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Laboratory Evaluation of Dust-Control Effectiveness of Pen Surface Treatments for Cattle Feedlots

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Emission of particulate matter (PM) is one of the major air quality concerns for large beef cattle feedlots. Effective treatments on the uncompacted soil and manure mixture of the pen surface may help in reducing PM emission from feedlots. A laboratory apparatus was developed for measuring dust-emission potential of cattle feedlot surfaces as affected by pen surface treatments. The apparatus was equipped with a simulated pen surface, four mock cattle hooves, and samplers for PM with equivalent aerodynamic diam. ≤10 μm (PM_{10}). The simulated pen surface had a layer of dry, loose feedlot manure with a compacted soil layer underneath. Mock hooves were moved horizontally on the manure layer to simulate horizontal action of cattle hooves on the pen surface. High-volume PM_{10} samplers were used to collect emitted dust. Effects of hoof speed, depth of penetration, and surface treatments with independent candidate materials (i.e., sawdust, wheat straw, hay, rubber mulch, and surface water application) on PM_{10} emission potential of the manure layer were investigated. Our laboratory study showed PM_{10} emission potential increased with increasing depth of penetration and hoof speed. Of the surface treatments evaluated, application of water (6.4 mm) and hay (723 g m^{-2}) exhibited the greatest percentage reduction in PM_{10} emission potential (69 and 77%, respectively) compared with the untreated manure layer. This study indicated application of hay or other mulch materials on the pen surface might be good alternative methods to control dust emission from cattle feedlots.

Emission of particulate matter (PM) is one of the major environmental challenges for large, open cattle feedlots. The pen surface is a major source of PM emission from cattle feedlots; other sources include unpaved roads and feed processing areas (Auvermann et al., 2006; Razote et al., 2007). Factors that influence PM emission from pen surfaces include pen surface characteristics (i.e., water content [WC] and presence of loose, uncompacted manure layer), degree and nature of cattle activity, various activities in the feedlot such as manure harvesting, and weather conditions. Of the above factors, WC of the pen surface is one of the most important (Miller and Woodbury, 2003). Field studies have shown dust concentrations downwind of feedlots decrease with increasing pen surface WC (Razote et al., 2007; Sweeten et al., 1988). According to Sweeten et al. (1988), WC of the pen surface should be in the range of 260 to 310 g kg^{-1} and 350 to 410 g kg^{-1}, respectively, for loose surface manure and compacted manure to a depth of 25 mm under the corral surface for controlling dust to limits of 150 and 260 μg m^{-3} for total suspended particulates (TSP). These TSP limits were based on the national ambient air quality standards during the 1980s. Other researchers have also suggested that pen surface WC should be maintained at 250 to 350 g kg^{-1} on the basis of odor and dust control, as well as the economy of treatment (Auvermann et al., 2006). On the basis of a laboratory test protocol, Miller and Woodbury (2003) also concluded that pen surface WC and organic matter content are key factors that regulate dust emission from pen surfaces.

The following methods for controlling PM emissions from cattle feedlots have been investigated or recommended: pen surface sprinkling, frequent pen scraping, stocking density manipulation, and topical application of crop residues (Bonifacio et al., 2011; Razote et al., 2006; Auvermann, 2003; Romanillos, 2000; Sweeten, 1979; Carroll et al., 1974). Pen surface sprinkling is one of the most common ways of controlling dust. Previous research (e.g., Carroll et al., 1974; Bonifacio et al., 2011) reported mean PM reduction efficiencies ranging from 32 to 80% for sprinkler systems for cattle feedlots. While water sprinkling may be effective in controlling PM emission in feedlots, the cost of installation and

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Abbreviations: APS, aerodynamic particle sizer; GMD, geometric mean diameter; GSD, geometric standard deviation; PM, particulate matter; PM_{10}, particulate matter with equivalent aerodynamic diam. ≤10 μm; TSP, total suspended particulates; WB, wet basis; WC, water content.

operation of a sprinkler system may be quite high; estimated total cost of water sprinkler systems ranged from \$1.24 to 2.34 per head marketed per year, depending on the capacity of the feedlot, turnover rate, and type of sprinkler system (Harner et al., 2008; Amosson et al., 2006, 2007). In addition, water resource may be limited (Pimentel et al., 1997).

Frequent pen scraping can be used to remove loose manure that contributes to dust emission (Auvermann et al., 2006; Davis et al., 2004). Stocking density (i.e., number of animals per unit of pen area) may be adjusted to compensate for increases in net evaporative demand, shifting the water balance in favor of PM control. Effectiveness of increased stocking density, however, is likely to decrease as daily net evaporation increases; it may also induce behavioral problems and reduce overall feed-to-gain performance (Rahman et al., 2008; Auvermann et al., 2006; Mitloehner, 2000). Another potential method for reducing emissions is topical application of crop residues and other materials onto the pen surface to enhance its moisture-holding capacity and reduce evaporative loss; the presence of amendments may also reduce the effect of hooves' shearing action by serving as a cushion (Auvermann et al., 2006; Razote et al., 2006; Davis et al., 2004).

