Pump and treat methods typically involve installing one or more wells to extract the contaminated plume from the ground. Extracted groundwater is used either directly into a treatment system or to store a holding tank until treatment can begin. The treatment system may consist of a single cleanup method such as activated carbon to clean the water. However, treatment often requires several cleanup methods including ion exchange system, anoxic/anaerobic bioreactor(s), aeration/membrane tanks, and air stripper systems if the groundwater contains different types of contaminants (Breedlove et al., 2011). Once treated water meets regulatory standards, treated water may be pumped back underground or into a nearby stream, or to irrigate soil and plants. Other wastes such as sludge, biosolids produced as a result of treatment are disposed of properly.

Pump and treat is a safe way as it does not expose people to that contamination although pumping brings contamination to the ground surface. It is ensured that the monitoring and treatment units are working as designed. Moreover, the groundwater sampling is done to ensure the plume is decreasing in concentration and is not spreading. Although, it is a safe and sound method to remediate the contaminated groundwater, the sustained costs over a long period of time from a few years to several decades for remediation can be onerous. The clean-up time depends on several factors such as contaminant concentrations, volume of contaminant plume, groundwater flow and complexity of flow path (Breedlove et al., 2011; EPA, 2012).

4.2.4 Passive remediation of contaminated groundwater and soil

Adsorption using permeable reaction barrier

Adsorption processes plays a continuing and important role in environmental remediation and protection with extensive research relevant to wastewater and drinking water treatment. Adsorption has been adopted as an efficient technology to remove contaminants including nutrients, antibiotics and heavy metals from wastewater, mainly industrial effluents (Chowdhury et al., 2016). This technology can be used to remediate groundwater contamination from carcass burial sites by installing PRB containing adsorbent(s) such as BC, zeolite, bentonite and zero-valent iron (Kim et al., 2016). The PRBs involve construction of permanent, semi-permanent, or replaceable units across the flow path of contaminant plume. The barrier contains adsorbent agent(s) (treatment zone) that are placed in the way of contaminant plumes to prevent further migration. Although the term ‘barrier’ is used to convey the idea that contaminant flow is impeded, the PRB is designed to be more permeable than the surrounding aquifer media in order to easily flow GW through the PRB (Gavasker et al., 2000; Guerin et al., 2002; ITRC, 2011).

Two types of PRB instalment such as continuous reactive barriers and funnel-and-gate systems are commonly used to remediate contaminated fluids. The reactive zone in these continuous barriers (Fig.4) contains adsorbent material. A funnel-and-gate system (Fig.4) consists of an impermeable segment (or funnel) that directs the captured groundwater flow toward the permeable reactive zone (or gate). This configuration can be helpful to control better the GW flow over the reactive zone. However, continuous reactive barriers are easier to set up and management compared to funnel-and-gate systems (Gavasker et al., 2000). Therefore, most recent PRB applications are continuous reactive barriers.

The PRBs can be installed in the presence of an active source of contaminants such as leaking burial sites. It may also be useful after removing the active source i.e., re-opening the burial site and transporting the sources away from the site for treatment. The PRBs can be installed near the sites, in the middle between the sites and receptors, or at the end of the plume (near the receptor) to reduce the negative environmental impacts of carcass burial (ITRC, 2011). As the leachate plume or GW containing carcass leachate flows through the treatment zone (i.e., adsorbent such as BC, zeolite), contaminants such as ammonium, the major contaminant of carcass leachate, come into the contact with the treatment medium and are adsorbed to the adsorbent's surface (Chowdhury et al., 2016). More details about the field application of PRBs can be found in reports by ITRC (2011) and Wilkin et al. (2008).

