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## Review

## Recycling manure as cow bedding: Potential benefits and risks for UK dairy farms



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## ABSTRACT

Material obtained from physical separation of slurry (recycled manure solids; RMS) has been used as bedding for dairy cows in dry climates in the US since the 1970s. Relatively recently, the technical ability to produce drier material has led to adoption of the practice in Europe under different climatic conditions. This review collates the evidence available on benefits and risks of using RMS bedding on dairy farms, with a European context in mind. There was less evidence than expected for anecdotal claims of improved cow comfort. Among animal health risks, only udder health has received appreciable attention. There are some circumstantial reports of difficulties of maintaining udder health on RMS, but no large scale or long term studies of effects on clinical and subclinical mastitis have been published. Existing reports do not give consistent evidence of inevitable problems, nor is there any information on clinical implications for other diseases. The scientific basis for guidelines on management of RMS bedding is limited. Decisions on optimum treatment and management may present conflicts between controls of different groups of organisms. There is no information on the influence that such 'recycling' of manure may have on pathogen virulence. The possibility of influence on genetic material conveying antimicrobial resistance is a concern, but little understood. Should UK or other non-US farmers adopt RMS, they are advised to do so with caution, apply the required strategies for risk mitigation, maintain strict hygiene of bed management and milking practices and closely monitor the effects on herd health.

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## Introduction

The concept of using material described as 'dairy waste solids', 'separated manure solids' or 'recycled manure solids' (RMS) as bedding for cattle (recently termed 'green bedding' in the UK) was established in the US in the 1970s (Keys et al., 1976; Timms, 2008a). Rising numbers of expanding housed US dairy herds increased the amounts of manure produced, but the ability to separate solid and liquid fractions using a screw or roller press facilitated handling the material.

The solid fraction of manure consists mainly of undigested fibres (Menaar and Smith, 1973) and the potential of using this fraction as bedding material was explored initially in hot dry areas in the Western United States, in 'dry lot' dairies, where maintaining 'a high dry matter content' (Timms, 2008a) was easy. Due to concerns about high bacterial load, further processing steps were incorporated, initially composting, which aimed to reduce bacterial numbers by

raising the temperature (Carroll and Jasper, 1978). Later, it became popular to use as bedding solid material extracted from the products of the anaerobic digestion of manure as a way of offsetting the cost of digesters (Timms, 2008b). Many combinations of separation, digestion and composting are now practised in the USA, allowing successful use of RMS bedding in cooler, wetter regions of the US (Timms, 2008a, 2008b, 2008c).

Increased marketing of high performance slurry separation machinery, that can produce separated manure solids with over 30% dry matter (DM), has generated interest in this practice in Europe, where there are very different climatic conditions (Zähler et al., 2009; Feiken and van Laarhoven, 2012; Marcher Holm and Pedersen, 2015). Livestock manures are Category 2 Animal By-products, as defined by EC Regulation 1069/2009. As such, their use as a 'technical product' (e.g. animal bedding) is only permitted if strict conditions apply which minimise the health risks involved. 'Safe end use' of a product derived from animal by-products is defined as use 'under conditions which pose no unacceptable risks to public and animal health' (EC Regulation 1069/2009). Member State jurisdictions are approaching this requirement in different ways. In the UK, the Department for Environment, Food and Rural Affairs (Defra) and the

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Scottish Office have allowed the use of this bedding under controlled conditions, while research is carried out, while in Wales and Northern Ireland the practice is currently (May 2015) prohibited.

This review article considers in a UK context the scientific basis for the opportunities and challenges presented by RMS bedding. In view of the limited peer reviewed literature on the subject, we also draw on conference proceedings and unpublished research reports.

### Potential benefits

Farmers' interest in RMS is based largely on economics, availability and cow comfort and this is true in UK as elsewhere (Leach et al., 2014). Economic calculations must be made at individual farm level, considering the capital cost of equipment, management time and running costs, set against the purchase and management costs of current bedding materials. Availability is more under the farmer's control than when depending on an external bedding supplier. UK farmers, for example, perceive 'more comfortable cows', longer lying times and fewer hock lesions than on previous bedding materials including paper, sawdust, or even sand (Leach et al., 2014).

Physical attributes of RMS suggest potential advantages for cow comfort. It is soft, non-abrasive, and readily available. DM content appears to influence cow preferences; cows chose to lie less on stalls with 'dewatered manure solids' (29% DM), compared with 'dehydrated manure solids' (81% DM), and sawdust (81% DM), at equal depth (Keys et al., 1976). Cows have also shown preference for cubicles bedded with 'manure separates' compared to straw, sand and sawdust (Adamski et al., 2011). Longer lying times were recorded on three commercial farms following a change from mats to deep beds of RMS (Feiken and van Laarhoven, 2012).

RMS has advantages for hocks over mats with or without sawdust or straw (Zähner et al., 2009), or dolomitic limestone (Hippen et al., 2007). However, hock lesion prevalences when on RMS of 40–53% for deep beds (Zähner et al., 2009; Husfeldt and Endres, 2012), and 63–72% for mattresses (Husfeldt and Endres, 2012) have been reported. From a survey of 297 dairies, Lombard et al. (2010) reported a higher prevalence of severe hock lesions in cows bedded on dry or composted RMS compared with sand, straw and sawdust. The main advantage may be that farmers are willing to use more generous amounts of RMS (Leach et al., 2014); deeper layers of bedding have been associated with lower prevalence of hock (Brenninkmeyer et al., 2013) and claw lesions (Barker et al., 2009).

In support of farmer perception of cow cleanliness (Leach et al., 2014), Hippen et al. (2007) reported a trend for cleaner cows on RMS than on dolomitic limestone, and Timms (2008c) an 'improvement' in cleanliness on RMS from a previous, unspecified bedding material. Feiken and van Laarhoven (2012) found cows on RMS to be dirtier than those on sawdust or wheat straw, but cleaner than those on compost. However, visual cleanliness does not necessarily mean absence of pathogens, and, in view of the bacterial load of the bedding, close attention should still be given to pre-milking teat preparation (Endres and Husfeldt, 2012).

