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The Environmental Impact of Lowering Dietary Crude Protein in Finishing Pig Diets—The Effect on Ammonia, Odour and Slurry Production

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Abstract: Excess nitrogen excretion, ammonia and odour are environmental pollutants associated with pig production. Reducing dietary crude protein (CP) will lower the amount of nitrogen excreted, reducing the potential for ammonia emissions, if diets are adequately formulated to supply amino acids and production performance is maintained. Crude protein content in diets for finishing pigs has been lowered recently, but the quantitative effect of this reduction on ammonia, odour, and slurry output is not well-established. The relationship between ammonia and odour is equivocal, and the effect on slurry production is unclear. The objective of this study was to investigate the effect of lowering dietary CP on ammonia emission, odour emission and slurry output of finishing pigs. Thirty entire boar pigs were individually housed in groups of six, from 10 weeks of age (30 ± 3.0 kg) and offered standard diets. At 75 kg (±1.5 kg) pigs were assigned to one of three treatment diets; (1) 180 g/kg CP, 11.0 g/kg total lysine (High CP), (2) 150 g/kg CP, 11.1 g/kg total lysine (Medium CP), and (3) 130 g/kg CP, 9.0 g/kg total lysine (Low CP). After three weeks on the experimental diets pigs were moved, six each week, to individual calorimetry chambers to measure ammonia and odour emissions. Pigs were offered treatment diets ad libitum. At the end of the recording period, the pigs were removed from the chamber, weighed and feed disappearance recorded to calculate intake. The slurry in each chamber was collected and analysed. The reduction in CP in the diet from 180 g/kg to 150 g/kg resulted in a 22% reduction in ammonia emissions, and from 180 g/kg to 130 g/kg resulted in a 47% reduction ($p < 0.001$). Slurry output from pigs offered the 130 g/kg CP diet was reduced by 39% ($p < 0.001$) and dry matter increased by 35% compared to slurry from pigs offered the 180 g/kg CP diet ($p < 0.05$). Water usage ($p = 0.017$), slurry output and nitrogen and phosphate in the slurry ($p < 0.05$, respectively) were found to decrease linearly with decreasing dietary CP content. There was no significant effect of reducing CP on performance or odour emission but hydrogen sulphide emissions decreased linearly ($p < 0.010$) with decreasing dietary CP. There was a weak positive relationship between odour emission and ammonia (linear: $R^2 = 0.25$, $p = 0.005$) with odour emission reduced as ammonia emission reduced. Reducing dietary CP in finishing pig diets could reduce ammonia emissions, water usage and slurry and nutrient output from pig production.

Keywords: crude protein; finishing pigs; ammonia; odour; slurry

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1. Introduction

Ammonia emissions have risen steadily since the industrial revolution and the intensification of agricultural production with agriculture (including fertiliser production) being responsible for almost 90% of global emissions [1]. As ammonia gas is an environmental pollutant, there is a world-wide drive to reduce ammonia emissions from agricultural production systems. Ammonia pollution results in a detrimental effect on areas of special

scientific interest with the loss of biodiversity. This loss of biodiversity not only negatively changes the natural environment but also reduces carbon sequestration ability, which has wider negative implications in terms of greenhouse gas emissions. Furthermore, ammonia is also a significant source of nitrous oxide, a potent greenhouse gas, which causes environmental damage at both local and global levels [2]. Ammonia from pigs is primarily produced through the mixing of urine and faeces. The nitrogen (N) in the urine, in the form of urea, is converted to ammonium through the action of the enzyme urease produced by microbial action in the faeces. When excreted, the process of ammonium production begins and depending on conditions (e.g., temperature and pH), the ammonium is dissociated to ammonia which is then volatilised as ammonia gas [3]. High levels of ammonia gas can cause health and welfare problems for humans and pigs [4], affects air quality and ultimately is deposited on land causing acidification, the loss of biodiversity and eutrophication. A reduction in the level of dietary crude protein (CP) may result in less nitrogen excreted in urine, and therefore a reduced potential for ammonia creation, provided CP and digestible amino acids are adequately supplied and the diet is formulated to ensure that production performance is maintained [5]. It has been estimated that a 1% unit reduction in dietary CP content can lead to an 8–10% reduction in ammonia production [6]. However, this relationship has not been established using pigs of current genetics, offered feed ingredients currently used in finishing rations with dietary CP less than 140 g/kg. Odour emissions from pig units are also problematic, which can cause issues with neighbours, and if in excess, hinder business expansion. The association between dietary CP content and odour production is not clear [7], but there is evidence to suggest that modifying the dietary CP content and other dietary ingredients such as fibre, affects the microbial profile within the gastrointestinal tract, which reduces the production of ammonia and odorous compounds [8]. Modifying the microbial profile can also influence the production of urease and thereby limit ammonia production. Furthermore, the effect of lowering dietary CP on slurry production has not been well established, although research has indicated that water intake is reduced as a result of lowering CP [9], reducing overall slurry production, which may have obvious benefits for storage and handling.

