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Dietary Composition and Particle Size Effects on Swine Manure Characteristics and Gas Emissions

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Abstract

Nutrients excreted from animals affect the nutritive value of manure as a soil amendment as well as the composition of gases emitted from manure storage facilities. There is a dearth of information, however, on how diet type in combination with dietary particle size affects nutrients deposited into manure storage facilities, and how this subsequently affects manure composition and gas emissions. To fill this knowledge gap, an animal feeding trial was performed to evaluate potential interactive effects between feed particle size and diet composition on manure characteristics and manure-derived gaseous emissions. Forty eight finishing pigs housed in individual metabolism crates which allowed for daily collection of urine and feces were fed diets differing in fiber content and particle size, with their urine and feces collected and stored in 446 L stainless steel containers over a period of 49 d. There were no interactive effects between diet composition and feed particle size on any manure or gas emission parameter measured. In general, diets higher in fiber content increased manure nitrogen (N), carbon (C), and total volatile fatty acid (VFA) concentrations, and increased manure VFA emissions, but decreased manure ammonia emissions. Decreasing the particle size of the diet lowered manure N, C,

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VFA, phenolics, and indole concentrations, and decreased manure emissions of total VFA. Neither diet composition nor particle size had an impact on manure greenhouse gas emissions (GHG).

Core Ideas

- Increasing dietary fiber increases swine manure N, C, and total VFA concentrations.
- Reducing dietary particle size reduces swine manure N, C, and total VFA concentrations.
- Neither dietary fiber content nor particle size affect swine manure GHG emissions.
- 10% and 16% of C intake is lost in the manure and gas emissions, respectively.
- 28% and 37% of N intake is lost in the manure and gas emissions, respectively.

Abbreviations:

ARISA, automated ribosomal intergenetic spacer analysis; C, carbon; CH_4, methane; CO_2, carbon dioxide; CSBM, corn-soybean meal; DistLM, Distanced-based Linear Model; DDGS, distillers dried grains with solubles; FFAP, free fatty acid phase; GC, gas chromatography; GHG, greenhouse gas; H_2S, hydrogen sulfide; MS, mass spectrometer; N, nitrogen; N_2O, nitrous oxide; NH_3, ammonia; NH_4-N, ammoniacal nitrogen; S, sulfur; SBM, soybean meal; SH, soybean hulls; TDS, thermal desorption; VFA, volatile fatty acids; VOC, volatile organic compounds; VSC, volatile sulfur compounds

Introduction

Feed represent approximately 70% of the cost of pork production (Schnept, 2011; Iowa State University Extension, 2018). As a consequence, diet formulation is an important component of economically viable swine production, where various feedstuffs are combined based on their total and digestible energy, as well as their nutrient contents, to meet energy and nutrient needs for animal maintenance and growth. Processing methods (e.g., grinding, extruding or roasting) and additives (e.g., enzymes) can improve the digestibility of feedstuffs for swine; however, diets fed to growing pigs are not fully digested in the animal's gastrointestinal tract even when feed additives or processing methods have been used to improve their digestibility (NRC, 2012). As a result, these undigested feed components are excreted as feces and urine and allowed to accumulate in manure storage systems (Kerr, 2003; Le et al., 2005). Within manure storage structures, undigested feed components undergo microbial degradation, which may be aerobic (mineralization) or anaerobic (fermentation) depending on the manure storage conditions, which results in emission of numerous gases over time (Trabue et al., 2016a). These gases include greenhouse gases (GHG; methane (CH_4); nitrous oxide (N_2O), ammonia (NH_3), hydrogen sulfide (H_2S), and volatile organic compounds (VOC) that cause malodor. Characterizing the impact of diet composition on manure characteristics and gas emissions has been an ongoing research theme (Canh et al., 1998a,b,c; Mroz et al., 2000; Otto et al., 2003; Shriver et al., 2003; Portejoie et al., 2004; Clark et al., 2005; Le et al., 2005; Panetta et al., 2006; Leek et al., 2007). However, little attention has focused on the impact of dietary particle size on swine manure composition and gas emissions, despite the fact that processing (e.g., grinding) improves the digestibility of many dietary components (Hancock and Behnke, 2001; Richert and DeRouchey, 2010). Therefore, an animal feeding trial was conducted to determine potential interactive effects of diet composition and diet particle size on manure carbon (C), nitrogen (N), and sulfur (S) contents, manure characteristics (i.e., pH, ammoniacal nitrogen (NH_4-N), sulfide, volatile sulfur compounds (VSC), and VOC), and gas emissions (NH_3, VSC, VOC, and GHG) when fed to finishing pigs using an experimental manure storage system.

Materials and Methods

Diets and Experimental Design

The experiment was approved by the Iowa State University Animal Care and Use Committee. Two groups of 24 gilts (initial body weight = 119.5 ± 8.0 kg) were randomly allotted to individual metabolism crates (1.2 × 2.4 m) that allowed for total but separate collection of feces and urine. Crates were equipped with stainless steel feeders and nipple waterers, which allowed the pigs unlimited access to fresh water. Ambient temperature in the metabolism room was maintained at approximately 18°C, and lighting was provided continuously. Gilts were fed twice daily (0700 and 1900 h) an amount of feed that approximated 3% of their body weight for 49 d, which is considered near full feed. Gilts were fed one of three corn-based diets in a 3 × 2 factorial arrangement, with the 3 diet formulations consisting of: (1) a low fiber, corn--soybean meal (CSBM) diet, (2) a high fiber diet containing corn and 35% corn-distillers dried grains with solubles (DDGS), or (3) a high fiber diet containing corn and 21% soybean hulls (SH). Each diet was formulated to meet or exceed the energy, amino acid, and mineral needs according to NRC (2012) recommendations. Composition of the three experimental diets is presented in Table 1. Total intake of dietary C, N, and S was calculated based on diet nutrient analyses data and actual feed intake (feed offered less feed not consumed), which was subsequently used to calculate output of nutrients in manure and volatilized gases as a percent of nutrient intake. Diets were fed either in their originally milled form or a ground to a reduced particle size using a hammer mill. The analyzed geometrical mean of particle size for the coarsely ground diet was 631 ± 35 µm and 374 ± 29 µm for the finely ground diet, as determined using a 13 sieve stack with automatic shaker (Tyler RoTap, Mentor, OH) as described by Baker and Herrman (2002).

