Manure belts for harvesting urine and feces separately and improving air quality in swine facilities.[1]

Report to the Smithfield Panel

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ABSTRACT: Modern swine facilities have not been designed to maximize manure value nor to minimize NH_3 emissions. These benefits can possibly be achieved by harvesting urine and feces separately using a conveyor belt placed at a 4° angle beneath the slats. Urine drains from this belt into a gutter leading to a closed storage vessel while feces remain on the belt for up to 24 h. Such a belt was evaluated in a partially slatted swine facility housing 80-100 grower pigs in five separate experiments. Fecal DM was determined as a function of both belt residence time and collection time-of-day. The driest feces were obtained with daily collections at 0600. Collections at this time of day resulted in a 9.8 ± 5.0% increase in DM over collection at 1500 ($P = 0.07$). Under steady state conditions, feces were collected at 49 ± 5% DM and output was 0.26 ± 0.05 kg $\text{DM}\cdot\text{pig}^{-1}\cdot\text{d}^{-1}$ giving an apparent feed DM digestibility of 82.8 ± 2 %. Urine production was 1.3 ± 0.2 $\text{L}\cdot\text{pig}^{-1}\cdot\text{d}^{-1}$, equivalent to 33 ± 6% of the water intake. When animal performance in the belt-based housing unit was compared with that from a conventional facility, a 5.5 % improvement in feed efficiency was observed ($P = 0.01$). Ammonia and CH_4 emissions from this facility were 1.03 ± 0.20 $\text{kg}\cdot\text{pig}^{-1}\cdot\text{yr}^{-1}$ and 1.05 ± 0.29 $\text{kg}\cdot\text{pig}^{-1}\cdot\text{yr}^{-1}$, respectively, substantially less than literature values for conventional houses. Thus, the equivalent of 5.9 ± 1.0% of the intake N was lost in NH_3 emissions and 0.64 ± 0.18% of the feed energy was lost in CH_4 emissions. In conclusion, the belt system was easy to operate, resulted in excellent animal performance, harvested feces at 49% DM, and resulted in only 1 kg, each, NH_3 and CH_4 $\text{emissions}\cdot\text{pig}^{-1}\cdot\text{year}^{-1}$.

Key Words: Ammonia, Belt conveyors, Housing, Manure, Methane, Swine

Introduction

Many environmental problems in swine production result from the way manure is collected as a single waste stream. These problems include odor, NH_3 and CH_4 emissions, and manure too dilute for value recovery. Anaerobic conditions in stored manure also promote formation of frequently odiferous volatile organic compounds and CH_4, a greenhouse gas (Zahn et al., 1997; Childers et al., 2001; US EPA, 2003).

Current collection methods utilize a slatted floor with liquid storage under the slats (slurry system) or a flush system with lagoon storage (Keener et al., 1999). Harvested manure is typically 1 to 10% DM (Smith et al., 2000), causing handling and transportation costs to limit utilization options. Lagoons are vulnerable to flooding, seepage, and spills, and repeated application of manure to spray fields risks nutrient saturation, run off, and eutrophication of surface and ground waters. Since urine contains most of the excreted N (Aarnink, et al., 1993) and feces the organic matter and P (Poulsen et al. 1999), collecting a single manure stream limits its utilization options.

Attempts to concentrate manure have focused on post-collection techniques such as centrifuges, settling basins, tangential flow and screen separators that leave a problematic, aqueous residual stream. Such systems also have low solids recovery efficiency and high investment costs for equipment, maintenance, and skills on the farm level (Westerman and Bicudo, 2000). Furthermore, such methods do not address barn emissions, the source of over 50% of the NH_3 emitted from hog farms (Doorn et al., 2002).

The objective of the research presented was 1) to demonstrate a manure collection system that allowed for the separate collection of urine and feces, and 2) To evaluate the impact of this manure collection system on the characteristics of the urine and fecal streams and on air quality and emissions.

Experimental Procedures

Approved animal care and use procedures were used. The building layout used was modeled after a conventional Murphy's Family Farm (Rose Hill, NC) grow-finish facility but constructed at 75% of full scale. Penning material, feeders, and the belt were supplied by Big Dutchman (Vechta, Germany). Pens were two-thirds solid floor, one-third slatted floor (tri-bar, Nooyen, Mt. Sterling, KY). The solid flooring had an 8% slope allowing liquids to run off into the belt gutter. Five contiguous pens, 2.25 x 4.5 m each, were constructed allowing 80 pigs to be housed at 0.63 m^2 pig^{-1}, similar to the commercial stocking density of 0.4 to 0.7 $m^2 \cdot pig^{-1}$ for pigs of 18 to 72 kg BW (Meyer et al., 1991). Solid partitions were used around the solid floor to direct defecation to the slatted-floor portion of the pen that was enclosed by open bar penning.

A 1 mm thick high-density polyethylene (HDPE) belt conveyor system was installed beneath the tri-bar (Big Dutchman, Vechta, Germany). In Exp. 1, 2, and 3, a "duct" belt design was used in which the belt was placed at a 4° angle, side to side, to facilitate liquid drainage into a covered metal gutter, running the length of the belt (Figure 1). The 1° lengthwise slope of the belt, designed to mimic the slope of a commercial building, insured that urine flowed continuously into an enclosed liquid collection vessel at the end of the belt. In Exp. 4 and 5, a "trough" shaped belt-design was used in which the lower edge of the belt itself formed the gutter. This was accomplished by laying the edge of the belt into a stainless steel gutter that provided support and molded the belt into an open gutter.