The objective of this study was to investigate the effect of offering finishing pigs high (traditional), medium or low dietary CP on ammonia and odour emissions and subsequent slurry production and nutrient output in slurry.

2. Materials and Methods

2.1. Experimental Design, Animals and Measurements

The trial was conducted under the Animals (Scientific Procedures) Act 1986 and procedures were approved by the AFBI Hillsborough Animal Welfare and Ethical Review Body.

Thirty entire boar pigs (Danish Duroc) were individually housed in five separate groups of six, from 10 weeks of age (30 $\pm$ 3.0 kg) and offered commercial pre-trial diets ad libitum (diet A: 185 g/kg CP, 15.0 MJ/kg digestible energy (DE) between 10 weeks of age and 45 $\pm$ 3.0 kg, followed by diet B: 165 g/kg CP and 14.3 MJ/kg DE to 75 $\pm$ 1.5 kg). Pigs were then assigned to one of three treatment diets ad libitum; (1) 180 g/kg CP, 11.0 g/kg total lysine (High CP), (2) 150 g/kg CP, 11.1 g/kg total lysine (Medium CP), and (3) 130 g/kg CP, 9.0 g/kg total lysine (Low CP). Treatments 1 and 2 were formulated to have the same total amino acid content but different CP and treatment 3 was formulated to have lower CP with the total lysine: CP ratio being comparable to treatment 2. Treatment 3 was formulated to 120 g/kg CP but when analysed was 130 g/kg hence treatment 3 is referred to as, and all calculations are based on, 130 g/kg. Diets were formulated by John Thompson and Sons Ltd. to the same DE (14.0 MJ/kg) and balanced for ideal protein according to BSAS (2003) [10] (Table 1). Individual pig performance (daily feed intake (DFI), average daily gain (ADG) and feed conversion ratio (FCR)) was determined for three weeks.

Table 1. Ingredient and formulated nutrient composition of experimental diets (g/kg).

	180 g/kg CP	150 g/kg CP	130 g/kg CP
Ingredient, g/kg			
Barley	210	275	250
Wheat	263	344	447
Maize	175	155	155
Maize DDGS	30	-	-
Pollard	75	50	50
Rapeseed meal	50	50	50
Soybean meal	164	80	-
Soya oil	10	10	12
DeviGainPG [a]	-	10	10
L-Lysine HCl	3.3	5.0	5.0
DL-Methionine	0.4	1.0	0.3
L-Threonine	0.9	1.7	1.4
L-Tryptophan	-	0.3	0.2
Limestone	8.8	9.1	9.4
Mono dicalcium phosphate	2.1	2.8	3.5
Salt	4.4	3.3	3.3
Mineral and vitamins [b]	3.0	3.0	3.0
Formulated composition, g/kg			
Crude protein	182.2	150.0	120.8
Oil A	32.4	29.6	30.6
Crude Fibre	39.3	36.5	35.0
Ash	45.5	40.5	37.6
Total Lysine	11.0	11.1	9.0
Total Methionine	3.2	3.8	2.8
Total Methionine and cysteine	6.6	6.75	5.4
Total Threonine	7.4	7.5	6.0
Total Tryptophan	2.3	2.1	1.7
Lysine:CP ratio	0.06	0.07	0.07
Calcium	6.9	7.0	7.0
Available phosphorus	3.2	3.0	3.0
Salt	6.5	6.5	6.5
Digestible Energy (MJ/kg)	14.0	14.0	14.0

[a] DeviGainPG® is a source of sugar-bound amino acids which are slowly released in the small intestine to optimise absorption, (Devenish Ltd., Belfast, UK). [b] Supplied per tonne of diet: vitamin A 8000 iu, vitamin D3 2000 iu, vitamin E 75 g, vitamin K 1 g, vitamin B2 2 g, vitamin B12 20 mg, biotin 0.05 g, calcium D-pantothenate 8 g, niacin 10 g, iodine 1 g, selenium 0.15 g, iron 100 g, manganese 30 g, copper 12.5 g, zinc 70 g, xylanase 50 g, phytase 750 FTU.