Information on the uses of PRBs to remediate contamination from carcass burial is scarce. Moreover, the applications of PRBs are generally limited to the mining industries for the remediation of hydrocarbons (Kao and Borden, 1997; Guerin et al., 2002), heavy metals (Bain et al., 2006; Wilkin et al., 2008; Beiyuam et al., 2016) and radioactive substances (Naftz et al., 2006) contaminated groundwater. However, the PRBs containing BC applications can be an effective option to remove contaminants such as ammonia, nitrate, phosphorous, antibiotics, chloride from the carcass leachate plume (Kim et al., 2016). Activated BC produced from $MgCl_2$ or $ZnCl_2$-enriched feedstock or other base-enriched adsorbents (i.e., modified zeolite or bentonite) in PRBs can be used to increase PO_4^{3-}—P removal efficiency, thereby effectively achieving the simultaneous removal of both positively and negatively charged contaminants (Rajapaksha et al., 2016). However, the success of PRBs application may depend on the working efficiency of adsorbent(s) used, amount of adsorbent(s) loading in PRBs, location and orientation of PRBs, contaminant concentrations and flow rate of GW (ITRC, 2011). Therefore, to ensure the successful field application of PRBs, continuous monitoring is warranted as the sorption capacity of adsorbent(s) may decrease with time.

Phytoremediation

Traditional methods such as landfilling, leachate/groundwater pumping and treating and re-opening burial sites for remediation of carcass contaminated soil and groundwater, are generally expensive. Phytoremediation is a low cost, sustainable, eco-friendly, aesthetically pleasing, solar energy driven clean-up technique and useful for both *in situ* and *ex situ* treatment of contaminated sites (UNEP, 2016). Phytoremediation techniques (Fig. 5) are one of the well-established processes in environmental clean-up studies. This technique has been applied to a broad range of toxic metals (Liu et al., 2000; Moreno et al., 2008; Gupta et al., 2009) and radionuclides and is also efficient for treating a wide range of contaminants including organic and inorganic compounds (Roy et al., 2005; Mwegoha, 2008; Tangahu et al., 2011).

As leachate contains significant amounts of nutrients, phytoremediation techniques can be an effective and low-cost strategy to control and remediate contaminated sites. However, the selection of plant species for phytoremediation must be done with knowledge of the ability of the plant to take-up contaminants whilst also being able to thrive in the local soil and climate (Rizwan et al., 2016). Plants with extensive roots and high nutrient uptake are preferred to reduce nutrients from carcass contaminated sites. Shallow rooted herbaceous and grass plants such as alfalfa, mustard, wheat, millet can be used to remediate contaminants on surface soils. Flory et al. (2015) evaluated phytoremediation techniques in shallow trenches excavated in native soil to a depth of between 460 and 710 mm (18 and 28 inches). Excavated soils were subsequently placed back after putting a single layer of animal carcasses in the trench and formed a mound on which a phytoremediation layer was established using wheat, ryegrass, fescue and pearl millet. No leachate, odours or flies were found, which indicate the efficiency of the technique. However, root growth was limited and did not penetrate greater than 200 mm (8 inches), i.e. roots were not grown into the areas around the carcass, which was identified as a main drawback in the study by Flory et al. (2015) and thereby requiring further investigation.

Woody plants having rapid growth rates, deep roots and high water use (high transpiration rates) are suitable to treat contaminations in the sub-surface zone or in groundwater regions. Hybrid poplar (*Populus deltoids x Populus spetrowskyana*) and willow (*Salix bebbiana*) are commonly used in phytoremediation to treat groundwater contaminated by nutrients (Kneteman, 2012). A consulting firm, Sand Creek Consultants (SCC, 2016) planted hybrid poplar and willow trees to remediate N (ammonia and nitrate) pollution of soil and groundwater caused by long-term leakage of liquid fertilizer from manufacturing equipment in Iowa, USA. The research team of SCC observed that significant quantities of water and nitrogen from the aquifer were removed over the course of several years; the trees grew to over 7 m (25 feet) and sharply reduced off-site migration of nitrogen-impacted groundwater. They also designed and installed the phytoremediation system using poplar and willow trees to control migration and contaminant concentrations of groundwater mixed with leachate from an unlined municipal landfill. Moreover, the SCC successfully implemented this technique to clean up residual petroleum in groundwater in Northern Wisconsin, USA by planting hybrid poplar trees on the site directly atop the contamination plume. The bioenergy buffers study by Andera et al. (2016) reports that phytoremediation techniques using willow trees are functional in agricultural fields to remove nitrate flowing from the field to the groundwater system.