Five experiments were conducted in the belt-based housing facility. There were 100 pigs of mixed sexes in Exp. 1, and 80 in each of the other experiments. Pigs were raised from approximately 25 to 55 kg (Table 1). After an adaptation period of one week, during which no data were collected, animals were maintained on trial for 4 to 5 weeks. They were provided ad libitum access to a corn-soybean meal grower ration containing 17.3% CP and consisting of 70% corn, 23% soybean meal, 4% fat, 0.25% vitamin/mineral mix, 0.35% salt, 0.9% limestone, and 1.25% dicalcium phosphate which met or exceeded the nutritional requirements of swine (NRC, 1998). Feed was dispensed from wet-dry feeders that allowed free access to water while minimizing water wastage. Animal weights and feed disappearance were recorded weekly. Water consumption was determined from a flow meter installed in the water line (trials two to five only).

Feces were collected from the belt by running the belt one complete cycle. A scraper blade mounted at the drive axle removed all material from the belt, and solids dropped into a collection bin. Harvested feces were weighed, and then thoroughly mixed, prior to withdrawing duplicate samples. Dry matter content was determined on these samples. Urine was collected continuously in an enclosed container and the volume was measured daily to determine output. Urine was mixed thoroughly prior to withdrawing samples for analysis. Room temperature, humidity, and water usage were recorded daily, and emissions of NH_3 and CH_4, when monitored, were recorded every 15 min in Exp. 1 and 2, and every 3 h in Exp. 3 to 5 by Fourier Transform Infrared spectroscopy (FTIR). Annualized data are calculated on a 350 $d \cdot y^{-1}$ housing occupancy basis.

In Exp. 1, DM as a function of belt residence time was evaluated by harvesting feces after 3, 6, 9, 12, 18, 24, 30, 36, and 48 h. Data for each of these residence times were collected in triplicate and the time of day of collection was randomized within each series of repetitions. In Exp. 2, feces was harvested every 27 h in order to determine the effect of collection time-of-day on the DM content of the feces with uniform residence time for all collections. Each collection time was tested in triplicate. For the remaining 12 d of Exp. 2 and in all subsequent experiments, the belt was operated under steady-state conditions in which feces were collected at 0600. Exp. 1, 2, 4, and 5 were conducted solely in the belt demonstration housing facility. For Exp. 3, however, 80 pigs each were assigned either to the belt demonstration facility or to the conventional housing unit at the NC State University swine farm ("Exp. 3, March '02 Reference" in Table 1). Animals from a single source were weight matched, distributed between the two facilities, stocked at 0.6 $m^2 \cdot animal^{-1}$, and fed the same ration. In order to achieve comparable stocking density, there were seven $animals \cdot pen^{-1}$ at the conventional site and 16 $animals \cdot pen^{-1}$ in the belt-based housing unit.

Analytical Methods

Ammonia and CH_4 concentrations in the exhaust air from the belt housing facility were determined by FTIR according to the procedure of van Kempen (2001) and Kim et al. (2004). In brief, air samples were drawn directly through the gas cell (84 m path length) attached to the FTIR. At each sampling time, background levels in the input air were determined and subtracted from the output air. Emissions were calculated as the detected differential concentration times the ventilation rate at the time of analysis. The ventilation rate was maintained at 60 $m^3 \cdot pig^{-1} \cdot h^{-1}$.

Dry matter determinations were by passive drying in a 60°C oven until the weight loss in 24 h was less than 1% of the previous day's weight. Energy determinations were performed in an IKA Werke (Wilmington, NC) C5003 bomb calorimeter except that methane energy was taken as 13.3 kcal·g^{-1} (Merck Index, 1976). Data were analyzed using SPSS (Version 10, SPSS Inc., Chicago, IL).

Results and Discussion

Belt operation and excreta properties

The belt was operated automatically from a timer and ran unattended during the 8 min period required for one full revolution of the belt. Belt tracking was verified daily and no problems were observed throughout the course of these studies. The only manual action required was the daily cleaning of the belt-scraper, a process that required approximately one minute.

Belt operating variables were evaluated in the first two experiments in order to optimize operating conditions. Prior to data collection, it was hypothesized that the DM content would increase with belt residence time, which was evaluated in Exp. 1. Due to a sagging belt frame, urine did not properly drain off the belt. Nonetheless, statistical analysis showed a quadratic time of day effect ($P < 0.01$), with dry matter decreasing after 30 h (Figure 2A). Apparently, when the belt residence time was greater than 30 h, the increased fecal load trapped more of the urine thereby reducing the DM content. This trial was not designed to test time of day effects, but data suggested that time of day was confounding the experiment, and analysis revealed a sigmoidal effect of time of day ($P < 0.01$, Figure 2**B**). Thus, Exp. 2 was designed specifically to test the time of day effect after fortifying the frame to hold the belt taut. This trial confirmed that fecal DM exhibited a sigmoidal pattern relative to the time of day that collection occurred (Figure 3). Collections at 0600 resulted in a 9.8 ± 5.0% increase in DM over collections at 1500 ($P = 0.07$). The diurnal urination pattern of the pigs likely produced this result since little urine is deposited on the belt at night allowing the feces to dry more completely. From these two experiments, it was concluded that daily, early morning collections are favored. Thus, the belt contents were subsequently harvested every 24 h at 0600 for the last two weeks of Exp. 2 (steady-state) and in all subsequent trials.

