Effect of feed wastage on piggery manure characteristics and methane potential

**Final Report
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Executive Summary

Feed costs represent 65% of total pork production costs in Australia. On a national scale, a 5% change in feed wastage represents 82,000t feed/yr., with a current annual value of approximately $38 M. In addition to the direct financial implications, feed wastage also influences the characteristics of the effluent discharged from intensive piggery sheds. Reliable estimates of effluent characteristics are essential for effectively designing and operating piggery waste management systems to maximise the economic value of the nutrients and energy potential of the effluent, without causing adverse impacts on the environment or community amenity. Although it is widely recognised that feed wastage is an important issue that can have a major influence on the profitability of pork production, there are currently no simple or practical methods available for directly measuring feed wastage in piggeries.

To assist in developing improved predictive tools to assess and manage feed wastage at piggeries, the objectives of this project were to quantify the effects of different rates of feed wastage on piggery effluent characteristics and potential methane yields, and to validate the method for estimating piggery feed wastage incorporated in the PigBal 4 model.

To address these objectives, the research undertaken in this project involved mixing pre-determined proportions of pig feed, faeces, urine, flush water and shed effluent collected from a commercial piggery grower shed, to simulate samples of shed effluent having four different rates of feed wastage, ranging from approximately 0 to 15%. The resulting samples were then analysed to evaluate the effluent characteristics and methane potential. The AUSPIG model (Davies et al., 1998) was used to simulate the growth performance and feed intake of the grower pigs in the shed where the effluent samples were collected. The fundamental performance measures, feed conversion ratio (FCR) and average daily gain (ADG) measured for the pigs housed in the trial shed, were used along with the AUSPIG data, to validate the method for estimating piggery feed wastage incorporated in the recently released PigBal 4 model (Skerman et al., 2013a).

The level of feed wastage in the raw effluent (Treatment B) collected from the trial shed on the sampling day was calculated at 4.2%, based on the TS mass balance approach (using measured TS concentrations), and 6.9%, based on the AUSPIG simulation data. These results suggest that the actual feed wastage in the shed on the sampling day may have been around the practical minimum value achievable in commercial piggeries (generally considered to be approximately 5%). A visual inspection of the piggery shed on the sampling day confirmed high standards of feed management, with virtually no visible spilled feed on the shed floor, and feeders in good working order.

As anticipated, the analysis results confirmed that increasing levels of feed wastage resulted in incrementally increasing concentrations of Total Solids (TS), Volatile Solids (VS), Chemical Oxygen Demand (COD), most nutrients and Volatile Fatty Acids (VFAs) in the four treatment samples. However, the measured increases in TS and VS were lower than the values predicted by McGahan et al. (2010) based on previous PigBal modelling.

Increased methane yields were also observed with increasing feed wastage. In uncovered anaerobic ponds, this result implies potentially serious increases in greenhouse gas (GHG) emissions; however, if these emissions are collected in a covered anaerobic pond or digester, the resulting additional energy could be used to offset on-farm electricity and heating costs. A simple economic analysis suggested that the piggery energy cost savings would be insufficient to compensate for the increased feed costs associated with higher levels of feed wastage. Co-digestion, by directly adding low-cost by-products

to covered anaerobic lagoons or digesters, can provide a more economically viable method for generating additional on-farm energy, without wasting more costly dietary ingredients.

Comparison of the measured and modelled (PigBal) manure production with the values published in the National Environmental Guidelines for Piggeries (NEGP, Tucker et al., 2010) shows reasonable agreement at the lower feed wastage levels (Treatments A and B). Modelling efficiency (EF) values for the measured versus modelled (PigBal) data from this study were generally lower than the values reported by Skerman et al. (2015) for a more controlled experiment carried out in metabolic pens, with no feed wastage. The exception to this trend was the higher EF value (0.93) determined for P in this study.

A wide range of factors may have influenced the results of this study, including difficulties arising from field and laboratory sampling and sub-sampling methods and variable losses between fresh and aged sample ingredients. The impact of several of these factors on the experimental results could have been minimised by using only fresh feed, faeces and urine in preparing the samples for the various treatments. (Fresh ingredients were used in the preparation of the Treatment A samples, whereas flushed effluent was used in preparing the Treatment B, C and D samples.)

This study indicated that the current version of the PigBal 4 model did not accurately predict the feed wastage levels suggested by AUSPIG modelling, primarily because the standard live weight gain and feed ingestion curves incorporated in PigBal 4 resulted in higher feed consumption estimates in comparison to the AUSPIG predictions. Because AUSPIG is generally regarded as the most sophisticated model currently available for predicting pig production performance, consistency in the relevant outputs from AUSPIG and PigBal would be desirable, wherever possible. Consequently, further comprehensive AUSPIG simulations are recommended to provide revised growth curves and feed intake data for derivation of revised algorithms for inclusion in PigBal 4. The existing PigBal diet ingredient database should also be reviewed to improve consistency between measured and modelled feed composition.

The experiment described in this report should be repeated using only mixtures of fresh feed, faeces, urine, and flushing water to prepare several samples simulating piggery shed effluent having a range of feed wastage levels. This approach would eliminate some of the potential differential losses resulting from the use of a mixture of fresh and aged sample ingredients in this trial. It would also be desirable to collect and analyse several sets of samples, corresponding to the different diets fed to a batch of pigs over the wean-to-finish growth cycle.

Table of Contents

List of Tables

List of Figures

1. Background to Research

Feed costs represent 65% of total pork production costs in Australia (feed cost ≈ $1.87/kg live weight). A 1000 sow farrow-to-finish piggery consumes approximately 6000 t of feed annually, at an average feed cost of approximately $468/t (Queensland, mid-2016), resulting in an annual feed bill of $2.8 M. Consequently, a 5% increase in feed wastage represents 300 t feed/yr. at an annual cost of $140,000. This is equivalent to wasting 80 g feed/pig/day or one teaspoon/pig/hr.

On a national scale, a 5% change in feed wastage represents 82,000 t feed/yr., with an annual value of approximately $38 M.

Although it is widely recognised that feed wastage is an important issue which can have a major influence on the profitability of pork production, there are currently no simple or practical methods available for directly measuring feed wastage in piggeries.

In addition to the direct financial implications, feed wastage also influences the characteristics of the effluent discharged from intensive piggery sheds. Reliable estimates of effluent characteristics are essential for effectively designing and operating piggery waste management systems to maximise the economic value of the nutrients and energy potential of the effluent without causing adverse impacts on the environment or community amenity.

This project has provided data showing the effects of different rates of feed wastage on piggery effluent characteristics, which in turn influence effluent reuse management, potential methane yields, GHG emissions and energy production from anaerobic digestion. The resulting data have also been used to evaluate the relatively simple method for estimating piggery feed wastage incorporated in the PigBal 4 model.

2. Objectives of the Research Project

The project objectives are:

1. To quantify the effects of different rates of feed wastage on piggery effluent characteristics and potential methane yields.
2. To validate the method for estimating piggery feed wastage incorporated in the PigBal 4 model.

Ultimately, these objectives could contribute to the development of improved predictive tools to assess and manage feed wastage at piggeries.

3. Introductory Technical Information

Feed wastage is considered to be a priority issue by the pork industry. Willis (2000) and Carr (2008a, 2008b) described the problem of feed wastage in Australian piggeries and provided various practical strategies for minimising and managing the problem. Dunshea et al. (2003b) assessed the feasibility of using indigestible markers in pig diets for predicting feed wastage. However, it is unclear how the markers in the waste feed were to be distinguished from the residual markers in the digested feed. Hofmeyr et al. (2005) used acid insoluble ash, also as a marker for estimating feed wastage, but concluded that it did not provide reliable estimates. The difficulty in assessing and estimating feed wastage has led to problems with acknowledging the impact of this issue across the pork industry. It therefore remains highly desirable to have a robust method to quantify feed wastage.

In addition to directly affecting the profitability of production, feed wastage can also have a major positive/negative influence on shed effluent characteristics. McGahan et al. (2010) suggested that a 5% variation in feed wastage can result in a ±30% variation in the waste stream volatile solids (VS) content, for an average sized grower pig. This variation can significantly influence greenhouse gas (GHG) emissions from uncovered anaerobic lagoons (negative) but also the energy potential of piggery effluent managed in biogas capture, treatment and use systems (potential positive). Variations in effluent nutrient concentrations also affect land application rates required for sustainable crop/pasture production in effluent reuse areas.

While there are currently no simple or practical ways to directly measure feed wastage, the recently released PigBal 4 model includes algorithms for estimating grower herd feed wastage, based on average daily gain (ADG) and feed conversion ratio (FCR) values entered by the user. These fundamental performance measures are commonly calculated and recorded by piggery operators and may therefore form a reasonable basis for assessing feed wastage.