The lower dust levels reported with RMS compared with chopped straw or sawdust (Leach et al., 2014) or oat hulls (Meyer et al., 2007) may have benefits in terms of respiratory health for both animals and humans, and reduced transmission of pathogens via dust particles, but there is no information on the transmission of pathogens by aerosols related to this material.

### Risks posed by RMS used as bedding on dairy farms

The main potential risks of RMS bedding are to animal health, human health, product quality, and consumer perception. From the financial perspective of the farmer, there is also the risk of future prohibition if threats to animal or human health are deemed to be too high.

Based upon literature review and input by Defra (the UK 'Competent Authority') to a scoping study (Bradley et al., 2014), key micro-organisms that should be considered are shown in Table 1. Lungworm and most intestinal parasites have not been included since these would be unlikely to complete their full life cycle in the manure, and experience with other farm species indicates that total confinement systems are not associated with high parasite burdens. Information to evaluate risk for viruses is extremely limited.

Tables 2 and 3 summarise the data available on pathogen load in RMS before use, after separation only, and after further processing, respectively. Table 4 summarises data on pathogen load for various used bedding materials, including RMS. These data illustrate the fact that, although bacterial counts in RMS as a raw material are high, counts in many other materials can reach similar levels once in use as bedding.

Any increased potential for development and perpetuation of antimicrobial resistance caused by recycling manure would have implications for both animal and human health. There is one report of an association between use of RMS and presence of antimicrobial resistant strains of *Salmonella* in cattle faeces (Habing et al., 2012).

### Animal health risks

No studies were found that directly related RMS use to clinical incidence or prevalence of any infectious disease other than mastitis. The three health conditions for which there is any more than a theoretical basis for consideration of the risks associated with RMS bedding are discussed below.

### Udder health

In view of work that has linked risk of mastitis to pathogen numbers in bedding (Bramley and Neave, 1975; Carroll and Jasper, 1978; Hogan et al., 1989), RMS must be considered as at least a theoretical risk, based on the pathogen levels reported in the literature. However, evidence to quantify the risk of actual clinical outcomes compared with other bedding materials is limited, particularly from climates comparable to the UK.

Some case studies reported udder health problems, and others demonstrated no detrimental effects arising from changing to RMS bedding. Case studies in Italy (Locatelli et al., 2008) and the USA (New York State; Ostrum et al., 2008) have linked increases in environmental mastitis caused by *Escherichia coli* or *Klebsiella* spp. with separated manure solids that were stored before use. In three Dutch herds converting to RMS, no increased incidence of *Klebsiella* spp.-related mastitis or total cases of clinical mastitis was identified, although the concentration of *Klebsiella* spp. was higher in the RMS than in sawdust (Feiken and van Laarhoven, 2012).

On two American farms, Buelow (2008) failed to find a correlation between bacterial counts in RMS bedding and clinical or subclinical mastitis. Husfeldt and Endres (2012) reported a range of mastitis incidence of 9–109 cases per 100 cows per year on 34 farms in the American mid-West using RMS bedding. Cows were culled more frequently for mastitis on the study farms than in the national population, with mastitis being given as the most common cause of culling, compared with infertility for the national population.

Harrison et al. (2008) retrieved mastitis records and individual cow somatic cell count (ICSCC) data for six farms using different types of RMS bedding, but although mastitis incidence differed between 'experimental units' (farm/bedding strategy combinations), neither bacteria levels nor physical properties of bedding affected mastitis incidence. Prevalence of elevated SCC (>200,000 cells/mL for cows and >100,000 cells/mL for heifers) did not differ between three groups of animals kept on sand, separated and composted RMS on one of these farms. No detailed analysis has been made of ICSCC dynamics as cows are introduced to RMS bedding.

**Table 1**

Key micro-organisms in consideration of potential risks associated with use of recycled manure solids as bedding, and the availability of evidence of load.

Pathogen	Area of concern	Potential for high load in slurry	Other factors in assessment of relevance	Data sources on RMS load
<b>Bacteria</b>				
<i>Bacillus cereus</i>	A,H,F	Y		Driehuis et al. (2012, 2013) (spores); Feiken and van Laarhoven (2012)
<i>Campylobacter</i> spp.	A,H	Y		
<i>Coxiella burnetii</i>	A,H		Very low minimum infective dose	
<i>Enterococcus</i> spp.	A,H	Y	Particularly likely to perpetuate antimicrobial resistance	
<i>Escherichia coli</i>	A,H	Y		Bishop et al. (1981)* (composted RMS); Harrison et al. (2008); Zehner et al. (1986)*
<i>E. coli</i> 0157	A,H	Y		
<i>Listeria</i> spp.	A,H	Y		
<i>Mycobacterium avium</i> subsp. <i>paratuberculosis</i>	A,H	Y		Harrison et al. (2008); Timms (2008b); Pronto and Gooch (2009)
<i>Mycobacterium bovis</i>	A,H	Uncertain but unlikely with regular TB testing	Major UK animal health issue	
<i>Salmonella</i> spp.	A,H	Y	Reported association between use of composted or dried RMS and resistant strains (Habing et al., 2012)	Meyer et al. (2007); Timms (2008b) – presence/absence
<i>Klebsiella</i> spp.	A	Y	Reports of links between RMS and <i>Klebsiella</i> mastitis	Feiken and van Laarhoven (2012); Harrison et al. (2008); Hogan et al. (1999)*; Sorter et al. (2014)* Zehner et al. (1986)*
<i>Streptococcus uberis</i>	A	Y		
<i>Yersinia enterocolitica</i>	H	Y		
Mesophilic spore formers	F		High levels in other composted materials	Driehuis et al. (2012, 2013) (spores)
Thermophilic spore formers	F		High levels in other composted materials	Driehuis et al. (2012, 2014) (spores)
Extremely heat resistant spore formers	F		High levels in other composted materials	Driehuis et al. (2014)
<b>Spirochaetes</b>				
<i>Leptospira</i> spp.	A,H	Y		
Treponemes	A	Uncertain	Implicated in digital dermatitis	
<b>Viruses<sup>a</sup></b>				
Rotavirus	A,H	Less likely from adult population		
Food and mouth disease virus	A	Only in outbreak	Notifiable disease in UK	
Bovine coronavirus	A	Less likely from adult population		
<b>Parasites and protozoa<sup>b</sup></b>				
<i>Cryptosporidium</i> spp.	A,H	Y		
<i>Giardia</i> spp.	A,H	Y		
<i>Coccidia</i> spp.	A	Large contribution from adult population unlikely		
<b>Prototheca</b>				
<i>Prototheca</i> spp.	A	Y		

A, animal health; H, human health; F, food quality.