Operating under steady-state conditions, with fecal collections at 0600, average fecal DM was 49 ± 5% and ranged from 43% to 55% over the four trials where this was evaluated (Table 1). The DM variation appeared better correlated with defecation patterns of the animals than with differences in drying rate directly due to temperature. Average barn temperature and humidity, for all five trials, were 26 ± 3°C and 60 ± 6% respectively, with values ranging from 22°C to 30°C and 52% to 66% (Table 1). Highest DM values were found when the defecation pattern was scattered over all of the slatted area (subjective observations). At 50% DM, swine feces typically have a brittle, dry appearance, but larger particles still have a moist core. This material did not clump during handling and it had minimal odor. The nutrient composition of the feces are provided in Table 2.

Collected feces indicate a fecal DM production of 0.26 ± 0.05 $kg \cdot pig^{-1} \cdot day^{-1}$ (Table 1), similar to the 0.27 kg reported by Smith et al. (2000) for the grower pig. These data suggest an apparent total tract DM digestibility of 83 ± 2%, in line with the DM digestibility for a corn soybean meal diet (NRC, 1998), and thus suggesting that virtually all feces produced by the pigs were successfully harvested. The equivalent of 32.7 ± 5.8% of the recorded water intake was recovered as urine. A value of 34% can be calculated from literature reports on water consumption and urine production in grower pigs (Schiavon and Emmans, 2000; Smith et al., 2000), suggesting that effectively all urine produced was collected as such. Visual observation on both product streams indeed would suggest a low cross-contamination. The composition of the urine as harvested is provided in Tables 2 and 3.

Emissions

Absolute levels of NH_3 emissions averaged 1.0 ± 0.2 $kg \cdot pig^{-1} \cdot y^{-1}$ or 0.82 kg of $N \cdot pig^{-1} \cdot y^{-1}$ over the five experiments (Table 1). This is substantially lower than the literature value of 3.7 kg $NH_3 \cdot pig^{-1} \cdot y^{-1}$ for conventional barns (Doorn et al., 2002). The ration used was 17.3% CP, suggesting that a pig would consume 14.4 ± 1.5 kg N y^{-1}. At this level, NH_3-N emissions are equivalent to 5.9 ± 1.0% of the dietary N consumed (Table 1). The low levels of NH_3 are attributed to the minimal contact time between urea and the fecal microbes that metabolize it to NH_3 and CO_2 (Rom, 1995) and to the rapid sequestering of the urine in closed containers. These reasons apply to both belt designs, but a statistical difference ($P < 0.01$) in NH_3 emissions was noted between the duct and trough belts. The duct design resulted in 0.91 ± 0.15 kg $NH_3 \cdot pig^{-1} \cdot y^{-1}$ while the trough allowed 1.22 ± 0.03 kg $NH_3 \cdot pig^{-1} \cdot y^{-1}$. This is not surprising since the urine gutter in the duct design is partially enclosed, limiting air movement across the urine and thus NH_3 volatilization, but the urine gutter in the trough design is open. Still, the trough design offers advantages that offset the slight increase in NH_3 emissions. The trough design occupies less space, making retrofits easier. Furthermore, with the trough design the gutter is cleaned each time the belt is operated. With the duct design, ammonia emissions are reduced 75% relative to the literature value cited above, but the reduction is still a substantial 67% with the trough design. The ideal design is likely a trough integrated in the belt but with a cover that limits airflow across the urine.

Ammonia emission data from the steady-state period of Exp. 2 have been examined for diurnal effects (Figure 4). If the belt load was contributing substantially to these emissions, a (sigmoidal) increase in NH_3 emissions would be expected from 0600 to 0600 the next day, the time of maximum belt load. Since this was not observed, it can be concluded that NH_3 emissions from the belt are insignificant. Numerically, there was a small increase in ammonia emission from 6 to 9 h into the collection cycle (corresponding to 1200 to 1500), which coincides with a decrease in the DM contents of the feces (Figure 3). Odor and NH_3 emissions have been noted to increase with the moisture content of manure since such conditions are more favorable to the bacterial growth that generates these compounds (US EPA, 2003). Diurnal fluctuations in gas emissions, despite constant housing temperature, have also been reported previously (Osada et al., 1998) and pig activity, including defecation and urination, has been shown to increase in the afternoon (Zhu et al., 2000; Gallmann et al., 2002). This observation suggests that pig activity patterns may also impact NH_3 emissions in the belt housing system.

During Exp. 3, emissions of 0.6 ± 0.1 kg $NH_3 \cdot pig^{-1} \cdot y^{-1}$ were observed initially. However, due to an outbreak of exudative epidermitis or ‘greasy pig disease’ that altered elimination patterns, the solid flooring of the pen was fouled, resulting in transient NH_3 emissions of 2.0 ± 0.2 kg $NH_3 \cdot pig^{-1} \cdot y^{-1}$. Although 2 kg $NH_3 \cdot pig^{-1} \cdot y^{-1}$ is still less than the 3.7 ± 1.0 kg$\cdot$ $pig^{-1} \cdot y^{-1}$ reported for conventional barns (Doorn et al., 2002), such drastic increases in emissions should be preventable in properly designed and managed belt-based facilities. This observation supports the hypothesis that NH_3 emissions come largely from the floor surface of pig housing where urine may be retained and broken down to NH_3 and CO_2. Thus, it is essential to direct defecation to the slatted portion of the pen and have slats that do not retain urine or feces. The most effective means found to direct the defecation pattern was the addition of angle iron to the tribar creating continuous upright metal projections (5 cm) across the slatted portion of the pen spaced 30 cm apart (see Figure 1). Animals were able to walk in the slatted area with the angle iron in place, but did not use that portion of the pen as a resting area. This is in keeping with the recommendation of Meyer et al. (1991) that the dunging area should be the least comfortable part of the pen in order to direct elimination to this area.