Phytoremediation can also be used for ex situ treatment of soil and leachate collected from various landfill and/or mass burial sites, which is much more economic than that of traditional methods such as chemical washing, and pumping out and treating (Dimitriou and Aronsson, 2016). Phytoremediation using poplar and willow trees was found to be effective to treat leachate collected from different landfill sites (SCC, 2016; Dimitriou and Aronsson, 2016). Leachate was applied to the tree field as drip irrigation. The technique was successful even for the system with no liner beneath the soil as the quality of groundwater collected from monitoring wells at the site was not affected. Nissim et al. (2015) found that the willow vegetation was effective to treat irrigated wastewater. It was observed that *ca.* 90% of the N and 85% of the P found in wastewater were removed and thus the risk of environmental pollution by wastewater disposal was solved. Therefore, the contaminated soil produced from re-opening the carcass burial sites and leachate collected from different landfill and/ or mass burial sites could be treated by using phytoremediation techniques.

In regions of the world where engineering methods are not available, phytoremediation can be an effective and available option to remediate contaminations (James and Strand, 2009). However, the potential benefits of phytoremediation may be offset by some drawbacks such as duration and effectiveness of cleanup of the technique. Generally, long cleanup times are required in phytoremediation, which is the main drawback of this technique (Linacre et al., 2005). Nevertheless, biomass produced during phytoremediation can be used as raw material to produce BC which can then be applied in PRB and soil (Fig.6). Moreover, by increasing the effectiveness of cleanup, the potential benefits of the technique can be assured. The effectiveness of phytoremediation mainly depends on the efficiencies (water, nutrient use) of plants used, root depth, planting density, planting depth, groundwater flow rates and directions, contaminant loading and availability for plant uptake (Tangahu et al., 2011; Dimitriou and Aronsson, 2016; SCC, 2016). To get the maximum benefit from phytoremediation techniques, those factors should be taken into account during implementation to sites contaminated by carcass burial.

4.2.5 Termination of the burials

If leachate leaking occurs from burial sites, and poses a significant threat, immediate remediation actions are needed based on quality and quantity of contaminants found in the samples. Re-opening carcass burial sites refers to the process of excavating and removing the previously buried carcasses to prevent contamination to soil and groundwater. Re-opening the burial site and removing the decomposing carcasses and soil from the burial site and transporting to a treatment facility is quicken alternative to in-situ remediation measures for the vulnerable burial site. To identify the burial sites at risk of severe environmental pollution, an assessment of pit construction, volume of carcass buried and contaminants found in ground and surface water samples are imperative. Although reopening offers a quick solution, it can be more expensive than other remediation techniques such as phytoremediation and using PRB- permeable reactive barrier to remediate a contaminated fluid (Table 4). For instance, the total processing cost for escavation, removal and treatment was estimated much higher (US\$80,000/100m^3) than that of PRB technique (SAFE, 2016). Moreover, during the excavation of sites and transportation of excavation products (i.e., soil and decomposing carcasses), biosecurity (set of preventive measures taken to reduce the risk of transmission of infectious diseases) is a great concern as it should be maintained at all times to prevent further spread of disease. Therefore, it is required to ensure that during re-opening of carcass burial sites, precautionary measures are put in place to secure the safety of workers, public health and the environment. Vinneras et al. (2012) found that transportation and storage of materials can cause the spread of pathogens as they can escape through airborne pathways and cause infection. Vehicles carrying materials from animal burial sites should therefore be disinfected before they leave site. People who come into contact with infected carcasses can act as mechanical vectors to potentially serve as an ongoing source of further infection to livestock (Bender et al., 2006). Moreover, human health is not always entirely safe from animal disease agents. For instance, children in southern California were infected with a swine influenza virus (Ginsberg et al., 2009). Trifonov et al. (2009) also reported that the recent swine influenza A (H1N1) virus can be infecting to humans. Therefore, workers and visitors should be properly dressed with appropriate protective clothing and all items should be disinfected when leaving site. Wild animals, cats, dogs and vermin can act as fomites and carry infection from the site. However, the mechanisms of the virus to infect and cause disease and disseminate to other animals is still to be investigated (Arzt et al., 2011). Nevertheless, good biosecurity should be practised as part of the site health and safety procedures during re-opening of carcass burial sites.