Research is needed to evaluate the effectiveness of surface treatments and other methods in controlling PM emission rates. Several laboratory methods have been developed to test the dust emission potential of pen surfaces. Miller and Woodbury (2003) developed a protocol that involved mixing a small amount of feedlot sample in a modified laboratory blender to test samples for their ability to produce dust. Auvermann (2003) and Razote et al. (2006) have developed laboratory apparatuses, weight-drop test chambers, based on the vertical action of cattle hooves on the pen surface. Results indicated the impact energy of the cattle hoof affected the PM with equivalent aerodynamic diam. ≤10 μm (PM_{10}) emission potential more than the depth of the manure layer (Razote et al., 2006). However, the mode of hoof action on the pen surface has both vertical and horizontal components. Research is needed for emissions associated with the horizontal component of hoof action on the pen surface (Razote et al., 2006; Auvermann, 2003).

This research considered the horizontal shearing action of cattle hooves on the pen surface. The objectives of this study were (i) to develop a repeatable laboratory method, based on the horizontal component of hoof action on the pen surface, for measuring PM_{10} emission potential of pen surfaces and (ii) to compare the relative effectiveness of surface treatments in reducing PM_{10} emission potential.

Materials and Methods

Test Chamber

The laboratory apparatus was developed based on the weight-drop test chamber developed by Razote et al. (2006). Figure 1a shows a schematic diagram of the apparatus. It had a 3.7-m-long bench-top enclosure with a 0.61-m by 0.61-m cross-section mounted over a simulated feedlot pen surface, four mock cattle hooves, and samplers for PM_{10}. The simulated feedlot pen surface had a layer of loose, dry manure (0.51 m by 0.41 m by 0.1 m), with a compacted base soil (0.51 m by 0.81 m by 0.91 m) underneath. The four mock hooves (dried cattle hooves) had average height, length, and width of 9.3 ± 0.3 cm, 9.9 ± 0.2 cm, and 8.9 ± 0.1 cm, respectively (Fig. 2). They were moved horizontally over a distance of 0.24 m on the manure layer using a pneumatic cylinder. Stroke time and force exerted by the hooves on the manure layer were measured using a precalibrated load cell connected to the back of the hydraulic cylinder (Fig. 1b). By changing valve settings in the cylinder (Fig. 1b), speed of the hooves was controlled.

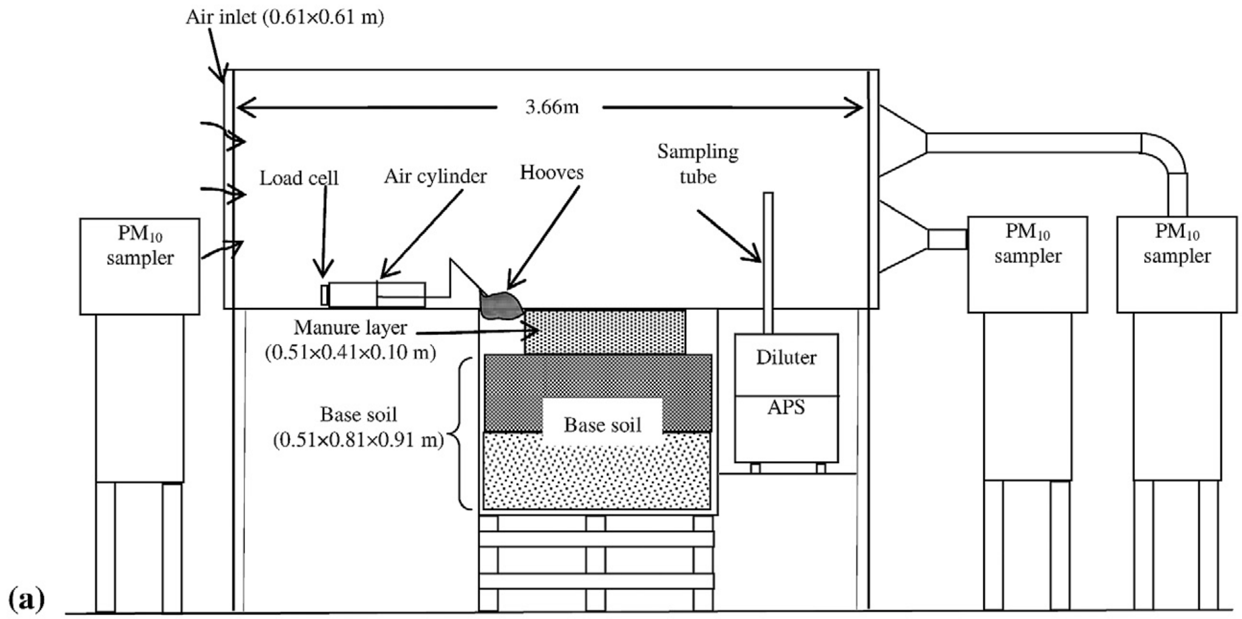
The chamber was equipped with five, high-volume PM_{10} samplers (Model 1200, Thermo Electron, Atlanta, GA). One PM_{10} sampler was placed at the inlet side of the chamber to account for the background PM_{10} concentration; four of the PM_{10} samplers at the outlet end of the chamber were used to collect PM_{10} emitted as the hooves moved through the simulated pen surface (Fig. 1b).

