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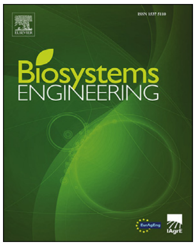

Research Paper

Factors affecting evaporation of water from cattle bedding materials

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In livestock farming, maintaining dry bedding is considered to be important for maximising animal performance and welfare. A better understanding of the mechanisms that regulate drying has the potential to improve bedding management and reduce production costs. A custom laboratory-scale method was developed to explore the effects of environmental conditions and bedding characteristics on drying rate (DR). Samples ($n = 256$) of different types of bedding materials were exposed to controlled environmental conditions by using a climate chamber equipped with a custom cabinet capable of simulating different levels of air velocity and bedding temperature. The effects of the type of material, bedding moisture content, bedding temperature, air temperature, air relative humidity (RH) and air velocity were evaluated in a full factorial experimental design. Under the experimental conditions tested, DR ranged from 0.28 to 6.04 kg m^{-2} d^{-1}, with an average of 2.03 kg m^{-2} d^{-1}. All variables significantly affected DR, but large variation in the magnitude of effects was found. Bedding moisture content, air velocity and air RH had considerably larger effects than the other variables, together accounting for more than 70% of the variance in DR. The DR from bedding samples increased with bedding moisture content and air velocity but decreased with increasing air RH. The results of the current study may have important implications in the design and management of bedded pack barns. To increase the DR and keep bedding dry, producers should focus primarily on providing adequate barn ventilation (both in terms of air velocity and air exchange), whereas maintaining a high pack temperature may yield poorer-than-expected results.

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1. Introduction

In livestock farming, keeping bedding dry is key to providing animals with a hygienic and comfortable environment (Cook, 2020). Dairy cattle prefer to lie on dry bedding, and spend more time standing when only wet bedding is available (Fregonesi et al., 2007). Because cattle prioritise lying over other behaviours, including feeding and drinking, managing the moisture content of the bedding is important for ensuring the cows are comfortable and have the freedom to express their preferred and high priority behaviours (Cooper et al., 2008; Munksgaard et al., 2005). Wet bedding conditions have been associated with poor cow hygiene and a higher risk of both mastitis and lameness, the most important health issues in dairy cattle (Blanco-Penedo et al., 2020; EFSA, 2009). Furthermore, emission of noxious gases, such as ammonia and GHG, increases with increasing bedding moisture content (IPCC, 2006). Wet litter is also an important management consideration in poultry production as it has been associated with tangible animal welfare issues (Dunlop et al., 2016).

Maintaining adequately dry bedding can pose some challenges, because animal excreta typically contain large amounts of water (Nennich et al., 2005). Water added with animal excreta is considered the most important input in the water balance of a bedded pack, whereas evaporation generally represents the main output (Leso et al., 2020). Ideally, to maintain a constant moisture content, the amount of water that leaves the bedding should equal the amount added. In most situations, however, owing to high stocking rates or unfavourable climatic conditions, evaporation does not match the water inputs, and thus bedding moisture tends to accumulate (Leso et al., 2013). The addition of dry materials and periodic removal of exhausted bedding are common management practices that allow producers to control the bedding moisture content (Bewley et al., 2017; Leso et al., 2020). Although adding bedding materials is an effective way to absorb excess moisture, purchasing bedding can substantially increase farm operating costs (Smith et al., 2017).

Improving evaporation from the bedded pack has the potential to reduce bedding usage and associated costs; however, to date, knowledge regarding the mechanisms regulating pack drying remains lacking. Physics research has shown that evaporation is dependent on the properties of the material and the conditions of the environment, such as air temperature, air humidity, and air speed and turbulence (Poós & Varju, 2020). Because of the numerous changing and variable parameters, accurate determination of evaporation from bedded packs is known to be a complex problem. In addition, because measuring evaporation directly poses several challenges, most published studies that have examined evaporation in open pack barns for dairy cows have been based on mathematical modelling and have not been fully validated (Leso et al., 2020). The objective of the current experiment was to conduct a fully controlled study to determine water evaporation from livestock bedding materials, on the basis of empirical evidence. A custom method was developed to explore the effects of environmental conditions as well as bedding characteristics.

2. Materials and methods

An experiment was designed and conducted at the laboratory of the Department of Agriculture, Food, Environment and Forestry (DAGRI) of the University of Florence (Italy) to allow for assessment of the evaporation of water from different bedding materials under controlled conditions. The study lasted 4 months, from February to May of 2018.

2.1. *Collection and preparation of the bedding samples*

Four different types of bedding material (MatType) were used for the experiment: wheat straw (STW), sawdust (SWD), wheat straw pellets (pSTW) and wood pellets (pWOO). To obtain representative bedding samples, we collected all materials directly from bedded areas in four commercial livestock farms in Northern Italy. A 20-L composite sample was collected for each MatType and transported in a sealed plastic bag. Because the materials were being used as bedding, the collected samples were naturally contaminated with animal excreta, which is known to affect the properties and drying rate of bedding (Dunlop et al., 2015). Care was taken to ensure a homogeneous content of excreta among the bedding materials collected. At the time of collection, the humidity content of the bedding samples ranged from 52.4% to 63.1%. After collection, all materials were dried in an oven at 80 °C until a constant mass was achieved.