5. Challenges associated with managing carcass burial

Identification of the challenges associated with safe carcass management is imperative. The major challenges that affect the disposal process include financial factor, time, transportation, disposal equipment and skilled personnel. As financial support is commonly involved in each step and adequate budget is important to overcome the challenges, it is not considered for discussion in this study.

Time: Disease agent transmission for specific outbreaks are a critical factor and diseases can be further spread after an outbreak and may cause a new incident if infected carcasses are not disposed of in a time sensitive and manner after the outbreak. Therefore, it is important to securely move the carcasses to a safe place as soon as possible prior to the further spread of the disease. In a large-scale event, carcass removal within a short period of time is a great challenge to the carcass management process. To manage the carcasses successfully in such an event, a number of transport vehicles are needed, as well as disposal equipment and skilled manpower ready for use. The lack of availability of vehicles (i.e., carrier), equipment (i.e., digger etc.) and skilled labourers will increase disposal management time therefore increasing the chance of new incidents. Removing carcasses in a time sensitive fashion is critical and depends on proper pre-planning and the availability and efficiency of all units involved in the process.

Transportation: The transportation of large numbers of carcasses requires sufficient quantities of vehicles/carriers in order to dispose them in a timely fashion (i.e. before further spreading of the disease). It also requires appropriate planning and preparation to prevent further spreading of the disease/virus to susceptible animals or human populations during transportation. It has been assumed that the vehicles used for feed delivery and manure collection were the source for the spreading of FMD during the outbreaks in 2010 in Korea (Kim and Pramanik, 2015). Well organized and specific protocols for transportation are crucial to a safe and successful disposal plan. The protocols should be developed prior to disasters (i.e., FMD/AI outbreak) which outline the necessary preparations and response to solve/minimize the issues involving carcass transportation (i.e., travel route, number of stops, disinfection and decontamination).

Equipment: A significant number of equipment is required for handling carcasses and constructing burial sites. Lack of proper equipment may cause delays in disposal and thus increase the chance of secondary infection. Personnel involved in carcass management processes may also be exposed to infections by the pathogen due to lack of personal protective equipment (PPE) and improper carcass handling techniques. Therefore, in order to protect personnel, PPE should be stockpiled and ready in the event of a disease outbreak as well as appropriate equipment for handling carcasses and the construction of approved burial sites. If these things are in place ahead of time, delays due to improper PPE, personnel, and construction equipment can be minimized.

Skilled manpower: Availability of equipment operators, supervisors, and drivers is crucial to manage carcasses effectively during a disease outbreak. There may be significant health risks, stress variables, and emotional trauma associated with the handling and transportation of diseased animals. Manpower with the necessary training and guidelines can be helpful to overcome these problems and thus skilled laborers play important role to manage large disposal projects safely and timely. Therefore, failure to have enough skilled personnel during a mass mortality event may cause further negative impacts on the surrounding environment.

Land allocation: Geo-physiochemical characteristics are important for the selection of burial sites and land evaluations generally take time. Moreover, land allocation for mass burial sites may be impractical due to land deficiencies. Pre-selection of burial sites are preferred to prevent/reduce the environmental impacts from burial sites.

