The influence of manure composition on emissions of odour and ammonia from finishing pigs fed different concentrations of dietary crude protein

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Abstract

An investigation was conducted into the influence of manure composition on the odour emission rate (OER) and the emission rate of ammonia (NH₃), when diets containing 130, 160, 190 and 210 g kg⁻¹ crude protein (CP) were fed to finishing pigs. A group of four boars and four gilts, housed in environmentally sealed pens, were assigned to each diet for a 23-day experimental period which was replicated three times (n = 3). Ventilation air from each pen was sampled for NH₃ and odour, by olfactometry, on four days during the trial period. Simultaneous collections of manure were taken from the surface and base of each pit. The pH and the concentrations of dry matter, total Kjeldahl nitrogen (TKN), total ammoniacal nitrogen (TAN) and volatile fatty acids in the manure were measured. Manure composition differed between samples from the surface and base of the pit (P < 0.05). Reducing dietary CP concentration decreased the emission of NH₃ (linear, P < 0.001). The acetic acid:propionic acid ratio in manure samples was correlated to OER (r = 0.79, P < 0.001). There was a quadratic relationship between dietary CP concentration and OER (P < 0.05). OER decreased between 210 g kg⁻¹ and 160 g kg⁻¹ CP and increased between 160 g kg⁻¹ and 130 g kg⁻¹ CP. In conclusion, reducing dietary crude protein levels could be used effectively to reduce ammonia emissions and OER, although no significant advantage was to be gained in OER from reducing crude protein level below 160 g kg⁻¹.

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Keywords: Pigs; Crude protein; Pig manure; Ammonia; Odour

1. Introduction

Intensive pig production leads to the production of environmental contaminants. These contaminants include organic nitrogen outputs and emissions of ammonia and odour. High rates of nitrogen loading, derived from both organic and gaseous sources, cause eutrophication of nitrogen sensitive ecosystems and acidification of water and soils (Pitcairn et al., 2002). Intensification of livestock production and an increasing urban influx and influence on rural areas has increased objections to odour emissions from pig units (Mackie et al., 1998) and concerns have been raised regarding the impact of odour emissions on human health and well being (Schiffman et al., 1995). It is pertinent, therefore, to employ methods of production that minimise the generation of these contaminants.

Previous research has indicated that reducing the concentration of dietary crude protein decreases nitrogen excretion and the volatilisation of NH₃ from manure (Canh et al., 1998a; Hayes et al., 2004; Leek et al., 2005). Volatile fatty acids (VFA) in manure reflect bacterial activity and cause a decrease in manure pH that may be helpful...
in controlling ammonia volatilisation (Canh et al., 1998b). It is reported that the concentration of manure VFA decreases as the concentration of dietary crude protein is reduced (Shriver et al., 2003). Thus, it is necessary to assess whether such an effect on the concentration of manure VFA, associated with changes in the dietary crude protein concentration, may influence the ammonia emission response.

The production of the most pungent and greatest variety of obnoxious smelling compounds emanating from pig production has been attributed to fermentation of nitrogenous material (Hobbs et al., 1997). Fermentation of dietary carbohydrate may also contribute to the formation of odorous metabolites (Hobbs et al., 1996; Miller and Varel, 2003). Changing the concentration of dietary crude protein may affect the nitrogen and carbohydrate composition of the diet (Hobbs et al., 1996). The reported effects of the concentration of dietary crude protein on odour emission have been conflicting. Several studies indicated a decrease in odour from a decrease in crude protein (Hobbs et al., 1996; Hayes et al., 2004), while Otto et al. (2003) reported an increase. The latter authors attributed the increase in odour to changes in the concentration of VFA in the manure. VFA represent the largest group of odorous compounds released from manure (Williams, 1984; Zhu et al., 1999). It may be possible, therefore, to establish relationships between the concentration of total VFA, or individual VFA in manure, and odour emission. Identification of odour indicator compounds by chemical analysis of manure could facilitate a less involved and more economical means of odour assessment than olfactometry methods.

Precise analysis of manure composition would enable producers to predict and record nutrient outputs for the completion of manure management plans. However, it is well known that stratification of manure components occurs within the vertical profile of stored manure (Zhang and Day, 1996). Consequently, the analytical composition of manure samples is likely to be affected without thorough mixing of stored slurry. This could lead to inaccuracies in nutrient planning.