The manure sample used in the test chamber was taken from a feedlot and was dried and sieved to remove large clods. Standard laboratory analysis of this sample at the Kansas State University Soil Testing Laboratory indicated an organic matter content of approximately 80 g kg^{-1}, based on total carbon content. From a particle size perspective, sieve analysis showed that the sample contained sand, silt, and clay contents of 660, 120, and 220 g kg^{-1}, respectively.

Experiments

This study first investigated effects of hoof speed and depth of penetration on the PM_{10} emission potential of the simulated pen surface. Three levels of hoof speed (i.e., high [0.57 ± 0.01 m s^{-1}], medium [0.29 ± 0.01 m s^{-1}], and low [0.25 ± 0.01 m s^{-1}]) and three levels of depth of penetration (i.e., 1.3, 2.5, and 5.1 cm) were considered (Table 1). Each treatment combination of hoof speed and depth of penetration had three replicates. Water contents of the manure layer and materials applied on the simulated pen surface were determined using the ASTM D 2216–10 oven-drying method (ASTM, 2010). The mean WC of the loose manure layer, as measured by the oven-drying method, was 80 g kg^{-1} wet basis (WB), ranging from 70 to 90 g kg^{-1} WB (Table 1). From these tests, the combination of hoof speed and depth of penetration that resulted in the highest PM_{10} emission potential was identified and used in the second set of experiments.

In the second set of experiments (Table 1), the effectiveness of surface treatments with independent candidate materials in controlling PM_{10} emission was evaluated. Organic residues, including unprocessed wheat straw, sawdust, and unprocessed hay, were considered in this study because they can improve the quality of the manure-composting process (Chalker-Scott, 2008) and due to their relative size and weight. Wheat straw and hay are fibrous, whereas sawdust is smaller in size (Table 1). For comparison, rubber mulch (made from recycled tires) was also considered because it was much heavier and much larger than sawdust (Table 1). The bulk densities of the materials were 6.6, 9.3, 77, and 350 kg m^{-3} for hay, wheat straw, sawdust, and rubber mulch, respectively. The minimum amounts of mulches applied in this study were predetermined to roughly cover the surface of the manure layer. The amounts were then increased to fully cover the surface of manure layer. The amounts of wheat straw (WC = 76 g kg^{-1} WB), sawdust



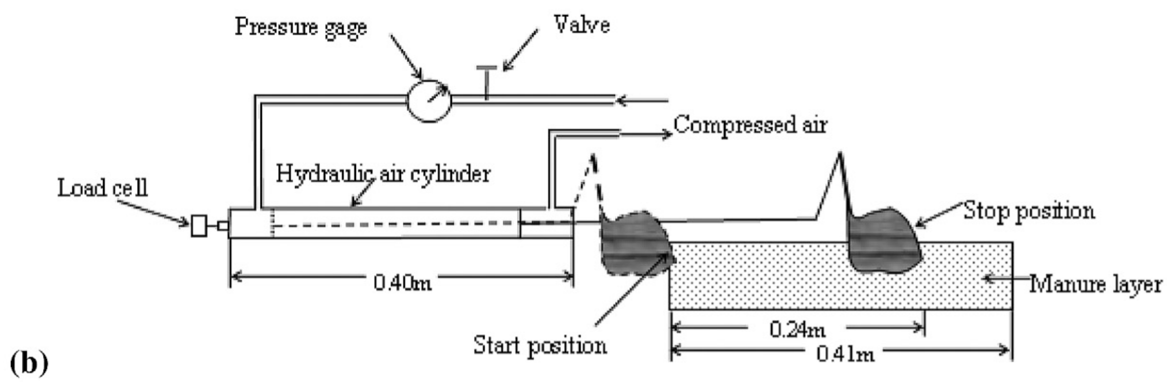


Fig. 1. Schematic diagram of (a) the laboratory apparatus and (b) the hoof-action system (not drawn to scale).

(WC = 68 g kg^{-1} WB), and hay (WC = 83 g kg^{-1} WB) applied on the manure layer were 241, 482, and 723 g m^{-2}, respectively. Corresponding thicknesses were approximately 3, 5, and 7 cm for wheat straw, 0.5, 0.7, and 1 cm for sawdust, and 4, 7, and 10 cm for hay. For the rubber mulch, amounts applied on the manure layer were 1415, 2834, 4253, and 9217 g m^{-2}, and corresponding thicknesses were approximately 0.7, 1.3, 2, and 3 cm. These materials were uniformly placed on the surface of the manure layer.

In this study, water application treatment was also evaluated and compared with the performance of the mulches. Predetermined amounts of water (~380 and 720 mL) were applied uniformly on the manure layer with a manual sprayer. The wetted surface was allowed to stand for 30 min after sprinkling to allow the applied water to gradually infiltrate into the manure layer at 3.2 and 6.4 mm, similar to typical water application rates in commercial feedlots.