The PigBal 4 user manual (Skerman et al., 2013b) outlines the method and equations used in calculating the grower herd feed wastage estimate on the model's 'Feed details' sheet. This estimate, which is intended to assist users in entering a realistic grower herd feed wastage value, is based on a generic relationship (second-order polynomial) between feed intake and pig live weight, derived from previous AUSPIG simulation modelling provided by Willis (2013). While the developers of the PigBal 4 model recognise that a number of additional factors such as genotype, health status, dietary factors, physical, social and climatic conditions influence feed intake, they believe that the resulting estimate may provide useful guidance, particularly in cases where users have limited experience with pig production. While the performance of PigBal 4 for predicting manure production was validated by Skerman et al. (2015), the feed wastage predictions of the model have not previously been tested or validated; hence the research outlined in this report.

The AUSPIG growth and production simulation program (Davies et al., 1998) models pig growth and performance by simulating energy and amino acid utilisation in a pig of any age, in response to its intake of nutrients and to its physical and social environment (Black et al. 1988). AUSPIG allows users to evaluate the complex interactions that influence the growth of the animal simultaneously (Smits and Mullan, 1995). It predicts live weight change, body composition, back-fat thickness and the weight and value of the carcass for entire males, females and castrates, taking into account the pig genotype, sex and stage of maturity, diet, feeding method and physical and climatic environment (Black et al., 1988).

4.   Research Methodology

The research undertaken in this project involved mixing varying quantities of pig feed with faeces, urine, flush water and shed effluent collected at a commercial piggery grower shed, to simulate samples of shed effluent having four different rates of feed wastage. The resulting samples were then analysed to evaluate the effluent characteristics and methane potential. The AUSPIG model (Davies et al., 1998) was used to model the growth performance and estimate the feed intake of the grower pigs in the shed where the effluent samples were collected. These estimates were used along with feed conversion ratio (FCR) and average daily gain (ADG) data for the pigs housed in the trial shed to validate the method for estimating piggery feed wastage incorporated in the recently released PigBal 4 model (Skerman et al., 2013a). The detailed methodology is described in the following sections.

4.1   Piggery and trial shed effluent system description

Effluent, faeces, urine and flushing/drinking water samples were collected from a trial shed at a commercial grower piggery located in southern Queensland. This shed houses approximately 1080 grower pigs which are grown out in batches, entering and exiting the shed at average live weights and ages of 25–30 kg at 9–10 weeks and 100–110 kg at up to 22 weeks, respectively. Feed is distributed to feeders in the individual grower pens using a robotic feeder which accurately measures the mass of feed supplied to each pen. Twenty-four shallow flushing channels, running longitudinally under the fully-slatted trial shed floor, are flushed individually for approximately 40 seconds each to transfer the manure and waste feed from the shed to the effluent management system. A gravity pipeline conveys the flushing water, from a 22,000L above-ground polyethylene tank, to a pipe manifold which distributes the flushing water to the individual channels through manually-actuated valves. The flushing water conveys the manure and waste feed through the 66 m long flushing channels into a transverse effluent collection channel at the end of the shed. From this point, the flushed effluent is piped by gravity to a nearby in-ground concrete sump, having a total capacity of approximately 20,000 L. A submersible pump installed in the sump is used to pump the effluent to a static rundown screen which removes a proportion of the solids from the effluent, prior to discharge into an anaerobic treatment pond. A recirculation line, coming off a tee in the effluent delivery line, is used to agitate the effluent in the sump by directing some of the pumped effluent back towards the base of the sump. The recirculation flow can be adjusted using a gate valve installed on the recirculation line. This arrangement effectively keeps the majority of the solids suspended in the effluent during pump-out, minimising the build-up of settled solids in the sump.

4.2   Sample collection

The grower shed was flushed 24 hours prior to the sample collection. Immediately following the shed flushing, the sump was pumped down so that the volume of effluent retained in the sump was minimal at the start of the 24-hour collection period. While the sheds at this piggery are generally flushed at 3 day intervals, for the purpose of this trial, the waste collection period was reduced to 24 hours to minimise the opportunity for losses of volatile compounds from the effluent during temporary storage in the shed flushing channels and sump. Over the following 24-hour waste collection period, a trickle flow, consisting of waste drinking water, urine and traces of faeces drained by gravity into the sump. At the end of the 24-hour effluent collection period, the depth of effluent in the sump and the sump diameter were recorded and approximately 11,000 L of clean bore water was used to flush the mixture of manure and waste feed from the 12 channels servicing half the shed. The entire flushing volume from half the shed was collected in the sump. Once the recirculation pump was effectively mixing the sump contents, a valve on the delivery line from the pump was opened to commence transferring the

effluent to the pre-treatment screen. Over the ensuing 20-minute sump pump-out cycle, 5 x 5 L sub-samples of pumped effluent were collected in a 25 L drum, at approximately 3-minute intervals. This sampling process produced a 25 L composite sample which was representative of the entire waste discharge from half the trial shed, over the previous 24-hour period.

Separate faeces, urine, feed and flushing water samples were collected from the trial shed, immediately following the end of the flushed effluent sampling. Faeces and urine samples were collected directly from the pigs, while they were defecating and urinating (female pigs), to minimise the risk of contamination and to ensure that the samples were as fresh as possible. The flushing water, which is supplied from the same bore water source as the pig drinking water, was sampled directly from the flushing tank. A feed sample was collected directly from one of the feeders in the shed.

On the sampling day, there were 535 grower pigs housed in the half of the shed from which the effluent was collected. The average live weight and age of the pigs were estimated by the piggery operators at 45 kg and 13 weeks, respectively. The pigs were fed a wheat and barley-based Grower 2 diet on the sampling day (and during several preceding days). Further details of this diet are provided in Table A9 (Appendix). The total mass of feed fed to the pigs during the 24-hour effluent collection period prior to sampling, was 970 kg (as fed) which is equivalent to 1.81 kg/pig/day. The pre-flushing trickle effluent volume and flushed effluent volume were estimated at 1,405 and 11,000 L, respectively, resulting in a total estimated effluent volume of 12,405 L, based on sump depth measurements.

All samples were placed on ice in a cooler box for transport from the piggery to the DAF Toowoomba laboratory.

4.3 Sample preparation

Duplicate samples representing the four levels of feed wastage (Treatments A–D) outlined in Table 1, were prepared in the DAF Toowoomba laboratory.

Table 1 Feed wastage levels simulated in treatments A to D.

Treatment	Feed wastage levels simulated:
A	Simulated 0% feed wastage (mixture of faeces, urine and flush water).
B	Raw shed effluent (including some unknown amount of in-shed feed wastage).
C	Raw shed effluent + additional feed ≈ 5% feed wastage.
D	Raw shed effluent + additional feed ≈10% feed wastage.

The samples were prepared by weighing out the required masses of the various ingredients into 1 L wide mouthed sample bottles, according to the recipes shown in Table 2. These recipes were derived from spreadsheet calculations using measured values, values from literature and assumed values, prior to the sampling, as shown in Table A1 (Appendix).

One set of samples was transported to the UQ AWMC laboratory in Brisbane while the other duplicate set of samples was retained at the DAF Toowoomba laboratory for parallel analysis.

Table 2 Masses of various ingredients used in preparing samples for treatments A to D.

Ingredients	A	B	C	D
Flushing water	865.4	0.0	0.0	0.0
Urine	74.6	0.0	0.0	0.0
Faeces	58.9	0.0	0.0	0.0
Added feed	0.0	0.0	4.1	8.5
Raw shed effluent	0.0	1,000.0	993.2	985.8
Total mass (g)	998.9	1,000.0	997.3	994.3
Total volume (L)	1.000	1.000	0.996	0.992

4.4   Sample analysis

Replicated sub-samples of each of the 4 treatments and the urine and feed were analysed at the UQ AWMC laboratories to determine the following parameters:

- Total solids (TS), volatile solids (VS) and fixed solids (FS) or ash.
- Total chemical oxygen demand (tCOD), Soluble chemical oxygen demand (sCOD), Ammonium nitrogen (NH_4-N), Phosphate phosphorus (PO_4-P), Total volatile fatty acids (tVFA), Total Kjeldahl nitrogen (TKN), Total Kjeldahl phosphorus (TKP).
- Various individual volatile fatty acids (VFA).
- Various trace elements and nutrients.
- Biochemical methane potential (BMP).

The TS concentrations were measured in triplicate using the methods recommended by Greenberg et al. (1992). The concentrations of various trace elements and nutrients were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES, Perkin Elmer Optima 7300DV, Waltham, MA, USA). This involved digesting the media samples with a 6:2:2 ratio of HCl, HNO_3 and HF, using a Milestone Ethos-1 microwave digester, prior to analysis using a Varian Vista Pro ICP-OES instrument. The samples analysed for P and K were solubilised using acid digestion, followed by microwave digestion, before being analysed using ICP-OES.

For analysis of TKN, samples were diluted directly for measurement. Then 0.5 to 20mL of homogenous sample was digested with sulfuric acid, potassium sulphate and copper sulphate catalyst in a block digester (Lachat BD-46). After the evaporation of the water the digestion is run for 3.5 hours at 380°C. The digested samples are analysed on a Lachat QuikChem8000 Flow Injection Analyzer using QuikChem method 10-115-01-1-D for TKP (analysis of phosphate) and 10-107-06-2-D for TKN (analysis of ammonia).