Each group of gilts was fed for a 49-d period. After each of the twice-daily feedings, the total amount of feces and urine from each metabolism crate was collected from under the metabolism crate and added in totality to its assigned enclosed manure storage container (one crate assigned to its corresponding storage container). Each stainless steel manure storage container measured 61 cm high and was 96.5 cm in diameter. The lid on each container was fitted with threaded couplers to accompany fittings and piping from which to add manure and take air samples. Each sealed container contained an individual fan system that pulled a constant stream of air over the manure surface (approximately 2.95 m^3/min) for 2 wk prior to the end of the trial. At the end of the trial (d 49), the gilts were removed from the room, the room cleaned with water and thethe tank manures allowed to sit for 2 d (no urine or feces added) between the end of the feeding trial (d 49) and air sampling (d 51) to reduce the influence of any animal-generated gases. Following air sampling, manure samples for analysis were obtained (d 54) after mixing each tank with a polyvinyl paddle to obtain a homogenous manure sample. After manure sampling from the first group of gilts, the manure in the tanks was mixed and drained to leave 10 cm of manure, which served as a fermentative seed stock for the second group of animals, prior to moving the gilts into the room.

Diet and Manure Analyses

Diets and manures were analyzed for C, N, and S by thermocumbustion (VarioMAX, Elementar Analysen Systeme GmbH, Hanau, Germany). Immediately after manure mixing, manure temperature was measured using a thermocouple thermometer (Fluke 51-Series II, Fluke Corp., Everett, WA) and pH using a pH meter (Corning Model 530, probe #476436, Corning Inc., Corning, NY). Manure total ammoniacal nitrogen (NH_4-N) was analyzed using an ammonium probe (Thermo Orion Meter 290A+, probe #9512) that was previously described in Trabue and Kerr (2014). In brief, 3 g of manure was weighed into a 100-mL beaker, after which 99 mL of deionized water and a stir bar were added. While mixing, 2 mL of ionic strength adjuster solution (Orion 951211, Thermo Fisher Scientific Inc.) were added. The pH of the mixture was maintained at ≥11 in order for the probe to accurately measure NH_4-N. The probe was inserted into the beaker, and the concentration was recorded. For manure sulfide, a sulfide probe (Thermo Orion Meter 290A+, probe #9616) was used to quantify sulfide levels as previously described in Trabue and Kerr (2014). In brief, 2 g manure was weighed into a 100 mL beaker, followed by 38 mL of degassed deionized water, 40 mL of SAOB solution (a glycine-ascorbic acid mixture used to prevent sulfide oxidation; Thermo Fisher Scientific Inc.), and a stir bar. The calibrated probe was inserted into each beaker and the sulfite concentration was recorded.

Manure volatile fatty acids, phenols, and indoles were analyzed as discussed in Weber et al. (2010). In brief, 4 g of manure was placed into a 15-mL polypropylene centrifuge tube and centrifuged at 21,000 × g for 23 minutes at 4°C. One mL of supernatant was removed and added to a 20 mL headspace vial (Agilent Technologies, Inc., Santa Clara, CA) in which it was acidified with 145 µL of o-phosphoric acid to a target pH of 2.0 to 2.5, salted with 0.3 g of NaCl, and then sealed with a screw-on cap with an injectable septum port (Part No. 5188-

2759, Agilent Technologies, Inc.). Samples were incubated at 70°C for 15 min on a robotic autosampler (MPS2, Gerstel, Inc.) and headspace contents sampled for 5 min using solid phase microextraction fibers (Cat No 57354-U, Supelco, Inc, Bellefonte, PA). Fibers were desorbed at 230°C for 300 s in the gas chromatography (GC) system inlet (Model 7980, Agilent Technologies, Inc.) equipped with a flame ionization detector and free fatty acid phase (FFAP) column (30 m × 0.25 mm × 0.25 μm; Agilent Technologies, Inc.). The GC parameters were as follows: splitless mode; inlet temperature, 230°C; inlet pressure, 24.56 psi; septum purge flow, 30 mL min^{-1}; constant column flow 1 mL min^{-1} (helium); and detector temperature, 300°C. The GC oven temperature program was: initial temperature, 100°C, 2 min hold; ramp of 10°C min^{-1} to the final temperature of 240°C, hold for 2 min.