6. Case study: FMD and AI outbreaks and burying mortalities: Korean recent episode

Since the year 2000, four FMD outbreaks have occurred in Korea (Park et al., 2013; Ozawa et al., 2006; Wee et al., 2008). After almost a century without an incident, two outbreaks occurred within quick succession in 2000 and 2002. A total of 15 cases of infected cattle were reported during the FMD outbreak in 2000 (Ozawa et al., 2006). Measures were deployed to control the outbreak and included a mixed programme of "stamping out" animals from infected premises and vaccination for animals in premises deemed "dangerous contacts". As part of the control measure 2,216 animals were culled (Ozawa et al., 2006). Carcasses were disposed through the only option available-by burial on the farm site (Wee et al., 2008; Lee, 2013). In 2002, a new outbreak of FMD was detected in fifteen pig farms and one cattle farm. In this case, measures deployed for controlling the disease focused on stamping out all infected premises and dangerous contacts. As part of containment measures 160,155 animals were culled, and the carcasses were again disposed through burial on farms (Ozawa et al., 2006; Lee, 2013).

In 2010/2011 (from December 2010 to March 2011), following 8 years of disease free status, two new incidents of FMD and AI were reported in Korea in quick succession. Throughout the outbreaks, 3,234 farms were identified as having animals testing positive for FMD and/or AI (Park et al., 2013; Kim and Pramanik, 2015). A "stamping out" policy was implemented for all animals infected in the first two weeks following confirmation of the first outbreak, alongside a national vaccination strategy. Constrained by legal barriers, the Korean government was limited to disposal through on-farm burial as the only option. As a result, 3.48 million animals (151,425 cattle, 3,318,299 pigs, 8,071 goats, and 2,728 deer) were disposed of in 4,583 on-farm burial sites (Table 5: Burial sites in Korea) (Park et al., 2013; Lee, 2013).

The Ministry of Environment (MOE, 2010) adapted the guidelines for construction of burial pits to bury the infected animals. The main purpose of these guidelines was to isolate the infectious FMD/AI virus during decomposition from the environment. Figure 3 shows the schematic diagram of the carcass mass burial site as per the construction guidelines (MOE, 2010; Kim and Pramanik, 2015). According to the guidelines, burial pits are appropriately sized based on the amount of livestock mortalities. The livestock mortalities are placed in the pit at least 2 m depth from the ground surface. The floor slope of 2% is preferred for the standard pit. Soil mixed with bentonite is spread on the floor as well as along the walls of the pit to reduce the permeability. A waterproof synthetic liner is laid in the pit to prevent leaking of leachate into the surrounding environment including soil, GW and surface water. A leachate collecting pipe having a perforated wall at the bottom is installed on the liner floor of the pit to collect leachate from the decomposed carcasses. A gravel layer is arranged around the perforated portion of the pipe in order to facilitate the leachate flow through perforated pipe. A 1 m soil layer is then placed on the liner floor, as well as a 5 cm lime layer. Carcasses are placed on the soil layer and capped with soil. Another perforated pipe is installed in the carcass chamber and surrounded by gravel to exhaust the gasses formed during the decomposition process. The rest of the pit is then filled with soil, and a soil embankment with 2 % slope is formed up to a height of 1.5 m from the ground surface on top. Additional lime is spread on the top of the embankment. Deodorant and sawdust can be spread around the leachate and gas exhaust pipes to reduce malodor produced during carcass decomposition.

During the FMD/AI outbreak in 2010/2011, the suspected livestock were slaughtered by methods of pithing, electrical stunning and euthanasia by lethal injection. However, shortages of euthanization chemicals and laborers forced the burial of living animals. Although burial of the mortalities were attempted to be carried out as per government specifications (Fig. 3), it was not always possible to maintain the standards for all of the burial sites due to lack of time, equipment and laborers in order to prevent the rapid spread of the diseases. As a result, many pits remained unlined or partially lined (Lim et al., 2012). The pit liners were also damaged due to burying the livestock alive. These inappropriately constructed and damaged burial sites posed a potential risk of environmental pollution (Kim and Pramanik, 2015).