After three weeks on the experimental diets, six pigs from each of the batches were moved on a weekly basis, for five consecutive weeks, to individual indirect open-circuit calorimetry respiration chambers (2 mL × 1.5 mW × 1.8 mH) to measure ammonia and odour emissions. Hence, there were ten replicates for each treatment, two pigs per treatment per week for five weeks. Ventilation in the chambers was supplied between 16 and 20 m^3/h by suction pumps which operated by creating a slight negative pressure. Temperature was maintained at 19 °C and relative humidity was set between 60 and 70%. The exhaust air was removed from six chambers separately for measurement of volume, temperature, humidity and pressure. The airflow was recorded from each chamber by thermal mass flow meters (FCIST50, Fluid Components International LLC, San Marcos, CA, USA) installed in the six ducts between each chamber and the photoacoustic gas analyser. The meters were calibrated by a Testo417-Vane Anemometer (TestoAG, Lenzkirch, Germany). Ammonia concentrations were measured in the air in, and the air out, of each chamber every 14 min (intervals for each chamber was set at 120 s) using a photoacoustic gas monitor (Innova 1412i, LumaSense Technologies, Santa Clara, CA, USA). The monitor was calibrated weekly using oxygen-free nitrogen. After ~24 h in the chambers, the analysers recorded ammonia production for a total of ~73 h. Pigs were offered treatment diets ad libitum.

At ~28 h of recording, odour samples were collected into Nalphan NA sample bags through PTFE sampling pipe. The sample bags were fitted in rigid "barrels", which were partially evacuated to provide the vacuum to draw air along the sample tube into the bags (lung principle). The vacuum was generated by porTable 12 v battery electric pumps. Air velocity measurements were recorded at the time of sampling from AFBI automatic data logger. The bags were transferred to Silsoe Odour (Bedfordshire, UK) and hydrogen sulphide and odour emission concentrations were measured. Hydrogen sulphide was determined by Jerome® 631X Hydrogen Sulphide (Arizona Instruments LLC, Chandler, AZ, USA) monitor and odour emissions were measured using dynamic olfactometry (BSEN13725:2003). At the end of the recording period, the pigs were removed from the chamber, weighed and their feed disappearance recorded to calculate intake. Water usage was continuously recorded via water meters. Water was provided ad libitum through nipple drinkers. The slurry in each chamber was collected, weighed, stored for five months and analysed for volatile odorous compounds. Dry matter of the fresh slurry was calculated by sub sampling the slurry, weighing, drying at 80 °C for 48 h and then reweighed. Dried samples of the fresh slurry were analysed as per the chemical analysis described in Section 2.2 below.

Thirty slurry samples, which equated to the total slurry in each chamber from each pig, were collected in 10-Litre containers and stored sealed for five months. After the storage period, duplicate samples (5 g) of each slurry sample were weighed into 20 mL vials and the volatiles were collected by dynamic headspace extraction. After equilibration with shaking at 45 °C for 5 min, the solid phase microextraction (SPME) fibre was exposed above slurry in the vial headspace for 10 min. Analysis was by DHS TDU using an Agilent 7890B GC/5977B MS with a Gerstel multipurpose sampler. To calibrate, three mixes of authentic compounds over a calibration range of 1–100 ng/µL were analysed using the same instrument with liquid injection. The data were analysed using Mass Hunter software (Agilent Technologies, Inc., Santa Clara, CA, USA). Slurry samples were also analysed for dry matter and mineral analysis to determine nutrient content in slurry and to calculate nutrient output per pig.

2.2. Chemical Analysis

Experimental diet samples were analysed for DM, ash, N, oil (ether extract), fibre and energy content using standard methods [11]. Dietary amino acid contents were determined by ion-exchange chromatography and conducted by Scientec Ltd., Selby, UK, according to methods of the European Commission [12]. Slurry samples were analysed for DM, potassium, phosphorus, magnesium, sulphur and zinc according to the method of Riles [13]. Nitrogen content in slurry was determined using the method described in AOAC [11]. Potassium, phosphorus, magnesium, sulphur and zinc were converted to potash, phosphate, magnesium oxide, sulphate and zinc oxide using the following conversion factors, respectively; 1.205, 2.291, 1.658, 2.500, 1.245.

2.3. Statistical Analysis

Data were analysed using Genstat 19th Edition (Lawes Agricultural Trust, Rothamsted Experimental Station) to determine statistical differences between the dietary treatments. The data were analysed using linear mixed model methodology (REML estimation method). Batch and replication within batch were fitted as random effects while treatment was fitted as a fixed effect. If the overall effect of treatment was significant (assessed using an F-test) then pairwise differences between the levels of treatment were examined using Fisher's Least Significant Difference test. In addition, linear effects of the treatment levels were assessed using F-tests.

3. Results

3.1. Diet Composition

The experimental diets were analysed to contain 184 g/kg, 148 g/kg and 132 g/kg on a fresh basis (Table 2). The analysed values for the two higher CP treatments (180 g/kg and 150 g/kg) were very similar to the formulated values but the 130 g/kg treatment contained higher CP than formulated (132 vs. 120 g/kg). However, the analysed levels of essential amino acids in the 130 g/kg CP treatment were in line with formulated values whereas, the analysed levels for the 180 g/kg and 150 g/kg were somewhat lower than formulated. Thus, the lysine:CP ratios were lower than formulated in these diets.