Air Analyses

Sampling occurred over a 3-d period, with the 3-d average used as headspace gas concentration for data analyses. Concentrations of NH_3, H_2S, CH_4, carbon dioxide (CO_2), and N_2O were measured from ambient room air and from exhaust air for each manure storage tank using a photoacoustic multi-gas analyzer (Model 1312, INNOVA AirTech Instruments A/S) and an H_2S analyzer (API Model 101E, Teledyne Technologies, Inc.). Sampling details are discussed in Trabue and Kerr (2014). Concentrations of odorous VOC were measured from samples taken from ambient room air and exhaust air from each manure storage tank. Air samples were collected on sorbent tubes for thermal desorption (TDS) gas chromatography analysis as detailed in Trabue et al. (2010). In brief, air samples were collected on sorbent tubes at 100 mL min^{-1} for approximately 12 L using individual personal gas samplers (Models 220 or AirCheck 2000, SKC, Inc.). Sorbent tubes were analyzed by TDS (model TDSA, Gerstel, Inc.) using a GC system (model 6890N GC, Agilent Technologies, Inc.) equipped with a mass spectrometer (MS) detector (5973N Inert MSD, Agilent Technologies). The TDS/GC/MS system was equipped with a programmed temperature vaporizer inlet (CIS 4, Gerstel, Inc.) and 30 m × 0.25 mm × 0.25 mm FFAP column (J&W Scientific, Inc.). The TDS, programmed temperature vaporizer inlet, and GC oven program were previously described in Trabue et al. (2010). The MS was operated in selective ion monitoring/scan mode. Compounds were identified using mass spectra and retention times of reference standards. External standard curves were used for quantitation of samples. Greenhouse gas equivalence was determined based on the global warming potential of each gas measured as: $GHGeq = CO_2 + (CH_4 \times 25) + (N_2O \times 298)$ (IPCC, 2007).

Concentrations of volatile S compounds were measured from samples taken from ambient room air and exhaust air from each manure storage tank. Air samples were collected as grab samples (less than 10 min) in evacuated glass canisters as previously reported in Trabue et al. (2008, 2010). Analysis of canister headspace was performed using a canister system (Entech Instrument, Inc., Simi Valley, CA) that was coupled to a GC system (Agilent 6890N, Agilent Technologies, Inc.). The GC was equipped with gas separation column (30 m

× 0.32 mm × 0.25 μm) (GS-Gaspro, Agilent Technologies, Inc.) using helium gas at a constant flow of 0.7 mL min^{-1}, and equipped with a MS detector (5973 Inert MSD, Agilent Technologies). For determining concentrations of target VSC, the following molar mass values were monitored: 34 (hydrogen sulfide); 48 (methanethiol); 60 (carbonyl sulfide); 76 (dimethyl sulfide); 62 (dimethyl sulfide); and 94 (dimethyl disulfide). External standard curves were used for quantitation of samples. Total gas emissions of C, N, and S were determined based on specific gas emissions and their respective elemental composition (i.e., C, N, and S).

Calculations and Statistical Methods

Data were analyzed as a randomized complete block design with the group used as the block. The dietary treatments were arranged in a 3 × 2 factorial design with the main effects being diet type (CSBM, DDGS, SH) and particle size (coarse or fine). The individual pig (i.e., manure tank) was used as the experimental unit for all reported data, resulting in 8 observations per diet × particle size treatment combination (48 pigs/tanks across 6 treatments). Data were subjected to analysis of variance using Proc GLM (SAS Inst. Inc., Cary, NC) with treatment means reported as LSMEANS. Because no interactions were noted between diet type and particle size ($P \geq 0.10$), the interaction term was omitted from the statistical model, with only the main effects of diet type or particle size reported along with their corresponding SEM. Differences among means were considered significant at $P \leq 0.10$. While the effect of diet type and particle size on manure microbial community composition has been previously reported (van Weelden et al., 2016a), it was of interest to examine the relationship between manure C, N and total VOC, and the microbial community structure. To accomplish this, the automated ribosomal intergenetic spacer analysis (ARISA) data reported by van Weelden et al. (2016a) was reanalyzed using a Distanced-based Linear Model (DistLM) on the square root transformed ARISA abundances and the S17 Bray-Curtis similarity matrix, looking more specifically at the relationships among the microbial population and measured manure parameters (Bray and Curtis, 1957; Anderson, 2001).

Results

There was no effect of diet type or particle size on average daily feed intake by growing pigs (Table 2). Pigs fed the SH diet were more efficient in feed conversion (gain:feed) compared to pigs fed the CSBM or DDGS diets ($P \leq 0.05$), but average daily gain was unaffected ($P = 0.35$). Pigs fed the diets in a reduced, fine particle size were more efficient in feed conversion and grew at a faster rate than pigs fed the diets in coarse form ($P \leq 0.01$).

Manure NH_4-N and sulfide was highest in pigs fed the DDGS diet compared to pigs fed either the CSBM or SH diet ($P \leq 0.05$), and manure pH and S content (g L^{-1}) were higher in pigs fed the CSBM and DDGS diets compared to pigs fed the SH diet ($P \leq 0.05$) (Table 3). Manure N and C content was highest in pigs fed the DDGS diet, intermediate for pigs fed the SH diet, and lowest for pigs fed the CSBM diet ($P \leq 0.05$). Pigs fed coarse particle size diets had greater manure NH4-N, N and C content, but lower pH, compared to pigs fed the finely ground diets ($P \leq 0.02$).

Total VFA content in the manure was greatest in pigs fed the high fiber diets (i.e., DDGS and SH) compared to pigs fed the CSBM diet, and manure total phenolics were greatest in pigs fed the DDGS diet ($P \leq 0.05$) (Table 4). Manure total indoles were greatest in pigs fed the SH diet, least in pigs fed the DDGS diet, and intermediate in pigs fed the DDGS diet ($P \leq 0.05$). Pigs fed the coarse diets had the greatest concentrations of total VFA, phenolics, and indoles compared to pigs fed the finely ground diets ($P \leq 0.08$).

