**REVIEW PAPER**

A Review of the Environmental Effects of Different Livestock Manure Storage Systems, and a Suggested Procedure for Assigning Environmental Ratings

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There are concerns over a range of adverse environmental effects resulting from the storage of livestock manures on farms. The objectives of this study were to examine all the likely environmental effects of different storage methods, and to recommend which were the most desirable options.

Literature reviews were undertaken to identify the likely environmental consequences of each commonly used storage method, in terms of water pollution risks, odour and ammonia emissions, greenhouse gas emissions and survival of microorganisms during storage. Planning and landscape aspects were considered and the most feasible options for abatement of ammonia emissions were identified. An 'environmental rating' for different storage systems was then devised, with the aim of obtaining a balance between water pollution, aerial emissions and other concerns.

The environmental rating exercise favoured the more sophisticated and hence most expensive storage methods. No large differences emerged between ratings for slurry systems and solid systems when ease of adding ammonia control measures was excluded. For pigs, slurry systems appear to have a slight advantage, because of the greater ammonia emissions from the solid pig manure. The use of such a rating system could be developed further as more data become available. Whilst the method indicates the relative desirability of systems at a national scale it could be adapted to take account of local considerations or those of individual farm sites. © 2002 Silsoe Research Institute. Published by Elsevier Science Ltd. All rights reserved

1. Introduction

Approximately, 70 million tonnes of manures and slurries are collected from housed animals in England and Wales each year (Mitchell *et al*., 1996). Approximately, half this total is stored as solid manure and half as slurry. The majority of solid manure is stored in field heaps, not sited on a prepared base, and an estimated 70% of slurry is stored in earth-banked structures (Nicholson & Brewer, 1997), which raises concern over the potential for groundwater pollution (Goody *et al*., 2001). Other forms of storage, such as cylindrical above-ground tanks are impermeable but may fail if the structure deteriorates (Sangarapillai *et al*., 1994). The number of water pollution incidents arising in England and Wales from failure or mismanagement of storage structures has, however, decreased from 1013 to 416 between 1994 and 1998 (Environment Agency, 1999).

Concerns also arise over emissions of ammonia, odours and greenhouse gases from stored excreta. Ammonia (NH₃) causes acidification and nitrogen enrichment and contributes to eutrophication after deposition to soils (Roeloffs & Houdijk, 1991), with indications that, even if maximum feasible reductions in emissions of sulphur dioxide (SO₂) and oxides of nitrogen (NOₓ) were achieved, deposition of NH₃ would exceed critical loads for acidity in some parts of Europe (Hettlelingh *et al*., 1992). The majority (ca. 80–90%) of NH₃ emissions are from agriculture (Pain *et al*., 1998). The greatest proportion (ca. 47%) of these emissions take place during housing and storage. The potential to apply ammonia emission abatement measures to various storage systems varies in both practicality and cost. Other factors, such as the potential for harmful microorganisms to persist during the storage period, and the visual appearance of structures also need to be...
taken into account in any overall environmental appraisal.

This study had two main objectives: first, to review all the likely effects of different storage methods for livestock manures and slurries on the environment (including water pollution, gaseous emissions, pathogen abatement and visual appearance), together with ammonia emission abatement strategies that might be applied to each system; second, to suggest a method of 'environmental rating', and to predict which are likely to be the most environmentally desirable storage options in the long term.

2. Methodology

2.1. Storage systems considered

The systems considered were those typically in use in England and Wales, as indicated in Table 1. Whilst below-house storage is practised for slurry and in-house storage for solid manures, such systems were not been included per se, because in terms of gaseous emissions inventories (Pain et al., 1998), they are regarded as an integral part of the housing system. Material from such housing systems is often stored for an additional period, by one of the methods listed, before being spread to land.

2.2. Literature review

A literature review was undertaken to identify the likely environmental consequences of each commonly used storage method, in terms of surface and ground water pollution risks, odour and ammonia emissions, greenhouse gas emissions, and the viability of microorganisms after storage. Planning consultants' experience was used to provide informed opinion on visual appearance of different storage systems. The feasibility and cost of options for abatement of gaseous emissions (in particular, ammonia) from the storage methods were identified, drawing on experience in the Netherlands and elsewhere in Europe.

2.3. Environmental rating exercise

Factors outlined above were drawn together to give a simple overall 'environmental rating' for each of the major storage methods. The Environment Agency was consulted on factors to be included. The range of scores for individual factors was arbitrarily assigned as shown in Table 2, with the aim of obtaining a reasonable balance between the risks of water pollution, aerial emissions and factors such as visual appearance. Scores were assigned on the basis of the general outcome of the literature review. A high score was used to indicate better environmental performance. As there are factors associated with livestock type, in respect of ammonia emissions, the scoring exercise was carried out separately for cattle, pigs and poultry.

For a number of factors, insufficient data (e.g. relating to nitric oxide emissions) or practical experience of certain techniques (e.g. of covering lagoons) were available to allow scores to be derived on an objective basis. Subjective judgements were made in these cases. The general basis on which scores were assigned for each environmental effect is given at the end of each of the relevant sections, 3–7, below.