An untreated dry manure sample (i.e., with no candidate abatement materials applied on the surface) served as the control. All tests used the high-speed setting and 5.1-cm-depth of hoof penetration into the manure layer, since this combination resulted in the highest PM_{10} emission potential from the first set of experiments. Each surface treatment consisted of three replications. After each test, the manure layer and material applied on the surface were removed and replaced with new samples.

Particulate Sampling

Each PM_{10} sampler was operated at a sampling flow rate of 1.13 m^3 min^{-1}. The combined flow rate of the four samplers generated airflow within the chamber equivalent to ~0.22 m s^{-1}

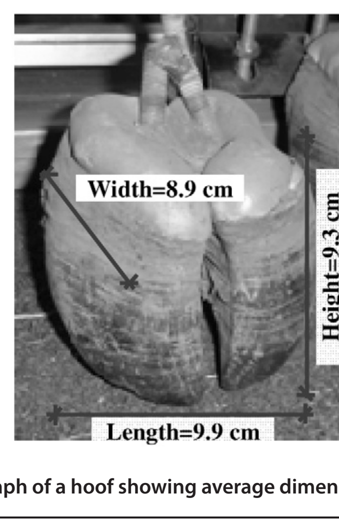


Fig. 2. Photograph of a hoof showing average dimensions.

average wind speed, as measured by an omnidirectional probe (Model 8475, TSI, Inc., Shoreview, MN). The samplers were operated for 11 min to collect emitted particulates, after which the filters were immediately removed and placed in the conditioning chamber as described below.

Filters in the PM_{10} samplers were 20 cm by 25 cm, type A/E, glass-fibers (Gelman Sciences, Ann Arbor, MI.). They were conditioned in a conditioning chamber (25°C, 40% relative humidity) for 24 h before weighing (for both presampling and postsampling weights) to minimize humidity effect on the filter weights. Room air temperature and atmospheric pressure were measured during all tests. Air temperatures ranged from 20 to 27°C, with an average of 24°C; pressures ranged from 0.96×10^5 Pa to 1.01×10^5 Pa, with an average of 0.98×10^5 Pa.

For tests involving hay, an aerodynamic particle sizer (APS) spectrometer (Model 3021, TSI, Inc., St. Paul, MN) with a diluter (Model 3302A, TSI, Inc., St. Paul, MN) was used to measure particle size distribution at the center of the chamber downstream of the simulated pen surface. The APS measures particle size distribution from 0.5 to 20 μm by determining the time of flight of individual particles in an accelerating flow field (Volckens and Peters, 2005). The APS was operated continuously during each test at a sampling flow rate of 5 L min^{-1} and average time of 20 s.

Data Analysis

The PM_{10} emission potential (in mg) for each replicate was determined as the mass difference between PM_{10} collected on the four downstream high-volume PM_{10} samplers and that collected on the upstream PM_{10} sampler. For particle size distribution, geometric mean diameter (GMD) and geometric standard deviation (GSD), as well as the mass concentration for different size ranges, were determined from the APS data. Density of particles used for APS was 1.8 g cm^{-3}, based on measurements with a multipycnometer (Quantachrome Instruments, Boynton Beach, FL). Analysis of Variance, General Linear Model procedure, and Tukey multiple comparisons test in SAS (SAS v9.1, Cary, NC) were used in analyzing PM_{10} emission potential, GMD, and GSD at the 5% level of significance (SAS Institute, 1990).

Results

Effects of Speed and Depth of Penetration

For each speed setting, in general, emission potential increased significantly ($P < 0.05$) with increasing depth of penetration (Table 2), except for the low-speed setting in which the 2.5- and 5.1-cm depths were not significantly different ($P > 0.05$). These results suggest that the depth of penetration of the hooves greatly affected PM_{10} emission potential associated with the horizontal component of hoof action on the pen surface. As the depth of hoof penetration on the loose manure surface increased, there was an increase in the amount of manure in contact with the moving hooves—resulting in more manure moved and more particles suspended in the air.

For each depth of penetration, PM_{10} emission potential generally increased with increasing hoof speed (Table 2). The faster the hoof speed, the higher the energy exerted by the hoof on

Table 1. Experimental parameters.

Test	Factors investigated	Speed setting†	Depth of hoof penetration into the manure layer	Amount of material applied on the simulated pen surface	Water content of manure layer
			cm		g kg^{-1} wet basis
1	Speed and depth of penetration	Low	1.3, 2.5, 5.1	0	81
		Medium	1.3, 2.5, 5.1	0	81
		High	1.3, 2.5, 5.1	0	81
2	Surface treatments‡				
	Wheat straw	High	5.1	0, 241, 482, 723 g m^{-2}	76
	Sawdust	High	5.1	0, 241, 482, 723 g m^{-2}	73
	Hay	High	5.1	0, 241, 482, 723 g m^{-2}	75
	Rubber mulch	High	5.1	0, 1415, 2834, 4253, 9217 g m^{-2}	96
	Water	High	5.1	3.2, 6.4 mm	95

† Speed settings: high = 0.57 (±0.01) m s^{-1}, medium = 0.29 (±0.01) m s^{-1}, and low = 0.25 (±0.01) m s^{-1}.