Methane emissions over all trials averaged 1.05 ± 0.29 $kg \cdot pig^{-1} \cdot y^{-1}$ throughout the grower period studied here (Table 1), substantially less than the 2.8 to 4.5 $kg \cdot pig^{-1} \cdot y^{-1}$ reported for conventional hog houses (Hahne et al., 1999). Energy lost as CH_4 represented only 0.64 ± 0.18% of the dietary energy consumed. This is consistent with findings of Noblet and Shi (1993) that energy lost as CH_4 due to enteric fermentation represents 0.44% of the energy in the feed consumed. Furthermore, it has been reported that dry, solid feces produces very little CH_4 (US EPA, 2003. In a separate study, when CH_4 levels of pigs housed in environmental chambers were monitored, emissions increased rapidly with the introduction of animals into the chambers, but fell back to near zero when the animals were discharged and only manure remained (Kaspers, 2002). Given the lack of CH_4 from dry feces, and the near zero emissions of CH_4 in the absence of animals, data suggest that CH_4 is coming from the animals themselves not from feces on the belt.

In addition to the measurements recorded by this laboratory, emissions from the belt-based housing were also evaluated by an independent group known as the Odor, Pathogens, and Emissions of Nitrogen team, or OPEN team, which is reviewing potentially environmentally superior technologies under the Smithfield Agreement (2000). Although their report cites concentration data only, thereby limiting comparisons between systems with different ventilation rates and different micro-climate conditions, this third party evaluation of the belt system was encouraging. According to their data, the level of volatile organic compounds (VOC's) ranged from 13 ppb to undetectable at distances from 5 to 25 m, respectively, downwind of the belt-housing ventilation fan; these levels were less than the background level of 23 ppb detected 18 m upwind of the fan (Schiffman, personal communication). The predominant VOC's detected were ethanol, methanol, acetone, and acetaldehyde (Blunden, 2003). The fact that the test facility is located in an urban setting adjacent to a major thoroughfare probably impacts the environmental measurements taken outside the building (Blunden, 2003). However, it is noteworthy that the building exhaust did not substantially elevate the VOC levels above background. When indoor measurements were evaluated, 60% of the indoor VOC was Freon 22 (Blunden, 2003) suggesting contamination from leaks in the air conditioning system rather than substantial VOC emission from pigs or their excreta.

Hydrogen sulfide emissions are a concern with animal confinement operations since this gas can be fatal with acute exposure to 100,000 ppb or greater (Donham et al., 1986; Chenard et al., 2003). Such concentrations are possible when manure, stored in the barn beneath the pigs, is agitated (Donham, 1990). Chronic exposure to much lower H_2S levels, for example 10,000 to 15,000 ppb, can produce edema and irritation to mucous membranes (Chénard et al., 2003; Donham et al., 2003) and Donham et al. (2003) suggest that the 1 h time-weighted average exposure not exceed 70 ppb at the property line. The aerobic conditions existing on the belt make such elevated levels of H_2S highly unlikely. Indeed, the OPEN team reported 12 ppb H_2S when 5 m downwind of the fan, but only 5.6 ppb when 25 m downwind. The upwind value was 6.2 ppb. All these values are substantially less than the limits mentioned above.

The OPEN team's odor data, expressed in odor units (OU), indicate 1.9 $OU \cdot animal^{-1} \cdot sec^{-1}$ directly at the ventilation fan. This is approximately a 60% reduction from the 4.7 $OU \cdot animal^{-1} \cdot sec^{-1}$ reported by Jacobson et al. (1998) for conventional housing. These data match subjective observations by both visitors and our research group that odor was much less problematic in the test facility and the first commercial belt operation (see below) than in conventional housing systems with similar rates of ventilation. The reason for the lower odor is likely the quick removal of urine from the house. Phenolics produced in the intestinal tract of the pigs are typically absorbed, conjugated with glycine in the liver, and excreted in the urine as glucuronides. Contamination of urine with feces introduces glucuronidases into the urine, which break these compounds down into their constituent phenolics (Spoelstra, 1977), resulting in the extremely unpleasant, strong smell of aged urine. Fecal material is a source of volatile fatty acid production, but upon drying the water activity in this fecal material is likely to drop quickly to the point that bacterial activity is strongly inhibited. In practice, the feces harvested retained an odor but this was not deemed as strongly unpleasant.

By switching from a wet to a dry waste collection system it was thought that dust levels might increase. The OPEN team, however, measured dust concentrations of 33 $\mu g/m^3$, much lower than the values reported by Predicala et al. (2001) of 2190 $\mu g \cdot m^{-3}$ and well below the recommended maximal concentration of 2400 $\mu g \cdot m^{-3}$ suggested by Donham (1991). It is not clear why such drastically lower dust levels were observed. An observation that may provide insight is that a large amount of dust settled on the belt, which may have been caused by some form of electrostatic interaction between the belt polyethylene and the dust particles (Tranbarger and Mamoun, 1991).