Table 2. Analysed nutrient composition of experimental diets (g/kg).

Nutrient, g/kg	180 g/kg CP	150 g/kg CP	130 g/kg CP
Dry matter	875.4	870.0	867.8
Crude protein	183.0	148.0	132.0
Oil A	29.0	24.6	25.3
Crude fibre	43.3	34.8	35.7
Ash	39.2	32.6	32.7
Gross energy (MJ/kg)	16.42	16.07	16.00
Alanine	8.20	5.60	5.20
Arginine	10.90	7.20	6.80
Aspartic acid	14.30	9.40	8.70
Glutamic acid	35.80	29.80	28.70
Glycine	7.60	5.60	5.30
Histidine	4.40	3.50	3.00
Iso-leucine	7.10	4.90	4.80
Leucine	13.30	9.70	8.70
Lysine	9.80	9.20	8.80
Methionine	2.80	2.40	2.60
Phenylalanine	7.30	5.50	5.50
Proline	14.30	10.90	9.90
Serine	7.90	5.90	5.50
Threonine	6.60	5.80	5.60
Tyrosine	2.90	1.90	1.50
Valine	9.00	6.20	6.00
Tryptophan	2.10	1.60	1.60
Lysine:CP ratio	0.053	0.062	0.067

3.2. Experimental Measurements

There was no significant effect of lowering CP on overall performance as measured from pigs housed individually prior to being transferred to the chambers (Table 3).

Table 3. The effect of reducing dietary CP on individual pig performance (pre-chamber performance).

	180 g/kg CP	150 g/kg CP	130 g/kg CP	SED	*p*-Value	*p* Lin
Intake (kg/d)	3.40	3.49	3.34	0.149	0.603	0.797
ADG (kg/d)	1.28	1.37	1.35	0.053	0.182	0.139
FCR (kg/kg)	2.68	2.57	2.49	0.152	0.493	0.240

The effects of dietary treatment on nitrogen intake, water usage and ammonia, odour and slurry output are shown in Table 4. As expected, reducing the dietary CP resulted in a significant and linear reduction ($p < 0.001$) in N intake corresponding to the level of CP in the diet. The reduction in CP in the diet from 180 g/kg to 150 g/kg resulted in a 22% reduction in ammonia emissions, and from 180 g/kg to 130 g/kg, led to an overall reduction of 47% (231 vs. 434 g/h, $p < 0.001$). Lowering CP to either 150 g/kg or 130 g/kg linearly reduced water usage ($p = 0.017$) and slurry output per day ($p < 0.001$) (Table 4). The DM of the slurry increased linearly ($p < 0.001$) as dietary CP was reduced. There

was a linear reduction in hydrogen sulphide emissions (p = 0.010) which equated to a 44% reduction as dietary CP was reduced from 180 to 130 g/kg (Table 4). Although not statistically significant, there was a 20% reduction in odour emission as dietary CP was reduced from 180 to 130 g/kg.

Table 4. The effect of reducing dietary crude protein on N intake and water usage and on ammonia, odour, hydrogen sulphide and slurry output.

	180 g/kg CP	150 g/kg CP	130 g/kg CP	SED	*p*-Value	*p* Lin
Nitrogen intake (g)	280.3 ^{b}	259.5 ^{b}	200.9 ^{a}	18.89	<0.001	<0.001
Ammonia (mg/h)	434 ^{b}	338 ^{b}	231 ^{a}	44.8	<0.001	<0.001
Water usage (L/day)	6.3	5.4	4.6	0.68	0.055	0.017
Slurry output (L/day)	3.3 ^{b}	2.3 ^{a}	2.0 ^{a}	0.34	0.001	<0.00
Slurry DM (%)	8.5 ^{a}	10.4 ^{ab}	12.7 ^{b}	1.47	0.017	0.005
Odour emission (OuE/Second)	2.13	1.92	1.70	0.408	0.567	0.290
Hydrogen Sulphide (ppm)	2.13 ^{b}	1.38 ^{a}	1.19 ^{a}	0.353	0.031	0.010

^{a,b} superscripts indicate significance. Means without identical superscripts are significantly different ($p < 0.05$).

Table 5 shows the nutrient profile of slurry on a fresh and dry matter basis and the nutrient output in slurry in g/d. When considering the nutrient profile on a fresh basis, slurry from pigs offered the lower CP diets contained significantly higher levels of nitrogen and zinc oxide ($p < 0.05$). There was no difference in slurry nutrient profile on a DMB with the exception of potash content which was higher (p = 0.003) in slurry from pigs offered 180 g/kg diet and linearly reduced ($p < 0.001$) with decreasing dietary CP. Nitrogen, phosphate, potash and magnesium oxide output in the slurry in g/d basis reduced linearly ($p < 0.05$) with decreasing dietary CP.