3. Water pollution

3.1. Point source

Failure or mismanagement of slurry storage structures has often caused point source water pollution in the past. Numbers of substantiated water pollution incidents in England and Wales (1987–1998) from agriculture and from slurry/manure stores are given in Table 3. Category 1 incidents, usually caused by catastrophic failure or mismanagement of slurry storage structures, decreased dramatically, from 99 in 1991 to 22 in 1998. This reduction appeared to be due to: heightened awareness of the need for careful system operation; the installation of improved structures, encouraged by the availability of generous Ministry of Agriculture Fisheries and Food (MAFF) grant-aid; and the introduction of the Control of Pollution Regulations in 1991 (DoE, 1991, 1997). It was not possible to determine the number of incidents arising from different types of store. Badly designed, installed or mismanaged earth-banked structures can collapse, particularly if overfilled. Weeping-wall stores may pose a risk from

### Table 1

<table>
<thead>
<tr>
<th>Types of storage system considered in the study</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slurry storage</strong></td>
<td><strong>Solid manure storage</strong></td>
</tr>
<tr>
<td>Cylindrical above-ground tank</td>
<td>Concrete pad—with tank</td>
</tr>
<tr>
<td>Weeping wall store</td>
<td>Concrete pad—no tank</td>
</tr>
<tr>
<td>Unlined lagoon</td>
<td>Field heap—same site each year</td>
</tr>
<tr>
<td>Lined lagoon</td>
<td>Field heap—different site each year</td>
</tr>
<tr>
<td>Below-ground concrete tank</td>
<td>Roofed store with concrete base</td>
</tr>
</tbody>
</table>
uncontrolled ‘spurting’ of liquid store contents not contained within the perimeter channel. Above-ground steel circular stores can collapse if panel joints become severely corroded, although the degree of corrosion and loss of strength are not necessarily correlated with the age of store (Sangarapillai et al., 1994). Accidental discharges may occur through sluice valves jamming or being left open.

3.2. Pollution of groundwater

The Control of Pollution Regulations (DoE, 1991, 1997) introduced, for the first time, minimum requirements for the sizing and siting of new or substantially modified slurry storage structures. The degree of impermeability required for earth-banked structures was not defined in these Regulations. However, a maximum permeability of $10^{-9}$ m s$^{-1}$ was suggested (CIRIA, 1991), which rules out all but sites with at least 1 m depth of impermeable clay, as suitable for installation of a new unlined structure of this type.

3.2.1. Pre-fabricated and concrete stores

Provided above-ground structures of this type have not developed defects in the floor slab, they should present minimal risk of groundwater pollution. There is evidence, however, that extensive leakage can occur

<table>
<thead>
<tr>
<th>Type of emission or control (max. score)</th>
<th>Factor</th>
<th>Score range</th>
<th>Assessment of rating values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water pollution (30)</td>
<td>Point source</td>
<td>0–10</td>
<td>10, low risk; 0, high risk</td>
</tr>
<tr>
<td></td>
<td>Ground-Water</td>
<td>0–10</td>
<td>Taking account of typical structures, and assuming reasonable maintenance and management</td>
</tr>
<tr>
<td></td>
<td>Storage period</td>
<td>0–5</td>
<td>5, &gt;4 months; 2, &lt;4 months</td>
</tr>
<tr>
<td></td>
<td>Flexibility of emptying</td>
<td>0–5</td>
<td>5, no constraints; 1, limited</td>
</tr>
<tr>
<td>Gaseous emission level (40)</td>
<td>NH$_3$</td>
<td>0–10</td>
<td>5 or 10, low emission; 0, high emission, relative to other storage methods. Based on published data where available, for storage system without emission control measures.</td>
</tr>
<tr>
<td></td>
<td>Odour</td>
<td>0–5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CH$_4$</td>
<td>0–10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N$_2$O</td>
<td>0–10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NO</td>
<td>0–5</td>
<td></td>
</tr>
<tr>
<td>Pathogen control (10)</td>
<td>Microbial pathogens</td>
<td>0–10</td>
<td>Based on relative die-off of major pathogens during typical storage period and conditions: good, 5; poor, 0</td>
</tr>
<tr>
<td>Subtotal score</td>
<td>0–80</td>
<td>Total of three items above</td>
<td></td>
</tr>
<tr>
<td>Ammonia (NH$_3$) emission control measures (20)</td>
<td>Practicality</td>
<td>0–10</td>
<td>10, easily done</td>
</tr>
<tr>
<td></td>
<td>Cost</td>
<td>0–10</td>
<td>0, relatively impractical; 10, low or zero cost; 0, high cost m$^{-3}$ stored</td>
</tr>
<tr>
<td>Visual appearance (5)</td>
<td>Planning approval</td>
<td>0–5</td>
<td>Likely attitude to system under current planning controls. 5, ‘easy’; 0, ‘difficult’</td>
</tr>
<tr>
<td>Subtotal score</td>
<td>0–25</td>
<td>Total of two items above</td>
<td></td>
</tr>
<tr>
<td>Overall rating</td>
<td>0–105</td>
<td>Total of all scores</td>
<td></td>
</tr>
</tbody>
</table>

Table 2

Factors, method and scores used to obtain overall ‘environmental rating’; a high score denotes a better overall rating.
from below-ground concrete tanks which are poorly designed, or installed with no special precautions to seal the joints between the floor and the walls, particularly if exposed to high water tables (Barrington et al., 1991).

3.2.2. Earth-banked structures for slurry

Structures with an impermeable synthetic liner should present minimal risk of groundwater pollution provided the liner remains intact. Leakage detection systems for such structures have been proposed (CIRIA, 1991), but as far as is known, none is in use in the UK. One study showed that failure of a clay liner in a lagoon over a highly permeable soil caused serious groundwater contamination (Ritter & Chirnside, 1983). There is conflicting evidence regarding the extent of such risks with unlined structures. Monitoring around large-scale structures (Miller et al., 1985; Rowsell et al., 1985; Ritter et al., 1984) has sometimes shown no adverse effects on groundwater, even when constructed on sandy material. This has often been attributed to the self-sealing effects of slurry. Laboratory studies have shown slurries to have a significant self-sealing effect, by causing physical blockage of soil pores. In one study, permeability of a range of soils was reduced to $10^{-8}$ m s$^{-1}$ within 30 days (Rowsell et al., 1985) and in another by at least one order of magnitude, e.g. from $10^{-8}$ m s$^{-1}$ to $10^{-9}$ m s$^{-1}$ (Owen, 1996).