Animal Performance

Animal performance was evaluated in each of the trials (Table 1). The ADFI was 1.69 ± 0.18 $kg \cdot pig^{-1} \cdot d^{-1}$ and ADG was 0.83 ± 0.08 $kg \cdot pig^{-1} \cdot d^{-1}$. The G/F ratios averaged 0.50 ± 0.02 across the five belt-based housing trials. In Exp. 3, where performance in the belt-based housing was compared to that in conventional flush system barns, there was a significant improvement in the

G/F ratio of 5.5% ($P = 0.01$) for the belt-based animals despite the fact that housing density, diet, and animals were matched and despite the fact that there was a greasy-pig outbreak in the test facility during this trial. Experiments 1, 2, 4 and 5 combined yielded an 11% improvement in feed efficiency when compared to the Exp. 3 Reference or to other trials carried out in the conventional housing system. The reference farm had a lower group size (7 animals·pen^{-1} compared to 16 animals·pen^{-1} in the belt-based facility) necessitated by the desire to match housing density despite different pen sizes. Group size has been shown not to impact the G/F ratio, although larger groups may reduce both FI and growth rate (Hyun and Ellis, 2001; Wolter et al., 2001). The environment within the house, however, has been associated with increased incidence of pig disease and diminished productivity (Donham, 1991). The source of the G/F improvement requires further investigation, but may be due to improvements in air quality resulting from the separate collection of urine and feces. This explanation is supported by results obtained under field conditions with the belt. Already one commercial hog facility has adapted the belt for one of their facilities and this farm houses 4200 pigs in a two-story facility commissioned in September, 2003. Slaughter records to date from over 700 pigs show a 95% reduction in the incidence of lung lesions (0.9% incidence) compared to the general population of pigs processed at the same facility (21% average incidence). Improved air quality within the house is the most likely explanation.

Practical installations

Belts have been used successfully in the poultry industry for many years. There is thus a large amount of experience with belt material, frame construction, drive axles, and the handling of manure solids harvested with a belt. Current belts are typically high-density polyethylene, available in widths up to 3 m and suitable for building lengths of well over 150 m. The life expectancy for belts in the poultry industry, where loading rates are higher but running frequency is lower, is around 8 years. Worn belts are typically replaced by welding a new belt onto the old belt, and using the old belt to pull the new one in place. Thus, access to the belt underneath the slats is not required (Big Dutchman, personal communication).

The belt setup as tested is suitable for both new construction and retrofit. When retrofitting, slats will have to be removed for installation of skirts that prevent excreta and wash water from getting underneath the belt (critical to prevent insects from breeding underneath the belt). Slat removal can be done in small sections. The minimum space required under the slats for the belt consists of approximately 10 cm above the belt for fecal collection, 5 cm below the belt to allow for flushing underneath the belt for possible dust removal, 3 cm for spacing between the upper and lower belt, 0.2 cm for the two belts themselves, and 5 to 6 cm for accommodating the slope of the belt, dependent on the width of the manure channel (2.4 or 3 m, respectively). The total pit depth required is thus 23.2 to 24.2 cm. For long buildings, positioning the belt in a V shape allowing the urine to drain to the center of the belt is likely preferred as this minimizes the risk of the belt tracking poorly. This configuration has been used in the commercial farm with good success.

Another adaptation required is that the belt needs to extend beyond the animal housing for at least 50 cm, so that the drive axle is easily accessible, and at least another 50 cm is required as a work area to allow for adjusting the belt and cleaning the scraper. In existing facilities, this area can be created either by removing a portion of the end pens and the slats in the opened-up area, or by opening the front and back building walls to extend the belt outside of the building. The latter has as advantage that access to the belt is outside the animal areas and no animal space is lost.

Underneath the drive axle, a fecal collection system needs to be installed. The most practical solution for this is a transverse conveyor belt that connects to a feces collection area such as a covered concrete pad. In this, feces can be directly deposited in a truck bed for transportation off-site or collected on the floor for storage. Alternatively, a collection bin can be positioned below the drive axle. Possible uses of feces include land application as a high organics fertilizer, for compost, or as an energy source (composition is listed in Table 2).

Urine is collected continuously from the belt and is ideally moved to a closed storage facility to avoid ammonia and odor emission. Possible uses of urine are for land application as a high nitrogen and potassium fertilizer as-is or after concentration using e.g., nano-filtration, or the urine can be treated using nitrification/denitrification or using constructed wetlands (composition is listed in Tables 2 and 3).

An interesting advantage of the belt system is that it allows for multi-level swine buildings. The first such building housing 4200 pigs and consisting of two stories is already a reality. Construction costs of this facility were 40% lower per pig place than a conventional facility with an otherwise similar layout.

Cost Projections.

For the first commercial farm with the belt, the costs of both the belt system and the manure channel in which the belt was placed were approximately \$10·pig place^{-1}. This facility was partially slatted with approximately 50% open floor under which the belts were positioned, and the building was 50 m long. This cost includes \$0.39 for the belt (2.4 m wide), \$3.69 for the frame that supports the belt and also forms the manure pit (for retrofitting, a simpler frame can be used as the pit already exists), \$3.42 for the drive, and an estimated \$2.50 for the labor to install the system. If the 5.5% improvement in feed efficiency is confirmed under commercial conditions, these efficiencies will result in a payback time for the belt of well under two years. Any other benefit, including possible benefits on animal and worker health, reduced emissions, and flexible waste streams further improve the economic feasibility of this system.

Implications

Both belt designs proved successful in harvesting two separate excreta streams, but the trough design offers distinct operational advantages in cleaning and maintenance. Feces can be harvested with a DM content approaching 50% when collected early in the morning. The recovered feces can be used in a variety of applications since the reduced mass makes transportation cheaper and easier. Emissions of NH_3 and CH_4 are approximately 1 $kg \cdot pig^{-1} \cdot y^{-1}$, each, substantially less than reported values, resulting in environmental improvements through housing design. The 5.5% improvement in the G/F ratio suggests that production costs may be reduced, and the health benefits observed in the commercial farm may translate into additional savings. Despite initial costs, belt-based housing promises to be more economical than current conventional housing while offering substantial environmental benefits.