Major gas emissions are presented in Table 5. Ammonia emissions from manure of pigs fed the CSBM diet was greater than from manure of pigs fed the DDGS diet, and lowest from manure of pigs fed the SH diet ($P \leq 0.05$). Manure from pigs fed the SH diet had the highest emission of total VFA compared to manure from pigs fed the CSBM diet ($P \leq 0.05$), with pigs fed the DDGS diet being intermediate. In contrast, total phenol emissions were highest in manure from pigs fed the DDGS diet, lowest in manure from pigs fed the SH diet, and intermediate in manure from pigs fed the CSBM diet ($P \leq 0.05$). Manure from pigs fed the coarse diets had slightly lower emissions of NH_3, but higher emissions of VFA and VOC, compared to pigs fed the finely ground diets ($P \leq 0.06$). Neither diet type nor particle size had an effect on greenhouse gas emissions (Table 6).

Total manure and nutrient output in gaseous emissions, as a percent of nutrient intake, are presented in Table 7. Pigs fed the high fiber diets (i.e., DDGS and SH), had greater amounts of manure C and N as a percent of N and C intake compared to pigs fed the CSBM diet ($P \leq 0.05$). Pigs fed the CSBM or DDGS diets had greater manure S as a percent of S intake compared to pigs fed the SH diet ($P \leq 0.05$). Feeding a larger particle size increased manure C, but decreased manure S, as a percent in C or S, respectively, compared to pigs fed the finely ground diets ($P \leq 0.03$). Diet type affected gaseous losses of N as a percentage of N intake, where pigs fed the CSBM diet had the greatest loss of intake N, while pigs fed the SH diet had the lowest loss of intake N and pigs fed the DDGS diet had intermediate gaseous N losses ($P \leq 0.05$). Pigs fed the coarse particle size diets had reduced amounts of N and S losses in the air relative to N and S intake, respectively, compared to pigs fed the finely ground diets ($P \leq 0.01$). Diet particle size did not influence the percentage of C intake that was lost in gaseous forms ($P = 0.39$).

Irrespective of the relationship between diet and particle size to the microbial community structure, as reported by van Weelden et al. (2016a), it was of interest to determine if manure VOC, C or N were related to the manure microbiome. Based on this analysis, both manure C and VOC affected the microbial community structure ($P \leq 0.01$), where manure C content described 7.4% of the variability in the microbial community and manure VOC described 4.5% of the observed variability in the microbial community (data not shown). Manure N was similar to manure C in affecting manure community.

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Discussion

Performance data (gain,, feed intake, and feed efficiency) are not typically reported in balance-type trials because animals are not fed *ad libitum* and performance data from individually-fed pigs does not accurately mimic pen-reared pig performance. Nevertheless, performance data in the current trial are presented to demonstrate that animal nutrition was supportive of positive body weightFge gains over the 49-d experiment and did not greatly affect how the gilts responded to the dietary treatments (Table 2). It is noteworthy to state, however, that pigs fed the finer-ground diets exhibited greater rates of gain and better feed efficiency compared to pigs fed the coarser-ground diets. This is supported by previously published research on diet particle size and pig performance (Hancock and Behnke, 2001; Liu et al., 2012). The current data is also in agreement with others (Kerr et al., 2006, 2015, 2017, 2018; Trabue and Kerr, 2014), indicating that if diets with a moderate amount of fiber are balanced for energy, pigs will perform comparably to pigs fed a low-fiber diet.

It is well known that manure composition, properties, and microbial ecology can be affected by diet composition (Canh et al., 1998a,b,c; Mroz et al., 2000; Le et al., 2005; Panetta et al., 2006; Kerr et al., 2006, 2018; Ziemer et al., 2009; Trabue and Kerr, 2014; Trabue et al., 2016b; van Weelden et al., 2016ab). Increasing dietary fiber in swine diets is generally thought to lower manure pH and NH_4-N concentrations (Kerr et al., 2006, 2018; Trabue and Kerr, 2014; van Weelden et al. 2016b), but this is not always a consistent observation (van Weelden et al., 2016b). The current data was no exception to this lack of consistency. In the current experiment, manure from pigs fed the DDGS diet had higher manure NH_4-N, but no change in manure pH, compared to pigs fed the CSBM diet; while pigs fed the SH diet produced a manure with similar NH_4-N, but lower pH, compared to manure from pigs fed the CSBM diet (Table 3).

The impact on manure C and N from pigs fed different dietary fiber levels was more consistent (Table 3). Kerr et al. (2006) reported that increasing dietary fiber by adding 16% SH to a diet resulted in increased manure C, but not manure N. In contrast, Trabue and Kerr (2014) and Kerr et al. (2018) reported that increasing dietary fiber by adding 35% and 30% DDGS, respectively, resulted in increased manure C and N. While there were some differences in manure C and N between pigs fed the DDGS or SH diets in the current experiment, C and N concentrations of these higher fiber diets were greater than in manure obtained from pigs fed the CSBM diet. Swine diet composition has been shown to impact manure S contents (Trabue et al., 2019ab). Relative to increasing dietary fiber, adding SH has been shown not to impact manure S (Kerr et al., 2006), while adding DDGS has been show to increase manure S (Kerr and Trabue 2014, Kerr et al., 2018) due to the higher S content of DDGS compared to a CSBM diet (Kerr et al., 2008; Andersen et al., 2012). This, however, was not noted in the current trial, where the S content of manures from DDGS and CSBM diets were both ~0.094 g L^{-1}, and SH contained only 0.07 g S L^{-1}. The impact of diet particle size on manure composition has not been thoroughly studied, but it would be assumed that any diet composition or diet processing method that increased nutrient digestibility by an animal would increase nutrient retention, thereby reducing its “input” in the manure storage system (Kerr et al., 2017, 2018). As previously reported in pigs fed the same diets as used in the current study (Saqui-Salces et al., 2017), decreasing particle size resulted in an increase in the digestibility of DM (used as a surrogate for C), and N,and S, which in the data reported herein corresponded to a decrease in manure NH_4-N, C, and N, but not manure sulfide or S.