The samples analysed for NH_4-N were centrifuged at 2500g and the supernatant filtered through a syringe filter (0.4-mm PES membrane). The solutions were further diluted with Milli-Q water such that the concentrations of the samples were within the range of the standards. The diluted samples were analysed on a Flow Injection Analyser (Lachat QuikChem8000, Lachat Instruments, Loveland, CO, USA) using the QuikChem method.

BMP analyses were carried out on triplicate samples using the manual method described by Jensen et al. (2011). The BMP testing was performed in 160 mL (working volume 100mL) non-stirred media bottles. Inoculum for the BMPs was obtained from a mixed mesophilic digester in South East Queensland (Australia) treating primary and secondary municipal sludge, and was added at an

inoculum-to-substrate ratio (ISR) of two, on a volatile solids (VS) basis. Bottles were flushed with 100% N_2 gas for about 1 min (4 L min^{-1}), after which they were immediately sealed with a rubber septum which was retained with an open top screw cap. Tests were performed in triplicate and background methane production from blanks (substrate-free assay, containing only inoculum) were subtracted. Biogas samples were periodically collected from the headspace of each vial for measurement of methane produced. Biogas volume was measured using a manometer and methane content was determined by gas chromatography (Shimadzu GC-2014 with a HAYESEP Q80/100) using the method as described by Astals et al. (2015). Tests were mixed by swirling after every sampling event, but not in-between sampling events.

For comparison purposes, TS, VS and FS analyses were also carried out on triplicate samples at the DAF Toowoomba laboratory. BMP testing was carried out at the DAF Toowoomba laboratory using the Automatic Methane Potential Test System (AMPTS II, bioprocess control, Sweden). The BMP values for the four treatments were calculated using the equations in the AMPTS II Operation and Maintenance Manual (Bioprocess Control, 2012) and using the Aquasim calculation method described in Section 4.7. The mean analysis results and 95% confidence intervals are presented in Tables A2 to A6 in the Appendix.

4.5   Feed wastage calculations

The mass of waste feed in the raw effluent sample (Treatment B) collected from the trial shed was calculated from the measured TS concentrations of the raw effluent and waste feed and the mass of the raw effluent, as shown in Equations 1 and 2.

$$m_{re} \times TS_{re} = (m_{re} - m_{wf}) \times TS_{re\text{-}wf} + m_{wf} \times TS_{wf} \quad\text{...Equation 1}$$

Rearranging:

$$m_{wf} = m_{re} \times (TS_{re} - TS_{re\text{-}wf}) / (TS_{wf} - TS_{re\text{-}wf}) \quad\text{...Equation 2}$$

Where:
m_{wf} = mass of waste feed (g)
m_{re} = mass of raw effluent (g)
TS_{re} = TS concentration of raw effluent (%)
$TS_{re\text{-}wf}$ = TS concentration of raw effluent without any waste feed (%)
        (assumed to be equal to the Treatment A TS concentration)
TS_{wf} = TS concentration of waste feed (%)
$m_{re\text{-}wf}$ = mass of raw effluent without any waste feed (g)

The mass of waste feed in the treatment A sample was assumed to be zero because it was formulated from samples of faeces, urine and clean flushing water which were not contaminated with feed residues. The total masses of waste feed in the treatment C and D samples were determined by adding the calculated mass of waste feed in treatment B to the masses of feed added to the treatment C and D samples. Feed wastage values for treatments B, C and D were determined using Equations 3 and 4, based on the calculated masses of waste feed in the samples, the measured values of feed fed to the pigs in the trial shed and the total effluent volume discharged from the shed, over the 24 hour effluent collection period.

$FW = 100 \times m_{wf} / m_f$ ....Equation 3

$m_f = v_{eff\ sample} \times m_{f\ shed} / v_{eff\ shed}$ ....Equation 4

Where:

FW = feed wastage (%)

m_f = mass of feed fed (g)

$v_{eff\ sample}$ = volume of effluent sample (L)

$m_{f\ shed}$ = mass of feed fed to the trial shed (g)

$v_{eff\ shed}$ = volume of effluent discharged from shed (L)

4.6   AUSPIG Modelling

Data provided by the piggery operator for the batch of pigs housed in the trial shed (Table 3) were entered into the AUSPIG growth and production simulation model (Davies et al., 1998). This model was used to simulate the age, live weight, P2 back-fat and feed intake for the pigs over their entire growth cycle (wean-to-finish), including the 24 hour effluent collection period.   The modelling parameters were adjusted so that the modelled mass of feed offered to the batch of pigs in the trial shed (9 weeks to finish) matched the measured mass of feed offered to the pigs (190 t).

4.7   Data analysis

ANOVA was performed for the TS, VS, FS, COD, VS/TS and VS/COD analysis results for the four treatments. Least Significant Difference (l.s.d.) tests were performed at the 5% level to determine which treatments (levels of feed wastage) resulted in significantly different concentrations of the above traits. The ANOVA procedure of the GENSTAT software (Payne et al., 2011) was used.

The cumulative methane production data derived from the UQ manual BMP procedure were analysed using the Aquasim 2.1d package, to perform a non-linear least-squares fit of a simple first-order kinetic model (Equation 5) to the measured cumulative methane produced (B_t) at incubation time (t) (Jensen et al., 2010):

$B_t = B_0(1 - e^{-k_{hyd} \cdot t})$ ....Equation 5

Where:

B_0 = degradation extent or degradability (L CH_4. Kg VS_{fed}^{-1})

k_{hyd} = fitted first-order kinetic rate coefficient (day^{-1})

t = time (days)

Regression analyses were carried out on the cumulative methane production data resulting from the DAF AMPTS II analyses, by fitting Gompertz curves [Y = A + C*EXP(-EXP(-B*(X-M)))] to the data.

4.8   PigBal model validation

The PigBal model was used to predict the effluent characteristics and feed wastage over the 24-hour effluent collection period. The piggery operators provided the data presented in Table 3 following the exit of the batch of finished pigs from the trial shed. Some of this data were based on kill sheets provided by the abattoir after the pigs were processed. Because the pigs were not actually weighed

on the sampling day, the average pig age and live weight were estimated by interpolating the AUSPIG model output, based on the known feed usage figure which was accurately measured on that day.

Table 3 Data supplied by the producer relating to the batch of pigs housed in the trial shed over the entire pig life cycle and on the effluent sampling day.

Batch of pigs (grower/finisher shed)			
No of pigs at entry	pigs	1,110	Measured
No of pigs at exit	pigs	1,030	Measured
Average No of pigs in shed	pigs	1,050	Estimated
Total live weight at entry	kg	27,660	Measured
Total live weight at exit	kg	102,640	Measured
Average entry live weight	kg	25.6	Measured
Average exit live weight	kg	99.6	Measured
Average entry age	weeks	9.1	Measured
Average exit age	weeks	21.0	Measured
Average daily live weight gain (ADG)	g/day	669	Measured
Total feed fed (birth–finish)	t	223.87	Measured
Total feed fed per pig (birth–finish)	kg/pig	213	Measured
Sampling day			
No of pigs (half shed)	pigs	535	Measured
Average live weight	kg	45	Estimated
Average pig age	weeks	13	Measured
Feed fed	kg/day	970	Measured
Feed fed	kg/pig/day	1.81	Measured

The feed wastage values used in the PigBal modelling for the four treatments were estimated from the AUSPIG output data, assuming that the feed ingested values remained constant across the four treatments and that the feed fed values increased in proportion to the mass of feed added to the effluent samples for treatments C and D.

The resulting pig numbers, average live weights, ages, diets, feed fed, feed wastage, average daily gains and feed conversion ratio values were entered into the PigBal 4 model (Skerman et al., 2013a). The model provided estimates of the feed wastage and TS, VS, FS, N, P and K in the waste stream produced by the pigs housed in the trial shed over the 24 hour effluent collection period, for each of the four treatments.

Statistical validation measures for the four treatments were calculated, as suggested by Mayer and Butler (1993), to assist in validating the PigBal predictions against the trial data. These included modelling efficiency (EF) and simple linear regression parameters (R^2, slope and intercept) obtained by fitting the measured trait as response and the PigBal estimate as explanatory variables. Simultaneous F tests, for slope = 1 and intercept = 0, were also applied to the data. The calculated EF is an overall measure of agreement between observed and simulated values (Mayer and Butler, 1993). An EF value of 1 corresponds to a perfect match of modelled data to the observed data. An EF value of 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an EF value less than 0 occurs when the observed mean is a better predictor than the model. Essentially, the closer the EF value is to 1, the more accurate the model is, and any model with a negative EF cannot be recommended.

5. Results

5.1 Effluent analysis results

Tabulated results of the analyses for the four treatments (mean values and 95% confidence intervals) are provided in the Appendix.

The feed wastage values shown in Table 4 were calculated for treatments A to D using equations (2), (3) and (4) (Section 4.5). The values of feed fed, feed ingested and feed wasted, as shown in Table 4, were determined based on the measured mass of feed fed to the 535 pigs housed in half of the trial shed over the effluent collection period (970 kg/day) and the calculated feed wastage values.

Table 4 Calculated masses of feed fed, feed ingested and feed wasted for the effluent collection period.