The experimental objective was to investigate the influence of manure composition on the emission rates of ammonia and odour from finishing pigs fed diets containing four different concentrations of dietary crude protein. Manure samples were collected from the surface and base of the pit to evaluate the effect of sampling from these locations on manure composition.

2. Methods

2.1. Diets

Dietary composition and analysis is presented in Table 1. Diets A, B, C and D were formulated to contain 130, 160, 190 and 210 g kg⁻¹ crude protein (CP) respectively. The diets were formulated using standard feeding values for the ingredients (O’Grady, 1996). Downward adjustment of CP was achieved by increasing the wheat:soyabean meal ratio. Diets were isocaloric, formulated to an estimated net energy (NE) density of 9.7 MJ kg⁻¹. Diets were

<table>
<thead>
<tr>
<th>Diet</th>
<th>Formulated crude protein concentration (g kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>A</td>
<td>130.0</td>
</tr>
</tbody>
</table>

Table 1

<table>
<thead>
<tr>
<th>Ingredient inclusion (g kg⁻¹)</th>
<th>Diet A</th>
<th>Diet B</th>
<th>Diet C</th>
<th>Diet D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>886.7</td>
<td>810.0</td>
<td>722.5</td>
<td>637.5</td>
</tr>
<tr>
<td>Soya bean meal</td>
<td>60.0</td>
<td>136.7</td>
<td>224.2</td>
<td>309.2</td>
</tr>
<tr>
<td>Soya oil</td>
<td>13.3</td>
<td>13.3</td>
<td>13.3</td>
<td>13.3</td>
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<tr>
<td>Amino acid pack</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Vitamin and mineral pack</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Composition (g kg⁻¹)</th>
<th>Diet A</th>
<th>Diet B</th>
<th>Diet C</th>
<th>Diet D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter</td>
<td>875.7</td>
<td>870.1</td>
<td>877.0</td>
<td>872.9</td>
</tr>
<tr>
<td>Crude protein (N × 6.25)</td>
<td>133.2</td>
<td>157.4</td>
<td>190.0</td>
<td>206.4</td>
</tr>
<tr>
<td>Ash</td>
<td>38.6</td>
<td>48.3</td>
<td>49.2</td>
<td>51.1</td>
</tr>
<tr>
<td>Crude fibre</td>
<td>13.3</td>
<td>24.7</td>
<td>29.5</td>
<td>27.6</td>
</tr>
<tr>
<td>Ether extract</td>
<td>31.1</td>
<td>26.4</td>
<td>28.3</td>
<td>28.6</td>
</tr>
<tr>
<td>Starch</td>
<td>512.9</td>
<td>472.9</td>
<td>427.1</td>
<td>382.6</td>
</tr>
<tr>
<td>Gross energy (GE, MJ kg⁻¹)</td>
<td>15.73</td>
<td>15.63</td>
<td>15.79</td>
<td>15.88</td>
</tr>
</tbody>
</table>

a The mineral and vitamin premix (Devenish Nutrition, Belfast, N. Ireland) provided (per kg feed): 6000 IU vitamin A, 800 IU vitamin D₃, 60 mg vitamin E, 1 mg vitamin K₂, 2 mg thiamine, 3 mg riboflavin, 10 mg panthenolic acid, 2 mg pyridoxine, 15 mg nicotinic acid, 2 g phosphorus as monocalcium phosphate, 6 mg copper as copper sulphate, 100 mg iron as ferrous sulphate, 100 mg zinc as zinc oxide, 0.2 mg selenium as selenomethionine, 10 mg manganese as manganous oxide and 0.2 mg iodine as calcium iodate on a calcium carbonate/calcium carbonate carrier.

b The amino acid pack contained supplementary L-Lysine HCl to maintain a total dietary lysine concentration of 11 g kg⁻¹, and L-Methionine, L-Threonine and L-Tryptophan on a calcium carbonate carrier providing total dietary levels relative to lysine of 60% Methionine + Cysteine, 65% Threonine and 20% Tryptophan.

c Calculated concentration.
formulated to contain 11.0 g kg⁻¹ of total lysine. All amino acid requirements were met relative to lysine (van Lunen and Cole, 2001). The diets were milled and mixed on site and fed ad libitum in meal form from single space feeders. A composite sample of each was collected during bagging off and retained for analysis.