Similarly to observations on diet effects on manure nutrient composition, diet composition also affected manure VOC concentrations (Table 4). Increasing dietary fiber through the addition of DDGS or SH resulted in an increase in manure total VFA. This increase in total VFA was expected as others have shown that adding SH (Kerr et al., 2006) or DDGS (Trabue et al., 2016b; Kerr et al., 2018) increases manure total VFA concentrations. The effects of increasing dietary fiber on total phenolic and indole concentrations in the manure were significant but difficult to interpret. Pigs fed DDGS had increased manure phenolics, but not manure indoles, while the addition of SH resulted in increased manure indoles, but not phenolics. In a similar inconclusive manner, Kerr et al. (2006) reported that adding SH to the diet had little to no effect on phenol or indole concentrations in the manure. Furthermore, Trabue et al. (2016b) reported that adding DDGS to the diet had variable effects on phenols and indoles, depending upon which specific compound was evaluated. Lastly, Kerr et al. (2018) reported that adding DDGS to the diet increased manure phenolic, but not indole, concentrations. No previous data could be found that described the relationship between diet particle size and manure VFA, phenolic, or indole concentrations. In the current trial it was observed that when diets were fed in a finer particle size, manure VFA, phenolics, and indoles were all reduced (Table 4), suggesting that finer diets were more digestible and resulted in lower levels of nutrient inputs for the formation of these volatile compounds in the manure.

Diet composition had variable effects on the emissions of major gases, where it was observed that increasing dietary fiber reduced NH_3 emissions, tended to increase VFA emissions and had variable impacts on phenol emissions (Table 5). However, diet composition did not affect H_2S, VSC, or indole emissions; such that total VOC emissions were not affected by the type of diet fed to the pigs. By in large these dietary effects were similar to that reported by others (Trabue and Kerr, 2014; Trabue et al., 2016b; Kerr et al., 2018), who reported addition of DDGS decreased manure NH_3 emissions, while VFA, phenol, and indole emissions were increased and H_2S and total VOC emissions were variable. A finer feed particle size resulted in higher emissions of NH_3 but decreased VFA and total VOC emissions (Table 5). No comparative data were found within the literature, so this represents a novel reporting of the effects of particle size on malodorous gases produced by swine facilities. There was no effect of diet composition or particle size on GHG emissions (Table 6). This agrees with Trabue and Kerr (2014) and Kerr et al. (2018) who reported that when 35 and 30% DDGS, respectively, were added to finishing pig diets, no differences in GHG emissions were observed compared to pigs fed a CSBM diet. Although Kerr et al. (2006) reported that manure N_2O emission was increased from pigs fed a diet supplemented with 16% SH, they reported no effect of diet on CH_4 emissions.

Beyond the specific impacts of diet or particle size on manure composition and gas emissions, the current trial is unique in that it partitioned nutrient flow in an animal feeding system. Using an estimated pig whole body composition of 24.02% C, 3.05% N, and 0.18% S (B. J. Kerr, personal communication), and respiratory losses of C (respiration of N and S from non-ruminants is negligible, Kerr et al., 2003; Trabue and Kerr, 2014), it is possible to estimate the flow of C, N, and S through an animal system. In the current experiment, whole body C retention was calculated to be 18% of intake and animal respiration of CO_2 was approximately 56% of C intake, which were within the ranges reported by others (Kirchgessner et al., 1991; Li et al., 2011; Trabue and Kerr, 2014). As presented in Table 7, estimates of C retention in the manure were 8 and ~12% of C intake for pigs fed the CSBM and the high fiber diets (i.e., DDGS and SH diets), respectively; with C emissions from the swine manure averaging 16% of C intake across all diets. This suggests there is a slight increase in manure C due to feeding pigs a higher fiber diet, but this shift in C flow could not be picked up by a change in gas emissions. It is worthy to note that approximately 74% of the C flow was animal-related, with only 26% related to manure excretion and gas emissions, Figure 1.

For N, whole body retention was calculated to be 35% of N intake, with no N assumed to be lost through animal respiration. As presented in Table 7, estimates of N retention in the manure were 21 and 30--32% of N intake for pigs fed the CSBM and the high fiber diets (i.e., DDGS and SH diets), respectively. Nitrogen emissions from the swine manure appeared to be inversely related to manure N, where it was observed that N emissions accounted for 49% of N intake for pigs fed the CSBM diet and 14--33% of N intake for pigs fed the high fiber diets. Consequently, there appears to be a clear shift in N partitioning when pigs were fed higher fiber diets, with an increase in manure N and a decrease in gas N emissions. Taken together, 35% of the flow of N was animal-related use for maintenance and growth, and approximately 65% was related to manure excretion and gas emissions, Figure 1.

For S flow, whole body S retention was calculated to be 41% of intake, with no S assumed to be lost by animal respiration. As presented in Table 7, S retained in the manure averaged 55% of S intake across all diets while gas S emissions averaged 4% of S intake across all diets. Unlike for C and N, there appeared to be no shift in S partitioning with 41% of S flow being animal related and approximately 59% was related to manure composition and gas emissions, Figure 1. Nutrient shifting relative to particle size was not as clear. Feeding pigs the diets in a finer particle size did not impact on manure N excretion, but increased N emissions. In contrast, feeding pigs the diets in a finer particle size resulted in a reduced manure C output, but did not change gaseous C emissions (Table 7).