Table 5. The effect of reducing dietary crude protein on nutrient profile of slurry (g/kg fresh and DMB) and on slurry nutrient output (g/d).

	180 g/kg CP	150 g/kg CP	130 g/kg CP	SED	*p*-Value	*p* Lin
Nitrogen (g/kg fresh)	1.89 ^{a}	2.44 ^{ab}	2.68 ^{b}	0.310	0.048	0.015
Phosphate (g/kg fresh)	2.95	3.78	3.82	0.564	0.231	0.111
Potash (g/kg fresh)	6.41	6.34	6.55	0.612	0.962	0.833
MgO (g/kg fresh)	1.39	1.64	1.68	0.264	0.485	0.247
Sulphate (g/kg fresh)	1.97	2.79	2.85	0.489	0.122	0.053
ZnO (g/kg fresh)	0.07 ^{a}	0.10 ^{b}	0.12 ^{b}	0.012	0.002	<0.001
Nitrogen (g/kg DMB)	22.65	22.02	21.76	2.202	0.914	0.673

Table 5. *Cont.*

	180 g/kg CP	150 g/kg CP	130 g/kg CP	SED	*p*-Value	*p* Lin
Phosphate (g/kg DMB)	33.70	33.98	30.91	2.769	0.468	0.344
Potash (g/kg DMB)	75.78 [b]	59.86 [a]	53.29 [a]	6.171	0.003	<0.001
MgO (g/kg DMB)	15.84	14.38	13.12	1.159	0.076	0.025
Sulphate (g/kg DMB)	22.86	23.55	21.8	3.329	0.871	0.783
ZnO (g/kg DMB)	0.82	0.86	0.94	0.065	0.185	0.079
Nitrogen in slurry output (g/d)	7.19 [b]	5.44 [a]	5.24 [a]	0.801	0.844	0.018
Phosphate in slurry output (g/d)	10.58	8.32	7.54	1.460	0.116	0.042
Potash in slurry output (g/d)	23.95 [b]	14.19 [a]	12.79 [a]	1.392	<0.001	<0.001
MgO in slurry output (g/d)	4.85	3.55	3.26	0.656	0.054	0.020
Sulphate in slurry output (g/d)	6.67	5.85	5.53	1.018	1.486	0.252
ZnO in slurry output (g/d)	0.25	0.21	0.23	0.024	0.440	0.352

[a,b] superscripts indicate significance. Means without identical superscripts are significantly different ($p < 0.05$).

When the slurry was analysed for volatile odorous compounds after five months storage, there was no significant effect of dietary CP on the majority of the compounds apart from on 2-decanone and skatole (Table 6). Levels of 2-decanone were linearly decreased with decreasing dietary CP ($p < 0.001$) and levels of skatole were significantly higher ($p = 0.007$) in the slurry from pigs offered the 130 g/kg CP diet with levels increasing linearly ($p = 0.006$) as dietary CP decreased.

Table 6. The effect of reducing dietary crude protein on volatile odorous compounds from stored slurry.

	180 g/kg CP	150 g/kg CP	130 g/kg CP	SED	*p*-Value	*p* Lin
Acetic acid (ng/g)	4.28	4.15	4.236	0.109	0.442	0.580
1H-Pyrrole, 3-methyl-(ng/g)	7.53	7.54	7.52	0.027	0.663	0.696
Disulfide, dimethyl (ng/g)	7.55	7.56	7.56	0.011	0.287	0.199
Toluene (ng/g)	8.24	8.26	8.25	0.011	0.242	0.219
4-Octene, (E)-(ng/g)	9.27	9.25	9.27	0.011	0.218	0.919
2-Heptanone (ng/g)	12.31	12.32	12.31	0.007	0.270	0.341
Nonane (ng/g)	12.53	12.51	12.54	0.034	0.614	0.829
Butyrolactone (ng/g)	13.46	13.58	13.54	0.075	0.305	0.244
Benzaldehyde (ng/g)	14.61	14.59	14.59	0.020	0.572	0.327
Dimethyl trisulfide (ng/g)	14.82	14.82	14.82	0.007	0.984	0.928
Phenol (ng/g)	15.20	15.19	15.18	0.012	0.249	0.099
2-Octanone (ng/g)	15.42	15.42	15.43	0.007	0.313	0.146
2-Nonanone (ng/g)	18.23	18.23	18.26	0.018	0.219	0.144
2-Decanone (ng/g)	20.70 [b]	20.68 [a]	20.68 [a]	0.004	<0.001	<0.001
Indole (ng/g)	23.20	23.19	23.19	0.008	0.476	0.281
Skatole (ng/g)	25.25 [a]	25.25 [a]	25.28 [b]	0.013	0.007	0.006

[a,b] superscripts indicate significance. Means without identical superscripts are significantly different ($p < 0.05$).