Other work involving long-term monitoring of unlined stores has, however, indicated that there are significant risks of groundwater contamination in certain conditions. Kanazawa et al. (1999) found persistent high total nitrogen concentrations in groundwater adjacent to a lagoon constructed on a soil with a high water table. One study (Phillips & Culley, 1985) found minimal effects on groundwater, except where structures were located on coarse-textured sand. Studies of one UK store located on the Upper Chalk have shown nutrient and bacterial contamination of pore-water at depths of up to 76 m, and it was deduced that contamination occurred as a result of fissure flow through the unsaturated zone beneath the structure (Withers et al., 1998). Loss of self-sealing effects and subsequent leakage was attributed to disruption of the self-sealing layer during emptying by mechanical excavator. Other studies have identified drying of exposed subsoil or embankment soil during recession of liquid levels (Ciravalo et al., 1979), and repeated freezing and thawing as factors causing loss of self-sealing (Gangbazo et al., 1989). It appears, therefore, that existing unlined stores of this type may pose significant groundwater pollution risks in certain situations. A recently completed study on eight stores (Goody et al., 2001) concluded that groundwater is most at risk where the water table is shallow, but that in the majority of UK situations, minimal threat is posed to potable groundwater drinking supplies.

3.2.3. Solid manure storage

New stores for solid manures are not covered by the Control of Pollution Regulations (DoE 1991, 1997) unless they have a concrete or similar base, in which case the effluent must be contained as if it were slurry. Storage of solid manures in field heaps is not therefore directly controlled by legislation, although the MAFF Code of Good Agricultural Practice for the Protection of Water (MAFF, 1998), recommends that such heaps should ‘not be put over field drains, within 10 m of a

<table>
<thead>
<tr>
<th>Year</th>
<th>Incidents due to slurry and manure storage</th>
<th>Category 1 incidents* due to agriculture</th>
<th>Total incidents due to agriculture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>1070</td>
<td>(not introduced until 1991)</td>
<td>3890</td>
</tr>
<tr>
<td>1988</td>
<td>1226</td>
<td>4141</td>
<td></td>
</tr>
<tr>
<td>1989</td>
<td>879</td>
<td>2889</td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>750</td>
<td>3147</td>
<td></td>
</tr>
<tr>
<td>1991</td>
<td>814</td>
<td>2954</td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>774</td>
<td>2770</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>729</td>
<td>3051</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>1013</td>
<td>3338</td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>621</td>
<td>2731</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>400</td>
<td>2111</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>315</td>
<td>1884</td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>416</td>
<td>2050</td>
<td></td>
</tr>
</tbody>
</table>

*Category 1 incidents are major incidents involving persistent effects on water quality or aquatic life. Source: Environment Agency, 1999.
watercourse or 50 m of a spring, well or borehole'. There appears to be little literature on the likely effects of solid manure storage on groundwater contamination. Whilst one study (Sowden & Hore, 1976) concluded that there was little risk from nitrate contamination, because of denitrification at or near the water table, other contaminants were not measured. Leachate from solid manures stored in uncovered heaps direct on the soil surface could, however, pose a risk in certain situations, e.g. over sensitive aquifers, particularly if heaps are situated near water abstraction points.

3.3. Environmental ratings

Slurry and manure storage systems with impermeable concrete bases, and steel or concrete wall panels, were assigned high ratings (8 or 10 out of a maximum 10) for a relatively low risk of groundwater pollution, whilst earth-based or unlined earth-banked structures for both slurry and manure were regarded as higher risk, being assigned scores of 0 or 2. Pre-fabricated circular above-ground stores, which are emptied by pump, were rated 5 out of a maximum of 5 for the ability to allow land spreading when conditions are favourable, whereas those such as weeping wall stores, which are often emptied in a single annual ‘campaign’, were assigned a score of 3.

4. Gaseous emissions

4.1. Liquid manures (slurry)

4.1.1. Odours

Odours from manures usually comprise a complex mixture of volatile organic compounds, produced by microbial degradation of fibre and protein. O’Neill and Phillips (1992) identified 168 such volatile compounds in livestock wastes. No satisfactory chemical test or marker compound has been identified which is applicable to a wide range of odours (Pain, 1994). Olfactometry, which uses a group of panellists, is the generally accepted assessment technique for odour concentration. Odour threshold value is the number of volumes of odour-free air needed to dilute an odour until it is detected by only 50% of panellists; this value is often expressed as odour units per unit volume of air (OU m⁻³ [air]). Approximately 20% of complaints regarding odours from livestock farms in England and Wales relate to slurry and manure storage. The source of the manures (livestock type), store geometry, period of storage and ambient conditions are all likely to affect emissions (Pain, 1994). Carney and Dodd (1989) found that agitated poultry, pig and cattle slurries generated odour concentrations, adjacent to the storage facility, of 222, 200 and 167 OU m⁻³ [air], respectively. Management is also important, with slurry mixing leading to greater odour concentrations in air samples collected above stored slurry (Copelli et al., 1986; Carney & Dodd, 1989). De Bode (1991) carried out experiments with 4·5 m³ tanks and found that odour concentrations generated were greater in summer than in winter and greater from pig slurry than cattle slurry. Odour emission is reduced by covering stores, the magnitude of the reduction depending on the type of cover (Mannenbeck, 1986). For example, in one series of experiments, a purpose built ‘airtight’ cover gave 70–90% reduction and a crust created by floating straw gave 60–70% reduction (De Bode, 1991).