\* Peer reviewed paper.

<sup>a</sup> For the majority of viruses (e.g. Bovine Coronavirus, Rotavirus), there is no quantitative information on the levels likely to be in RMS or even levels in slurry.<sup>b</sup> Other intestinal parasites and lungworm have not been included since these would be unlikely to complete their full life cycle in the manure and experience with other species indicates that total confinement systems are not associated with high parasite burdens.**Table 2**

Examples of bacterial counts in separated manure solids.

Units (log 10 colony forming units)	Total bacterial count	Coliforms	Gram -ve bacteria	<i>Bacillus</i> spp.	Environmental streptococci	Staphylococci	<i>E. coli</i>	<i>Klebsiella</i>	<i>Bacillus cereus</i> spores	MAS	Reference
per g	6–8	2–4			5–8						Timms (2008a)
per g		2–3	4–5		4–5						Timms (2008b)
per g	8.3–9.1				6.6		4.4–5.5	3.1–4.2			Feiken and van Laarhoven (2012)
per g									2.3	6.7	Driehuis et al. (2013)
per mL		4.1		6.5	6.4	3.0					Husfeldt and Endres (2012)*
per mL			4.5–4.7		4.3–5.4	0–0.3	0.3–1.7	1.7–2.0			Harrison et al. (2008)

MAS, mesophilic aerobic spore formers.

Less frequently found: *Bacillus* spp. (Husfeldt et al., 2012), enterococci (Zähner et al., 2009), Enterobacteriaceae (Carroll and Jasper, 1978; Zähner et al., 2009), propionic acid bacteria (Zähner et al., 2009), and *Proteus* spp. (Harrison et al., 2008).

\* Peer reviewed paper.

The widespread use of RMS in the US could be taken to suggest that success is common but it should be remembered that the requirements for bulk milk somatic cell counts (bmSCC) are less stringent in the US than in the UK (US, 750,000 cells/mL; EU,

400,000 cells/mL). A telephone survey of 38 farmers in the upper mid-west States indicated that those using digested manure solids were able to keep bmSCC consistently below 250,000 cells/mL, while for those using separated solids bmSCC exceeded 450,000 cells/mL

**Table 3**  
Examples of bacterial counts in separated manure solids after composting or digestion.

Processing	Units (log 10 cfu)	Coliforms	Gram –ve bacteria	<i>Bacillus</i> spp.	Environmental streptococci	Staphylococci	<i>E. coli</i>	<i>Klebsiella</i>	Reference
Separated, compacted, covered and stored 5 weeks	per g	9.4							Feiken and van Laarhoven (2012)
Composted	per mL	0		3.9	4.0	1.0			Husfeldt and Endres (2012)
Composted	per g	<2	2–6		4–6				Timms (2008c)
Composted (and stored)	per g	4–6							Timms (2008c)
Composted	per mL		2.9–5.1		2.6–3.1	0	0	0–2.0	Harrison et al. (2008)
Digested	per g	0	4–5						Timms (2008b)
Digested	per mL	1.73		4.6	4.1	1.5			Husfeldt and Endres (2012)
Digested	per mL		4.6		5.2	0.2	0.2	0.5	Harrison et al. (2008)

**Table 4**  
Examples of bacterial counts in used bedding – in cubicles unless otherwise specified.

Material	Units (log 10 cfu)	Total bacterial count	Coliforms	Gram –ve bacteria	Streptococci	Staphylococci	<i>E. coli</i>	<i>Klebsiella</i>	Reference
Straw in loose yards	per g		7.2–7.6		7.9–8.4				Ward et al. (2002)*
Straw in loose yards (mean of four seasons)	per g DM		6.4		7.4			4	Hogan et al. (1989)*
Straw	per g		6.5		7.7	8.9		4.8	Rendos et al. (1975)*
Chopped straw (mean of four seasons)	per g DM		6.3		7.8			3.7	Hogan et al. (1989)*
Straw	per g	9.6			7.7		5.5	4.6	Feiken and van Laarhoven (2012)
Sawdust	per g		7.7		7	8.5		6.6	Rendos et al. (1975)*
Sawdust	per g	9.9			3.1		<2	1.9	Driehuis et al. (2012)
Sawdust	per mL				7.3	3.0	4.9	0.2	Harrison et al. (2008)
Sawdust on cubicles after 1 week	per g		7.1					6.4	Fairchild et al. (1982)*
Sawdust and lime after 1 week	per g		7					6.9	Fairchild et al. (1982)*
Sand	per mL				7.6	1.6	2.4	4.5	Harrison et al. (2008)
Sand after 1 day	per g		6		6.5			4.1	Zdanowicz et al. (2004)*
Sand after 2 days	per g		6.1		6.9			4.3	Zdanowicz et al. (2004)*
Sand after 6 days	per g		5.8		7.2			4.1	Zdanowicz et al. (2004)*
Sand (mean of four seasons)	per g DM		5.7		7			3.2	Hogan et al. (1989)*
Separated RMS	per mL	3.1	2.1		2.9	2.2			Husfeldt and Endres (2012)*
Digested RMS	per mL	2.9	2.0		2.6	2.3			Husfeldt and Endres (2012)*
Drum composted RMS	per mL	3.2	2.0		2.9	2.45			Husfeldt and Endres (2012)*
Composted RMS	per mL		8.7		8.2	8.2			Bishop et al. (1981)*
Drum composted RMS	per mL				7.2	2.0	1.6	5.9	Harrison et al. (2008)
Windrow composted RMS	per mL				7.3	0.3	1.4	4.3	Harrison et al. (2008)
Digested RMS	per mL				7.2	1.5	2.9	3.2	Harrison et al. (2008)
Separated RMS	per mL				7.2	1.1	1.3	5.6	Harrison et al. (2008)
RMS dried by forced air	per mL				7.2	5.4	5.3	4.0	Harrison et al. (2008)
Partially composted RMS	per mL				7.7	2.1	3.6	2.7	Harrison et al. (2008)
Mature composted RMS	per mL				7.6	2.4	5.3	2.6	Harrison et al. (2008)
Separated RMS	per g	10.1			7.5		5.5	6.2	Feiken and van Laarhoven (2012)
RMS 30% DM	per g	10			6.6		4.2	3.1	Driehuis et al. (2012)
RMS on back of mattress replaced daily from pile at front	per g DM							5.7	Sorter et al. (2014)*
RMS on deep bed after 1 day	per g DM							6.2	Sorter et al. (2014)*
RMS on deep bed after 2 days	per g DM							6.6	Sorter et al. (2014)*
RMS on deep bed after 6 days	per g DM							6.5	Sorter et al. (2014)*
RMS after 1 day	per mL		6	8.2	8			6.5	Hogan et al. (1999)*
RMS after 2 days	per mL		6.8	8.2	7.8			6.5	Hogan et al. (1999)*
RMS after 6 days	per mL		6.4	7.9	7.8			6.3	Hogan et al. (1999)*
RMS with lime after 1 day	per mL		5.7	7	7.7			5	Hogan et al. (1999)*
RMS with lime after 2 days	per mL		6.7	8	8			6	Hogan et al. (1999)*
RMS with lime after 6 days	per mL		6.2	7.8	8			6.2	Hogan et al. (1999)*