To evaluate environmental impacts resulting from these carcass burial sites, a number of disposal sites have been monitored by the MOE and other organizations (i.e., SAFE) after the 2010/2011 FMD/AI outbreak in Korea. It was informed that partially decomposed of buried carcasses was found in the burial site even after two years of burying due to low air and moisture contents as air and water do not penetrate into the burials. According to actual monitoring of burials, almost 70% of burials constructed result of FMD/AI was reported the low decomposition rate (SAFE, 2015).

The authorities outlined the detailed environmental impacts of the carcass burial sites constructed during the outbreak (Kim and Pramanik, 2015; Lim et al., 2012; MOE, 2010). The negative environmental impacts that occurred due to carcass burial sites constructed during the 2010/2011 Korean FMD/AI outbreak are summarized in Table 6 (Table 6). The most important impacts that were identified include (i) emissions of nuisance gases to the air (ii) ground and surface water pollution occurred due to leachate leaking and (iii) soil pollution occurred locally mainly by N and BSE.

7. Conclusions

Due to the simplicity and cost effectiveness, burial is the most commonly used method for carcass disposal among various methods including incineration, composting, alkaline hydrolysis, lactic acid fermentation and anaerobic digestion. However, in spite of its potential logistical and economic advantages, some possible impacts on the surrounding environment including soil, surface and ground water are documented. Potential hazards related to carcass burial sites include nutrient pollution, pathogenic agents and antibiotics transport. The hazards related to carcass burial may be influenced by some factors such as hydrogeophysical properties of burial site, carcass placement depth and volume, and lining materials. The hazards produced by carcass burial can be reduced/controlled by proper pre-planning to meet the challenges associated with the management of mass mortalities. However, following the updated rules and regulations of burial sites and pre and post management options for carcass burial are equally important to manage the hazards related to carcass burial.

8. Research priorities

Lack of information on the effects of livestock carcass burial (Freedman and Fleming, 2003; Kaown et al., 2015; Bartikova et al., 2016), will result in research in this area being useful to producers, researchers and policymakers. Research options outlined below are therefore prioritised.

(i) It can be argued after reviewing the guidelines available that the guidelines for the selection of burial sites would be more selective and comprehensive by adapting some site specific characteristics. For example, hydro-geochemical properties of site could also be taken into account during the selection of a burial site as positive correlation between the contaminant concentrations, redox conditions, microbial community and hydro-geochemical conditions of site leachate can be found (Kaown et al., 2015). Therefore, these hydro-geochemical properties of site could be incorporated into the guideline for better understanding to select a burial site.

(ii) Improved technical information on pollutant sources and pathways are needed for the assessment of environmental impacts by burial. Research can be carried out to better understand the survival and potential migration of various disease agents within burial systems. Moreover, research can be conducted on the use of soil amendments incorporating prion/disease agent degrading microbes which may stimulate prion/disease agent degradation.

(iii) Acute toxicity of veterinary drugs for non-target species is generally very low due to low concentration of VD in the environment (Santos et al., 2010). However, longer-term and unknown effects are more likely to take place than acute environmental impacts. These chronic effects from long-term and low-level exposures to VD have not been comprehensively understood. Moreover, the behaviour of mixture of VD or interaction of VD with other chemicals in the environment is still unknown. Beside these, the studies of toxicity impacts on plants, which are rare (Bartikova et al., 2016), can be carried out to select the suitable plant species for phytoremediation of VD.

(iv) As carcass residues are relatively homogeneous organic materials, there is a significant possibility of energy recovery. Although the technologies to produce biogas and biofuel from carcasses are available, practical oriented tests of the technologies should be carried out using carcass mortalities taken into account of surrounding environment and biosecurity.

(v) Importantly the amount and concentration of leachate from burials is needed to determine the extent to which leachate effects groundwater quality within watersheds. Environmental risk assessments of groundwater quality at watershed scale has not yet been understood from research studies.

(vi) Rhizobarrier (plant roots based PRB where soil can be mixed with BC) concepts are potentially useful to remediate the groundwater contaminated by leachate leaking from burial sites. Laboratory and field scale studies carried out to assess the sustainability and efficiency of the rhizobarrier to remove the contaminants from the system would provide valuable information for these remediation methods.

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