4.1.2. Ammonia

Emissions of ammonia from housed livestock arise mainly from the ammoniacal and uric acid–N in urine and manures, i.e. from the total ammoniacal N (TAN). De Bode (1991) measured NH₃ emissions equivalent to 5–15% of total N over 180–250 day storage periods from circular tanks. The emission rate for cattle slurry stored over winter changed little with time, but there were large differences between winter and summer emissions. Emission rates quoted in the available literature range from 2·1 to 14·4 g [N] d⁻¹ m⁻², the latter isolated figure relating to measurements on pig slurry stored during summer in the Netherlands (De Bode, 1991). Phillips et al. (1997), provide the only comparison of emissions from a circular tank (cattle), lagoon (pigs) and weeping wall (cattle), together with data from a solid manure heap (pigs). Measurements, of NH₃, N₂O and methane (CH₄), were taken from full-sized stores, but it was not possible to use the same measurement technique for all stores. Ammonia emissions from the lagoon and weeping wall store were each estimated by two methods: a downwind flux frame (Michorius et al., 1995) and passive diffusion samplers (Ferm, 1986, Schorringer et al., 1992) for the lagoon, and a modification of the passive diffusion sampler technique (Karlsson, 1994) and a Lindvall (1970) hood for the weeping-wall store. However, the passive diffusion (Ferm, 1986) tube estimate for the circular tank (445 g [N] d⁻¹ m⁻²) was much greater than that obtained using Karlsson’s modified approach, also using passive diffusion tubes, of 2·4 g [N] d⁻¹ m⁻². The latter figure was much closer to those reported by earlier workers. The same technique gave an estimate of 0·75 g [N] d⁻¹ m⁻² for the weeping-wall store. An estimate of 2·5 g [N] d⁻¹ m⁻² for the weeping-wall store was obtained using a Lindvall hood. The passive diffusion tube estimate from the lagoon was
2.9 g[N] d⁻¹ m⁻² which is similar to, albeit smaller than, those quoted from other studies.

4.1.3. Nitrous oxide

Nitrous oxide emissions differ considerably between different storage management systems. Emissions of N₂O from aerobically treated slurry can be relatively much larger, at 9–13% of total N, than ammonia emissions at <1% of total N as measured in the same study (Willers et al., 1996). These results were similar to those reported in other studies of aerobic slurry treatment. In consequence, the default emission factors in the Intergovernmental Panel on Climate Change (IPCC) Guidelines range from 0.1% of N excretion for anaerobic storage of manure, to 2% for aerobic storage (IPCC/OECD, 1997; Mosier et al., 1998).

4.1.4. Methane

Phillips et al. (1997) reported results from three types of store, but concluded that the technique used had underestimated CH₄ emissions, as earlier estimates indicated 25 g[CH₄] d⁻¹ m⁻³ for an above-ground tank, and 20–70 g[CH₄] d⁻¹ m⁻³ for a lagoon.

4.2. Solid manures (litter-based)

4.2.1. Odours

There appear to be no scientific studies, in the literature, on odour emissions from stored solid manures. It can be inferred that manure moisture content and management, during storage, are likely to have important effects. In-house drying of poultry manure is claimed to reduce odour emissions during storage and may also reduce emissions during subsequent spreading operations. Strategies for controlling odours from manure storage, including covering, were proposed by Powers (1999). Conventional wisdom suggests that odours from well-managed solid manure systems, where some composting takes place, are generally less offensive than from slurry-based systems. However, it is known that in anaerobically stored solid manures, odorous breakdown products may become entrapped causing considerable odour release when the heap is disturbed for spreading. Possible measures to control ammonia emissions, such as compaction or covering of heaps, might therefore have an adverse effect on odour nuisance at spreading.

4.2.2. Ammonia, nitrous oxide and methane

Comparisons may be made between different approaches to treatment and handling of solid manures, in particular with respect to whether or not aerobic composting was encouraged, and whether extra carbonaceous material (usually straw) was added in an attempt to immobilize the ammoniacal N (TAN) which is the source of ammonia emissions. Kirchman and Witter (1989) summarized a substantial body of earlier work comprising studies on aerobic and anaerobic manure storage. As early as 1917, greater N losses had been observed from aerobic composting of manure from anaerobic storage. However, two effects of aerobic composting need to be considered. Additional litter may reduce the potential for NH₃ loss by immobilizing TAN, but increase the rate of gaseous exchange by reducing manure density. Increasing the carbon to nitrogen (C:N) ratio for poultry manure from 18:1 to 36:1 decreased NH₃ losses (as % total N) from 44 to 8% in a chamber study (Kirchman & Witter, 1989). Dewes (1997), Maeda and Matsuda (1997) and Beck et al. (1997) all measured decreases in NH₃ emissions from increasing the C:N ratio of manure. Beck et al. (1997) also used a chamber study to quantify the effect of aeration rate on NH₃ emissions. Losses of NH₃ increased as aeration rate was increased from 10 to 30 l kg⁻¹ [dm] h⁻¹, but thereafter the effect was not consistent. Huther et al. (1997) also noted the increase of NH₃ emissions with increasing aeration of manure and there were also large increases in N₂O and CH₄ emissions as the aeration rate increased from 0.6 to 1.8 m³ m⁻³ [manure] h⁻¹, although emissions decreased with further increases in aeration rate. The increase in N₂O emissions was attributed to the proximity of aerobic and anaerobic zones in the partially aerated compost. The provision of easily oxidizable organic acids by aerobic bacteria, which could be used as substrates by methanogenic bacteria, was postulated to explain the increase in CH₄ emissions. Römer et al. (1994) reported differences in NH₃ emissions due to ratio of surface area to volume (2 or 1 m² m⁻³). Smaller emissions were measured from the heap with smaller surface area/volume ratio, and this was considered to be due to aerobic conditions in the heap with the greater surface area/volume ratio. Thus, under constant conditions, increasing the C:N ratio can reduce NH₃ losses, but if additional litter reduces density and increases gaseous exchange, NH₃ emissions may increase.

When poultry manures at three C:N ratios were stored anaerobically, there were no significant differences in NH₃ emissions, which were only ca. 1% of total N (Kirchman & Witter, 1989). These small emissions were attributed to reduced pH in the anaerobic manure (5.0–6.2, compared with 8.4–8.9 in the aerobic) caused by the production of acids as a result of incomplete oxidation of carbohydrates under oxygen-limited conditions. Dewes (1997), again in a chamber study, examined the effects of three litter rates and three storage densities on NH₃ emissions. Increasing applied
pressure from 0 to 800 kPa, at an excreta:litter ratio of 1:0.18, reduced NH₃ losses from 9 to 3.5% total N. Schulze Lammers et al. (1997) carried out a chamber study to measure emissions of NH₃ and N₂O from four types of straw-based manure. Included was a comparison of emissions from 'standard' (density 450 kg m⁻³) compacted (density 750 kg m⁻³) and aerobically composted pig manure. Emissions of NH₃ were 27, 5 and 40%, respectively, of the total N present in the manure at the beginning of the experiment.