RMS, recycled manure solids.

\* Peer reviewed.

(Endres, 2008). On 34 farms, (9 using raw solids, 21 digestate, and 4 composted material), average bmSCC was 274,000 cells/mL ( $\pm$ SD 98,000 cells/mL) (Husfeldt and Endres, 2012). When Harrison et al. (2008) followed the bmSCC patterns of nine farms that converted to RMS (including fresh, composted and digested), some increased and some decreased after conversion. An attempt was made to

compare the change in bmSCC over a 7 year period on these farms with the whole state population; this unpublished analysis indicated that a linear score for bmSCC increased more rapidly on the RMS farms than in the whole state population, but, since the bedding types in the whole state were not known, the authors were reluctant to draw conclusions.

Early experiences in Europe suggest that acceptable bmSCC levels can be achieved on RMS, but variation between farms is wide. Feiken and van Laarhoven (2012) monitored three farms in The Netherlands for 2 years after changing to RMS. With a previous annual mean bmSCC range from 147,000 to 272,000 cells/mL, two of the three farms reduced bmSCC. Only the farm with the lowest cell count increased (to 183,000 cells/mL) in the second year. The authors considered that success with RMS was associated with high quality management of the bedding. One year after introduction of RMS bedding on 11 Danish farms, annual average bmSCC was lower on four farms, and higher on seven, than in the previous year (Marcher Holm and Pedersen, 2015).

The overall conclusion from studies and data collated to date is that there is no consistent impact on SCC of the use of RMS, and any effect on clinical mastitis has not been clearly demonstrated. Case studies illustrate the fact that mastitis problems can be experienced, but cannot give definitive information on the likelihood, reasons or mitigation strategies.

#### Johne's disease

Survival of *Mycobacterium avium* ssp. *paratuberculosis* (MAP) in slurry is temperature dependent. MAP may survive for 250 days at low temperatures, but <1 day if heat treated at ~50 °C. These figures relate to storage in a tank or pit where conditions are largely anaerobic (Elliott et al., 2015). Harrison et al. (2008) tested 15–36 samples of unused RMS bedding from each of nine types of bedding from six farms – including composted and digested materials. Both composting (Bonhot et al., 2011) and anaerobic digestion (Timms, 2008b; Pronto and Gooch, 2009) significantly reduced MAP levels. However, on at least one occasion, MAP was found in all but one of the materials, albeit at low levels, indicating that neither composting nor digestion can guarantee elimination of this pathogen. The highest prevalence was positive results from 12/24 samples of freshly separated material from one farm, with a mean load of 174 cfu/g. For this reason, and because of the high risk of MAP transmission in early life, it is recommended that RMS is not used to bed any areas where cows are kept for the late dry period or calving, or housing for calves or young stock.

#### Lameness

The only peer reviewed figures for lameness on RMS bedding (of various types) report a 95% confidence interval of 13–16% prevalence for deep beds, and 18–22% for mats, based on locomotion scoring on a single visit (Husfeldt and Endres, 2012). These figures are similar to those reported in Minnesota, USA, by Wells et al. (1993) and lower than those reported in high production groups of cows in a number of American states by von Keyserlingk et al. (2012).

Timms (2008c) commented that 'foot and leg health improved' with the introduction of composted RMS but gave no specific information on either the previous bedding material or the absolute levels of lameness. Adamski et al. (2011) remarked that the hooves of cattle housed on RMS were dry, which is likely to be beneficial for foot health.

Two anecdotal reports have suggested that alleyways can be more slippery when using RMS bedding than when sand is used (Ostrum et al., 2008; M. Endres, unpublished data), the former linking this finding with more leg injuries.

#### Pathogens in general

As distinct from other bedding materials (except recycled sand), RMS is used in a 'closed cycle', in the housing environment in close contact with livestock and humans. This contrasts with the traditional fate of manure and slurry (which are spread on the fields) and could result in selection for organisms, including pathogens,

that thrive in these specific conditions, rather than being restricted or destroyed by exposure to outdoor conditions. However, there is little or no information on the influence that such a 'closed cycle' will have, either on the virulence of pathogens or (of particular current concern) on the genetic material conveying antimicrobial resistance. One US study of antimicrobial resistant *Salmonella* spp. found that those dairy herds with at least one resistant strain of *Salmonella* isolated from faeces were more likely to be using composted or dried manure as bedding than those with no resistant strains (Habing et al., 2012).