2.2. Animals and housing

Thirty-two finishing pigs, 16 boars and 16 gilts, the progeny of Large White × Landrace sows were selected from the finishing herd. Eight pigs, four boars and four gilts, were assigned to each dietary treatment. Each treatment was balanced for sex and initial live weight. The experimental period lasted 23 days. This procedure was replicated three times (n = 3). The pigs were allowed a 14-day dietary adaptation period after which time they were transferred to the sealed pens (day 1). Pigs were weighed at the start and end of the period. Pigs were housed in partially slatted pens (30:70 slat:solid floor ratio). There was capacity for four weeks manure storage under the slatted area in 800 mm-deep pits. The entire pen and respective manure pit were sealed off from the rest of the house. Each pen was individually ventilated via a fan sited in the external wall above the slatted area. Supplementary heat was provided by electric bar heaters. Mean pen temperature was 18.7 °C (s.d. 1.44) over the experimental period. Water was available from a nipple drinker above the slatted area. Two sealed pens were available allowing two diets to be fed simultaneously. Diets A and C and diets B and D were studied in run 1, diets A and D and diets B and C were studied in run 2 and diets A and B and diets C and D were studied in run 3.

2.3. Sample collection

The manure was sampled on days 9, 14, 21 and 23 at two depths, less than 100 mm below the manure surface (surface) and less than 100 mm from the base of the pit (base). Samples were collected using a probe constructed from a PVC pipe and fitted with a bung, which could be opened and closed at the desired depth using a centrally located bar. This allowed the manure to be sampled from the base of the pit. On each occasion, three samples of manure were collected from the base and surface of the pit. The three samples from each depth were amalgamated into a composite sample. Further samples from both levels were combined also to make a composite sample.

On the same days as the manure was sampled, measurements of ammonia (NH₃, nitrogen × 1.216) in the exhaust air from each pen were taken using Dräger tubes (Dräger, 1998). The NH₃ emission was expressed as grams of NH₃ per day per animal (g d⁻¹ animal⁻¹). Air samples were collected using the method described by Hayes et al. (2004) and analysed for odour threshold according to Comité Europeen de Normalisation (1999). The odour emission rate (OER) was expressed as European odour units emitted per second per animal (OUₑ s⁻¹ animal⁻¹) (1 OUₑ ≈ 40 ppb of n-butanol).

2.4. Laboratory analysis

The pH and temperature of the composite slurry sample were taken immediately after sampling using a portable electrode (HI-98128, Hanna Instruments, Rhode Island, USA). A sub-sample was frozen and retained for laboratory analysis. The remaining sample was weighed and dried to a constant weight in a fan-assisted oven at 100 °C for the calculation of Dry matter (DM). Proximate analysis of diets for DM and ash was carried out according to the Association of Analytical Chemists (1995). The total Kjeldahl nitrogen (TKN, ppm) of manure samples and the CP (TKN × 6.25) concentration of feed were analysed by the macro-Kjeldahl technique using a Buchig digestion distillation apparatus. Total ammoniacal nitrogen (TAN = NH₃ + NH₄⁺) was determined by direct steam distillation of 5 g manure samples suspended in 150 ml distilled deionised water containing 10 g magnesium oxide (MgO). The distillate was collected in 50 ml 2% boric acid and the TAN content was determined by a colorimetric back-titration against 0.1 N HCl (Stevenson, 1982). Thawed slurry samples were analysed for volatile fatty acid (VFA) concentration and profile using the method of Leek et al. (2004). Analysis of all samples was performed in duplicate.

2.5. Statistical analysis

An analysis of variance was computed using the GLM procedure of SAS 6.14 for Windows (1996, SAS Institute Inc., Cary, NC, USA). The model used included the effect of diet, sampling level (i.e. manure surface or pit base), run number, day of sampling and the associated two and three-way interactions. There was no significant interaction between the main effects. Linear and quadratic effects of CP concentration (g kg⁻¹ analysed) were examined. Results are presented as LSMEAN of dietary treatment and sampling depth. Effects could be considered significant when contrast probabilities were below 0.05. Pearson correlations were used to relate measurements of manure composition and emissions of odour and ammonia. Multivariate regression analyses between CP content, manure components, OER and NH₃ emissions were performed using Excel® spreadsheet. For the purpose of analysis, pH values were transposed into the linear scale hydrogen ion concentration (H⁺, mmol l⁻¹) and are reported as pH values in tables and text (pH = −log[H⁺]).