In a larger-scale study using a large open dynamic chamber, enabling heaps of ca. 3:5 t to be monitored, Amon et al. (1997) measured the effect of aerobic composting and anaerobic storage of manure on emissions of NH₃, N₂O and CH₄. Ammonia emissions were much greater from the composted manure by a factor of ca. 3. Emissions of N₂O were small but ca. 50% greater from anaerobic storage. Large losses of CH₄ were measured, and were greater from the anaerobic treatment by an order of magnitude. No manure analysis before storage was given. The manure was from dairy cows, and if similar manure analysis to UK cattle is assumed, then the NH₃ losses represent ca. 14% of total N for the composted manure, and ca. 5% for the anaerobically stored manure, the latter being similar to that obtained by Schulze Lammers et al. (1997) for anaerobically stored pig manure. Losses from composted manure reported by Amon et al. (1997) were less than those reported by Schulze Lammers et al. (1997), but Hüther et al. (1997) observed greater losses of NH₃ from composted pig manure than from cattle manure.

Thus, emissions of ammonia are likely to be less when manure is stored in dense anaerobic heaps, due to reductions in gaseous exchange and pH. Anaerobic storage is also likely to reduce N₂O emissions but may lead to greater CH₄ losses.

4.3. Comparison of slurry and solid manure

4.3.1. Ammonia

Some workers have found losses of NH₃ during storage to be greater from solid farm yard manure (FYM) than from slurry. Svensson (1991) quotes losses of 2–10% total N from slurry, and 17–23% from FYM (increasing with length of storage). The UK Ammonia Emission Inventory (Pain et al., 1998) uses emission factors for cattle and pigs, respectively, of 4-4 and 4.3 g[N] d⁻¹ m⁻² for circular stores, 2.1 and 2.4 g[N] d⁻¹ m⁻² for lagoons, and 2.5 and 6.4 g[N] d⁻¹ m⁻² for solid manures. However, such emission factors, given on an area basis, do not take account of dilution, manure density, storage depth or exposed surface areas associated with these storage methods. If these figures were corrected to a raw (undiluted dung and urine) excreta basis, using the typical dilutions, depths and manure heap dimensions given by Nicholson and Brewer (1997), it was possible to show that in the case of both pigs and cattle, emissions from circular stores and lagoons were similar (between 1-13 and 1-41 g[N] d⁻¹ m⁻³ raw excreta). This was due to the greater depth and smaller exposed surface area associated with circular stores. Calculated emissions from stored solid manures were, however, considerably larger than from slurries for both cattle and pigs at 2.52 and 6.4 g[N] d⁻¹ m⁻³ raw excreta, respectively.

4.3.2. Nitrous oxide

A number of tentative emission factors, including greenhouse gases, for stored animal manures, were set by the Intergovernmental Panel on Climate Change (IPCC,1996) and have been subsequently developed further (Mosier et al., 1998). For N₂O, suggested losses were expressed as a per cent of manure N in store and for a temperate climate were 1% for slurries and 2% for solid manures. This ratio of relative emissions from stored slurries and solids is broadly in agreement with differences quoted in the literature outlined above.

4.3.3. Methane

Safley and Westerman (1998) measured wide variations in CH₄ production from anaerobic lagoons. Husted (1994) measured emissions from four farm scale storage facilities and concluded there were large spatial and seasonal variations in emissions, with estimated annual emissions for pig slurry, cattle slurry, pig solid manure and cattle solid manure of 8.9, 15.5, 27.3 and 5.3 kg animal⁻¹ yr⁻¹, respectively. Appropriate IPCC guidance figures (IPCC, 1996) are expressed per head of livestock and for a temperate climate are given as 49, 19 and 0.8 g cow⁻¹ yr⁻¹ for lagoons, tanks and solid manures, and 13, 5 and 0.2 g pig⁻¹ yr⁻¹ for lagoons, tanks and solid manures, respectively. No explanation or source is given for these figures. Whilst the large differences between slurry and solid manure systems are to be expected, the apparent difference between lagoons and tanks is difficult to explain. Emissions of methane are however likely to increase with anaerobic storage of solid manures. Amon et al. (1997), suggested differences of an order of magnitude between emissions from solids stored under aerobic and anaerobic conditions.

4.4. Environmental ratings

4.4.1. Slurry

Concern over emissions from slurry stores is likely to be dominated by NH₃. While there are few data to allow
comparison of emissions between store types, the smaller surface area to volume ratio, and greater facility for sub-surface filling, suggest that above-ground tanks are likely to emit less NH₃ per unit volume of slurry than are other slurry storage facilities. However, all slurry stores were assigned a rating of 7 (out of a maximum of 10) for ammonia emissions. All types of slurry storage, except weeping-wall stores, were assigned an equal, low rating (2 out of a maximum of 10) for methane emissions.

4.4.2. Solid manures

It is difficult to make a balanced comparison of losses from solid and liquid systems. However, the data available usually suggest that ammonia losses are generally greater from solid manure than from slurry. This may be a consequence of the tendency for aerobic composting to occur with solid manures, and if this can be prevented then there may be no disadvantage in any trend toward straw-based rather than slurry-based systems. However, the evidence suggests that any move toward greater aerobic composting of solid manures is likely to lead to greater NH₃ emissions. Solid manure storage systems were therefore given a lower rating than slurry systems in terms of ammonia emissions. Data on the effect of anaerobic storage on N₂O emissions are inconsistent, but it seems clear that anaerobic storage does not, axiomatically, lead to increased N₂O emissions. If conditions are sufficiently anaerobic to prevent nitrification, then N₂O losses may be reduced. Solid manure storage was assigned a rating of 4 (out of a maximum of 10) for nitrous oxide emissions, as compared to slurry storage systems which were assigned a score of 8.