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Table 1. Experimental parameters and animal performance for five trials designed to evaluate a housing system employing a belt for harvesting urine and feces separately. Data are expressed on a per animal basis, except where indicated.

Trial date and Number	Aug 01 1	Jan 02 2	Mar 02 3	Oct 02 4	Apr 03 5	Mar 02 3 Reference	Mean ± SE
N, number of animals	100	80	80	80	80	80	
Avg. T, °C	28	30	26	22	25		26 ± 3
Avg. humidity, %	66	54	52	64	64		60 ± 5
Gutter design	duct	duct	duct	trough	trough	none	
Weights in and out, kg	23-57	27-55	23-51	30-57	32-56	24-53	
ADG, $kg \cdot d^{-1}$	0.79	0.76	0.82	0.97	0.83	0.83	0.83 ± 0.07
ADFI, $kg \cdot d^{-1}$	1.54	1.52	1.72	1.96	1.73	1.84	1.69 ± 0.16
Gain/Feed	0.51	0.50	0.48[a]	0.48	0.51	0.45[b]	0.50 ± 0.02
Fecal output, kg $DM \cdot d^{-1}$	0.23	0.26	0.22	0.34	0.26	ND	0.26 ± 0.04
Apparent DM digestibility, %	83.4	81.0	85.8	80.7	83.3	ND	82.8 ± 2
Fecal DM as collected, %	§	52	54	43	46	ND	49 ± 4
H_2O intake, $L \cdot d^{-1}$	ND	3.9	3.9	3.6	4.8	2.6	4.1 ± 0.4
Urine output, $L \cdot d^{-1}$	ND	1.05	1.54	1.27	1.42	ND	1.32 ± 0.19
Urine collected as % of H_2O intake	ND	26.9	39.5	35.3	29.2	ND	32.7 ± 5.8
NH_3 emission, $kg \cdot y^{-1}$[c]	1.08	0.80	0.84	1.20	1.24	ND	1.03 ± 0.18
NH_3-N as % of N intake	6.8	5.1	4.7	5.9	6.9	ND	5.9 ± 0.9
CH_4 emission, $kg \cdot y^{-1}$	1.27	1.06	0.75	1.39	0.76	ND	1.05 ± 0.26
CH_4 energy as % of energy intake	0.85	0.72	0.45	0.73	0.45	ND	0.64 ± 0.16

[a,b] Means in the same row lacking a common superscript differ (*P* < 0.05)

[c] Based on trials two to five, a significant difference in ammonia emission between duct and trough belt design was observed (*P* < 0.01)

ND=not determined

§=no steady state data from this trial

Table 2. Nutrient composition of urine and feces as harvested with the belt system.

	Feces, DM basis	Urine as-is
C, %	43.4	0.75
N, %	3.89	0.69
P, %	1.88	0.02
Ca, %	1.82	0.01
Mg, %	0.75	0.00
K,%	1.88	0.46
Na,%	0.38	0.07
Cl, %	0.40	0.20
Cu, ppm	138	1
Zn, ppm	1992	15
Energy, kj/g	19.7	

Table 3. Composition of urine as harvested with the belt system.

	Urine, as-is
Kjehldahl nitrogen, mg/l	6,936
Ammonia-N, mg/l	4,818
% NH3	71
Chemical oxygen demand, mg/l	31,180
Total organic carbon (TOC), mg/l	9,580
Total carbon (TC), mg/l	10,515
%TOC/TC	91
Total solids, %	2
Volatile solids, %	60
Fixed suspended solids, mg/l	6,521

Figure legends.

Figure 1. Schematic diagram of the pen and belt layout as tested. The belt is positioned beneath the slats so that animals defecate most on the highest portion of the belt. Urine is allowed to run off into a gutter that continuously carries it out of the room, by gravity flow, into a closed container. The “duct” and “trough” gutter designs are shown in the expanded views of the boxed pen area.

Figure 2. Panel A: The effect of belt residence time on fecal DM content. Panel B: effect of time of day of fecal collection on fecal DM. Belt DM decreased after approximately 30 h residence time, and time of day had a significant effect on dry matter. These data were confounded by the fact that this trial was not designed to study time of day effects.

Figure 3. Effect of collection time-of-day on feces DM content. Belt residence time was constant at 27 h and each time-of-day was evaluated in triplicate.

Figure 4. Evaluation of diurnal variation in ammonia emission levels when manure was collected daily at 0600. Ammonia emissions were monitored throughout the day during the steady state period of Exp. 2.