#### Impact on human health

There is very little evidence available to evaluate the risks but, in general, it would be expected that personal hygiene and protective equipment, along with pasteurisation of milk, would be the main risk mitigation strategies for farm workers and consumers, respectively. The reported reduction in dust could be beneficial. Key pathogens (among others) to consider with respect to food safety would be *Salmonella* spp. and *E. coli* (especially O157). The risk of increased levels of these organisms in RMS is not well defined, but mitigation is relatively straightforward if milk is pasteurised.

The main exception is the food borne zoonotic pathogen *Bacillus cereus*, whose spores are able to survive heat treatment. Levels of 1.1–1.4 log<sub>10</sub> cfu/g *B. cereus* spores were found in fresh RMS by Driehuis et al. (2013), meaning this pathogen cannot be ignored. However, the authors did not find that levels of spores in either bedding or bulk tank milk were any higher in farms using RMS bedding than in those using straw or sawdust. Further work on RMS and zoonotic pathogens is ongoing in The Netherlands, but has not yet been published.

#### Impact on food quality

Micro-organisms transferred from bedding to milk may affect the keeping properties of the milk if they survive pasteurisation. Recent work in The Netherlands has focused on this aspect of food quality. Mesophilic, thermophilic (Driehuis et al., 2012), and extremely-heat resistant (Driehuis et al., 2014), aerobic spore formers were studied, and freshly separated manure solids was one of the bedding materials evaluated. On average, freshly separated manure solids did not show elevated levels of these spores, but all composted materials (which in this trial did not include composted RMS) did. The elevated levels in composted bedding were translated to farm bulk milk, with spore concentrations of the mesophilic group being six times higher and the thermophilic group being 100 times higher in milk from farms using composted materials. Although composted RMS was not included in that trial, the implication is that similar patterns would be likely for this material also. Several Dutch milk buyers discourage or prohibit the use of composted bedding materials to protect the long-life storage qualities of milk products.

#### Public perception

There is a risk that the concept of bedding animals on manure based products would be unattractive to consumers. However, public perception of the practice has not been formally gauged.

#### Practical questions: How should RMS be prepared and managed?

##### Additional processing

Methods for reducing pathogens in whole manure and slurry (see review by Heinonen-Tanski et al., 2006) include composting of solid

material, either in the open or in a reactor, aeration of slurry, anaerobic treatment (digestion), addition of lime or peracetic acid, and heat treatment.

Only digestion and composting have been widely employed in converting slurry to bedding material. Bishop et al. (1981) found bacterial counts decreased in RMS composted over 14 days and considered the material suitable for bedding. Reductions in coliform counts to below levels of detection by culture have been reported after composting manure waste, either in windrows or in enclosed mechanical units (Carroll and Jasper, 1978; Husfeldt et al., 2012). However, on beds, levels rapidly increase again (see, for example, Carroll and Jasper, 1978; Harrison et al., 2008; Feiken and van Laarhoven, 2012); whether this is through multiplication of surviving organisms or re-contamination is unknown. Composting will be conducive to food spoilage bacteria and the pathogenic *B. cereus*, whose spores will survive pasteurisation. Some jurisdictions (including England and Scotland, in June 2014), and milk buyers, have therefore prohibited use of composted materials for bedding.

Pathogen populations in digestate depend on the feedstock and temperature in the digester (Meyer et al., 2007; Timms, 2008b; Tulloch et al., 2009). In general, bacterial levels are considerably reduced and coliforms often undetectable by culture after digestion (Meyer et al., 2007; Tulloch et al., 2009). However, the temperature in the digester is critical; mesophilic digesters running at temperatures of 30 °C–38 °C can increase bacterial numbers (J. Tulloch, personal communication). With mesophilic anaerobic digestion of beef cattle slurry, the time taken for *E. coli*, *Salmonella enterica* serotype Typhimurium and *Yersinia enterocolitica* to reduce by 90% (T90) ranged from 0.7 to 0.9 days during batch digestion and from 1.1 to 2.5 days during semi-continuous digestion. *Listeria monocytogenes* took longer to reduce (T90 = 37 days during semi-continuous digestion and 12 days with batch digestion). Anaerobic digestion had little effect on viable numbers of *Campylobacter jejuni* (Kearney et al., 1993). MAP has been shown to be reduced (Timms, 2008b; Pronto and Gooch, 2009), but not necessarily eliminated (Harrison et al., 2008) by digestion.

### Practical management

The scientific basis for appropriate practical management of RMS bedding is limited. Both laboratory based studies (Zehner et al., 1986) and farm comparisons (Harrison et al., 2008) suggest that management of bedding has greater influence on bacterial load than the type of material. However, RMS has specific properties of high initial bacterial load, and large capacity for water uptake and release (Misselbrook and Powell, 2005), of which users need to be aware. Patterns of microbial growth in maritime climates may differ from those in continental climates; transferability of management practices is not guaranteed. The hygroscopic nature of RMS (Misselbrook and Powell, 2005) means it should be prepared under cover and used only in well ventilated buildings.

Although the general advice is that RMS should not be stored, with a Dutch method of storage in a compacted, covered heap, total bacterial count, *E. coli* and *Klebsiella* spp. were not significantly increased after 6 weeks (Feiken and van Laarhoven, 2012). The material was largely unaltered physically and chemically as a lack of rapidly metabolisable carbohydrate prevented fermentation and anaerobic conditions prevented composting activity.

One decision for farmers considering RMS as cubicle bedding is whether to use it on mats or mattresses, or in deep beds. Deep beds per se are likely to improve physical cow comfort, but depth will affect the environment for bacteria. Shallow beds and frequent replacement are likely to give better control of coliforms, particularly *Klebsiella* spp., than can be achieved in deep beds that are infrequently replenished (Sorter et al., 2014), but streptococcal counts

are likely to be higher in shallow beds (Husfeldt et al., 2012; Sorter et al., 2014). Sorter et al. (2014) suggested this might stem from the more frequent addition of material, because initial levels of streptococci were high, although in this trial the effects of bedding depth and frequency of replenishment cannot be separated.

Schwarz et al. (2010, 2011) compared daily and weekly addition of RMS to deep bedded stalls, on two commercial farms, and found that season had a greater effect on bacterial numbers than frequency of bedding; the authors concluded that daily bedding did not necessarily improve bacterial levels, milk quality or mastitis, compared with weekly bedding.