4.4.3. Effect of livestock type

Where comparisons are available, losses of NH₃, as a per cent of N in the manure, are usually greater, and often much greater, from pig manure than from cattle manure. This applies to both slurry and solid manures and is likely to be partly in consequence of TAN being a greater proportion of total N in pig manure than in cattle manure. These apparent differences between ammonia emissions from cattle and pig solid manure were taken into account in assigned scores which were 5 in the case of cattle, and 2 in the case of pigs, out of a maximum of 10. While in absolute terms, losses of NH₃ are greater from cattle manure than from pig manure, putting greater emphasis on reducing NH₃ emissions during manure storage on pig enterprises may be a more cost-effective approach, because of the greater percentage losses from pig manures.

5. Microbial pathogens

5.1. Review of information

Animal manures and slurries contain a variety of different pathogenic microorganisms, e.g. bacteria, including Salmonella spp., Campylobacter spp. and E. coli O157, parasitic protozoa including Cryptosporidium parvum and Giardia lamblia and viruses (Ostling & Lindgren, 1991). The recycling of these wastes to agricultural land thus creates the risk of enteric pathogens contaminating the environment (Mawdsley et al., 1995), entering the food chain (House of Commons Agriculture Committee, 1998: Food and Drug Administration, 1998), or infecting livestock (Jones, 1976; Rankin & Taylor, 1969).

Reduction of pathogen levels in livestock wastes during storage is desirable in order to minimize these risks. A review of the literature reveals that there has been minimal research undertaken on this subject but the available information is used here to consider the microbiological implications of different animal waste storage systems. Composting of sewage sludge (Clark et al., 1984; Epstein & Epstein, 1985, 1989) and municipal solid waste (MSW) (Deportes et al., 1998) has been shown to eliminate pathogens present in these materials primarily because of the heating that occurs. Levels of bacteria used as faecal indicators, i.e. faecal coliforms and faecal enterococci, were reduced from 2·1 × 10⁸ colony forming units (cfu) g⁻¹ to less than 100 cfu g⁻¹ and from 2·0 × 10⁹ to 8·7 × 10⁴ cfu g⁻¹, respectively, in MSW composted for 20 days (Deportes et al., 1998). Since composting is the process which occurs when solid manures are stored in heaps and the pathogens present in animal wastes are broadly similar to those in sludge (Stranch, 1991) it seems safe to assume that similar reductions in pathogen levels will occur within solid manure stores, particularly when considerable heating has taken place. Several studies have been made into the effects of slurry storage on pathogen levels. A 90% reduction of Salmonella occurred within 2-4 weeks in anaerobically stored cattle slurry and within 2 days in aerated slurry (Jones & Mathews, 1975). Aeration also increased reduction of Campylobacter in dairy slurry (Stanley et al., 1998). Research has shown that pathogens survive longest in slurries with a total solids content of 5% or more and at temperatures of below 10°C (Jones, 1976; Kearney et al., 1993). Aeration of farm-scale slurry tanks, under winter ambient conditions, increased the temperatures to between 19 and 40°C and reduced Salmonella levels by over 99% after 2–5 weeks for both cattle slurries contaminated with S. infantis and pig slurry contaminated with S. typhimurium. In this study, similar effects were found for
Yersinia, Listeria, faecal coliforms, enterococci and coliphages (Heinonen-Tanski et al., 1998). Several researchers have shown a relationship between pH and the rate of pathogen reduction (Jones, 1976; Heinonen-Tanski et al., 1998; Henry et al., 1983). However, it was concluded that the effect was more likely to be due to the antimicrobial activity of chemicals produced during storage rather than the direct effect of pH. All the above studies have concentrated on Salmonella spp. More recently other pathogens, particularly E. coli O157 and the parasitic protozoans Cryptosporidium parvum and Giardia lamblia, have caused concern. E. coli O157 is a robust pathogen which can survive many weeks in cattle faeces and many days in slurries (Maule, 1997). Parasitic protozoa can survive for several weeks in slurry but, as with the bacterial pathogens, composting of manures and aeration of slurries have been advocated to reduce their levels (Deng & Cliver, 1992).

5.2. Reduction of pathogen levels during storage

Storage of animal manures and slurries can reduce the levels of pathogenic microorganisms pathogens which they contain. Various factors affect the rate of pathogen reduction during storage. Different pathogens have varying survival characteristics, e.g. protozoa are more resistant to a range of conditions and survive for longer than bacteria. Reduction of pathogens during storage is significantly enhanced by heating which occurs during composting or aeration, at a total solids content of less than 5%, and at high or low pH.

Therefore, to maximize the reduction of pathogen levels in animal manures and slurries the storage system should:

1. allow composting to occur and achieve as high a temperature as possible;
2. allow a minimum of 4 weeks storage to ensure significant pathogen reduction; and
3. avoid the continual addition of fresh manure/excreta to the store.

5.3. Environmental ratings

The majority of systems involve storage periods in excess of 4 weeks. It is likely, however, that solid manure storage systems, particularly those encouraging high dry matter manure and hence higher temperatures, will facilitate a greater kill of microbial pathogens than slurry systems where storage temperatures are unlikely to rise much above ambient, and fresh slurry is regularly added to that already in store. Solid manure storage systems were therefore assigned a higher rating (8–10 out of a possible 10) for pathogen reduction than slurry systems (4 or 6).

6. Planning and landscape aspects

6.1. Legislation

Under the Town and Country Planning (General Permitted Development) Order 1995, any excavation or engineering operation, which is reasonably necessary for the purposes of agriculture, is ‘permitted development’ subject to certain conditions. One of these conditions is that, if the development includes a building or structure to be used for livestock or for storage of slurry, within 400 m of a protected building, then planning permission will be required. In a later amendment to the legislation, only holdings above 5 ha were given permitted development rights. Many intensive livestock units on small areas of land were then forced to apply for planning permission for all slurry and muck storage facilities, giving local authorities much greater control over the construction of slurry and manure stores and what is allowed in certain locations.