‡ For wheat straw and hay, the average lengths were 163 (50–300) and 210 (50–310) mm. The average widths were 3.7 (1.4–9.3) and 1.7 (0.7–5.2) mm. The average thicknesses were 0.7 (0.2–1.9) and 0.4 (0.2–0.8) mm, respectively. Sawdust had a geometric mean diam. (GMD) of 3.2 mm and geometric standard deviation (GSD) of 1.4, whereas rubber mulch had a GMD of 8.7 mm and GSD of 1.8.

Table 2. Effects of hoof speed and depth of penetration into the manure layer on particulate matter with equivalent aerodynamic diam. ≤10 μm (PM_{10}) emission potential of the simulated pen surface.†‡

Depth of hoof penetration into the manure layer	PM_{10} emission potential§‡					
	High speed		Medium Speed		Low speed	
	Mean	SE	Mean	SE	Mean	SE
cm	mg					
1.3	11.28 Aa§	1.08	6.44 Ba	0.98	3.36 Ca	0.47
2.5	26.87 Ab	3.38	9.96 Bb	0.50	8.82 Cb	0.77
5.1	48.68 Ac	3.85	26.31 Bc	2.55	8.61 Cb	1.02

† Each data point is the average of three replicates.

‡ Amount of PM_{10} suspended in the air with one stroke of hoof movement on a pen surface of 0.51 m by 0.41 m by 0.1 m.

§ For the same hoof speed, mean values with the same lowercase letters are not significantly different at the 5% level; for the same depth of hoof penetration into the manure layer, mean values with the same uppercase letters are not significantly different at the 5% level.

the manure layer—causing particles to be displaced at greater distances. This greater movement of the manure layer caused larger particles to be displaced and smaller particles suspended in the air. The highest PM_{10} emission potential (48.7 mg) was observed at the high-speed setting and deepest penetration; this was about 14 times the smallest emission potential (3.4 mg), which was observed for the case involving the low-speed setting and shallowest depth of penetration.

Surface Treatments

Compared with an untreated control, topical application of wheat straw, sawdust, and hay significantly reduced PM_{10} emission potential of the manure layer (Table 3), except for wheat straw and sawdust, when applied at the minimum rate of 241 g m^{-2}. In general, for each surface treatment, PM_{10} emission potential decreased with increasing amounts of material applied on the manure layer, with the highest amount (723 g m^{-2}) resulting in the smallest PM_{10} emission potential. However, there was generally no significant difference ($P >$ 0.05) between the two intermediate levels (241 and 482 g m^{-2}) for each surface treatment. Of all treatments, application of hay at the highest rate (i.e., 723 g m^{-2}) resulted in the smallest PM_{10} emission potential of the manure layer. This reduction was equivalent to a mean percentage reduction in PM_{10} emission potential of 77%.

For tests involving application of rubber mulch on the simulated surface, results showed no significant reduction in PM_{10} emission potential of the surface (Table 4). As expected, application of water decreased emission potential of the manure layer (Table 4). Also, the greater the depth of water applied, the greater the reduction in PM_{10} emission potential. Application of 6.4 mm of water resulted in a mean reduction in PM_{10} emission potential of 69%.

Maximum reductions in PM_{10} emission potential using wheat straw, sawdust, and water were 46% (with amount applied of 723 g m^{-2}), 41% (with amount applied of 482 g m^{-2}), and 69% (with 6.4 mm penetration into the manure layer), respectively. The maximum reduction in PM_{10} emission potential with application of rubber mulch was only 23% (with amount applied of 9217 g m^{-2}). Generally, from among the candidate abatement materials tested, hay reduced PM_{10} emission potential better than all other materials at all application rates. Reduction in PM_{10} emission potential with application of hay (48 to 77%) was comparable with that of water sprinkling (42 and 69% for 3.2 and 6.4 mm of water applied, respectively).

The GMD of the emitted particles varied with time for the surface treatment involving hay at 723 g m^{-2} and untreated surface (Fig. 3). Note that it took from 0.5 to 1.0 s to move the hooves a distance of 0.24 m over the manure surface. After the hooves were moved, GMD increased rapidly within the first 3 min and then gradually decreased to near background levels as shown in Fig. 3. The maximum GMD values and corresponding GSD values for the manure layer treated with hay and control are summarized in Table 5. Mean maximum GMD for

Table 3. Effect of surface treatments (wheat straw, sawdust, hay) on particulate matter with equivalent aerodynamic diam. ≤10 μm (PM_{10}) emission potential of the simulated pen surface.†

Amount	PM_{10} emission potential‡					
	Wheat straw		Sawdust		Hay	
	Mean	SE	Mean	SE	Mean	SE
g m^{-2}	mg					
0	43.3 A a§	6.0	43.3 A a	6.0	48.7 A a	3.8
241	39.4 A ab	1.1	37.3 AB ab	9.8	25.5 B b	0.1
482	30.7 A bc	3.1	25.6 AB b	1.4	18.3 B bc	2.1
723	23.6 A c	1.8	30.5 A b	2.2	11.1 B c	0.2

† Emission tests were done with hoof speed at high level and depth of penetration of 5.1cm. Each data point is the average of three replicates.