There was a weak positive linear relationship between ammonia and odour emissions indicating that as ammonia levels decrease, odour levels decrease (Figure 1, R^2 = 0.25, p = 0.005).

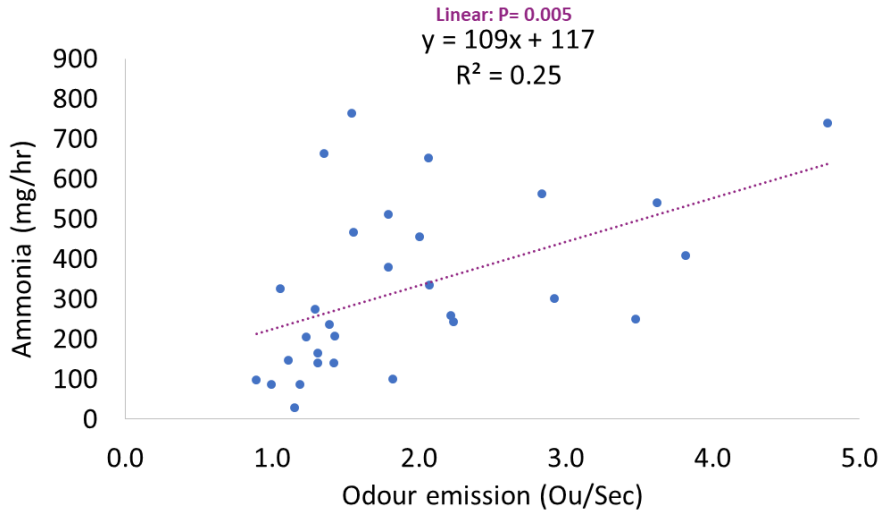

Figure 1. The relationship between ammonia emissions and odour emissions.

4. Discussion

4.1. Diet Analysis

The diets contained common dietary ingredients used across finishing diets in Europe. Wheat, barley and maize were used as the cereal component and maize DDGS, wheat pollard and rapeseed meal comprised the by-product component. Soybean meal inclusion was decreased substantially to reduce the dietary CP content and in the 130 g/kg CP diet there was a zero inclusion of soybean meal. Formulating and producing diets with lower levels of soybean meal reduces the reliance on imported soybean meal and reduces the carbon footprint of production. It has been reported that reducing the soybean meal component of pig diets reduces the global warming potential (GWP) from production [14]. Soybean meal has a high GWP per kg due to deforestation and importation, thus any reduction in inclusion leads to a reduction in GWP. When the GWP of diet formulations were calculated [15], the values were 0.89, 0.70 and 0.49 kg/CO_2 eq. for the 180 g/kg CP, 150 g/kg CP and 130 g/kg CP diets, respectively. Thus, reducing the soybean content substantially reduced the GWP of the diet production. There was excellent agreement between formulated and analysed dietary CP levels of the 180 g/kg and 150 g/kg treatments but the formulated 120 g/kg treatment was analysed at 132 g/kg fresh basis. This highlights the difficulty of formulating lower CP diets and may be a result of the absence of soybean meal and the higher level of wheat in the lowest CP treatment and the way in which the analysed CP content is derived. CP measurement in feeds is not a direct determination but a product of the determination of nitrogen and the application of a conversion factor to convert to protein content. A historic conversion factor of 6.25 has been universally used for over 80 years and is based on the assumption that all proteins had a nitrogen content of 16% and that all nitrogen was derived from protein [16]. It is now widely accepted that the nitrogen:protein ratio varies according to feedstuff and as such, the use of specific correction factors would be more scientifically correct although practically impossible to implement [17]. It has been accepted that in general, the use of 6.25 conversion factor overestimates the CP content of diets [18]. Applying this default 6.25 correction factor to the nitrogen content of diets containing higher levels of cereal and no soybean meal (as is the case for the lowest CP treatment) further exacerbated the overestimation of CP thus making the analysed level appear higher than the formulated. This is supported by the good correlation between the formulated and analysed contents of limiting amino acid in the diets. Based on diet analysis, it can be concluded that dietary treatments of relative

differences in CP were achieved thus making it possible to address the aim of the trial to examine the effect of different CP levels on ammonia, odour and slurry production. The higher level of CP (180 g/kg) is a more traditional level with the majority of the UK and European industry having now moved to lower CP levels in the finishing stage. The lower level of 130 g/kg is not typical of finishing diets for entire boar systems and was included in this work to establish the potential to reduce overall nitrogen excretion.