Treatment	Feed wastage (%)	Feed fed		Feed ingested		Feed wasted	
		(kg/day)	(kg/pig/day)	(kg/day)	(kg/pig/day)	(kg/day)	(kg/pig/day)
A	0.00	929.16	1.74	929.16	1.74	0.00	0.00
B	4.21	970.00	1.81	929.16	1.74	40.84	0.08
C	9.43	1,025.89	1.92	929.16	1.74	96.74	0.18
D	15.20	1,095.74	2.05	929.16	1.74	166.58	0.31

Graphs showing the analysis results plotted against the calculated feed wastage values (Table 4) for the four treatments are provided in Figures 1 to 5. Error bars in these figures show the 95% confidence intervals.

Figure 1 shows the mean TS, VS and COD concentrations increasing linearly with feed wastage, as expected. The ANOVA and l.s.d. analyses indicated that the mean values for these traits were significantly different from each other for the four treatments (P<0.05). Five percent increases in feed wastage resulted in increases in the effluent TS, VS and FS concentrations of 12%, 13% and 8%, respectively. The variations in TS and VS are lower than the ±30% variation suggested by McGahan et al. (2010), based on previous PigBal modelling.

The mean FS concentrations remained relatively constant for the four treatments. The ANOVA and l.s.d. analyses indicated that the mean values for treatments B, C and D were not significantly different from each other (P>0.05) but that mean value for treatment A was significantly different (P<0.05) from the mean values for each of the other three treatments. This result appears to suggest that the FS contributions from waste feed were indistinguishably low.

Figure 2 suggests that there is a general increase in the VS/TS ratio with increasing feed wastage. The ANOVA and l. s. d. analyses indicated that the mean values for treatments B, C and D which ranged from 82% to 84% were significantly different (P<0.05) from each other, but that the mean value for treatment A was not significantly different from the treatment C mean. These effluent VS/TS ratios were higher than the mean values of 74% and 72% measured by Skerman et al. (2015) and Skerman and Collman (2012), for grower pigs in metabolic pens where feed wastage was eliminated from the effluent stream, and for shed effluent at a commercial breeder piggery employing static pits, respectively.

The VS/COD ratio remained relatively constant with a mean value of 0.55 across the four treatments. This value was lower than the mean values of 0.65 measured by Skerman et al. (2013c) and higher than the mean value of 0.52 measured by Birchall (2010) for screened wastewater from a large commercial piggery in Victoria.

There were no significant differences between the mean TKN and TKP concentrations for treatments B and C; however, the mean values for all of the other traits plotted in Figure 3 were significantly different ($P<0.05$) for the four treatments. The relatively large differences between the Treatment A and B concentrations for TKN, NH_4-N and K (Figures 3 and 4) reflect the higher concentrations of these nutrients in the raw feed compared to the raw effluent. This observation is consistent with a large proportion of the nutrient intake being digested by the pigs and converted to live weight gain, rather than being excreted in the manure.

While some differences between the results for treatments A and B could be attributed to the absence of waste feed in treatment A, some differences may be due to the timing of the sampling and the pre-sampling storage conditions. The treatment A samples were collected directly after excretion from the pigs' bodies, placed on ice and transported to the laboratory, whereas the treatment B samples were taken after shed flushing, effluent collection and mixing in the below-ground sump. The mixture of manure, flush water and waste feed collected in treatment B had been stored in either the shed flushing channels or sump for a period up to 24 hours before flushing. During this time, micro-organisms are likely to have commenced breaking down organic matter with some transformations of compounds, e.g. mineralisation of organic-N to ammonium-N, and there may also have been some gaseous losses of volatile components. Furthermore, the sump would have contained some residual effluent which had not been pumped out prior to the trial collection period, providing an inoculum to promote the rapid onset of anaerobic digestion (< 24 hours). This fermentation effect is likely to have been responsible for the significantly higher total VFA and acetic acid levels in the treatment B, C and D samples compared to the treatment A sample (Figure 5). The relatively warm ambient conditions (maximum temperature 28°C) at the site on the sampling day (1 March 2016) may have contributed to the supposed rapid fermentation of the organic matter in the shed effluent stream.

Further increases in feed wastage from treatments B to C and C to D did not result in stark increases in NH_4-N and VFAs, which suggests that the added feed was not the original source of these components, but that they were likely decay products.