To obtain different levels of sample moisture content (SampleM), a controlled amount of distilled water was added to all dry materials and mixed thoroughly. For each material, two levels of SampleM were selected, 40% and 70% (expressed as ratio of the mass of water to the mass of dry material). Such levels of SampleM were selected based on previous studies on compost-bedded pack barns for dairy cows, which have consistently indicated that the optimal bedding moisture content ranges from 40% to 65% (Leso et al., 2020). Although 70% SampleM is slightly higher than the recommended range, it was considered to be representative of the wet pack conditions likely to occur during the winter in commercial bedded pack barns (Leso et al., 2013). Before the beginning of the evaporation tests, a 1-L sub sample of each material at both levels of SampleM was analysed to determine actual moisture content (by drying samples at 105 °C to constant mass). This analysis confirmed that the method used to achieve the desired levels of SampleM was accurate. Actual moisture content ranged from 38.9 to 39.9% and from 68.8 to 70.9% for samples prepared at 40 and 70% SampleM, respectively.

For the evaporation tests, the bedding materials at different levels of SampleM were placed in plastic sample jars. The sample jars had a capacity of 80 ml (tapered, top diameter = 50 mm, bottom diameter = 40 mm, depth = 50 mm) and the area exposed for each sample was 0.00196 m^2. According to the methods of Dunlop et al. (2015), jars were over-filled with bedding material and then tapped five times to allow the material to settle. Any excess was carefully scraped off the top, leaving the bedding sample level with the top of the jar. In total, 320 sample jars were prepared (64 for experiment 1 and 256 for experiment 2). To avoid alterations in SampleM, all jars filled with the bedding materials were stored at −20 °C in vacuum plastic bags.

2.2. *Chemical, biological and physical analyses of bedding materials*

A 2-L subsample of every bedding material prepared at both levels of SampleM was collected and sent to an external laboratory (MADE HSE, Mantua, Italy) for chemical, biological and physical analyses. The chemical analyses included the assessment of total N (Kjeldahl method), NH_4–N (with a spectrophotometer; Hach DR6000, Loveland, US-CO), total organic carbon (TOC; with a TOC analyser; Shimadzu SSM-5000A, Kyoto, Japan), C:N ratio (with a calculation method), P and K (with an optical SCD detector; PerkinElmer Optima 8300, Waltham, US-MA) and organic matter (with calculation method). The pH was determined in a 10% deionised water suspension with a calibrated pH metre (Hach MM41, Loveland, US-CO). The ash content was measured by incineration of sample materials at 550 °C. Total bacterial counts were determined on standard aerobic plate count agar after a 24 h incubation at 37 °C. Particle size distribution was determined by passing the material (as is) through a sieve stack with a set of four sieves (20, 4, 2 and 1 mm) on shakers for 5 min.

2.3. *Simulation of air velocity and sample temperature*

A custom container (Fig. 1) was designed and built to allow exposure of the bedding samples to different levels of air velocity (AirVel) and sample temperatures (SampleT). The custom container was built by modification of a standard 19-inch rackmount pc case (485 mm wide × 315 mm long × 155 mm high). The internal container space was divided into four areas or clusters (A, B, C and D; Fig. 2) to obtain all possible combinations of two levels of AirVel and two levels of SampleT. Each cluster included a 50 mm thick polystyrene panel that was drilled to hold four sample jars; thus, the custom container was able to hold 16 sample jars in total. Sample jars were positioned within each cluster in an evenly spaced grid. The holes in the panel were made with a custom drill bit to align perfectly to the sample jars. Each hole was numbered to allow for recording of the cluster and position within the cluster of every sample jar used during the experiments. Because the sample jars were 50 mm high, the top of the sample was aligned with the upper surface of the polystyrene panel, and the bottom of the jar was aligned with the lower surface of the panel.

To simulate the effect of the temperature increase that occurs in deeper layers of bedded packs due to microbial activity (Leso et al., 2020), we installed a heated plate below the polystyrene panel, allowing contact with the bottom of the sample jars in the regions corresponding to areas A and C (Figs. 1 and 2). To ensure an even distribution of heat and to minimise temperature fluctuations, we used a 10 mm-thick aluminium plate for the heated plate. The plate included four evenly distributed Peltier cells with a maximum heat load of 63 W each. A temperature-controlled switch equipped with a temperature probe attached to the aluminium plate was used to control the Peltier cells. The control system was set to maintain the temperature of the heated plate at 35 °C.

This SampleT was selected based on the results of previous studies conducted in compost-bedded pack barns, which indicated that the temperature of actively composting packs increases with depth, generally being very close to ambient temperature at the pack surface and reaching a maximum of 50–60 °C at 25–30 cm depth (Bewley & Taraba, 2017). So, as the sample jars used in the current experiment were only 50 mm deep, a temperature of 35 °C can be considered representative of an intense pack composting process. To simulate the conditions occurring in a pack that was not actively composting, we did not equip areas B and D of the custom cabinet (Figs. 1 and 2) with a heating system. In addition, a 6 mm-thick

Fig. 1 – The custom container used to simulate air velocity and sample temperature (the top cover was removed to provide a view of the inside).