4.2. Pig Performance, Water Usage, Slurry Output and Ammonia and Odour Emissions

This study focused primarily on the effect on emissions but the effect and implications of reducing dietary CP on production performance is of paramount importance. It is necessary to maintain performance otherwise overall N excretion on a per pig or per kg basis will increase due to increased days to slaughter weight. Under the conditions of this study, where pigs were housed individually and received optimum husbandry and management, there was no significant effect of lowering CP on performance as assessed by feed intake, growth rate and FCR. While it was important to measure individual performance in this study to ensure pigs were adjusted to diets for entry to the calorimetry chambers, it is not applicable to transfer these performance results across to the commercial setting where pigs are kept in groups. Further studies have been conducted within our group to fully establish and validate the effect of lower CP diets on performance and preliminary findings have been disseminated [19,20]. Maintenance of performance is critical to realising benefits from lower CP diets, and the potential reductions in emissions discussed below must be viewed within that context.

The reduction in CP in the diet by 50 g/kg led to a 47% reduction in ammonia. This magnitude of reduction is in keeping with previously published work conducted in countries with similar environmental conditions and production systems as those in this study. For example, Kay [21] reported a reduction of around 10% in ammonia emission for every 10 g/kg decrease in dietary CP. Additionally, Webb et al. [22] summarised six studies and concluded that ammonia emissions decreased by 8% for every 10 g/kg unit decrease in dietary CP. In the current study, considering the reduction in ammonia emissions by offering 130 g/kg cf. 180 g/kg, ammonia emissions reduced by 10% for every 10 g/kg decrease in dietary CP. This is a critical finding as it not only validates the relationship between dietary CP reductions and ammonia emissions but it also provides evidence that pig producers have reduced ammonia emissions since the move away from the traditional higher levels (180 g/kg) of CP in finishing diets.

Lowering CP to either 150 g/kg or 130 g/kg reduced water usage and slurry output per day. The reduction in water intake equated to 27% less water usage and 40% less slurry produced per day. The higher level of water usage on the 180 g/kg CP diet indicated that amino acids were supplied in excess which the pig had to deaminate and excrete the excess as urea in the urine—a process which requires energy and water [23]. Reducing water intake directly reduced urine and therefore slurry output and the observed reduction of 40% less slurry is in keeping with the magnitude of reductions reported by others. For example, Portejoie et al. [24] reported a 38% reduction in slurry output when dietary CP was reduced from 200 to 120 g/kg. Reducing overall slurry output, will have obvious practical benefits for pig producers in relation to slurry management.

Reducing dietary CP also has benefits on overall nutrient output despite the expected concentrating effect of increasing DM in slurry from pigs offered the lower CP diets. It is well established that increasing DM, concentrates nutrients within a sample [25]. However, the concentrating effect on the nutrient profile was limited, only significant for nitrogen and was negated by the reduction in the overall output from pigs offered lower dietary CP and in the case of nitrogen, the lower nitrogen intake. Therefore, when nutrient output in slurry was calculated there was a reduction in g/d output of nitrogen, phosphate, potash and magnesium oxide from pigs offered the lower CP diets. This is an important finding in terms of accurate prediction of nutrient excretion, in adhering to environmental legislation and correctly profiling the nutrient content of pig slurry. It is acknowledged that the

nitrogen content of the slurry from pigs in this study is substantially lower than other published values. The Nutrient Management guide [26] states that the average pig slurry of 4% DM contains 3.6 g/kg nitrogen which equates to 90 g/kg on a DMB. In the current study, the average slurry nitrogen content was 2.3 g/kg fresh basis and 22.1 g/kg DMB and the difference can be explained through the loss of nitrogen in the period between excretion, sample collection and analysis. It was necessary to sub-sample and freeze the samples prior to analysis and nitrogen would have been lost as the samples were de-frosting. This freezing/de-frosting process would only have affected the nitrogen content and despite the absolute value being lower than anticipated, the comparative differences between treatments are valid as all samples underwent the same process. Thus, decreasing dietary CP from 180 g/kg to 150 g/kg reduced overall nitrogen in the slurry by 24%. This is in keeping with the overall ammonia reduction and is a result of lower nitrogen intake, lower water intake and reduced slurry output. This reduction is in agreement with other studies that have focused on overall nitrogen excretion [22] but the present study is the first to show the combined effect on nitrogen output and slurry output. The potash content of the slurry is also of interest and this was highest in slurry from pigs offered the highest dietary CP. This diet contained the highest level of soyabean meal, a dietary ingredient high in potassium, and therefore contained the highest potassium content which carried through to slurry output. Published values for potash content in pig slurry are 55 g/kg DMB [26] which is similar to the content of slurry from pigs offered 15 g/kg and 130 g/kg CP diets but lower than slurry from pigs offered the 180 g/kg CP diet. Magnesium oxide levels are similar to those in the published standards (17.5 g/kg DMB, [24]) but sulphate contents are higher in slurry from the current study (22.7 vs. 17.5 g/kg DMB). It is important to have an accurate profile of the nutritive value of slurry to enable accurate nutrient balance plans and accurate application to crop requirements when land spreading. This is particularly the case for nitrogen and phosphate as both are environmental pollutants and cause problems to freshwaters [27]. It is interesting to note that pig slurry from pigs offered the commercial-like diets in this study contain 12% lower levels of phosphate than that quoted in the published standards (37.5 vs. 32.9 g/kg DMB). This can be attributed to the use of phytase and lower levels of total phosphate in modern pig diets and indicates a need to up-date the current standards.