3. Results

3.1. Effect of dietary crude protein concentration

The effect of dietary CP and sampling depth on manure composition is shown in Table 2. Manure pH decreased
Table 2
The effect of crude protein concentration and sampling depth on manure characteristics

<table>
<thead>
<tr>
<th>Diet</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>s.e.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysed crude protein concentration (g kg⁻¹)</td>
<td>133.2</td>
<td>157.4</td>
<td>190.0</td>
<td>206.4</td>
<td></td>
</tr>
<tr>
<td>Dry matter (g kg⁻¹)</td>
<td>17.1</td>
<td>24.2</td>
<td>21.7</td>
<td>18.0</td>
<td>3.20</td>
</tr>
<tr>
<td>pH</td>
<td>7.45</td>
<td>7.33</td>
<td>8.48</td>
<td>8.42</td>
<td>8.13</td>
</tr>
<tr>
<td>Manure temperature (°C)</td>
<td>15.42</td>
<td>15.45</td>
<td>14.38</td>
<td>14.95</td>
<td>0.479</td>
</tr>
<tr>
<td>Total Kjeldahl nitrogen (TKN, ppm)</td>
<td>1925</td>
<td>2365</td>
<td>3133</td>
<td>3578</td>
<td>278.57</td>
</tr>
<tr>
<td>Total ammoniacal nitrogen (TAN, ppm)</td>
<td>1562</td>
<td>1725</td>
<td>2425</td>
<td>2490</td>
<td>98.16</td>
</tr>
<tr>
<td>Acetic acid:propionic acid ratio</td>
<td>4.66</td>
<td>4.25</td>
<td>4.77</td>
<td>5.84</td>
<td>0.174</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>7.39</td>
<td>10.24</td>
<td>9.64</td>
<td>8.30</td>
<td>1.143</td>
</tr>
<tr>
<td>Butyric acid</td>
<td>4.16</td>
<td>12.96</td>
<td>7.06</td>
<td>6.30</td>
<td>2.322</td>
</tr>
<tr>
<td>Isobutyric acid</td>
<td>0.57</td>
<td>0.83</td>
<td>0.72</td>
<td>0.68</td>
<td>1.099</td>
</tr>
<tr>
<td>Volatile fatty acids (mmol l⁻¹)</td>
<td>0.858</td>
<td>0.783</td>
<td>0.807</td>
<td>0.793</td>
<td>0.060</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>33.33</td>
<td>40.65</td>
<td>44.74</td>
<td>47.53</td>
<td>4.131</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>7.39</td>
<td>10.24</td>
<td>9.64</td>
<td>8.30</td>
<td>1.143</td>
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<td>7.06</td>
<td>6.30</td>
<td>2.322</td>
</tr>
<tr>
<td>Isovaleric acid</td>
<td>1.57</td>
<td>ND</td>
<td>1.30</td>
<td>3.00</td>
<td>0.613</td>
</tr>
<tr>
<td>Valeric acid</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>Total volatile fatty acid g</td>
<td>47.15</td>
<td>64.30</td>
<td>62.73</td>
<td>64.47</td>
<td>7.445</td>
</tr>
<tr>
<td>TAN:TKN ratio</td>
<td>0.858</td>
<td>0.783</td>
<td>0.807</td>
<td>0.793</td>
<td>0.060</td>
</tr>
<tr>
<td>pH</td>
<td>7.45</td>
<td>7.33</td>
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<td>0.858</td>
<td>0.783</td>
<td>0.807</td>
<td>0.793</td>
<td>0.060</td>
</tr>
</tbody>
</table>

**Notes:**

- a Linear effect of CP concentration (P < 0.05).
- b Linear effect of CP concentration (P < 0.01).
- c Linear effect of CP concentration (P < 0.001).
- d Quadratic effect of CP concentration (P < 0.05).
- e Effect of sampling depth (P < 0.05).
- f Effect of sampling depth (P < 0.01).
- g Effect of sampling depth (P < 0.001).
- h ND = not determined (<1.0 mmol l⁻¹).
- i The s.e. of H⁺ was 7.52 nmol l⁻¹ (crude protein) and 5.17 nmol l⁻¹ (depth).