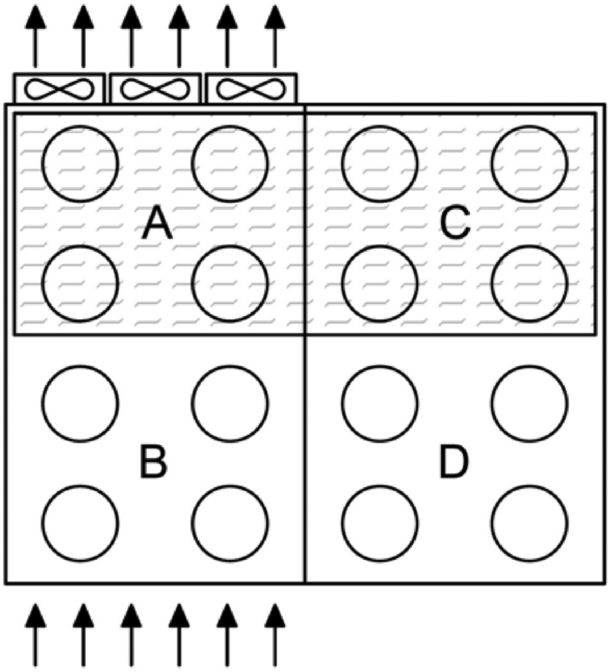

Fig. 2 – Layout of the four areas (or clusters) within the custom container used to simulate air velocity and sample temperature (A = ventilated, heated; B = ventilated, unheated; C = non ventilated, heated; D = non-ventilated, unheated).

polyurethane panel was installed next to the heated plate to prevent heat from spreading to the sample jars placed in clusters B and D.

To reproduce different levels of AirVel, we equipped the custom cabinet with a forced ventilation system. A plastic panel was installed to separate the air space above clusters A and B from that of clusters C and D (Fig. 1). Three fans (MB60101V1-000U-A99, Sunon, Kaohsiung, Taiwan; 60 mm diameter, maximum airflow 27.1 m^3 h^{-1}) were installed on one side of the cabinet to provide controlled airflow above clusters A and B. A variable voltage power supply was used to control the rotational speed of the fans and therefore the airflow. To achieve the desired level of AirVel, we placed a hot wire anemometer (AP471S2, Delta OHM, Padova, Italy) within the ventilated section of the custom cabinet (at 1-cm height above the sample jars), and the fan was regulated accordingly.

The ventilation system was set to maintain an air flow of 1 m s^{-1} above clusters A and B. After the speed of the fans had been set, several measurements made with an anemometer confirmed that the AirVel above clusters A and B remained in the range 0.92–1.06 m s^{-1}. Such level of AirVel was selected based on measurements collected in commercial compost-bedded pack barns (at pack level) with the fans over the resting area turned on (unpublished results). No forced ventilation systems were installed for clusters C and D. However, a series of holes were drilled in the side of the container corresponding to these clusters to allow consistent air exchange with the external environment without increasing AirVel above the sample jars. Anemometer measurements above clusters C and D (at 1-cm height) confirmed that the AirVel remained in the range 0.00–0.08 m s^{-1}. This custom cabinet configuration allowed us to create four areas or clusters in which samples could be simultaneously exposed to all combinations of SampleT and AirVel (A = ventilated, heated; B = ventilated, unheated; C = non ventilated, heated; D = non-ventilated, unheated).

2.4. *Simulation of air temperature and air humidity*

For the simulation of environmental parameters, namely air temperature (AirT) and relative humidity (AirRH), the custom cabinet containing the bedding samples was placed in a constant climate chamber capable of controlling both AirT and AirRH (model KBF 115, Binder, Tuttlingen, Germany; temperature range 0–70 ± 0.1 °C and relative humidity range 10–80 ± 2%). Two levels of AirT and two levels of AirRH were used for the experiments. Samples were exposed to 40% or 80% AirRH and to 10 °C or 25 °C AirT in all possible combinations. These levels of AirRH and AirT were selected to achieve a relatively wide variation while remaining in a range representative of the environmental conditions normally occurring in most dairy barns in temperate climates (Hill & Wall, 2015). Because we were unable to expose samples to different environmental conditions simultaneously, we repeated tests with different combinations of AirT and AirRH. Care was taken to ensure that the same procedure was repeated for every test. A technician was adequately trained before the actual tests. A checklist was used to ensure the repeatability of the experimental procedures.