While fresh feed was added to the treatment C and D samples, the waste feed component present in the treatment B sample may have been sitting in a mixed, wet condition in the shed flushing channels or sump for a period of up to 24 hours, prior to shed flushing and sampling. Fermentation during this period may have resulted in the breakdown of organic matter and possible gaseous losses of volatile components, resulting in variations in TS, VS and N concentrations between treatments.
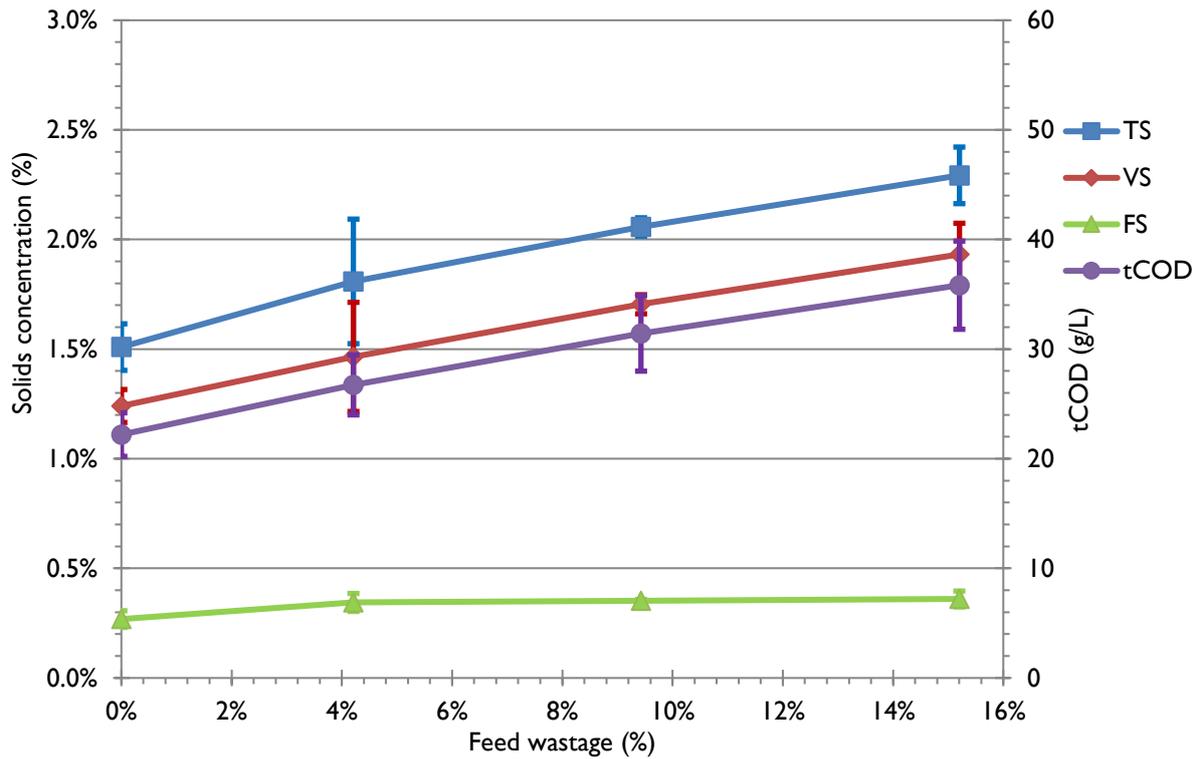
Figure 1 TS, VS, FS and tCOD concentrations plotted against the calculated feed wastage values, for the four treatments.
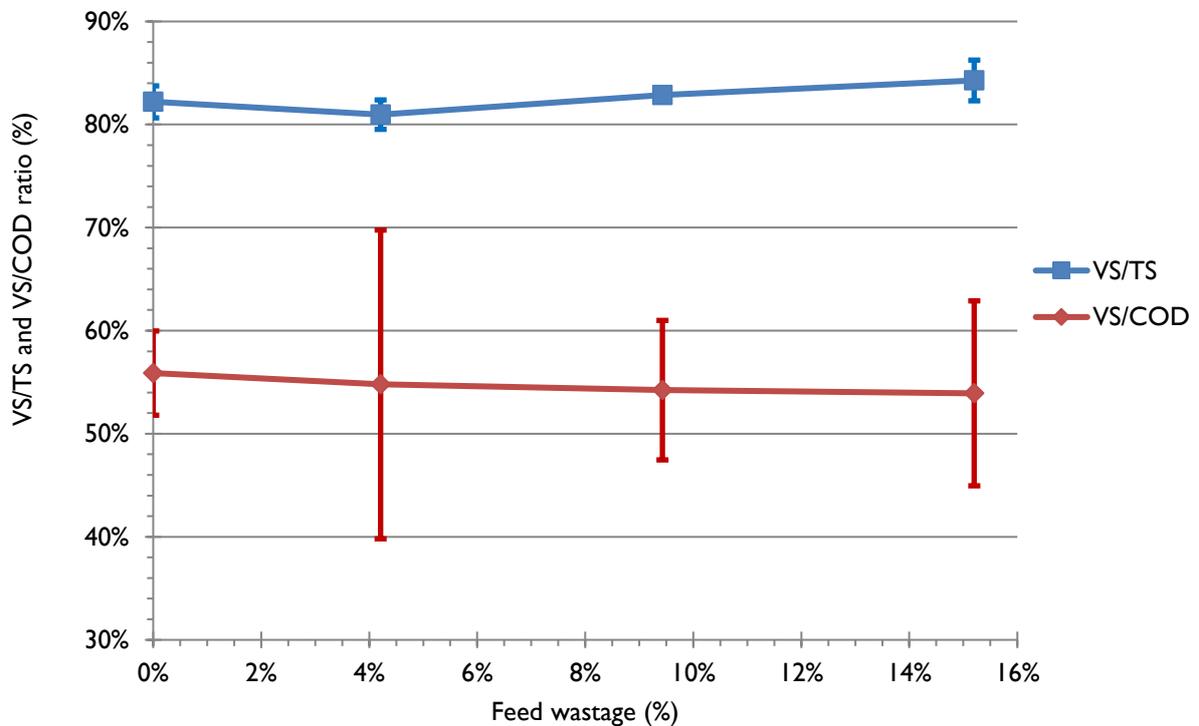
Figure 2 VS/TS and VS/COD ratios plotted against the calculated feed wastage values, for the four treatments.
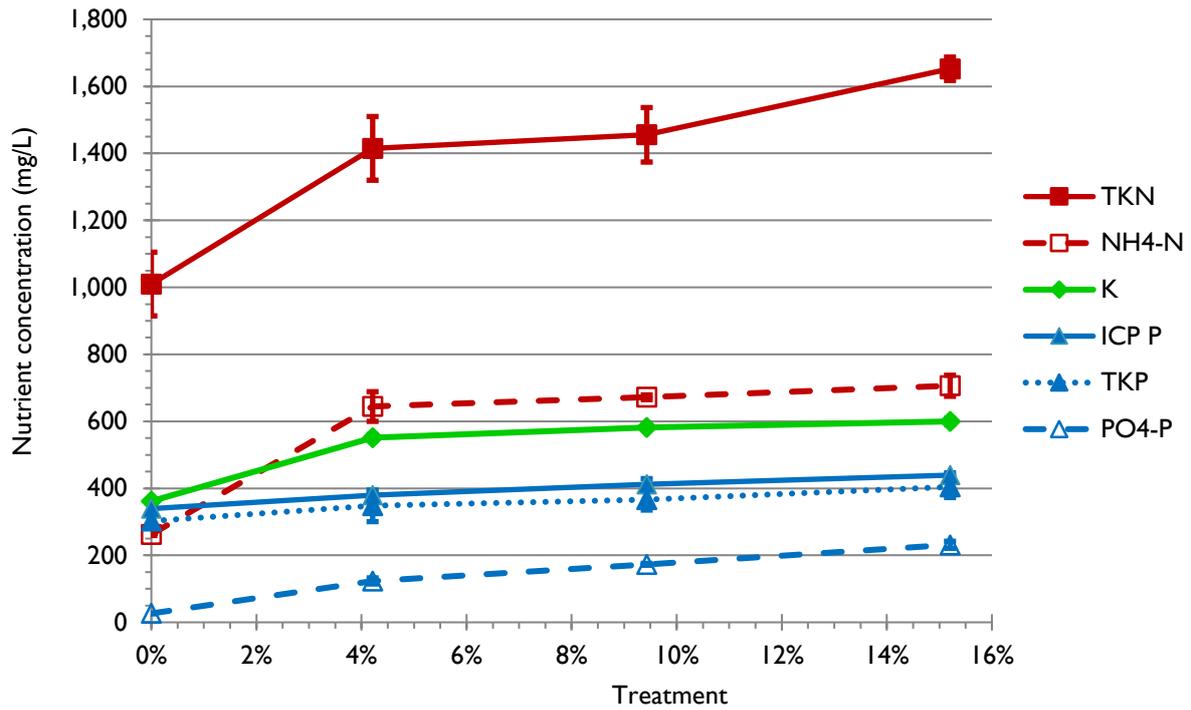
Figure 3 TKN, NH$_4$-N, K, ICP P, TKP and PO$_4$-P concentrations plotted against the calculated feed wastage values, for the four treatments.
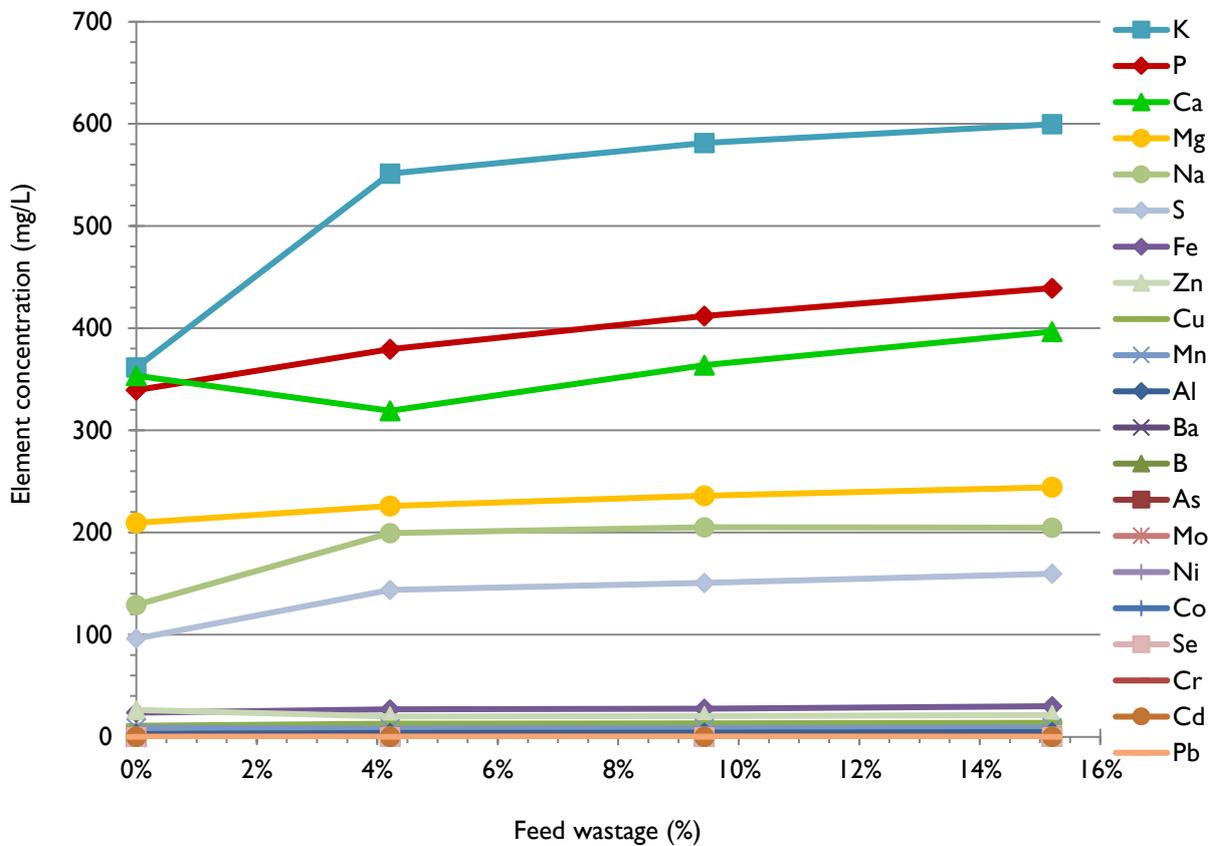
Figure 4 Concentrations of various elements determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) analysis, plotted against the calculated feed wastage values, for the four treatments.
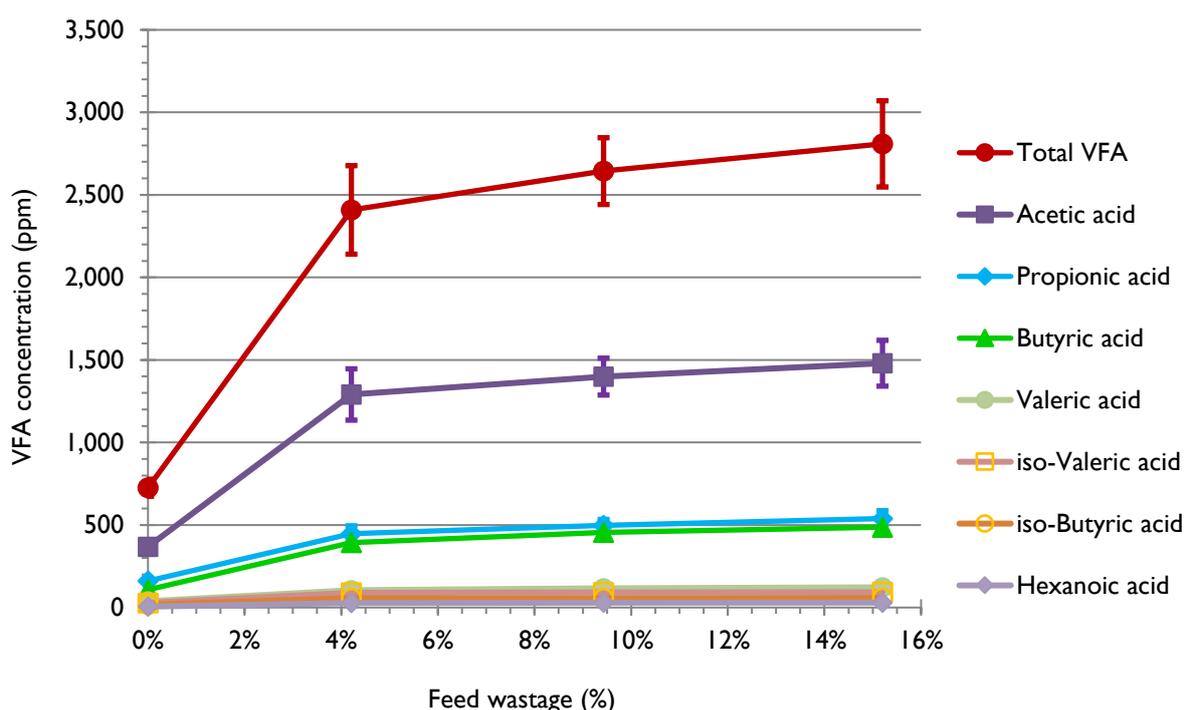
Figure 5 Concentrations of VFAs plotted against the calculated feed wastage values, for the four treatments.