(linear, P < 0.001) as dietary CP was reduced. As the dietary CP concentration decreased, there was a reduction of the TKN (linear, P < 0.01) and TAN (linear, P < 0.001) concentrations in the manure, although the TAN:TKN ratio was not affected. The concentration of acetic acid declined as the dietary CP concentration decreased (linear, P < 0.05). The acetic:propionic acid ratio was affected by dietary CP concentration (quadratic, P < 0.001). Individual contrasts indicated that manure from pigs fed diet B contained a higher concentration of butyric acid than that from pigs fed diets A or D (P < 0.05).

There was a quadratic (P < 0.01) relationship between OER and the concentration of dietary CP (10.17, 8.65, 11.73 and 13.80 O₂ U⁻¹ s⁻¹ animal⁻¹, s.e. 0.838, for 130, 160, 190 and 210 g kg⁻¹ CP diets respectively). Individual contrasts indicated that pigs fed diet D had higher OER (P < 0.01) than pigs fed diets A or B. The OER of pigs fed diet B was lower (P < 0.05) than that of pigs fed diet C. NH₃ emission increased with increasing CP concentration (2.38, 3.19, 4.94 and 6.38 g d⁻¹ animal⁻¹ for 130, 160, 190 and 210 g kg⁻¹ CP diets respectively, s.e. 0.615, linear, P < 0.01).

3.2. Effect of sampling depth

Analysis of manure samples collected from the base of the pit indicated higher concentrations of DM (P < 0.001), TKN (P < 0.01), TAN (P < 0.01), tVFA (P < 0.001), acetic acid (P < 0.001), propionic acid (P < 0.001) and isobutyric acid (P < 0.05). The pH (P < 0.01), temperature (P < 0.05) and TAN:TKN ratio (P < 0.01) were lower in the samples collected from the base of the pit.

3.3. Relationship between manure composition, OER and ammonia emission

Pearson correlations between manure measurements and emissions of odour and ammonia are shown in Table 3. OER was correlated with the acetic acid:propionic acid ratio (r = 0.79, P < 0.001), TAN concentration (r = 0.53, P < 0.05) and H⁺ concentration (r = −0.51, P < 0.05). The emission of NH₃ was correlated with TAN concentration (r = 0.74, P < 0.001), H⁺ concentration (r = −0.60, P < 0.05) and the acetic:propionic acid ratio (r = 0.59, P < 0.05). There was a correlation between OER and NH₃ (r = 0.63, P < 0.01).

Regression analysis was performed between emissions, the dietary CP content and the manure composition. The regression equations are summarised in Table 4. The OER was estimated as: (i) a quadratic function of dietary CP concentration (R² = 0.56, P < 0.01, Eq. (1)), (ii) a linear function of the acetic acid:propionic acid ratio (R² = 0.55, P < 0.001, Eq. (2)) and (iii) a multivariate function of acetic acid and propionic acid concentrations in samples collected
from the base of the pit ($R^2 = 0.84$, $P < 0.001$, Eq. (3)). The NH$_3$ was estimated as: (i) a linear function of dietary CP concentration ($R^2 = 0.63$, $P < 0.001$, Eq. (4)), (ii) a multivariate function of dietary CP concentration and TKN ($R^2 = 0.72$, $P < 0.001$, Eq. (5)) and, (iii) a multivariate function of TKN and total VFA in samples collected from the pit surface ($R^2 = 0.70$, $P < 0.001$, Eq. (6)).

4. Discussion

4.1. Effect of dietary crude protein concentration

Reducing dietary CP concentration by 10 g kg$^{-1}$ resulted in a 6.7% decrease in TKN concentration. The response is lower than the decrease of total nitrogen excretion reported to be equivalent to 8.4% (Kerr, 1995) and 8.7% (Leek et al., 2005) per 10 g kg$^{-1}$ CP reduction. Furthermore, TAN concentration only decreased by 4.8% per 10 g kg$^{-1}$ reduction in CP concentration, whereas Aarnink et al. (1993) estimated that TAN decreased by 9% per 10 g kg$^{-1}$ reduction of dietary CP concentration. However, the concentration of manure components will be affected by the dilution of manure by water wastage (Aarnink et al., 1993). There is evidence that water wastage contributed substantially to the manure volume in this experiment. On average, the DM concentration of the manure collected from the pits was lower than the DM of manure collected directly from pigs without water contamination in a previous balance experiment using identical diets (20.8 vs 78.5 g kg$^{-1}$) (Leek et al., 2005). The manure dilution factor appears to be high in the current experiment. Canh et al. (1998a) reported that manure DM was 42% lower in a barn experiment than in a balance experiment. In the current study, the DM concentration of the manure was not affected by dietary CP content. Previous reports have indicated that decreasing the concentration of dietary CP reduces water intake (Pfeiffer et al., 1995), manure volume (Kay and Lee, 1997) and manure DM concentration (Leek et al., 2005). The results suggest that wastage of water by the pigs diluted the manure and influenced the dietary effect on manure compositional analysis. With nipple drinkers, pigs have been known to play with nozzles and rather more water loss can occur. Unfortunately the water usage was not measured in the current study.