For S flow, a smaller diet particle size appeared to result in increases in both manure S concentration and gas S emissions.

Using manure storage model systems, it has been concluded that the diet type fed to the pigs and the age of the manure affects microbial ecology (Ziemer et al., 2009; Trabue et al., 2016a; van Weelden et al., 2016b; Kerr et al., 2011, 2018). In manure samples obtained from this experiment, the microbial community was distinctly different among manure samples obtained from pigs fed CSBM, DDGS, and SH diets, with the assumption that this was due to the amount of C and N deposited into the manure due to the type (cellulose versus hemicellulose) and amount (low versus high) of dietary fiber the pigs consumed (van Weelden et al., 2016a). In addition, diet particle size also caused a distinct impact on microbial community, albeit a smaller impact than diet type, within each diet. Because "diet" or "particle" size is ambiguous relative to inputs for microbial growth, disassociating these two classifications from the microbial community assessment and to relate manure characteristics (i.e., manure C, N, and total VOC) to bacterial community automated ribosomal intergenic spacer analysis (Yannarell and Triplett, 2005; Kent et al., 2007) seems relevant. While a significant relationship was found, the fact that only 7.4% and 4.5% of the variability in microbial community could be described by the variation in manure C and VOC content, respectively, indicates that more research is needed to determine how diet composition impacts manure microbial community.

Conclusion

Manure composition and gas emissions were impacted by diet composition and feed particle size fed to growing pigs. Increasing dietary fiber or increasing dietary particle size, each of which reduce digestibility, resulted in increased manure N, C and total VFA concentrations, and tended to increase total VFA; but neither had an effect on manure GHG emissions. In general, 20% of dietary C was retained in the body, 10% was excreted in the manure, and 15% was lost via gas emissions; while for dietary N, 33% was used for growth and maintenance of the animal, 24% was excreted in the manure, and 43% was lost as gas emissions.

Conflict of Interest

The authors declare no conflict of interest.

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Figure 1. Relative flow, percentage of consumption, of nutrients in finishing pigs fed corn-soybean meal or corn soybean meal diets with added fiber. Data represents an average of 48 pigs, 120 to 160 kg bodyweight, fed diets of two different particle sizes for 49 d. Urine and feces were collected, combined, and added daily into a manure tank for manure composition and gas emission evaluation.

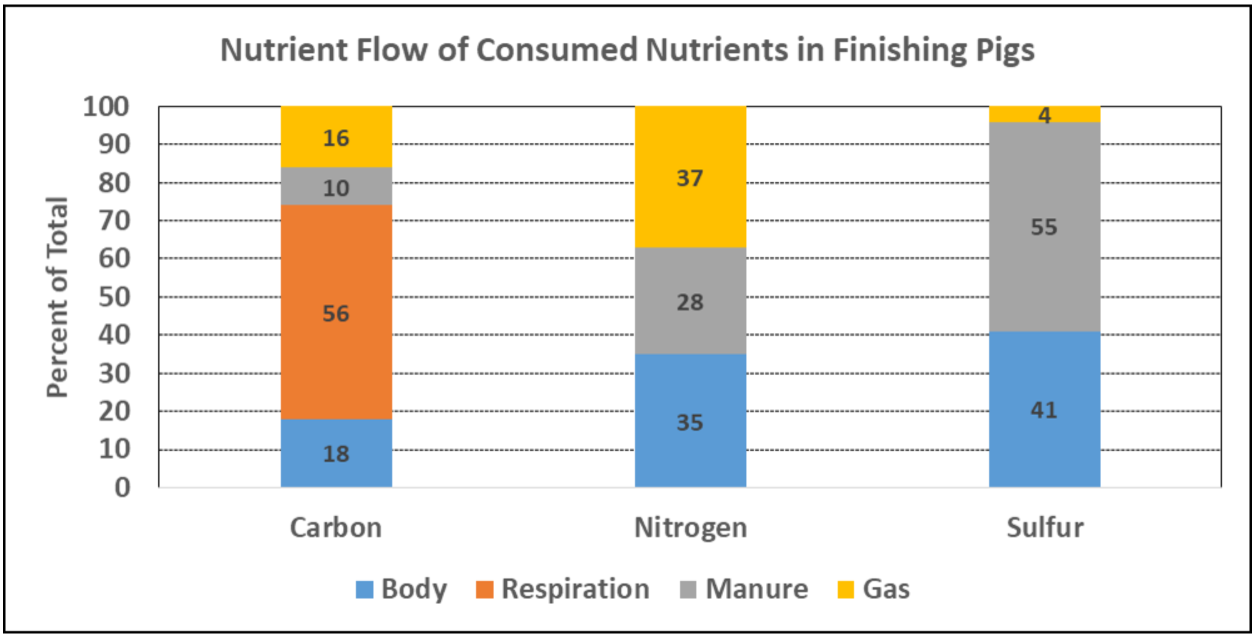

Table 1. Experimental diet formulation, as-fed basis

Ingredient, %	CSBM[1]	DDGS	SH
Corn, ground	79.72	62.51	57.34
Soybean meal	17.99	-	16.80
Distillers dried grains with solubles	-	35.11	-
Soybean hulls	-	-	20.75
Soybean oil	0.30	-	3.32
Monocalcium phosphate	0.41	0.10	0.49
Limestone	0.87	1.15	0.60
Sodium chloride	0.35	0.35	0.35
Vitamin mix[2]	0.20	0.20	0.20