5.2   BMP Analysis results

The results of the UQ manual BMP analysis are provided in Table 5 for the four feed wastage treatments and the pig feed sample.

Table 5 Biochemical methane potential (BMP) analysis results determined using the UQ manual analysis method.

Treatment:	A	B	C	D	SEM	Feed
Methane yield, B_0 (mL CH_4/g VS)	284 [a]	327 [b]	360 [c]	383 [d]	5.4	265 ± 28
First order kinetic, k_{hyd} (day^{-1})	0.29 [a]	0.27 [a]	0.25 [b]	0.22 [b]	0.008	0.39 ± 0.03

[abcd] Means in a row with different superscripts differ significantly (P<0.05).

The ANOVA and l. s. d. analyses suggest significant differences between the Bo values for each of the four feed wastage treatments and no significant differences between the Treatment A and B and Treatment C and D k_{hyd} values. The cumulative specific methane yields (corrected for inoculum methane production, per gram of VS) are plotted against time in Figure 6 for the four feed wastage treatments and the pig feed.

Figure 7 shows increasing Bo values with increasing feed wastage, across the four treatments. Skerman et al. (2013c) measured a mean Bo value of 362 L CH_4. Kg VS^{-1} for effluent produced by four grower pigs fed a similar wheat/barley diet in metabolic pens, where feed wastage was eliminated from the effluent samples. Clearly, this value is higher than the Treatment A value of 284 L CH_4. Kg VS^{-1} measured in this more recent trial and is closer to the Treatment C value which incorporates an estimated 12% feed wastage, based on AUSPIG modelling.

Both of these values are lower than the standard value of 450 L CH_4. Kg VS^{-1} adopted in the Carbon Credits Methodology Determination (Federal Register of Legislation, 2013) and the National Inventory Report (Commonwealth of Australia, 2014).
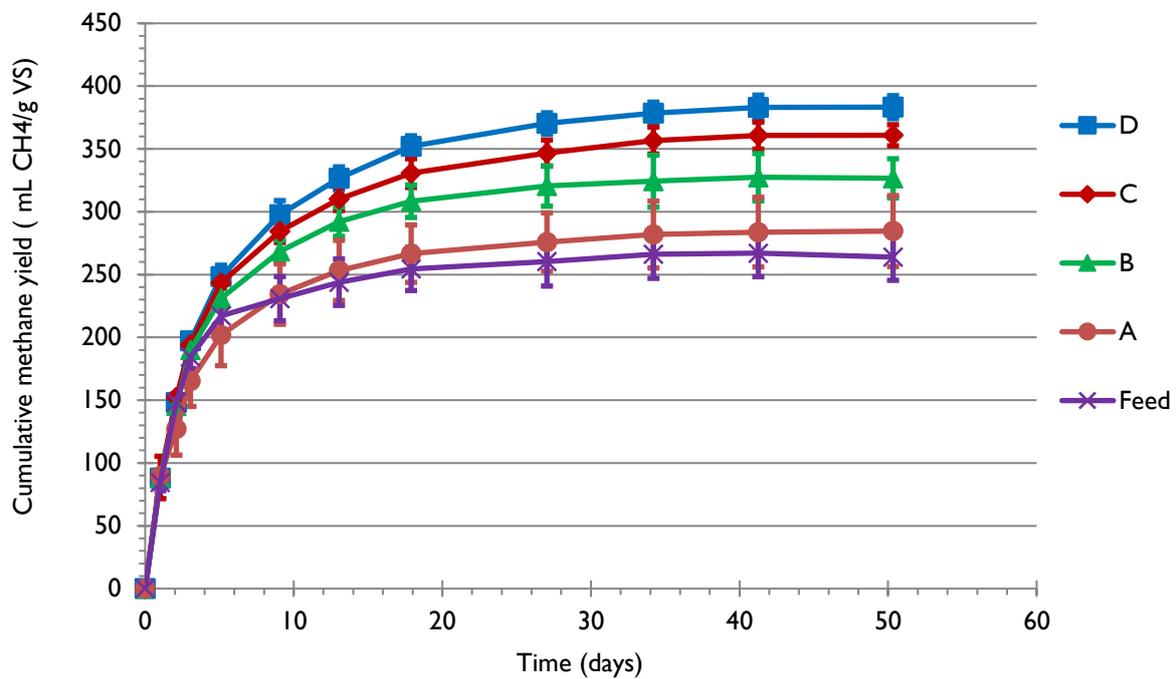
Figure 6 Cumulative specific methane production from the four treatment substrate and feed samples determined from the UQ analyses.
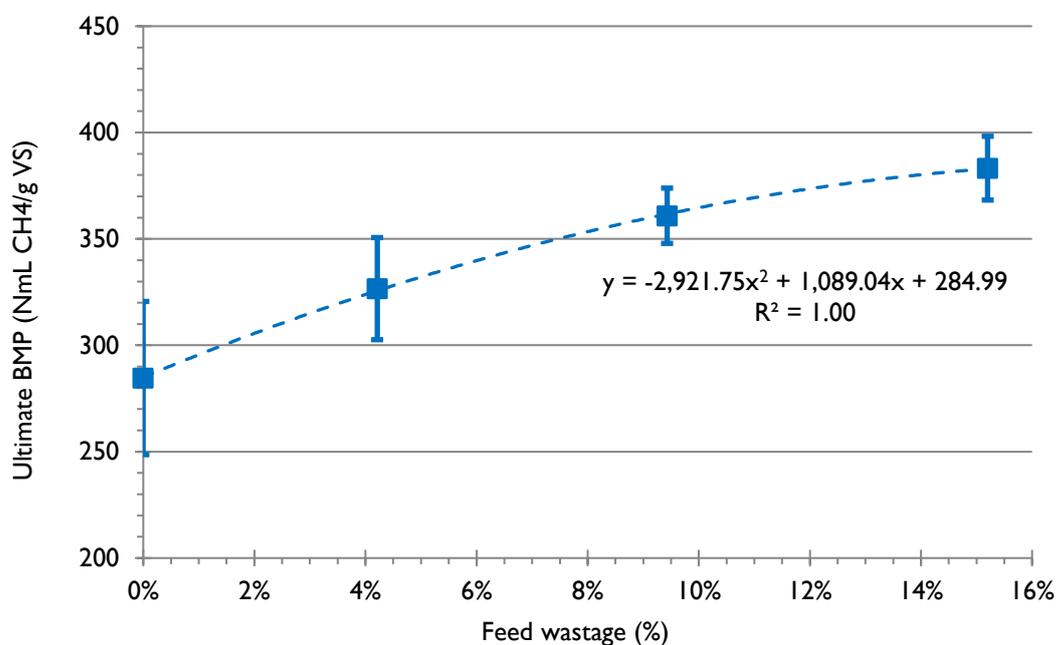
Figure 7 BMP values determined using the UQ manual analysis method and the DAF AMPTS II method plotted against the calculated feed wastage values, for the four treatments.