The concentration of total VFA in the manure samples was not affected by the concentration of dietary CP. Acetic acid is produced by the fermentation of protein (Zhu et al., 1999), and the positive relationships between acetic acid concentration and both dietary CP concentration and manure TKN suggest that the fermentation of nitrogenous material contributed to its presence. Conversely, butyric acid and propionic acid concentrations were positively related to manure DM but not total nitrogen concentration. Previous research has reported that the ratio of acetic acid to propionic acid decreases when carbohydrate

\[ \text{Acetic acid:propionic acid ratio} \]

\[ \frac{\text{Acetic acid}}{\text{Propionic acid}} \]

\[ < 0.1 \]

\[ < 0.001 \]

\[ < 0.05 \]

\[ < 0.01 \]

\[ < 0.001 \]
replaces protein as the fermentation substrate (Marounek et al., 2002). Specifically, Mackie (1995) reported that propionic acid is produced by the deamination of threonine, glutamate and aspartate, whilst acetic acid is produced by deamination of alanine, glycine, serine, glutamate and aspartate. As it is an essential amino acid, the dietary concentration of threonine was maintained as CP was reduced. Conversely, the concentrations of alanine, glycine, serine, glutamate and aspartate decreased as dietary CP was reduced. Therefore, the supply of amino acid contributing to propionic acid was maintained to a greater extent than the precursors of acetic acid and the result was a decrease in the acetic:propionic acid ratio. The results appear to confirm this, because the ratio between acetic acid and propionic acid decreased as the concentration of dietary CP decreased from 210 to 160 g kg⁻¹.

Reducing dietary CP concentration by 10 g kg⁻¹ decreased the rate of NH₃ emission by 8.6%. This decrease is similar to the 8.1% reduction reported in a previous study conducted in the same facility (Hayes et al., 2004). However, the decrease is less than that reported by Kay and Lee (1997) and Canh et al. (1998a). Differences in house design (van der Peet-Schwering et al., 1996) or the degree of pen fouling (Ni et al., 1999) are likely to account for the differences observed between studies.

Reducing the concentration of dietary CP from a high concentration of CP (i.e. 210 or 190 g kg⁻¹) to a low concentration of CP (160 or 130 g kg⁻¹) decreased OER. This is in agreement with Hobbs et al. (1996) and Hayes et al. (2004), who observed a decrease over similar ranges. The lower crude protein diets should not affect pig performance, as Carpenter et al. (2004) reported that a dietary CP content of 150 g kg⁻¹ is the optimum level in terms of live weight gain, feed conversion ratio (FCR), carcass gain and carcass FCR for the sex, genotype and environment present in the current study.

The results of this study indicate that the relationship between OER and the concentration of dietary CP was quadratic, suggesting that other factors influenced OER. Miller and Varel (2003) reported that fermentation of protein accounted for more than half of odour-generation in fresh pig manure, becoming increasingly prevalent as the protein content of the manure increased. Thus, the reduction in OER observed between 210 and 160 g kg⁻¹ is likely to be the result of decreased odourous products arising from the fermentation of protein. However, OER increased as the concentration of dietary CP was reduced below 160 g kg⁻¹, albeit remaining lower than the OER of diets containing 190.0 or 210 g kg⁻¹ CP. Hobbs et al. (1996) acknowledged that dietary factors, other than CP concentration, also affected the production of odourants. Miller and Varel (2003) reported that fermentation of starch in manure also contributes to the production of odourous compounds. In order to reduce the dietary CP concentration in this study, the inclusion of wheat was increased at the expense of soyabean meal. Wheat contains more starch than soyabean meal (Ewing, 1997), which caused the concentration of dietary starch to increase as the concentration of CP decreased. A proportion of dietary starch may resist digestion in the small intestine, supplying fermentable substrate to the microflora of the hindgut (Topping and Clifton, 2001). Thus, it appears that odour emissions may be minimised by achieving an optimum dietary balance between CP and starch.
4.2. Effect of sampling depth

The DM concentration was higher in samples collected from the base of the pit, which is consistent with previous reports (Zhang and Day, 1996). The concentrations of H⁺(pH), TKN, total VFA, acetic acid, propionic acid and isobutyric acid were positively correlated to DM (Table 3) and consequently, the concentrations of these components were highest in the samples collected from the base of the pit.