‡ Amount of PM_{10} suspended in the air with one stroke of hoof movement on a pen surface of 0.51 m by 0.41 m by 0.1 m.

§ For the same amount of material applied on the surface, mean values with the same uppercase letters are not significantly different at the 5% level; for the same type of material applied on the surface, mean values with the same lowercase letters are not significantly different at the 5% level.

Table 4. Effects of application of rubber mulch and water on particulate matter with equivalent aerodynamic diam. ≤10 μm (PM_{10}) emission potential of the simulated pen surface.†‡

Treatment	Amount applied on the surface	PM_{10} emission potential‡	
		Mean	SE
		mg	
Rubber mulch	0 g m^{-2}	17.5 a§	1.2
	1415 g m^{-2}	16.3 a	2.7
	2834 g m^{-2}	18.5 a	2.2
	4253 g m^{-2}	15.5 a	1.3
	9217 g m^{-2}	13.5 a	0.9
Water	0 mm	37.7 b	2.3
	3.2 mm	22.0 c	2.1
	6.4 mm	11.7 d	2.2

† Emission tests were done with hoof speed at high level and depth of penetration of 5.1cm. Each data point is the average of three replicates.

‡ Amount of PM_{10} suspended in the air with one stroke of hoof movement on a pen surface of 0.51 m by 0.41 m by 0.1 m.

§ For each treatment, column means with the same letter are not significantly different at the 5% significant level.

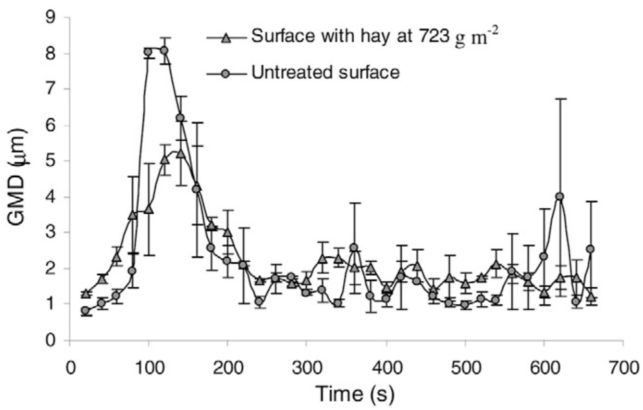


Fig. 3. The distribution of geometric mean diameter (GMD) of particulates over time as affected by hay surface treatment (vertical bars represent standard error).

the untreated surface (i.e., control), 8.2 µm, was significantly greater ($P < 0.05$) than for the surfaces treated with hay. The amount of hay applied did not significantly influence GMD ($P > 0.05$). In addition, surface treatment with hay reduced concentrations for all particle sizes from 0.5 to 20 µm as shown in Fig. 4, which presents the mass concentrations of particles emitted from the simulated pen surface during the period in which GMD was highest. As expected, reduction in concentration was higher for the larger particles because they can be easily entrapped by the hay fibers, whereas the smaller particles can go through the spaces between the fibers.

Discussion

Hay had greater effectiveness in reducing PM_{10} emission compared with other materials in this study, possibly because hay had long, interlocking fibers that formed a continuous blanket on top of the manure layer. When the mock hooves moved horizontally through the layer, they displaced the manure layer in their paths—forming valley ridges on both sides and in front of the hooves. Even after the hooves had moved through the hay and manure layer, the fibers held together and still covered the surface of the manure layer, including the ridges, perhaps capturing most of the dust generated. Although wheat straw had long fibers, they were thicker than those of hay and did not interlock. Therefore, for the same amount applied on the surface, wheat straw had relatively less thickness and surface area blocking the emitted particles compared with hay, resulting in less effective capture of particles. Sawdust and rubber did not provide effective barriers to capture dust particles. Although, at the highest application rate, they both totally covered the surface. Additionally, they both were loose and easily displaced and mixed with the loose manure layer by the moving hooves, which lowered their effectiveness in reducing PM_{10} emission potential.

For tests involving the rubber mulch, the manure sample was taken from another batch that was different from the one used in other tests. Compared with the untreated or control for the other surface treatments, the untreated manure layer (i.e., control) for the rubber mulch tests had relatively low PM_{10} emission potential (17.5 mg), which may also have affected the apparent effectiveness of rubber mulch. Consequently, another set of tests involving hay was conducted with the manure sample the same as that used for rubber mulch. Reductions in PM_{10} emission potential at 241, 482, and 723 g m^{-2} levels were 55, 56, and 64%, respectively. Compared with the values of 48, 62, and 77%, which were from the first set of hay tests, maximum reduction in PM_{10} emission potential of the second test was slightly less than that from the first set of hay tests. However, the effectiveness of hay in reducing PM_{10} emission was still greater than that of rubber mulch.