6.2. Criteria used for planning consent

A number of critical features can make a difference as to whether permission is forthcoming or not. The two primary factors with regard to manure and slurry stores are: the distance between the store and neighbouring property; and the wider landscape designation within that area, e.g. Area of Outstanding Natural Beauty, National Park, Special Landscape Area or Green Belt.

Secondary factors affecting any application tend to be more site specific: the receptors of any views, be they close or distant; the immediate landscape, e.g. the presence of trees/hedgerows, other buildings and the natural or man made contours; and the type of store.

6.3. Environmental ratings

The type of store is only one of many factors which a local planning authority would take into account and is not necessarily one of their main considerations. A local authority would generally favour the least visually intrusive option, i.e. below ground. An example proposal might involve erection of a store on a dairy farm 250 m from nearest dwellings and adjacent to existing buildings. In this particular case, the planning perception of each of the store types, where poor has a
value of 1 and good has a value of 5, might be as follows:

(a) above-ground circular store (steel or concrete)—rating 1;
(b) weeping-wall, earth-banked (lined or unlined)—rating 2;
(c) below-ground concrete—rating 3;
(d) solid manure stores on concrete base—rating 2; and
(e) field heap—rating 5 (no planning implications).

The above scores were assigned in the environmental rating exercise in respect of visual appearance.

7. Abatement of ammonia emissions

7.1. Slurry stores

Data suggest that emissions per unit area are similar for lagoons and above-ground tanks. However, because of the greater surface area to volume ratio of lagoons, then for a given volume of slurry, emissions from lagoons will be greater, and thus a move to replace them with above-ground tanks should lead to a reduction in \( \text{NH}_3 \) emissions. Muck et al. (1984) found that losses could be reduced by half by reducing the surface area of the tank. Beauchamp and Burton (1985) considered that the surface area to volume ratio should be as small as possible. However, the UK \( \text{NH}_3 \) Emissions Inventory (Pain et al., 1998) uses a smaller emission factor for slurry stored in lagoons (2.1 \( \text{g[N]} \cdot \text{m}^{-2} \cdot \text{d} \), compared with 4.4 \( \text{g[N]} \cdot \text{m}^{-2} \cdot \text{d} \) for tanks), on the basis that lagoons are likely to be at least partially crusted. However, above-ground tanks may also be allowed to develop a crust, and also more effective abatement measures may be applied to them. The use of covers on all new slurry stores and on all existing slurry storage tanks, has been proposed as a mandatory measure under the UNECE \( \text{NO}_x \) Protocol. Covers should be capable of reducing emissions by 50% or more. Existing slurry lagoons would be exempt.

Large differences in \( \text{NH}_3 \) emissions have been measured between lagoons filled from the bottom (3–8% total N) and the top (29–39%) (Muck et al., 1984). However, it is generally considered that sub-surface filling is more applicable to above-ground tanks than to lagoons.

7.1.1. Cylindrical above-ground stores

Purpose-built covers for above-ground tanks are available, and whilst expensive, offer the greatest potential for reducing \( \text{NH}_3 \) losses. Costs quoted in the UK, for an imported Dutch-made polyvinylchloride (PVC) cover on ‘umbrella’ supports for an 18 m diameter (1000 m\(^3\) capacity) store, were £19,500, installed. A rigid roof, with supports for the same store would cost approximately £15,000 installed. However, prices for similar covers in the Netherlands appeared to be considerably less, at £8–10,000. The disparity may be due to lack of demand for and experience of installing such equipment in the UK. It may not be possible to safely install covers on all existing above-ground stores, depending on their height and specification. In the Netherlands and Belgium, specification of the upper store panels is a heavier gauge where a cover is to be fitted, to cope with the additional wind loading imposed. Alternatively, a stronger circular steel angle around the top panels may be required. Anecdotal evidence suggests that fitting of covers may increase the rate of store panel corruption, due to the entrapment of \( \text{H}_2\text{S} \) and the formation of sulphuric acid. It can, therefore, be argued that it is inadvisable to fit covers to any existing tanks showing signs of corrosion.

7.1.2. Lagoons

Natural crusting of slurry containing excess bedding material offers a simple means of reducing emissions. Sommer et al. (1993) showed that a natural crust could reduce emissions to 20% of those from a stirred store. For pig slurry, which normally contains little bedding, a number of low-cost abatement measures, such as floating mineral-based granules, chopped straw and oil, have been shown to reduce \( \text{NH}_3 \) emissions from slurry by up to 90% (Hornig et al., 1999), though stability of the floating layer needs to be maintained during any store filling or mixing operations.

A MAFF-funded project to develop a floating lagoon cover and evaluate its practicality for use in UK, was undertaken recently by Silsoe Research Institute. It was concluded that costs of covering could be in the order of £10 m\(^{-2}\) or more (Williams & Scotford, 1999). Securing a cover at the edges, supporting it in the centre, removing excess rainfall, and coping with wind loadings all present potential practical problems, particularly with the large lagoons encountered on some pig units. At least one company in the Netherlands has developed flexible covers, secured at the bank tops and supported at 5 m intervals by expanded polystyrene floats on the surface of the slurry. Practicality of this approach for covering lagoons in the UK is currently being evaluated.

7.2. Solid manures

Here, differences in emissions will be related to management, rather than storage facility. Significant reductions in \( \text{NH}_3 \) loss have been demonstrated from the use of additional litter. Significant increases in \( \text{NH}_3 \)
losses have been measured when aerobic composting has been encouraged. Clear recommendations can therefore be made, first to aim for a C:N ratio of greater than 20:1 (or ratio of excreta to litter of at least 1:0.25, by weight) and second to compact the manure to produce anaerobic conditions during storage to prevent aerobic composting. The need for compaction is greater if additional straw is used, since the use of additional straw will reduce manure density, hence increasing air diffusion of gases throughout the heap, which could lead to increased NH₃ losses if this effect is not countered by consolidation.