Trace mineral mix[3]	0.15	0.15	0.15
L-lysine·HCl	-	0.39	-
L-threonine	-	0.03	-
L-tryptophan	-	0.03	-
TOTAL	100.00	100.00	100.00
Calculated composition			
Metabolizable energy, kcal/kg	3,325	3,325	3,325
Crude protein, %	15.15	15.15	15.15
Standardized digestible lysine, %[4]	0.62	0.62	0.62
Calcium, %	0.46	0.46	0.46
Phosphorus, %	0.42	0.39	0.41
Standardized digestible P, %	0.21	0.21	0.21
Sulfur, %	0.18	0.32	0.18
Neutral detergent fiber, %	8.7	19.0	19.0
Analyzed composition			
Carbon, %	39.86	41.10	41.04
Nitrogen, %	2.33	2.48	2.37
Sulfur, T	0.19	0.21	0.19
Neutral detergent fiber, %	6.39	12.33	17.96

[1]Abbreviations: CSBM = corn-soybean meal based diet, DDGS = diet containing corn-distillers dried grains with solubles, SH = diet containing soybean hulls. Average diet particle size, µm: C-SBM, 615 -coarse and 364 fine; C-SBM-DDGS, 603-coarse and 352 fine; C-SBM-SH, 675-coarse and 408 fine.

[2]Provided per kilogram of complete diet: 6,125 IU of vitamin A; 700 IU of vitamin D; 50 IU of vitamin E; 3.0 mg of vitamin K; 56 mg of niacin; 27 mg of pantothenic acid; 11 mg of riboflavin; 0.05 mg of vitamin B_{12}.

[3]Provided per kilogram of complete diet: Zn, 165 mg as $ZnSO_4$; Fe, 165 mg as $FeSO_4$; Mn,

39 mg as $MnSO_4$; Cu, 16.5 mg as $CuSO_4$; I, 0.3 mg as $Ca(IO_3)_2$; and Se, 0.3 mg as Na_2SeO_3.

[4]Diets formulated to a minimum of 0.59 sulfur amino acids:lysine, 0.66 threonine:lysine, 0.18 tryptophan:lysine, 0.54 isoleucine:lysine, 0.67 valine:lysine.

Table 2. Pig performance as affected by diet composition and particle size[1]

	Pig performance		
Diet	Average daily gain, g	Average daily feed intake, g	Gain:Feed
CSBM[2]	0.813	2.832	0.286[b]
DDGS	0.806	2.853	0.282[b]
SH	0.861	2.777	0.308[a]
SEM	0.029	0.037	0.008
P value	0.35	0.34	0.05
Particle size			
Coarse	0.781	2.795	0.278
Fine	0.871	2.846	0.306
SEM	0.024	0.030	0.006
P value	0.01	0.24	0.01

[1]Initial body weight = 119.5 kg, SD = 8.0 kg; final body weight = 160.0 kg, SD = 10.2 kg. Each trial lasted 49 d with 8 observations for each of 2 groups of gilts, resulting in 16 observations per diet and 24 observations per particle size. Feed intake and gain:feed ratio based on as-fed basis.

[2]Abbreviations: CSBM = corn-soybean meal based diet, DDGS = diet containing corn-distillers dried grains with solubles, SH = diet containing soybean hulls.

Values in a column not connected by the same letter within a column are significantly different at $\alpha = 0.05$.

Table 3. Manure characteristics as affected by diet composition and particle size[1].

			µM/g manure			Composition, g/L		
Diet	Vol., L	T,°C	NH4-N	Sulfide	pH	N	C	S
CSBM[2]	195	16.5	357[b]	0.33[b]	8.15[a]	0.43[c]	2.67[c]	0.093[a]
DDGS	211	16.4	446[a]	0.48[a]	8.01[a]	0.62[a]	3.99[a]	0.094[a]
SH	210	16.9	344[b]	0.35[b]	7.72[b]	0.53[b]	3.36[b]	0.074[b]
SEM	7	0.3	13	0.02	0.07	0.02	0.13	0.003
P value	0.20	0.49	0.01	0.01	0.01	0.01	0.01	0.01
Particle size								
Coarse	202	16.5	406	0.41	7.87	0.57	3.80	0.089
Fine	209	16.7	358	0.37	8.05	0.48	2.88	0.085
SEM	6	0.2	11	0.02	0.06	0.02	0.11	0.002
P value	0.38	0.60	0.01	0.19	0.02	0.01	0.01	0.21

[1]Initial body weight = 119.5 kg, SD = 8.0 kg; final body weight = 160.0 kg, SD = 10.2 kg. Each trial lasted 49 d with 8 observations for each of 2 groups of gilts, resulting in 16 observations per diet and 24 observations per particle size.

[2]Abbreviations: CSBM = corn-soybean meal based diet, DDGS = diet containing corn-distillers dried grains with solubles, SH = diet containing soybean hulls.

Values in a column not connected by the same letter within a column are significantly different at α = 0.05.

Table 4. Major manure volatile compounds as affected by diet composition and particle size[1].

	Fatty acid, mmol/g wet wt.				μmol/g of wet wt.	
Diet	Acetic	Propionic	Butyric	Total[3]	Phenolics[3]	Indoles[3]
CSBM[2]	111[b]	11[c]	7[c]	136[b]	1.3[b]	3.3[ab]
DDGS	183[a]	18[b]	12[b]	222[a]	1.6[a]	2.4[b]
SH	180[a]	24[a]	17[a]	232[a]	1.3[b]	5.0[a]
SEM	15	1	1	16	0.1	0.7
P value	0.01	0.01	0.01	0.01	0.03	0.03
Particle size						
Coarse	188	22	16	237	1.5	4.3
Fine	128	13	8	156	1.3	2.9
SEM	12	1	1	13	0.1	0.6
P value	0.01	0.01	0.01	0.01	0.01	0.08

[1]Initial body weight = 119.5 kg, SD = 8.0 kg; final body weight = 160.0 kg, SD = 10.2 kg. Each trial lasted 49 d with 8 observations for each of 2 groups of gilts, resulting in 16 observations per diet and 24 observations per particle size.