As mentioned above, water sprinkling is the most common method of controlling dust in cattle feedlots. In this study, percentage reductions in PM_{10} emission potential were 42 and 69% for water applications of 3.2 and 6.4 mm, respectively. These values were within the range of published values on field evaluation of particulate control efficiency of a water sprinkler system that had a maximum water application rate of 5 mm d^{-1} (Bonifacio et al., 2011). While water sprinkling may be effective in controlling PM emission, the cost of installation and operation of a sprinkler system may be quite high (Harner et al., 2008; Amosson et al., 2006, 2007) and water resource may be limited in some areas (Pimentel et al., 1997). Thus, application of hay or straw on the pen surface might be good alternative methods to control dust emission from cattle feedlots. Also, surface mulches will help retain and preserve moisture by slowing evaporation (PM10, 2007). In a study on crop residues, Klocke et al. (2009) observed that surface coverage and amount of dry matter of crop residues influenced soil water evaporation and that evaporation was reduced nearly 50% compared with bare soil. With the reduction in water evaporation, application of mulches also has the potential to reduce the amount of supplemental water needed for sprinkler systems for effective dust control. Surface mulches also can protect the manure layer from rain by reducing its impact and slowing runoff speed (PM10, 2007); however, that effect would need to be balanced against the more traditional management objective of ensuring rapid pen drainage to reduce odors and avoid muddy, performance-sapping conditions on the surface.

Table 5. Maximum geometric mean diameter (GMD) and corresponding geometric standard deviation (GSD) values, as measured by the aerodynamic particle sizer spectrometer for surface treatment with hay.†

Amount	GMD		GSD	
	Mean	SE	Mean	SE
g m^{-2}	——— µm ———			
0	8.2 a‡	0.25	2.1	0.00
241	6.1 b	0.38	2.0	0.12
482	5.9 b	0.19	1.9	0.19
723	6.5 b	0.09	1.9	0.06

† Emission tests were done with hoof speed at high level and depth of penetration of 5.1cm. Each data point is the average of three replicates.

‡ Mean values with the same letter within a column are not significantly different at the 5% level.

Results from the study indicate the potential of using hay or straw in reducing dust emission from pen surfaces. Note, however, that the PM_{10} emission potentials resulting from this study are relative values. Field studies should be conducted to verify results obtained from this study. Further research is also needed to determine the technical and economic feasibility of applying hay or other materials on the pen surface of cattle feedlots. Factors that should be established include the minimum amount and frequency of application under feedlot conditions, and costs associated with procurement and spreading. Depending on the size of the feedlot and amount of mulches, the cost might be considerable; however, in cases in which water availability is an issue, application of hay could still be a viable option for dust control.

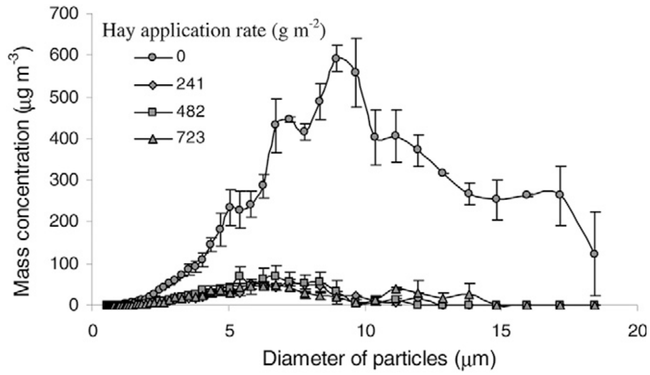


Fig. 4. Effect of application of hay on the mass concentration of particles (with size distribution of 0.5–20 μm) emitted from the simulated pen surface, as measured by the aerodynamic particle sizer spectrometer. Each data point is the average of three replicates; error bars represent standard error.

Conclusions

This study developed a simple, repeatable method for evaluating and quantifying relative particulate control efficiencies of potential abatement measures for open cattle feedlots. Results showed PM_{10} emission potential due to the horizontal shearing action of cattle hooves increased with increasing speed of hooves and depth of hoof penetration into the uncompacted manure layer. Results also showed topical application of mulches, or water application, significantly reduced PM_{10} emission potential of the simulated pen surface. Of the candidate abatement materials tested, hay and water were the most effective in reducing PM_{10} emission potential, with control efficiencies for hay ranging from 48% with an application rate of 241 g m^{-2} to 77% for hay with an application rate of 723 g m^{-2}. Control efficiencies for water ranged from 42% for an application rate of 3.2 mm of water to 69% for an application rate of 6.4 mm.

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References

Amosson, S.H., F. Bretz, L. New, and L.K. Almas. 2007. Economic analysis of a traveling gun for feedyard dust suppression. Presentation at the Southern Economics Association Annual Meeting, Mobile, AL. Available at http://ageconsearch.umn.edu/bitstream/34881/1/sp07am02.pdf (verified 24 June 2011).

Amosson, S.H., B. Guerrero, and L.K. Almas. 2006. Economic analysis of solid-set sprinklers to control dust in feedlots. Presentation at the Southern Agricultural Economics Association Annual Meeting, Orlando, FL. Available at http://ageconsearch.umn.edu/bitstream/35341/1/sp06am01.pdf (verified 24 June 2011).

ASTM. 2010. Standard test method for laboratory determination of water (moisture) content of soil and rock by mass. D 2216–10. Am. Soc. of Testing and Materials, West Conshohocken, PA.