'Conditioners' to alter the pH of bedding materials are sometimes recommended for control of microbial populations. Effects are usually short-lived, in the range of 24–48 h (Hippen et al., 2007). Hogan et al. (1999) included RMS as a substrate in an experiment testing the effect of 'bedding conditioners' on bacterial load. Specifically for 'raw' RMS, these authors reported that, although both acid and alkali conditioners reduced bacterial populations in unused material, only the alkali conditioner and hydrated lime inhibited bacteria in used bedding, and only for 1 day; use of an acid conditioner had little effect on bacteria in bedding. Sharkey et al. (2011) reported a more rapid and greater decline in *Klebsiella* counts in composted RMS stored in a pile, as a result of application of a proprietary conditioner (SOP-C COW), but there was no effect on streptococci. Feiken and van Laarhoven (2012) added lime and a proprietary alkali to RMS cubicles but found that the resulting pH change was insufficient to reduce most bacteria effectively, although there was a significant reduction in *B. cereus* with the proprietary conditioner.

Scientific evidence for optimum management (for example in terms of bed design, bedding frequency, aeration and replacement) is limited and sometimes conflicting. Since practical experience indicates that there can be udder health problems with wetter 'fresh' bedding, or damp climatic conditions, this area is in need of further research.

### Conclusions

Recycling manure solids as bedding material can present advantages for farmers in terms of availability, convenience and, in some cases, economics. UK farmers also perceive benefits for cow comfort and cleanliness, likely to be dependent on the previous bedding material used for comparison. The literature gives less evidence for the scale of absolute welfare benefits but there are definitely advantages of comfort compared with abrasive materials on mattresses. There are challenges and risks associated with the practice, not least in view of the dearth of information on many of the long term implications. Anecdotal reports of difficulties of maintaining udder health on RMS exist, but no large scale, long term studies of effects on clinical and subclinical mastitis have been published; nor is there any information on clinical implications for other diseases. Very little is known about the influence of maintaining the material in a 'closed cycle', the effects of its use on pathogen virulence and antimicrobial resistance, or the risk of airborne pathogens arising from it. Should farmers choose to adopt RMS bedding, they are advised to do so with caution, apply the required strategies for risk mitigation, maintain strict hygiene of bed management and milking practices and monitor the effects on herd health closely.

With current understanding, important factors in risk management on-farm are good machine maintenance and product monitoring, use in well-designed housing, and avoiding use of RMS in or from calving areas or for housing calves or youngstock. Care should be taken in transferring management approaches from hot dry climates to wetter, cooler areas.