[2]Abbreviations: CSBM = corn-soybean meal based diet, DDGS = diet containing corn-distillers dried grains with solubles, SH = diet containing soybean hulls.

[3]Total volatile fatty acids (acetate, propionate, butarate, isobutyrate, isovalerate, valerate, isocaproic, caproic, and heptanoic), phenols (phenol, cresol, ethylphenol, and propylphenol), and indoles (indole and skatol).

Values in a column not connected by the same letter within a column are significantly different at $\alpha = 0.05$.

Table 5. Major gas emissions, g d^{-1} AU^{-1}, from manure as affected by diet composition and particle size[1].

Diet	NH_3	H_2S	VSC[3]	VFA[4]	Phenols[4]	Indoles[4]	VOC[5]
CSBM[2]	200[a]	0.69	1.72	1.36[b]	0.25[ab]	0.001	1.61
DDGS	148[b]	0.61	1.76	2.19[ab]	0.30[a]	0.001	2.50
SH	55[c]	0.54	1.63	2.89[a]	0.14[b]	0.001	3.04
SEM	18	0.08	0.36	0.47	0.04	0.001	0.48
P value	0.01	0.42	0.97	0.08	0.02	0.85	0.12
Particle size							
Coarse	114	0.55	1.41	2.88	0.23	0.001	3.11
Fine	154	0.67	2.00	1.42	0.24	0.001	1.65
SEM	15	0.07	0.29	0.39	0.03	0.001	0.40
P value	0.06	0.20	0.16	0.01	0.84	0.94	0.01

[1]Initial body weight = 119.5 kg, SD = 8.0 kg; final body weight = 160.0 kg, SD = 10.2 kg. Each trial lasted 49 d with 8 observations for each of 2 groups of gilts, resulting in 16 observations per diet and 24 observations per particle size.

[2]Abbreviations: CSBM = corn-soybean meal based diet, DDGS = diet containing corn-distillers dried grains with solubles, SH = diet containing soybean hulls. Data reported in g d^{-1} AU^{-1}, with animal unit (AU) defined as 500 kg of animal weight.

[3]VSC, volatile sulfur compounds: sum of hydrogen sulfide, methanethiol, carbonyl sulfide, dimethyl sulfide, dimethyl sulfide, dimethyl disulfide.

[4]VFA, volatile fatty acids (acetate, propionate, butarate, isobutyrate, isovalerate, valerate, isocaproic, caproic, and heptanoic), phenols (phenol, cresol, ethylphenol, and propylphenol), and indoles (indole and skatol).

[5]VOC, volatile organic compounds = sum of VFA, phenols, and indoles.

Values in a column not connected by the same letter within a column are significantly different at α = 0.05.

Table 6. Greenhouse gas emissions, g d^{-1} AU^{-1}, from manure as affected by diet composition and particle size[1].

Diet	CH_4	N_2O	CO_2	GHG-eq[3]
CSBM[2]	27.9	1.45	2,629	3,759
DDGS	30.7	1.27	2,293	3,437
SH	33.5	1.42	3,031	4,291
SEM	5.6	0.26	484	530
P value	0.78	0.87	0.56	0.52
Particle size				
Coarse	31.8	1.49	2,482	3,722
Fine	29.5	1.27	2,819	3,936
SEM	4.6	0.21	395	433
P value	0.73	0.47	0.55	0.73

[1]Initial body weight = 119.5 kg, SD = 8.0 kg; final body weight = 160.0 kg, SD = 10.2 kg. Each trial lasted 49 d with 8 observations for each of 2 groups of gilts, resulting in 16 observations per diet and 24 observations per particle size.

[2]Abbreviations: CSBM = corn-soybean meal based diet, DDGS = diet containing corn-distillers dried grains with solubles, SH = diet containing soybean hulls, AU = animal unit defined as 500 kg of animal weight.

[3]GHG-eq, green house equivalence; = $CO_2 + (CH_4 \times 25) + (N_2O \times 298)$.

Table 7. Total manure and gas nutrient output, % of nutrient intake, as affected by diet composition and particle size[1].

	Manure nutrient			Gas nutrient		
Diet	N	C	S	N	C	S
CSBM[2]	21.2[b]	8.0[b]	57.4[a]	49.0[a]	16.5	4.8
DDGS	32.2[a]	12.4[a]	57.1[a]	32.5[b]	13.7	4.1
SH	29.9[a]	11.3[a]	52.1[b]	13.7[c]	18.7	4.6
SEM	1.1	0.5	1.3	3.6	2.9	0.7
P value	0.01	0.01	0.01	0.01	0.49	0.73
Particle size						
Coarse	28.6	11.5	53.9	25.9	14.9	3.5
Fine	26.9	9.6	57.2	37.7	17.8	5.5
SEM	0.9	0.4	1.0	2.9	2.4	0.5
P value	0.18	0.01	0.03	0.01	0.39	0.01

[1]Initial body weight = 119.5 kg, SD = 8.0 kg; final body weight = 160.0 kg, SD = 10.2 kg. Each trial lasted 49 d with 8 observations for each of 2 groups of gilts, resulting in 16 observations per diet and 24 observations per particle size.

[2]Abbreviations: CSBM = corn-soybean meal based diet, DDGS = diet containing corn-distillers dried grains with solubles, SH = diet containing soybean hulls.

Values not connected by the same letter within a column are significantly different at $\alpha = 0.05$.