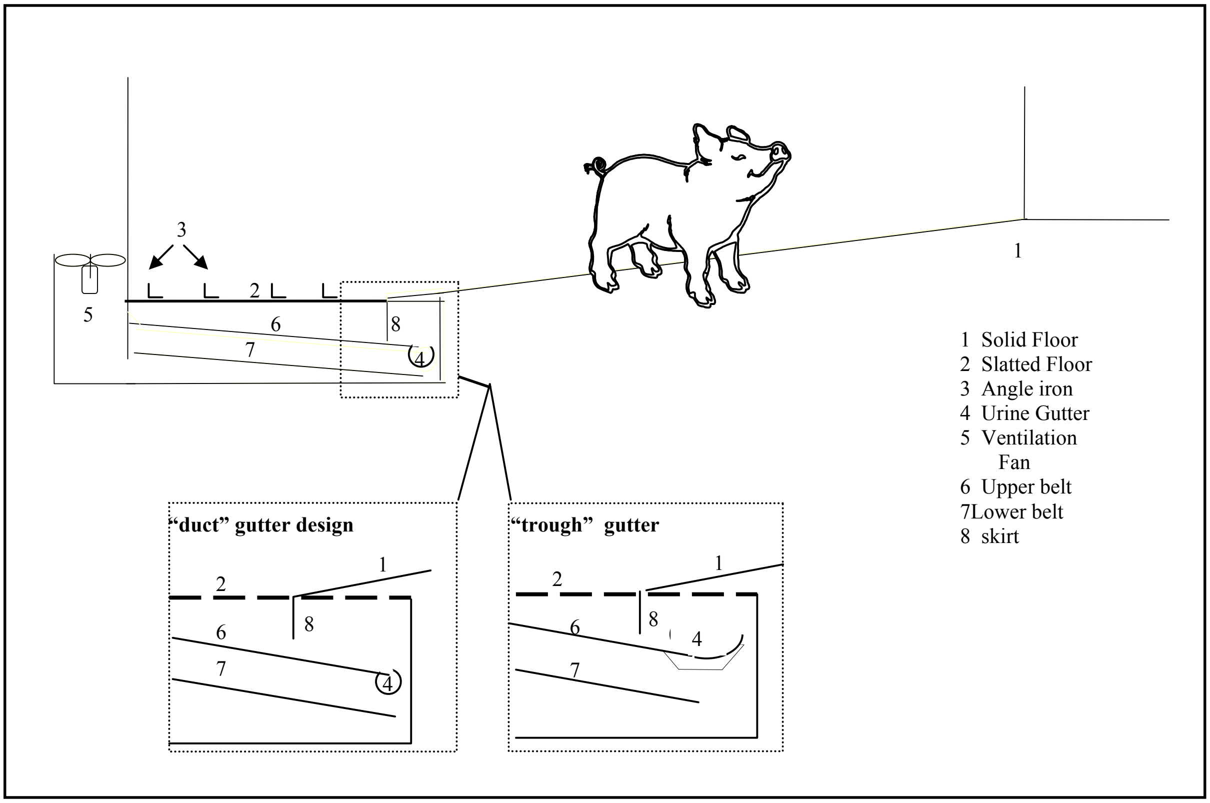
3
2
5
6
7
8
4
1
1 Solid Floor
2 Slatted Floor
3 Angle iron
4 Urine Gutter
5 Ventilation Fan
6 Upper belt
7Lower belt
8 skirt
"duct" gutter design
1
2
8
6
7
4
"trough" gutter
1
2
8
6
4
7

Figure 1.

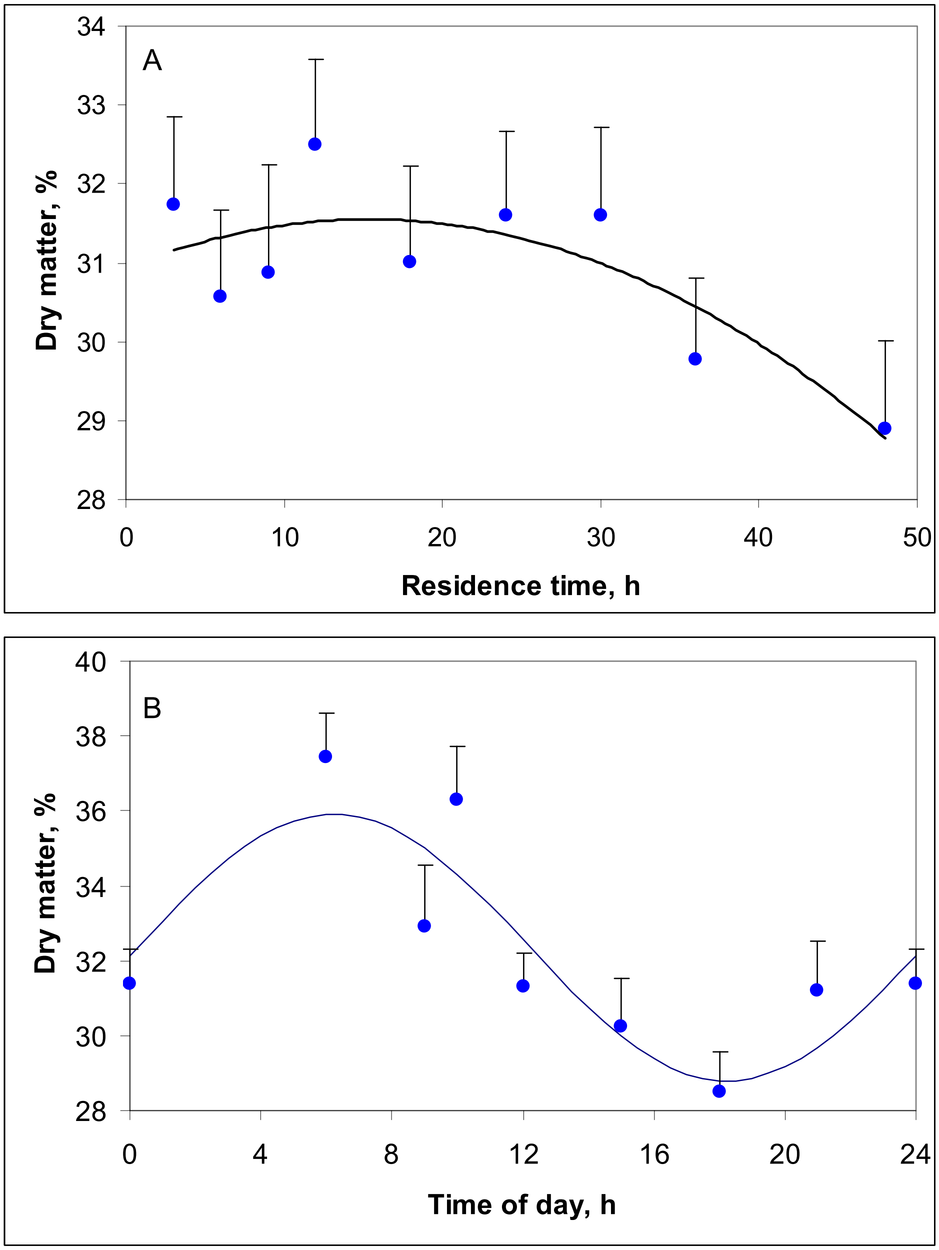
A
Dry matter, %
34
33
32
31
30
29
28
0
10
20
30
40
50
Residence time, h
B
Dry matter, %
40
38
36
34
32
30
28
0
4
8
12
16
20
24
Time of day, h