## Conflict of interest statement

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

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## References

- Adamski, M., Glowacka, K., Kupczynski, R., Benski, A., 2011. Analysis of the possibility of various litter beddings application with special consideration of cattle manure separate. *Acta Scientiarum Polonorum: Zootechnica* 10, 5–12.
- Barker, Z.E., Amory, J.R., Wright, J.L., Mason, S.A., Blowey, R.W., Green, L.E., 2009. Risk factors for increased rates of sole ulcers, white line disease and digital dermatitis in dairy cattle from twenty-seven farms in England and Wales. *Journal of Dairy Science* 92, 1971–1978.
- Bishop, J.R., Janzen, J.J., Bodine, A.B., Caldwell, C.A., Johnson, D.W., 1981. Dry waste solids as a possible source of bedding. *Journal of Dairy Science* 64, 706–711.
- Bonhotal, J., Schwarz, M., Stehman, S.M., 2011. How *Mycobacterium avium paratuberculosis* is affected by the composting process. *Trends in Animal and Veterinary Sciences* 2, 5–10.
- Bradley, A.J., Leach, K.A., Archer, S.C., Breen, J.E., Green, M.J., Ohnstad, I., Tuer, S., 2014. Scoping Study on the Potential Risks (and Benefits) of Using Recycled Manure Solids as Bedding for Dairy Cattle. Report prepared for DairyCo. Executive summary. <http://dairy.ahdb.org.uk/resources-library/technical-information/buildings/rms-bedding/> (accessed 10 July 2015).
- Bramley, A.J., Neave, F.K., 1975. Studies on the control of coliform mastitis in dairy cows. *British Veterinary Journal* 131, 160–169.
- Brenninkmeyer, C., Dippel, S., Brinkmann, J., March, S., Winckler, C., Knierim, U., 2013. Hock lesion epidemiology in cubicle housed dairy cows across two breeds, farming systems and countries. *Preventive Veterinary Medicine* 109, 236–245.
- Buelow, K., 2008. Holsum Dairy's experience with digested separated solids. In: Proceedings of the 47th Annual Meeting of the National Mastitis Council, New Orleans, USA, 20–23 January 2008, pp. 143–148.
- Carroll, E.J., Jasper, D.E., 1978. Distribution of *Enterobacteriaceae* in recycled manure bedding on California dairies. *Journal of Dairy Science* 61, 1498–1508.
- Driehuis, F., Lucas-van den Bos, E., Wells-Bennik, M.H.J., 2012. Risico's van Microbiële Contaminanten van Strooisels: Compost, Gescheiden Mest, Paardenmest en Vrijloopstallen. (Risks of Microbial Contaminants of Bedding Materials: Compost, Cattle Manure Solids, Horse Dung and Bedded Pack Barns). NIZO Report E2012\_119. NIZO Food Research BV, Ede, The Netherlands.
- Driehuis, F., Lucas-van den Bos, E., Wells-Bennik, M.H.J., 2013. Risico's van Het Gebruik van Gescheiden Mest as Beddingmateriaal Voor de Melkwaliteit: Sporen van *Bacillus cereus* en Botersuurbacteriën. (Risks of the Use of Cattle Manure Solids as Bedding Material for Milk Quality: *Bacillus cereus* and Butyric Acid Bacteria Spores). NIZO-Rapport E 2013/180. NIZO Food Research BV, Ede, The Netherlands.
- Driehuis, F., Lucas-van den Bos, E., Wells-Bennik, M.H.J., 2014. Sporen van Thermofiele Aërobe Sporevormers in Compost en Andere Beddingmaterialen Bij Melkveebedrijven Met Een Vrijloop- of Ligenboxenstal. (Spores of Thermophilic Aerobic Sporeformers in Compost and Other Bedding Materials Used by Dairy Farmers with a Bedded Pack or Freestall Barn). NIZO-Rapport E 2014/045. NIZO Food Research BV, Ede, The Netherlands.
- Elliott, G.N., Hough, R.L., Avery, L.M., Maltin, C.A., Campbell, C.D., 2015. Environmental risk factors in the incidence of Johne's disease. *Critical Reviews in Microbiology* doi:10.3109/1040841X.2013.867830.
- Endres, M.I., 2008. Overview of Trends in Use of Manure Solids and Compost Bedded Packs. In: Proceedings of the 47th Annual Meeting of the National Mastitis Council, New Orleans, USA, 20–23 January 2008, pp. 136–142.
- Endres, M.I., Husfeldt, A.W., 2012. Recycled Manure Solids for Bedding: Does it Work? University of Illinois Extension Online Resources. <http://livestocktrail.illinois.edu/dairy/paperDisplay.cfm?ContentID=10371> (accessed 6 May 2015).
- European Commission, 2009. Regulation of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal byproducts Regulation), 2009/1069/EC. *Official Journal L300*, 1–33.
- Fairchild, T.P., McArthur, B.J., Moore, J.H., Hylton, W.E., 1982. Coliform counts in various bedding materials. *Journal of Dairy Science* 65, 1029–1035.
- Feiken, M., van Laarhoven, W., 2012. Verslag van een praktijkonderzoek naar het gebruik van vaste fractie uit gescheiden mest als boxbeddingsmateriaal in ligboxen voor melkvee. Valacon Dairy. English translation Recycled manure solids (RMS) as biobedding in cubicles for dairy cattle. Considerations and tips for practice: <http://www.keydollar.eu/wp-content/uploads/2014/09/Biobedding-English-version.pdf> (accessed 31 July 2015).
- Habing, G.G., Lombard, J.E., Koprak, C.A., Dargatz, D.A., Kaneene, J.B., 2012. Farm-level associations with the shedding of *Salmonella* and antimicrobial-resistant *Salmonella* in U.S. dairy cattle. *Foodborne Pathogens and Disease* 9, 815–821.
- Harrison, E., Bonhotal, J., Schwartz, M., 2008. Using Manure Solids as Bedding. Final Report. Cornell Waste Management Institute, Ithaca, NY. <http://cwmi.css.cornell.edu/beddingfinalreport.pdf> (accessed 6 May 2015).
- Heinonen-Tanski, H., Mohtai, H., Karinen, P., Koivunen, J., 2006. Methods to reduce pathogen microorganisms in manure. *Livestock Science* 102, 248–255.
- Hippen, A., Garcia, A., Hammink, W., Smith, L., 2007. Comfort and Hygiene of Dairy Cows Lying on Bedding of Dolomitic Limestone or Reclaimed Manure Solids. In: Proceedings of the 6th International Dairy Housing Conference, Minneapolis, USA, 16–18 June 2007, pp. 27–33.
- Hogan, J.S., Smith, K.L., Hoblet, K.H., Todhunter, D.A., Schoenberger, P.S., Hueston, W.D., Pritchard, D.E., Bowman, G.L., Heider, L.E., Brockett, B.L., et al., 1989. Bacterial counts in bedding materials used on nine commercial dairies. *Journal of Dairy Science* 72, 250–258.
- Hogan, J.S., Bogacz, V.L., Thompson, L.M., Romig, S., Schoenberger, P.S., Weiss, W.P., Smith, K.L., 1999. Bacterial counts associated with sawdust and recycled manure bedding treated with commercial conditioners. *Journal of Dairy Science* 82, 1690–1695.
- Husfeldt, A.W., Endres, M.I., 2012. Association between stall surface and some animal welfare measurements in freestall dairy herds using recycled manure solids for bedding. *Journal of Dairy Science* 95, 5626–5634.
- Husfeldt, A.W., Endres, M.I., Salfer, J.A., Janni, K.A., 2012. Management and characteristics of recycled manure solids used for bedding in Midwest freestall dairy herds. *Journal of Dairy Science* 95, 2195–2203.
- Kearney, T.E., Larkin, M.J., Levett, P.N., 1993. The effect of slurry storage and anaerobic digestion on survival of pathogenic bacteria. *The Journal of Applied Bacteriology* 74, 86–93.
- Keys, J.E., Smith, L.W., Weinland, B.T., 1976. Response of dairy cattle given a free choice of free stall location and 3 bedding materials. *Journal of Dairy Science* 59, 1157–1162.
- Leach, K.A., Tuer, S., Green, M.J., Bradley, A.J., 2014. Separated Manure Solids as Bedding for Dairy Cows – a UK Farmer Survey. In: Proceedings of the British Mastitis Conference. Worcester, UK, November 12th, 2014, pp. 53–54.
- Locatelli, C., Scaccabarozzi, L.M., Casula, A., Gorrieri, F., Harouana, A., Moroni, P., 2008. Manure Solids Bedding as a Source of Clinical Environmental Mastitis. In: Proceedings of the 47th Annual Meeting of the National Mastitis Council, New Orleans, USA, 20–23 January 2008, pp. 224–225.
- Lombard, J.E., Tucker, C.B., von Keyserlingk, M.A.G., Koprak, C.A., Weary, D.M., 2010. Associations between cow hygiene, hock injuries, and free stall usage on US dairy farms. *Journal of Dairy Science* 93, 4668–4676.
- Marcher Holm, A., Pedersen, R., 2015. Fiberfraktion fra gylle som strøelse i sengebåse til malkekøer FarmTest Cattle Report 98. <https://www.landbrugsinfo.dk/Tvaerfaglige-emner/FarmTest/Sider/FarmTest-98-Fiberfraktion-fra-gylle-som-stroelse-i-sengebaase-til-malkekoeer.aspx> (accessed 14 May 2015).
- Meneer, J.R., Smith, L.W., 1973. Dairy-cattle manure liquid-solid separation with a screw press. *Journal of Animal Science* 36, 788–791.
- Meyer, D.J., Timms, L., Moody, L., Burns, R., 2007. Recycling Digested Manure Solids for Dairies. In: Proceedings of the 6th International Dairy Housing Conference, Minneapolis, USA, 16–18 June 2007, pp. 39–45. [http://elibrary.asabe.org/abstract.asp?aid=22821&redir=\[confid=dhc2007\]&redirType=conference.asp&dabs=Y](http://elibrary.asabe.org/abstract.asp?aid=22821&redir=[confid=dhc2007]&redirType=conference.asp&dabs=Y) (accessed 4 August 2015).
- Misselbrook, T.H., Powell, J.M., 2005. Influence of bedding material on ammonia emissions from cattle excreta. *Journal of Dairy Science* 88, 4304–4312.
- Ostrum, P.G., Thomas, M.J., Zadoks, R.N., 2008. Dried Manure Solids for Freestall Bedding: Experiences from a Northeast Dairy. In: Proceedings of the 47th Annual Meeting of the National Mastitis Council, New Orleans, USA, 20–23 January 2008, pp. 149–156.
- Pronto, J., Gooch, K., 2009. Anaerobic Digestion at Noblehurst Farms: Case Study. Cornell University. [http://www.manuremanagement.cornell.edu/Pages/Popular\\_Pages/Case\\_Studies.html](http://www.manuremanagement.cornell.edu/Pages/Popular_Pages/Case_Studies.html) (accessed 6 May 2015).
- Rendos, J.J., Eberhart, R.J., Kesler, E.M., 1975. Microbial populations of teat ends of dairy cows and bedding materials. *Journal of Dairy Science* 58, 1492–1500.
- Schwarz, M., Bonhotal, J., Staehr, A.E., 2010. Use of Dried Manure Solids as Bedding for Dairy Cows and 'How Frequently Should Stalls be Refreshed with New Bedding' Case Study. <http://cwmi.css.cornell.edu/useofDMs.pdf> (accessed 6 May 2015).
- Schwarz, M., Bonhotal, J., Staehr, E., 2011. How frequently should stalls be refreshed with new bedding? *Progressive Dairyman* 1, 57–58.
- Sharkey, H.L., Zanierto, A., Luparia, P., Poggianella, M., Moroni, P., Schukken, Y.H., 2011. SOP Treatment of Separate Manure Solids Reduced *Klebsiella* Bacteria Counts. In: Proceedings of the 50th Annual Meeting of the National Mastitis Council, Arlington, USA, 23–26 January 2011, pp. 185–186.
- Sorter, D.E., Koster, H.J., Hogan, J.S., 2014. Bacterial counts in recycled manure solids bedding replaced daily or deep packed in freestalls. *Journal of Dairy Science* 97, 2965–2968.
- Timms, L., 2008a. Preliminary evaluation of separated manure solids characteristics at the new ISU dairy. Iowa State University Animal Industry Report AS654, ASL R2318. [http://lib.dr.iastate.edu/ans\\_air/vol654/iss1/67](http://lib.dr.iastate.edu/ans_air/vol654/iss1/67) (accessed 4 August 2015).
- Timms, L., 2008b. Characteristics and use of separated manure solids (following anaerobic digestion) for dairy freestall bedding, and effects on animal health and performance in an Iowa dairy herd. Iowa State University Animal Industry Report AS654, ASL R2321. [http://lib.dr.iastate.edu/ans\\_air/vol654/iss1/70/](http://lib.dr.iastate.edu/ans_air/vol654/iss1/70/) (accessed 4 August 2015).
- Timms, L., 2008c. Characteristics and use of separated manure solids (following composting) for dairy freestall bedding, and effects on animal health and