2.5. *Experiment 1*

Experiment 1 was designed to assess the functioning of the custom cabinet, particularly the actual effect of the heated plate installed to recreate different levels of SampleT. A thermocouple-based penetration thermometer (TP437P, Delta OHM DO, Padova, Italy) was used to measure the actual temperatures of samples under different conditions. Each cluster in the custom cabinet was filled with samples of the four different bedding materials which were tested simultaneously in the climate chamber. Bedding samples were thawed at room temperature for 2 h before each test. Actual tests in the climate chamber lasted 2 h each. Besides SampleT (two levels: unheated and heated) and AirVel (two levels: 0 and 1 m s^{-1}), which were reproduced in the custom cabinet, the two levels of SampleM (40 and 70%) as well as the two levels of AirT (10 and 25 °C) were tested. To allow AirT and SampleT to stabilise, we set the climate chamber and the custom container (filled with the samples) to the desired conditions 2 h before the actual tests. In total, 64 bedding samples were tested in four sessions of 2 h.

During each session, the temperature probe was sequentially inserted in all 16 sample jars (at 25 mm-depth) contained in the custom cabinet. The actual sample temperature for each sample jar was measured during a 5-minute period. To allow the thermometer reading to settle, all measurement periods in each sample jar were preceded by a 2-minute adaptation period. For each sample, the average temperature recorded during the 5 min was used for the analysis as the actual SampleT. The temperature probe was connected to an external data logger, and the connection wire was passed through a sealed hole on the side of the climate chamber. However, between measurement periods, the door of the climate chamber was required to be kept open for a few seconds to allow the temperature probe to be moved from one sample jar to the next. The effects of these brief door openings had a negligible effect on AirT inside the climate chamber, which varied less than ± 1.0 °C compared to the desired AirT levels. To allow accessing the samples with the temperature probe while minimising disturbance on AirVel conditions, a custom container cover provided with sealable holes over each sample jar was constructed.

2.6. *Experiment 2*

Experiment 2, the main experiment of the current study, focused on evaluating the effects of environmental and bedding-related parameters on the evaporation of water from bedding materials. The experiment was designed to allow exposure of samples of different MatType (four levels: STW, SWD, pSTW and pWOO) prepared at different SampleM (two levels: 40% and 70%) to all possible combinations of AirRH (two levels: 40% and 80%), AirT (two levels: 10 °C and 25 °C), AirVel (two levels: 0 and 1 $m\ s^{-1}$) and SampleT (two levels: unheated and heated). The previously described custom cabinet and climate chamber were used for this purpose. Each cluster in the custom cabinet was filled with four samples of different MatTypes and placed in the climate chamber. The positions of samples within the clusters were randomly selected. Bedding samples were thawed at room temperature for 2 h before each test.

Actual evaporation tests in the climate chamber lasted approximately 24 h each (±12 min). To allow the internal AirT and AirRH to stabilise, we set the climate chamber to the desired conditions 2 h before the actual tests. Bedding samples were weighed immediately before and immediately after actual evaporation tests with a precision balance (BCE 4200, ORMA, Milan, Italy; ±0.01 g). Mass loss of samples (calculated as the difference between initial and final masses) was considered a proxy for water that evaporated during the test. All evaporation tests were performed in two replicates. In total, 256 bedding samples were tested in 16 sessions of 24 h.

2.7. *Drying rate calculation*

Evaporation of water from bedding materials is usually defined as the evaporation rate or as drying rate (DR), a measure of the amount of water evaporated from a given surface over time (Black et al., 2013; Dunlop et al., 2015). In the current study, DR was calculated with Equation (1).

$$DR = \frac{(W_i - W_f)}{A} \times \frac{1}{T_{exp}} \tag{1}$$

where DR = evaporation rate ($kg\ m^{-2}\ d^{-1}$), W_i = initial mass (kg), W_f = final mass (kg), T_{exp} = actual duration of the evaporation test (days), and A = sample area (m^2).

2.8. *Statistical analysis*

Statistical analyses were performed in R (R Core Team, 2019). Data collected in experiment 1 were analysed with a linear model to evaluate whether the actual sample temperatures differed among clusters within the cabinet (Fig. 2). Because air temperature was expected to affect the actual sample temperature, the model included the fixed effects of the cluster, the air temperature and their interaction. Data collected in experiment 2 were analysed by ANOVA (with type III sum of squares) to assess the effects of environmental conditions and bedding material characteristics on drying rate. The model included the fixed effects of air temperature, air relative humidity, air velocity, material initial moisture content, sample heating and the type of bedding material. All two- and three-way interactions were also tested. All explanatory variables were converted to factors before the analysis, and orthogonal contrasts were used. A backward stepwise elimination procedure was used to build the model until the remaining variables and interaction terms included were significant at $P < 0.05$. The normality and homoscedasticity of variance were visually evaluated with residual plots. Eta squared (η^2) was calculated in the *sjstats* package (Lüdecke, 2019) to compare the effects of explanatory variables and interaction terms (Lakens, 2013). Least-squares means were computed with the *emmeans* package (Lenth, 2019), and pairwise comparison (with Tukey method) was assessed with the *multComp* package (Hothorn et al., 2008). Differences were considered significant at $P \leq 0.05$.

3. Results

The materials used in experiments 1 and 2 were analysed to evaluate their chemical, physical and biological properties. The results of laboratory analyses are reported in Tables 1 and 2.