The observed reductions in both odour and hydrogen sulphide emissions may be important in the commercial setting. The odour emissions measurement used in this study is a standardised method to measure odour using the human sense of smell. A sample of the odour was taken from the calorimetry chamber and then presented to trained panel members who identified the level of dilution required for its minimum detection threshold to be reached. This is expressed odour units per m^3 and in this study, subsequently converted to odour units per second (OUe/second) using the air flow rate measured in the chambers. The lower the value, the less dilution required to reach the minimum detection threshold and therefore the lower odour. The average value (1.94 OUe/second) obtained for odour emissions in this study is substantially lower than other published values. For example, Hover et al. [28] reported average values of 28.7 OUe/second while Webb et al. [20] suggested a range of 10–20 OUe/second for finishing pigs. The lower values obtained in this study can be explained by the fact that odour emission measurements were taken from the chambers when pigs had only been in situ for around 28 h. The chambers were cleaned before entry and the slurry tanks were also clean and dry. Therefore, there was little time for odour to build up within the chamber and relatively little slurry for odour to be emitted from. However, as all pigs offered the different dietary treatments were treated identically, the comparative differences between odour arising from pigs offered the dietary CP levels stand. There are hundreds of different compounds and chemicals that contribute to pig odour and odour emissions from pig production. Twenty eight of the key problem chemicals have been listed and ranked in order of odour activity value [6]. The five most potent compounds were reported to be hydrogen sulphide, p-cresol, dimethylsulphide, ammonia and butanoic acid. Reducing dietary CP should in theory have

caused a reduction in odour production as these and other compounds are produced from the microbial breakdown of nitrogen and other nutrients in the slurry [29]. However, the fact that there was little time for slurry to build-up and for decomposition to occur, may have masked the potential impact of reducing dietary CP on odour concentration.

For this reason, the slurry was stored for five months and then analysed for volatile odorous compounds. There was no significant effect of dietary CP on the majority of the compounds which is in contrast to Sunback et al. [28] who reported a reduction in odour compounds as dietary CP was decreased. However, skatole levels were significantly higher ($p < 0.01$) in the slurry from pigs offered the 130 g/kg CP diet, albeit the numerical differences were very small and may not be biologically relevant. Nevertheless, this skatole result is difficult to explain as Sungback et al. [30] reported that lowering dietary CP caused a shift in the microbial profile within the gut and resulted in less skatole producing bacteria. This apparent adverse effect on skatole production in slurry from pigs offered lower CP diets warrants further investigation as skatole is an important odorant and also held responsible for "boar taint" (along with androstenone). Skatole arises as a result of hind-gut microbial fermentation of tryptophan and therefore a reduction in protein microbial fermentation through reduced dietary CP has shown reductions in skatole production [31]. However, there are interactions between dietary CP and dietary fibre which influence microbial fermentation and it could be argued that lowering the dietary CP resulted in a decrease in fermentable fibre in the 130 g/kg diet, thus causing an increase in skatole production [32].

Despite some studies listing ammonia as a potent, odorous compound, the relationship between ammonia and overall odour production has not been well established. In this current study when the relationship between ammonia emission and odour emission was statistically analysed, there was a weak positive relationship between odour and ammonia. This is in keeping with Hayes et al. [33] who measured ammonia and odour emissions from a number of pig production systems including sows, weaners and finishers. These workers did not calculate the relationship between ammonia and odour but when regression analysis was conducted on their results a strong, positive relationship ($R^2 = 0.83$, $p < 0.001$) was observed between ammonia and odour. Thus, mitigation strategies that reduces ammonia emissions may also reduce overall odour from pig production. However, it must be noted that the strategy of lowering dietary CP to lower odour may only be effective to a certain level as lower levels of dietary CP have been reported to increase odour. The reason for this has been attributed to the increased sulphur arising from the higher level of methionine supplementation to maintain production performance [22]. This was not the case in the current study.

5. Conclusions

Overall, ammonia emissions were lowered by on average 10% for a 10 g/kg reduction in dietary CP. Lowering dietary CP reduced water usage, slurry output and nutrient output in slurry. The numerical difference between odour emissions and the significant effect on hydrogen sulphide production suggest that lowering dietary CP may reduce odour and this is supported by statistically significant relationship observed between ammonia and odour. It is important to consider production performance when lowering dietary CP even when the dietary reductions are balanced to supply essential amino acids. Lower dietary CP reduces the reliance on imported soybean meal, thus reducing the GWP of diet production and the overall carbon footprint of pig production.

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