Figure 2.

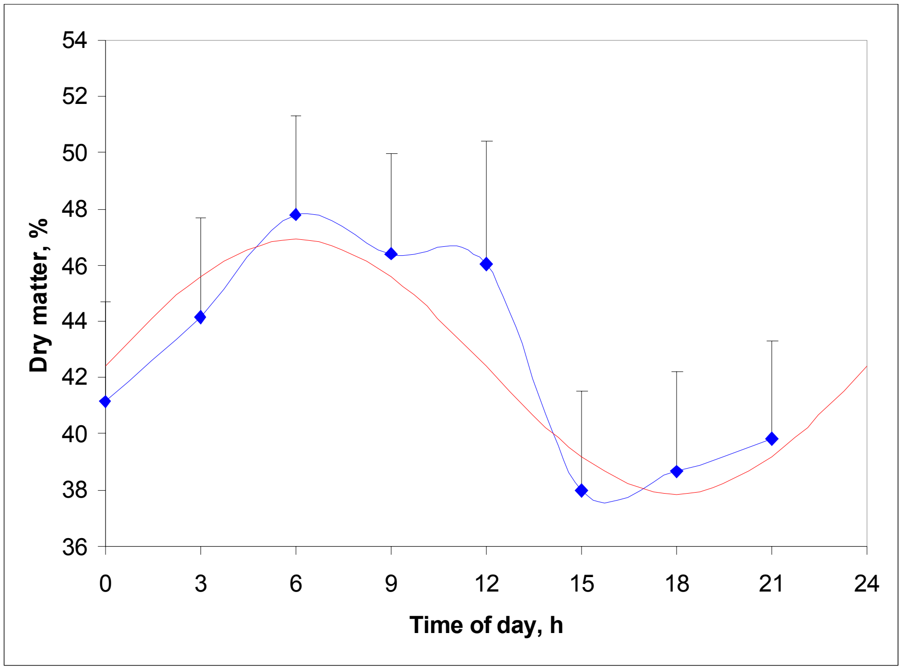
54
52
50
48
46
44
42
40
38
36
Dry matter, %
0
3
6
9
12
15
18
21
24
Time of day, h

Figure 3.

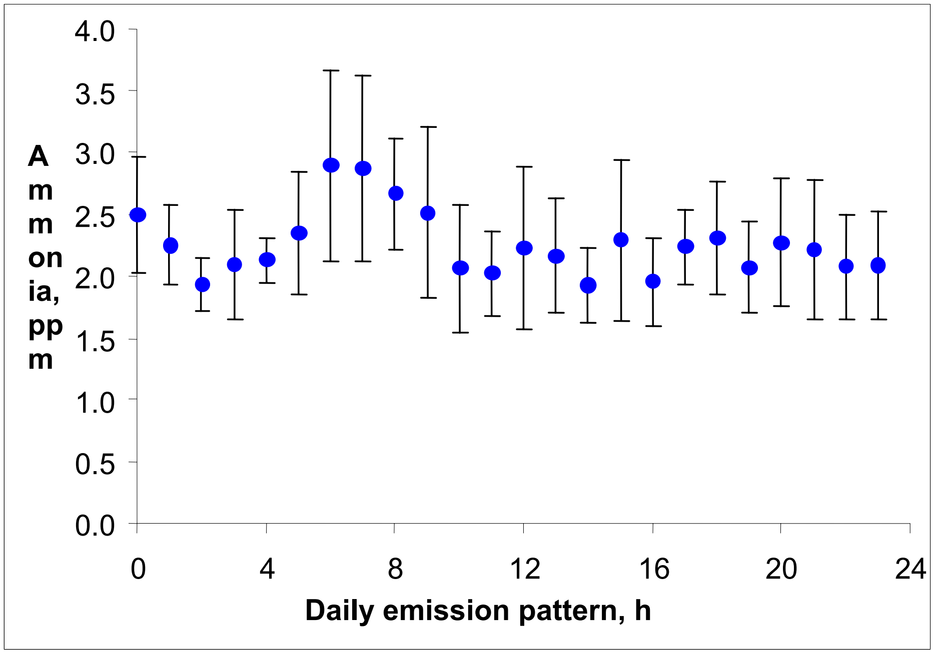
Ammonia, ppm
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
4
8
12
16
20
24
Daily emission pattern, h

Figure 4.