3.1. *Experiment 1*

Experiment 1 was designed to evaluate the effect of the heating plate installed in the custom cabinet on simulating different bedding temperatures. The results of experiment 1 are reported in Table 3. As expected, the actual sample temperature was higher in samples placed over the heated plate (clusters A and C; Fig. 2) than in samples that were not heated (clusters B and D; Fig. 2). The actual temperatures of the heated samples, however, remained lower than the temperature of the heated plate (35 °C). The differences in actual sample temperatures between the heated and unheated clusters were significant at both 10 °C and 25 °C AirT, but the differences were considerably larger at lower AirT. No differences were found in the actual sample temperatures between clusters A and C nor between clusters B and D at both 10 °C and 25 °C AirT, thus indicating that forced ventilation did not cause undesired effects on sample temperature. Overall, the results of experiment 1 confirmed that the custom cabinet functioned correctly and was capable of re-creating different conditions of SampleT and AirVel without producing undesired confounding effects.

Table 1 – Chemical analysis of the bedding materials used in the experiments (STW = wheat straw; SWD = sawdust; pSTW = wheat straw pellets; pWOO = wood pellets).

Item	Material			
	STW	SWD	pSTW	pWOO
pH	9.2	9.2	8.5	8.7
Total N (%)	1.7	1.8	1.4	<1.0
NH_4–N (%)	0.1	<0.1	<0.1	<0.1
Ash (%)	13.3	7.9	13.3	11.9
TOC[a] (%)	43.7	47.6	44.1	45.6
P (mg kg^{-1})	2675	3695	3124	3111
K (mg kg^{-1})	30100	14950	19430	15210
C:N	25.7	26.4	31.5	-[b]
Organic Matter (%)	87.4	95.2	88.2	91.2

[a] TOC = Total organic carbon.
[b] C:N is missing because Total N was below detection limit.

Table 2 – Particle size distribution of the bedding materials used in the experiments prepared at different levels of sample moisture.

Particle size	Target sample Moisture (%)	Material[a]			
		STW	SWD	pSTW	pWOO
>20 mm (%)	40	63	11	4	<1.0
	70	15	14	<1.0	<1.0
20 - 4 mm (%)	40	17	50	19	16
	70	64	53	47	37
4 - 2 mm (%)	40	12	15	17	15
	70	15	29	50	50
2 - 1 mm (%)	40	8	4	21	26
	70	6	2	2	14
<1 mm (%)	40	<1.0	20	39	43
	70	<1.0	2	<1.0	<1.0

[a] STW = wheat straw; SWD = sawdust; pSTW = wheat straw pellets; pWOO = wood pellets.

3.2. *Experiment 2*

Experiment 2 was designed to explore the effects of environmental conditions and bedding characteristics on DR. The DR recorded in experiment 2 (n = 256) ranged from 0.28 to 6.04 kg m^{-2} d^{-1}, with an average of 2.03 kg m^{-2} d^{-1}. The final model for DR included the main effects of AirT, AirRH, AirVel, SampleM, SampleT and MatType. The results of ANOVA are reported in Table 4. Although all main effects showed significant effects on DR, there was a large variation in effect sizes. SampleM, AirVel and AirRH showed considerably larger effect sizes than the other main effects, and together accounted for more than 70% of the variance in DR (Table 4). Overall, samples prepared at 70% SampleM had a significantly higher DR than those at prepared at 40% (2.84 vs 1.22 kg m^{-2} d^{-1}, $P < .001$). Samples exposed to a forced AirVel of 1 m s^{-1} had a significantly higher DR overall than samples that were not ventilated (1.40 vs 2.66 kg m^{-2} d^{-1}, $P < .001$). On average, a significantly higher DR was also recorded at 40% than at 80% AirRH (2.43 vs 1.63 kg m^{-2} d^{-1}, $P < .001$).

For SampleT, samples placed over the heated plate showed a significantly higher DR than unheated samples (2.25 vs 1.81 kg m^{-2} d^{-1}, $P < .001$). AirT also significantly affected DR: samples exposed to 25 °C showed higher DR than those at 10 °C (2.21 vs 1.85 kg m^{-2} d^{-1}, $P < .001$). Regarding MatType, analysis revealed that STW (1.77 kg m^{-2} d^{-1}) had the significantly lowest DR whereas no significant differences were detected among the other materials (2.03, 2.15 and 2.17 kg m^{-2} d^{-1} for SWD, pSTW and pWOO, respectively).

Table 4 – ANOVA results of the final model for drying rate.