Due to the solubility of NH₄+/NH₃ in an aqueous environment and its diffusion up the manure strata (Ruxton, 1995; Ni et al., 1999), the TAN concentration was not correlated to DM (Table 3). Whilst previous reports indicate a uniform distribution of TAN throughout the strata of stored manure (Zhang and Day, 1996), there was a higher TAN concentration in samples collected from the base of the pit in this study. Ammoniacal nitrogen is derived from the hydrolysis of urinary urea by faecal urease (Muck and Steenhuis, 1982) and to a lesser extent from the decomposition of faecal protein (Mroz et al., 1993). Due to the concentration of faecal solids, a high rate of TAN generation is reported to occur in bottom layers of the pit (Zhang and Day, 1996). The stratification of TAN concentration observed in this study may reflect a higher rate of ammonium generation in the base of the manure pit.

4.3. Relationship between manure composition, OER and ammonia emission

As expected, NH₃ emission was significantly related to TAN, TKN and H⁺ concentrations. Although NH₃ emission was linearly related to CP concentration, including the TKN concentration in manure increased the accuracy of the prediction (R² = 0.72) (Table 4) by introducing a measure of manure dilution to the model. This suggests that the manure TKN concentration or manure dilution factors should be considered when assessing the impact of CP concentration on ammonia emission. NH₃ emission could also be expressed as a function of TKN and total VFA concentrations (R² = 0.70) (Table 4). Paul and Beauchamp (1989) reported that the concentration of VFA in the manure was a controlling factor of ammonia emission and including VFA in the model acknowledges the influence of VFA on manure buffering systems (Sommer and Husted, 1995) and manure pH (Canh et al., 1998b). Whilst the response of OER to dietary CP was quadratic (R² = 0.56), there was a linear relationship between OER and the acetic acid:propionic acid ratio (R² = 0.55) (Table 4). The R² of the prediction was increased by expressing OER in terms of acetic acid and propionic acid concentrations in the base of the pit (R² = 0.84). More intense microbial activity and fermentation is likely to occur at the base of the manure pit than in the surface layers of the manure, due to the greater concentration of dry matter and nitrogenous material present there.

In agreement with the results of this study, positive relationships between ammonia emission and odour concentration have been observed previously (Pain et al., 1990). However, it is reported that ammonia does not contribute to odour concentration (Hobbs et al., 2000) and measurement of NH₃ emission does not provide a reliable indication of odour emission (Lui et al., 1993). The generation of NH₃ in manure is largely independent of the dynamics of protein fermentation and therefore the formation of odourous compounds, as NH₃ is derived predominately from the hydrolysis of urea (Spoelstra, 1980). Coincidently, manure that contains high concentrations of ammoniacal nitrogen is also likely to provide a greater quantity of nitrogenous substrate for microbial fermentation. Additionally, pH conditions that favour the volatilisation of NH₃ may also favour the volatilisation of odourous compounds that associate at high pH (e.g. indole, p-cresol and phenol), which was perhaps reflected by the inverse relationship between H⁺ and OER. Consequently, a synergy between NH₃ emission and OER may be expected, but as the dynamics of production are different, OER and NH₃ emissions should be regarded as separate entities.

5. Conclusions

From an environmental protection point of view, the current experiment would confirm that reducing dietary CP levels could be used effectively to reduce N excretion and ammonia emissions, although no significant advantage was to be gained in OER from reducing CP level below 160 g kg⁻¹. This optimum level of CP should not affect pig performance. The relationship determined between OER and the ratio of acetic acid to propionic acid provides an indication of the type of fermentation processes that were occurring within the manure. The results suggest that volatile emissions that contribute to the perception of malodour are associated with a high ratio of acetic acid to propionic acid in manure.

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