Auvermann, B.W. 2003. A mechanistic model of fugitive emissions of particulate matter from cattle feedyards, Part I: Introductory evaluation. p. 257–266. *In* Proc. Air Pollution from Agricultural Operations III Conference, Durham, NC. 2–15 Oct. 2003. ASAE, St. Joseph, MI.

Auvermann, B.W., R. Bottcher, A. Heber, D. Meyer, C.B. Parnell, Jr., B. Shaw, and J. Worley. 2006. Particulate matter emissions from animal feeding operations. p. 435–468. *In* J.M. Rice, D.F. Caldwell, and F.J. Humenik (ed.) Animal agriculture and the environment. National Center for Manure and Animal Waste Management White Papers. ASABE, St. Joseph, MI.

Bonifacio, H.F., R.G. Maghirang, E.B. Razote, B.W. Auvermann, J.P. Harner, J.P. Murphy, L. Guo, J.M. Sweeten, and W.L. Hargrove. 2011. Particulate control efficiency of a water sprinkler system at a beef cattle feedlot in Kansas. Trans. ASABE 54:295–304.

Carroll, J.J., J.R. Dunbar, R.L. Givens, and W.B. Goddard. 1974. Sprinkling for dust suppression in a cattle feedlot. Calif. Agric. 28:12–14.

Chalker-Scott, L. 2008. Dust mulches. MasterGardener. Available at http://www.puyallup.wsu.edu/~linda%20chalker-scott/horticultural%20myths_files/Myths/magazine%20pdfs/Dust%20mulches.pdf (verified 24 June 2011).

Davis, J.G., T.L. Stanton, and T. Haren. 2004. Feedlot manure management. Management, Livestock Series No. 1.220. Colorado State Univ. Cooperative Extension, Fort Collins, CO. Available at http://cospl.coalliance.org/fez/eserv/co:6629/ucsu2062212202002internet.pdf (verified 27 June 2011).

Harner, J., R.G. Maghirang, and E.B. Razote. 2008. Water requirements for controlling dust from open feedlots. *In* Mitigating Air Emissions from Animal Feeding Operations Conf., Iowa State Univ., Ames. Available at http://www.ag.iastate.edu/wastemgmt/Mitigation_Conference_proceedings/CD_proceedings/Animal_Housing-Treatment/Harner-Dust_control.pdf (verified 24 June 2011).

Klocke, N.L., R.S. Currie, and R.M. Aiken. 2009. Soil water evaporation and crop residues. Trans. ASABE 52:103–110.

Miller, D.N., and B.L. Woodbury. 2003. Simple protocols to determine dust potentials from cattle feedlot soil and surface samples. J. Environ. Qual. 32:1634–1640. doi:10.2134/jeq2003.1634

Mitloehner, F.M. 2000. Behavioral and environmental management of feedlot cattle. PhD diss. Texas Tech Univ., Lubbock, TX.

Pimentel, D., J. Houser, E. Preiss, O. White, H. Fang, L. Mesnick, T. Barsky, S. Tariche, J. Schreck, and S. Alpert. 1997. Water resources: Agriculture, the environment, and society. Bioscience 47:97–106. doi:10.2307/1313020

PM10 . 2007. Erosion control- mulching. PM10 Inc., Palm Desert, CA. Available at http://www.pm10inc.com/erosion-control-mulching.html (verified 24 June 2011).

Rahman, S., S. Mukhtar, and R. Wiederholt. 2008. Managing odor nuisance and dust from cattle feedlots. North Dakota State Univ. Extension Service, Fargo.

Razote, E.B., R.G. Maghirang, J.P. Murphy, B.W. Auvermann, J.P. Harner, III, D.L. Oard, D.B. Parker, W.L. Hargrove, and J.M. Sweeten. 2007. Air quality measurements from a water-sprinkled beef cattle feedlot in Kansas. ASABE Paper 074108. ASABE, St. Joseph, MI.

Razote, E.B., R.G. Maghirang, B.Z. Predicala, J.P. Murphy, B.W. Auvermann, J.P. Harner, III, and W.L. Hargrove. 2006. Laboratory evaluation of the dust-emission potential of cattle feedlot surfaces. Trans. ASABE 49:1117–1124.

Romanillos, A. 2000. Assessing the effect of stocking density on fugitive PM_{10} emissions from cattle feedyards and development of a cattle feedyard emission factor. MS thesis, Texas A&M Univ., College Station, TX.

SAS Institute. 1990. SAS/STAT user's guide. Version 9.1. SAS Inst., Cary, NC.

Sweeten, J.M. 1979. Water works for dust control. Feedlot Management 20:28–31.

Sweeten, J.M., C.B. Parnell, R.S. Etheredge, and D. Osborne. 1988. Dust emissions in cattle feedlots. Stress and disease in cattle, veterinary clinics of North America. Food Animal Practice 4:557–578.

Volckens, J., and T.M. Peters. 2005. Counting and particle transmission efficiency of the aerodynamic particle sizer. J. Aerosol Sci. 36:1400–1408. doi:10.1016/j.jaerosci.2005.03.009