Predictor[a]	SS	*df*	MS	F	*p*	η^2
AirRH	41.64	1	41.64	363.6	0.000	0.094
AirT	8.4	1	8.4	73.38	0.000	0.019
AirVel	102.33	1	102.33	893.43	0.000	0.232
MatType	6.6	3	2.2	19.21	0.000	0.015
SampleM	167.42	1	167.42	1461.75	0.000	0.380
SampleT	12.68	1	12.68	110.73	0.000	0.029
AirRH × AirT	3.18	1	3.18	27.75	0.000	0.007
AirRH × AirVel	3.86	1	3.86	33.71	0.000	0.009
AirRH × SampleM	11.77	1	11.77	102.78	0.000	0.027
AirT × SampleM	1.25	1	1.25	10.93	0.001	0.003
AirT × SampleT	1.69	1	1.69	14.79	0.000	0.004
AirVel × SampleM	41.34	1	41.34	360.9	0.000	0.094
AirVel × SampleT	1.76	1	1.76	15.34	0.000	0.004
MatType × SampleM	6.4	3	2.13	18.62	0.000	0.015
AirRH × AirVel × SampleM	3.65	1	3.65	31.83	0.000	0.008
Error	27.03	236	0.11			

[a] AirRH = Air relative humidity; AirT = Air temperature; AirVel = Air velocity; MatType = Type of bedding material, SampleM = Sample moisture content, SampleT = Sample temperature.

Table 3 – Actual sample temperature (Sample T; °C) measured in the different clusters of the custom container used to simulate air velocity and sample temperature.

Cluster[a]	Air Temperature			
	10 °C		25 °C	
	Mean Sample T	95% CI	Mean Sample T	95% CI
A (Ventilated + heated)	25.9^{a}	25.2–26.6	28.9^{a}	28.2–29.5
B (Ventilated)	11.0^{b}	10.3–11.6	25.6^{b}	24.9–26.2
C (Heated)	25.4^{a}	24.7–26.0	29.6^{a}	29.0–30.3
D	11.6^{b}	10.9–12.3	24.7^{b}	24.1–25.4

[a] Ventilated = samples exposed to forced ventilation at 1 m s^{-1}; Heated = samples placed over a plate heated at 35 °C.

Table 5 – Post-hoc pairwise comparison for the two-way interactions (that were not involved in higher order interactions) retained in the final model for drying rate (DR; kg m^{-2} d^{-1}). Letters indicate significant differences among LS means within each interaction (post hoc Tukey HSD test, <0.05).

Interaction[a]	Levels		Mean DR	95% CI
AirT x AirRH	AirT	AirRH		
	10	40	2.14^a	2.06–2.22
	25	40	2.73^b	2.64–2.81
	10	80	1.56^c	1.47–1.64
	25	80	1.70^c	1.61–1.78
AirT x SampleM	AirT	SampleM		
	10	40	1.11^a	1.03–1.19
	25	40	1.33^b	1.25–1.42
	10	70	2.59^c	2.50–2.67
	25	70	3.09^d	3.01–3.17
AirT x SampleT	AirT	SampleT		
	10	Unheated	1.54^a	1.46–1.63
	25	Unheated	2.07^b	1.99–2.15
	10	Heated	2.15^b	2.07–2.24
	25	Heated	2.35^c	2.27–2.44
AirVel x SampleT	AirVel	SampleT		
	0	Unheated	1.09^a	1.01–1.18
	1	Unheated	2.52^b	2.44–2.61
	0	Heated	1.70^c	1.62–1.79
	1	Heated	2.80^d	2.72–2.89
MatType x SampleM	MatType[b]	SampleM		
	SWD	40	1.25^a	1.13–1.36
	STW	40	1.20^a	1.08–1.32
	pSTW	40	1.26^a	1.14–1.38
	pWOO	40	1.18^a	1.06–1.29
	SWD	70	2.82^b	2.71–2.94
	STW	70	2.33^c	2.21–2.45
	pSTW	70	3.04^{bd}	2.93–3.16
	pWOO	70	3.16^d	3.04–3.28

[a] AirRH = Air relative humidity; AirT = Air temperature; AirVel = Air velocity; MatType = Type of bedding material, SampleM = Sample moisture content, SampleT = Sample temperature.

[b] STW = wheat straw; SWD = sawdust; pSTW = wheat straw pellets; pWOO = wood pellets.

The final model for DR included the two-way interactions of AirRH × AirT, AirRH × AirVel, AirRH × SampleM, AirT × SampleM, AirT × SampleT, AirVel × SampleM, AirVel × SampleT and MatType × SampleM. The results of post-hoc analysis for the two-way interactions that were not involved in higher order interactions are reported in Table 5. The only three-way interaction retained in the final model for DR was SampleM × AirVel × AirRH (Fig. 3), which were the most important factors affecting DR. The analysis of this interaction further confirmed that DR increased substantially with increasing SampleM. In addition, the effects of AirVel and AirRH were amplified at high SampleM, because both factors produced a noticeably larger effect at 70% than at 40% SampleM. The SampleM × AirVel × AirRH interaction resulted in a wide range of mean DR, which varied from a minimum of 0.81 kg m^{-2} d^{-1} (at 40% SampleM, 80% AirRH and no forced AirVel) to a maximum of 4.73 kg m^{-2} d^{-1} (at 70% SampleM, 40% AirRH and forced AirVel at 1 m s^{-1}).