A simple economic analysis, summarised in Table A12 (Appendix) and Figure 8, suggests that piggery energy cost savings resulting from higher levels of feed wastage and increased biogas production, would be insufficient to compensate for the associated increase in feed costs. This analysis was based on a 1000 sow, farrow-to-finish piggery, employing a combined heat and power (CHP) system, burning biogas to generate electricity and heat. Energy saving values of $0.25/kWh for electricity and $0.11/kWh for thermal energy were assumed, based on offsetting electricity supplied from the grid and LPG consumption valued at $0.80/L. The feed wastage level calculated for Treatment B (4.2%) was adopted as the baseline feed wastage level for this analysis, as this level of feed wastage represents the approximate minimum value practically achievable in commercial piggeries, being of a similar magnitude to the 5% value suggested by Willis, ed. (2000).
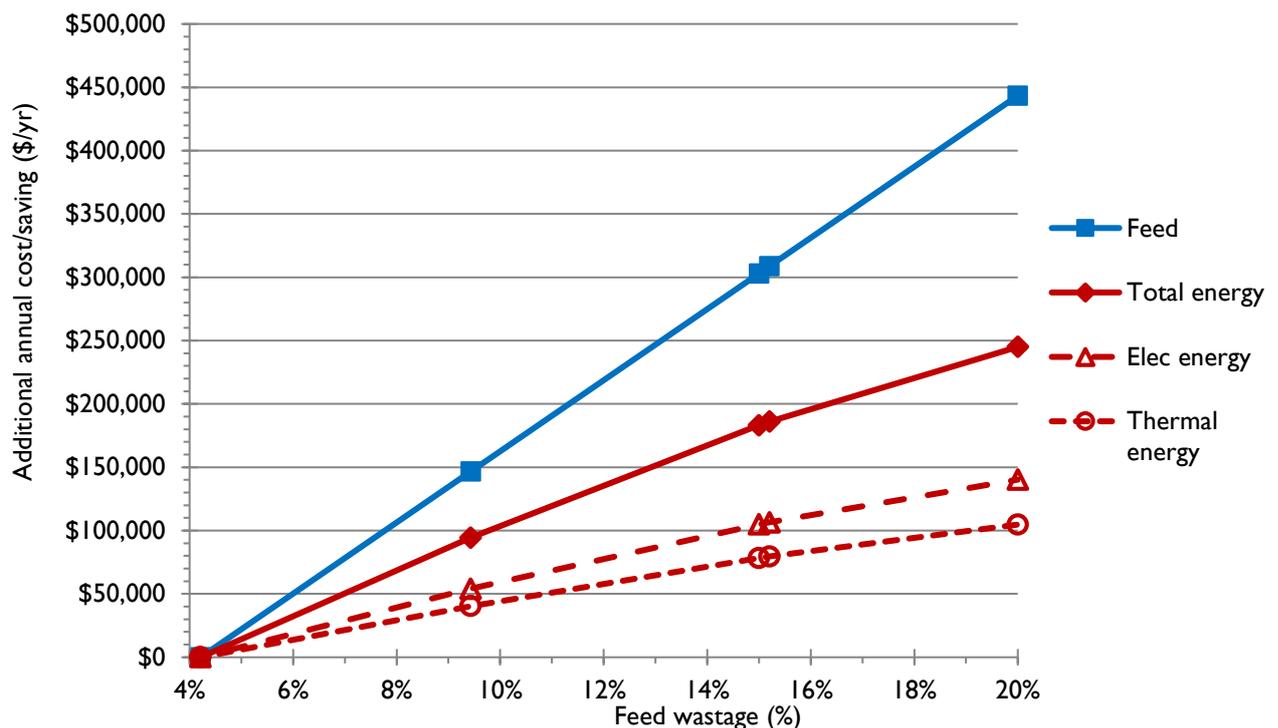
Figure 8 Comparison of piggery energy cost savings and additional feed costs associated with increased feed wastage resulting in higher biogas production.

Figure 8 shows that increasing feed wastage from the baseline level of 4.2% to 15%, would provide additional energy savings worth $183,000/ yr.; however, the additional feed cost would be $303,000/ yr., resulting in an overall financial loss of $120,000/yr. This simple analysis assumes that all of the energy can be used on-site and does not include any additional income from the sale of Australian Carbon Credit Units (ACCUs) under the Emissions Reduction Fund (ERF) or Renewable Energy Certificates (RECs).

5.3 AUSPIG modelling results

The AUSPIG model outputs are provided in Tables A9 and A10 (Appendix) and are summarised in Figures 9 to 11 which also show the polynomial regression equations fitted to the model predictions. PigBal model outputs and fitted regression equations are also shown on these figures for comparison purposes. Because the sampling day feed consumption was accurately measured at 970 kg for half the shed (535 pigs @ 1.81 kg/pig/day), the corresponding average pig live weights and ages were

interpolated from the AUSPIG output, as summarised in Table 6, using the fitted polynomial equations. These equations were also used to extrapolate the 100 kg live weight values given in the table.

Table 6 Summary of AUSPIG modelling results for the sampling day and at 100 kg live weight.

Parameter	Units	Value
Sampling day		
Age	weeks	12.77
Age	days	89.4
Live weight	kg	43.8
Feed fed	kg/day	970
Feed fed	kg/pig/day	1.81
Feed ingested	kg/pig/day	1.69
Feed wastage	%	6.9
100 kg live weight		
Age	weeks	21.33
Age	days	149.3
Live weight	kg	100
Feed fed	kg/day	1646
Feed fed	kg/pig/day	3.08
Feed ingested	kg/pig/day	2.86
Feed wastage	%	7.0
Feed wastage [1]	%	7.7
Average daily live weight gain (ADG) [1]	g/day	660
Feed conversion ratio (FCR) [2]		2.23

[1] birth – 100 kg live weight
[2] kg feed fed / kg live weight gain [birth to 100 kg live weight]

Based on the AUSPIG modelling, the feed wastage in the trial shed was 6.9% on the sampling day. This value, which is applicable to treatment B (raw effluent discharged from the trial shed without any additional waste feed), is higher than the calculated value (4.2%) determined using equations (2), (3) and (4) (Section 4.5). The overall feed wastage (birth to 100 kg live weight) was estimated to be 7.7%. In reality, some variation in feed wastage could be expected across the pig growth cycle due to changes in social, physical, environmental and nutritional factors.

The AUSPIG modelling results give a lower live weight on the sampling day compared with the standard growth curves adopted in the PigBal 4 model for the same ADG (Figure 9). Figures 10 and 11 also show that the standard feed intake equation used in PigBal 4 results in a higher feed intake than the AUSPIG modelling simulations.

$$y = -0.0074x^3 + 0.3766x^2 - 0.1221x + 2.6028$$
$$R^2 = 1.0000$$

$$y = -0.0037x^3 + 0.2845x^2 + 0.1896x + 2.7158$$
$$R^2 = 1.0000$$
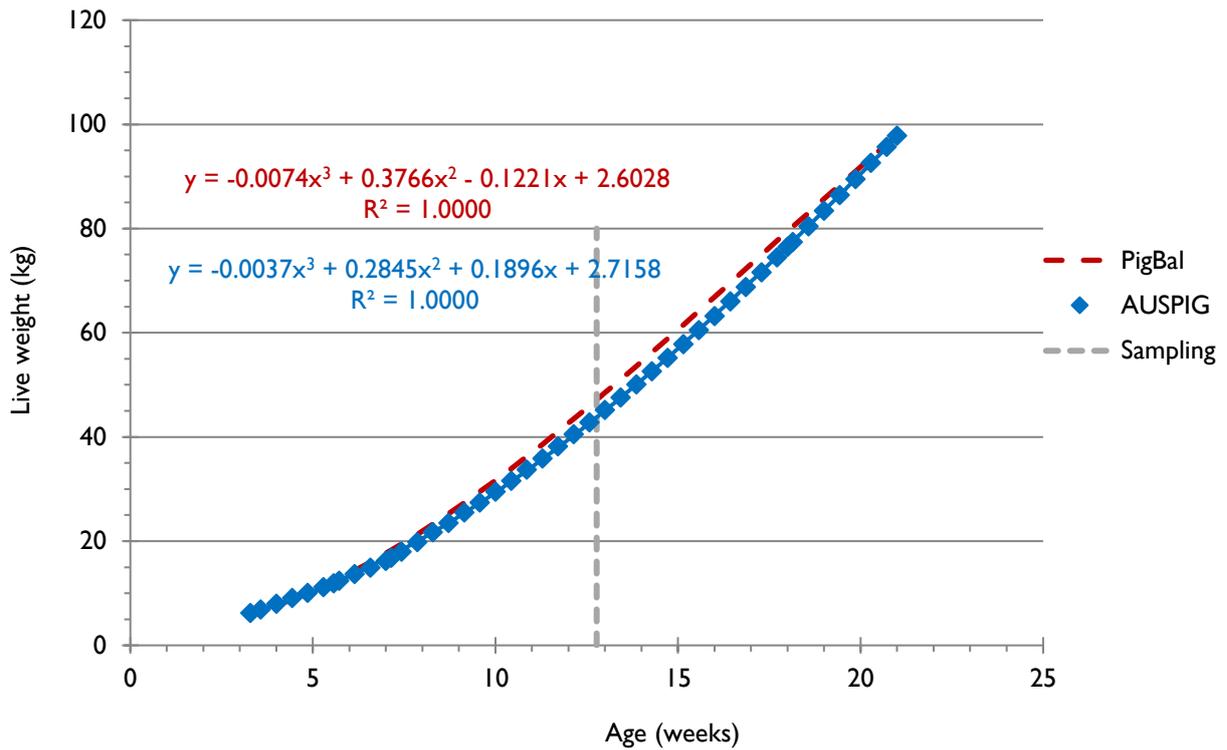
Figure 9 Pig growth curve predicted using the AUSPIG model plotted along with the standard growth curve assumed in the PigBal 4 model for an ADG of 660 g/day (birth to 100 kg live weight).