7.3. Effect of ammonia abatement measures on N₂O and CH₄ emissions

Hüther et al. (1997) investigated the effect of Leca granules, straw and floating foil on emissions of NH₃, N₂O and CH₄ from slurry. All three covers reduced NH₃ emissions by 72, 83 and 85%, respectively. The use of both Leca and straw increased emissions of N₂O by factors of × 3 and × 6, respectively. Emissions of N₂O with a straw crust, at ca. 1% of total N, were about half the losses of NH₃. Williams and Nigro (1997) studied the impact of slurry store covers on NH₃ and CH₄ emissions in laboratory and field studies. The cover was of corrugated steel, covered with plastic. In the laboratory, NH₃ emissions from pig and cattle slurry were reduced by 80 and 75%, respectively: improvements to the cover increased abatement to 93%. Methane emissions were reduced by half, and by 90% with the improved cover. In the field, the cover reduced NH₃ emissions from pig slurry by 68%, but CH₄ emissions were too variable to determine any effect of cover. However, the authors concluded that, since mixing at the end of the storage period greatly increased CH₄ emissions, a large proportion of the methane retained by covering is present in the slurry as bubbles, and much of any apparent benefit may be lost during subsequent mixing and following spreading.

7.4. Environmental ratings

As far as slurry stores are concerned, it appears reasonable to conclude that the selection of above-ground stores should be encouraged both to reduce NH₃ losses per se, and to provide greater potential for the introduction of abatement measures. Above-ground slurry stores were therefore given a combined score of 15 (out of a maximum of 20), for cost and practicality of adding ammonia emission control measures. Lagoons and solid manure stores were given a rating of 8. Enclosed below-ground stores, which are, by definition, already covered, were arbitrarily given a combined score of 10 (zero for practicality of installing measures and 10 for cost).

It must be noted that a reduction of ammonia loss during storage may subsequently lead to an increase in ammonia emissions during landspreading, unless practices such as injection or incorporation are adopted.

8. Environmental rating exercise

8.1. Results

Results are summarized in Table 4: where particular storage systems are not appropriate for a particular species, they are designated n.a. (not applicable). The first part of the Table 4(a) gives scores for environmental aspects of unmodified stores. The second part of the Table 4(b) gives the total overall scores which include an assessment of the ease and cost of adding ammonia control measures and an assessment of visual appearance/planning considerations.

9. Discussion

As can be seen, the exercise, not unexpectedly, favoured the more sophisticated storage methods: in the case of slurry, above-ground circular tanks, or in the case of solid manures, stores with a concrete base and/or roof. These higher scoring storage methods are also the most expensive in terms of capital investment. Current costs, based on a 1000 m³ slurry store, are approximately £30–34 m⁻³ for an above-ground tank, £22–24 m⁻³ for a weeping-wall store with effluent tank and irrigation system, £27–30 m⁻³ for a lined or concrete-based lagoon and £12–15 m⁻³ for an unlined lagoon.

When ease of adding ammonia control measures and planning aspects were excluded, no large differences emerged between ratings for slurry systems and solid systems: the best of each, i.e. those with impermeable bases and the worst, i.e. those with earth bases or banks, achieved similar scores. This was largely due to effect of methane and N₂O emissions and their attributed scores offsetting each other. If water pollution risks were also excluded from the score then again, for cattle, scores for gaseous emissions alone were broadly similar, but for pigs, slurry systems had a slight apparent advantage, because of the greater ammonia emissions from the solid pig manure. Overall scores were, however, highest for above-ground circular stores, mainly because of the relative ease of adding ammonia control measures in the form of a cover. It is possible that this apparent
‘advantage’ may be lost in future as methods of covering other types of store are developed.

Inter-relationships exist between factors, e.g. covering slurry stores may effectively control ammonia emissions and reduce water pollution risk from overfilling, but have little effect on methane emissions because of release during mixing at the end of the storage period. Such inter-relationships were not incorporated into the rating system. Any measures adopted to control ammonia emissions will affect the nitrogen content of the slurry or manure at the end of the storage period and subsequent emissions of ammonia when the material is spread to land. Assigning a different weighting to the range of scores given for risks of water pollution, gaseous emissions and other factors would obviously result in different overall ratings, but this has not been attempted in the current exercise, for reasons of simplicity.

Initial comments received from the Environment Agency broadly confirmed the approach used above in respect of water pollution risks. They suggested that factors should include structural stability (i.e. risk of loss of contents), permeability (i.e. risk of losses through leakage, spurtng, etc.), risk of loss during transfer (e.g. problems with valves on above-ground tanks), risk to surface water and risk to ground water.

The Environment Agency also suggested that the priority given to the risks will vary from catchment to catchment. Where there is a risk to groundwater this should probably be the greatest priority since amelioration is difficult. Pollution risk scoring systems have been devised to indicate water pollution risk from wastes on individual farms: in a system devised by Colman et al. (1994) contributory components included size and condition of slurry storage facilities and their proximity to watercourse as well as adequacy of facilities for handling and storing dilute runoff and silage effluent. The system described in this paper could be adapted to take account of site-specific factors.

10. Conclusions

The performance of the least sophisticated earth-banked/earth-based systems is obviously less good in
terms of water pollution risks. The environmental rating exercise indicated that when all factors were accounted for, no large differences emerged between ratings for slurry systems and solid systems.

Scores for gaseous emissions from unmodified stores are broadly similar for slurries and solid manures, largely due to effect of methane and N\textsubscript{2}O emissions and their attributed scores offsetting each other, but for pigs, slurry systems have a slight apparent advantage, because of the greater ammonia emissions from stored solid pig manure. Overall scores are highest for above-ground circular stores, because of the relative ease of adding ammonia abatement measures in the form of a cover, although such covers are expensive. It is possible that this apparent ‘advantage’ may be lost in future as methods of covering other types of store are developed.

The use of such a rating system could be developed further as more data become available. The use of a spreadsheet allows the relative scores assigned for different emissions to be altered as required. Whilst the method was developed to indicate the relative desirability of different storage systems at a national scale it could be adapted to take account of local considerations or those of individual farm sites.

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