4. Discussion

The results of the current study indicated that the DR of a bedded pack increases dramatically with increasing SampleM, which had the largest effect among all variables tested (Table 4). Analysis of interactions also showed that the effects of other variables, particularly AirVel and AirRH, were amplified at high SampleM. These findings are consistent with those reported by Dunlop et al. (2015), who conducted a similar experiment to study evaporation from poultry litter. In a study on compost-bedded pack barns for dairy cows, Black et al. (2013) reported that DR is directly proportional to the difference between the moisture at the bedding surface and the ambient water vapour concentration in the air. Because materials tend to gain or lose moisture and reach equilibrium with the surrounding environment, at high Sampel Moist and/or low AirRH, more water is lost by the bedding to reach the equilibrium state. The effect of AirVel is more complex, because it does not directly affect DR. As water evaporates from the bedding, the air immediately above the surface tends to saturate, and thus DR is locally reduced. Movement of air above the bedding carries away the saturated layer of air and replaces it with drier air (Poós & Varju, 2020). Therefore, forced air flow above the bedding samples accelerates this process and in turn increases DR by reducing the moisture concentration at the bedding surface.

Previous studies on the evaporation of water from compost-bedded packs for dairy cows have shown that DR is affected by the temperature, speed and humidity of air as well as the pack temperature (Black et al., 2013; Smits & Aarnink, 2009). The results of the present study support these findings, because SampleT, AirVel, AirT and AirRH significantly affected DR (Table 4). However, analysis of the effect sizes revealed a large variation in the effect magnitude of these variables. A relatively large effect was found for both AirVel and AirRH, whereas SampleT, AirT and MatType had only limited effects on DR (Table 4). These results may have important practical implications and only partially support previous management and design recommendations for bedded pack barns.

Early studies on compost-bedded pack barns consistently highlighted the importance of maintaining an active composting process, because heat developed by bacterial activity in the bedded pack was thought to have a large effect on DR (Black et al., 2013; Eckelkamp et al., 2016; Janni et al., 2007). Other studies, however, have indicated that achieving high pack temperatures (>40 °C) can be challenging, particularly during the winter (Leso et al., 2013). High pack temperature can support the growth of undesired bacterial populations, especially thermophilic aerobic spore-forming bacteria (Leso et al., 2020). The results of the current study confirmed that a high SampleT can increase DR, particularly at low AirT. However, the significantly larger effect sizes of AirVel and AirRH suggest that producers with bedded pack barns should focus primarily on providing adequate barn ventilation rather than on maintaining an active composting process.

The importance of ventilation in compost-bedded pack barns has already been emphasised in previous studies (Bewley et al., 2013). Maximising natural ventilation in this type of

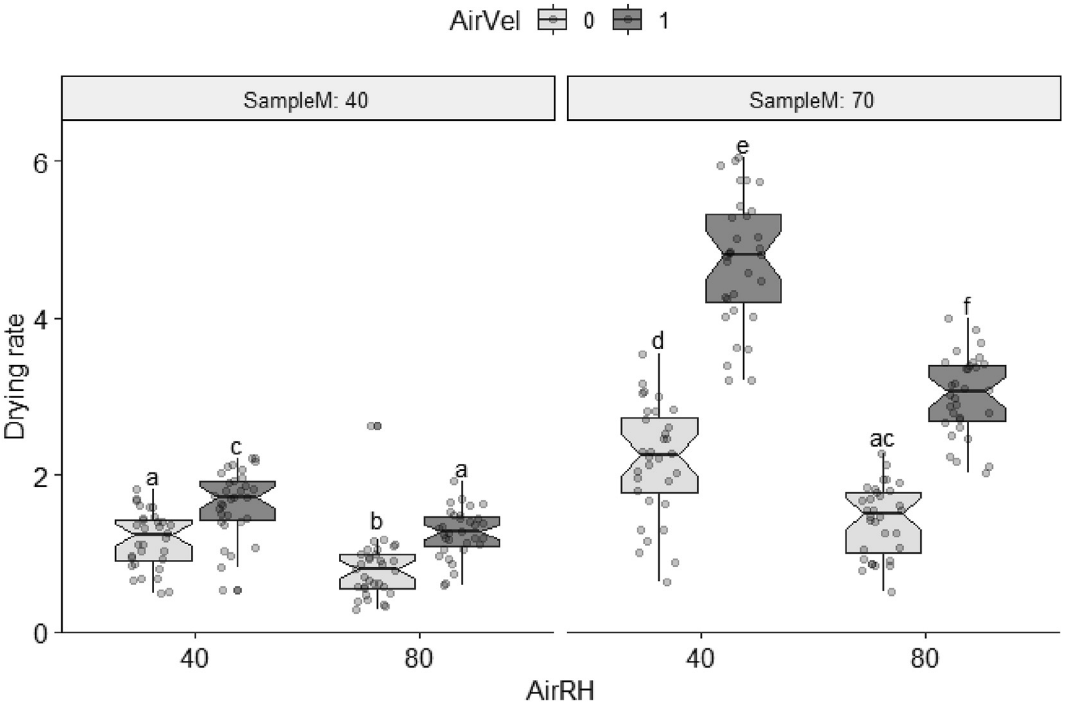

Fig. 3 – Effect of the three-way interaction among sample moisture (SampleM; %), air velocity (AirVel; m s^{-1}) and air relative humidity (AirRH; %) on drying rate (kg $m^{-2}d^{-1}$). Letters indicate significant differences among least square means (post hoc Tukey HSD test, <0.05).

housing is essential to remove the heat and moisture created not only by the animals but also by the composting process. Water evaporated from the bedded pack can build up within a barn and increase AirRH, which in turn limits DR. To maximise natural ventilation, open sidewall heights of 4–5 m, a roof pitch of at least 1/3 and a ridge vent opening of at least 2.5 cm for every 1.0 m of roof width are recommended for compost-bedded pack barns (Bewley et al., 2012). Circulation fans and high volume low-speed fans have also been suggested to enhance AirVel over the bedded pack (Black et al., 2013).