- performance in an Iowa dairy herd. Iowa State University Animal Industry Report AS654, ASL R2322. [http://lib.dr.iastate.edu/ans\\_air/vol654/iss1/71/](http://lib.dr.iastate.edu/ans_air/vol654/iss1/71/) (accessed 4 August 2015).
- Tulloch, J., O'Boyle, N., Sears, P., 2009. An Investigation into the Coliform Growth of Digested Manure Solids on a Large Commercial Michigan Dairy. In: Proceedings of the 42<sup>nd</sup> Annual Meeting of the American Association of Bovine Practitioners, Omaha, Nebraska, 10–12 September 2009, p. 213.
- von Keyserlingk, M.A., Barrientos, A., Ito, K., Galo, E., Weary, D.M., 2012. Benchmarking cow comfort on North American freestall dairies: Lameness, leg injuries, lying time, facility design, and management for high-producing Holstein dairy cows. *Journal of Dairy Science* 95, 7399–7408.
- Ward, W.R., Hughes, J.W., Faull, W.B., Cripps, P.J., Sutherland, J.P., Sutherst, J.E., 2002. Observational study of temperature moisture, pH and bacteria in straw bedding, and faecal consistency, cleanliness and mastitis in cows in four dairy herds. *Veterinary Record* 151, 199–206.
- Wells, S.J., Trent, A.M., Marsh, W.E., Robinson, R.A., 1993. Prevalence and severity of lameness in lactating dairy cows in a sample of Minnesota and Wisconsin herds. *Journal of the American Veterinary Medical Association* 202, 78–82.
- Zähler, M., Schmidtke, J., Schrade, S., Schaeren, W., Otten, S., 2009. Alternative einstreumaterialien in liegeboxen. Bautagung Raumberg-Gumpenstein 2009, 33–38. <http://www.raumberg-gumpenstein.at/cm4/de/forschung/publikationen/downloadsveranstaltungen/viewdownload/381-bautagung-2009/3188-alternative-einstreumaterialien-in-liegeboxen.html> (accessed 6 May 2015).
- Zdanowicz, M., Shelford, J.A., Tucker, C.B., Weary, D.M., von Keyserlingk, M.A.C., 2004. Bacterial populations on teat ends of dairy cows housed in free stalls and bedded with either sand or sawdust. *Journal of Dairy Science* 87, 1694–1701.
- Zehner, M.M., Farnsworth, R.J., Appleman, R.D., Lantz, K., Springer, J.A., 1986. Growth of environmental mastitis pathogens in various bedding materials. *Journal of Dairy Science* 69, 1932–1941.