All housing systems based on open packs are known to require a large space per cow (Bewley et al., 2017). Because evaporation mainly occurs at the surface of the pack, increasing the area per cow increases the amount of water evaporated per cow (Black et al., 2013). A larger bedded area generally reduces utilisation of bedding materials as well as the relative cost. However, a larger area is also associated with higher initial barn costs. Therefore, the identification of the optimal space per cow in a bedded pack barn is complex and depends on several factors including the climate, cost and availability of bedding materials, as well as barn construction costs (Leso et al., 2020). To date, optimal space allowance in bedded pack barns remains a much-debated topic.

Smits and Aarnink (2009) have modelled the water balance of compost-bedded pack barns and found that the optimal space per cow depends on the DR. With increasing DR, the amount of water that evaporates from every square metre increases, thus reducing the total area needed to maintain a dry pack. The model approach proposed by Smits and Aarnink (2009) has provided a basis for the development of a numeric method to determine the optimal space per cow in compost-bedded pack barns but has not been validated with empirical evidence and has shown some limitations in real conditions (Galama, 2014; Galama et al., 2011). The main objective of the present experiment was to provide a fully controlled study of DR on the basis of empirical evidence. Reproducing real-world conditions in a lab environment, however, posed several challenges and had some inherent limitations.

The static sample methodology we used may not be fully representative of the dynamic conditions occurring in real bedded packs. In the present experiment no additional water was added to the samples during the 24-hour evaporation tests while, in real conditions, animals constantly add moisture through excreta. By walking and resting, animals can also affect the physical characteristics of the pack and, in turn, DR. Further, in the case of compost-bedded pack barns, the pack is regularly cultivated, which is believed by many authors to enhance DR (Leso et al., 2020). Originally, we planned to simulate pack cultivation but during the study design process this effect has been dropped because stirring the samples during the evaporation tests would have required the climate chamber to be opened for a relatively long time. The reduced scale, and especially the limited depth, of sample jars used in the evaporation tests (80 mL; 50 mm deep) may represent another matter of concern. The size of the sample jars was selected to allow fitting a reasonable number of jars in the climatic chamber simultaneously and therefore limit the time needed to run all the tests. Even though real bedded packs can be significantly deeper (up to more than 1 m, Leso et al., 2020), most of the evaporation is likely to occur at the surface of the pack so 50 mm deep jars were considered to produce representative results. Despite these inherent limitations, the approach used in the present study allowed DR to be measured directly and precisely under a relatively wide range of conditions. The results obtained can contribute to estimating pack DR, which has the potential to improve barn design as well as bedding management practices.

Previous studies have shown that different bedding materials have different moisture absorption properties (Ferraz et al., 2020). The effect of MatType on DR, however, had been largely unassessed. Among the four materials tested in the current study, STW was found to produce a significantly lower DR than SWD, pSTW and pWOO. Analysis of particle size showed that STW (prepared at both 40 and 70% SampleM) had a remarkably higher proportion of large particles (>20 mm and 4–20 mm) compared with the other materials tested, which may explain why STW produced a lower DR. It is known that in straw, intake of water results from the capillary action of the vegetable fibres (Bouasker et al., 2014). As water can only enter or leave through the cut ends of these fibres, the large particles (i.e. long fibres) found in STW can increase the time needed to absorb but also release moisture. These findings suggest that materials with large particle size (such as whole straw) may limit DR and should be processed (chopped or shattered) before being used as bedding. Also, in the case of compost-bedded pack barns, processing straw to <25 mm is also recommended to facilitate pack cultivation (Ferraz et al., 2020).

5. Conclusions

The results of the present study confirmed that DR is affected by several factors including environmental conditions and bedding properties. DR increased primarily with increasing SampleM, probably because of the increased availability of water in the material. The large effect sizes of AirVel and AirRH suggested that providing adequate barn ventilation is key to improving DR and maintaining dry bedding. Besides fostering airflow above the bedded areas, open pack barns should be designed to maximise the ventilation rate, because the additional moisture produced by the bedded pack must be quickly exhausted. In previous research on compost bedded pack barns for dairy cows, increasing pack temperature by maintaining an active composting process has consistently been indicated as an effective way to promote pack drying. However, the relatively low effect size of SampleT found in the present study may suggest that efforts to promote composting would produce only a limited effect on pack DR.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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