$$y = -0.00017x^2 + 0.04641x + 0.11453$$
$$R^2 = 0.99589$$

$$y = -0.00015x^2 + 0.04539x + 0.03232$$
$$R^2 = 1.00000$$

$$y = -0.00017x^2 + 0.04419x + 0.07821$$
$$R^2 = 0.99583$$
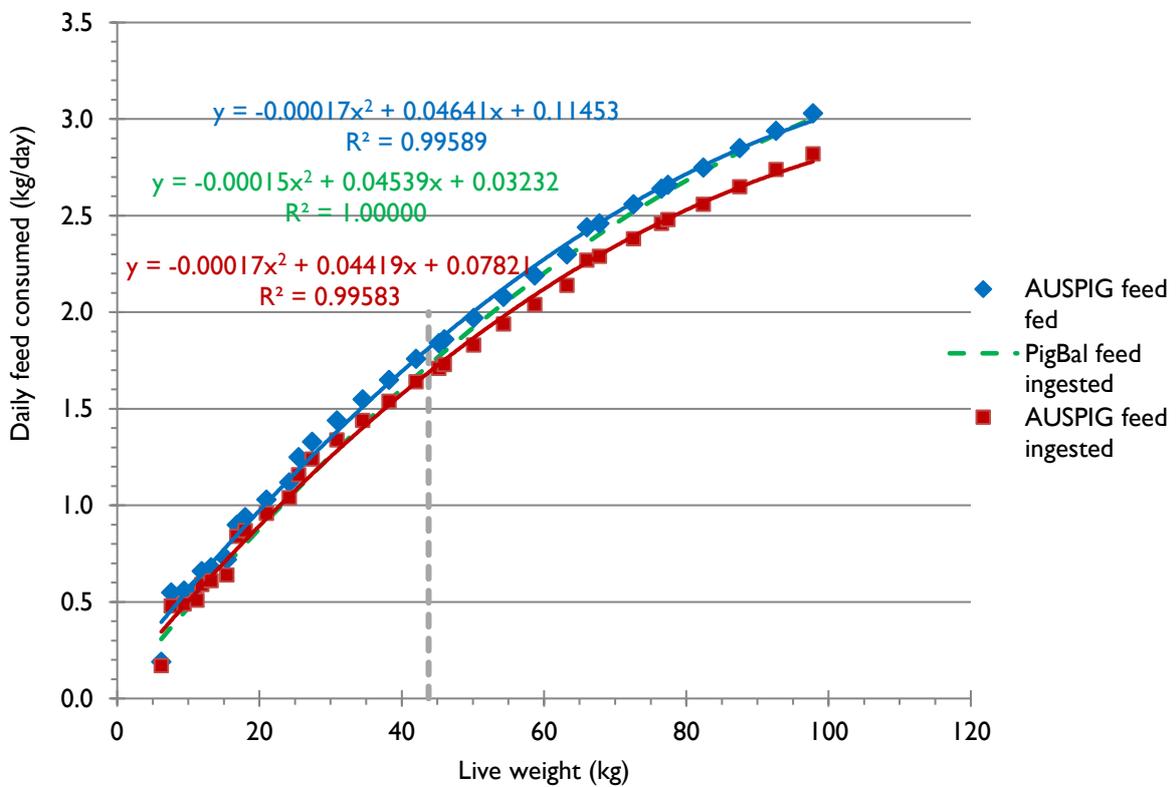
Figure 10 Masses of feed fed and feed ingested predicted using the AUSPIG and PigBal 4 models plotted against live weight.

$$y = -0.00014x^3 + 0.00470x^2 + 0.11315x - 0.10469$$
$$R^2 = 0.99715$$

$$y = -0.00036x^3 + 0.01352x^2 + 0.00893x + 0.14629$$
$$R^2 = 1.00000$$

$$y = -0.00013x^3 + 0.00398x^2 + 0.11354x - 0.14935$$
$$R^2 = 0.99727$$
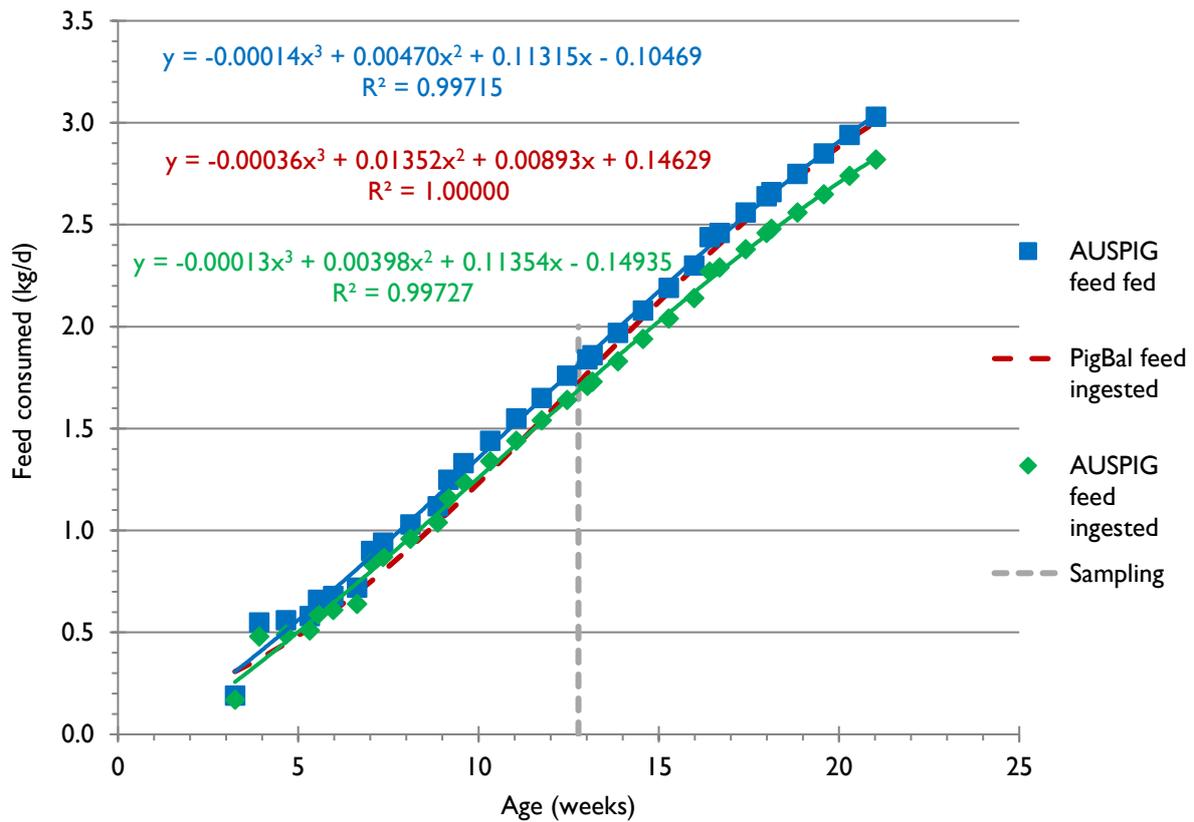
Figure 11 Masses of feed fed and feed ingested predicted using the AUSPIG and PigBal 4 models plotted against live weight pig age.

5.4   PigBal validation results

The PigBal input data shown in Table 7 was derived from the AUSPIG modelling results, assuming that the daily mass of feed ingested by the pigs was the same for each of the treatments and that the mass of feed fed varied in accordance with the feed wastage values. The waste feed values for treatments C and D were calculated by adding the treatment B value, derived from the AUSPIG modelling, to feed masses determined in proportion to the additional feed added to the original piggery effluent samples.

Table 7 PigBal input data derived from AUSPIG model runs for the four treatments, representing different levels of feed wastage.

Treatment	Units	A	B	C	D
Feed wastage	%	0.00	6.90	12.11	17.83
Average daily live weight gain (ADG) [1]	g/day	660	660	660	660
Feed conversion ratio (FCR) [2]		2.06	2.23	2.34	2.51
Sampling day					
Age	days	89.4	89.4	89.4	89.4
Age	weeks	12.77	12.77	12.77	12.77
Live weight	kg	43.8	43.8	43.8	43.8
Feed fed	kg/pig/day	1.69	1.81	1.92	2.05

| Feed ingested | kg/pig/day | 1.69 | 1.69 | 1.69 | 1.69 |
| Feed wasted | kg/pig/day | 0.00 | 0.13 | 0.23 | 0.37 |

[1] birth to 100 kg live weight

[2] kg feed fed / kg live weight gain [birth to 100 kg live weight]

Figure 12 provides measured versus predicted plots for the masses of TS, VS, FS, N, P and K in the effluent discharged from the trial shed, on the sampling day, for the four feed wastage treatments. These plots show the linear regression equations fitted to the data and the R^2 values, along with the 1:1 (y = x) line.
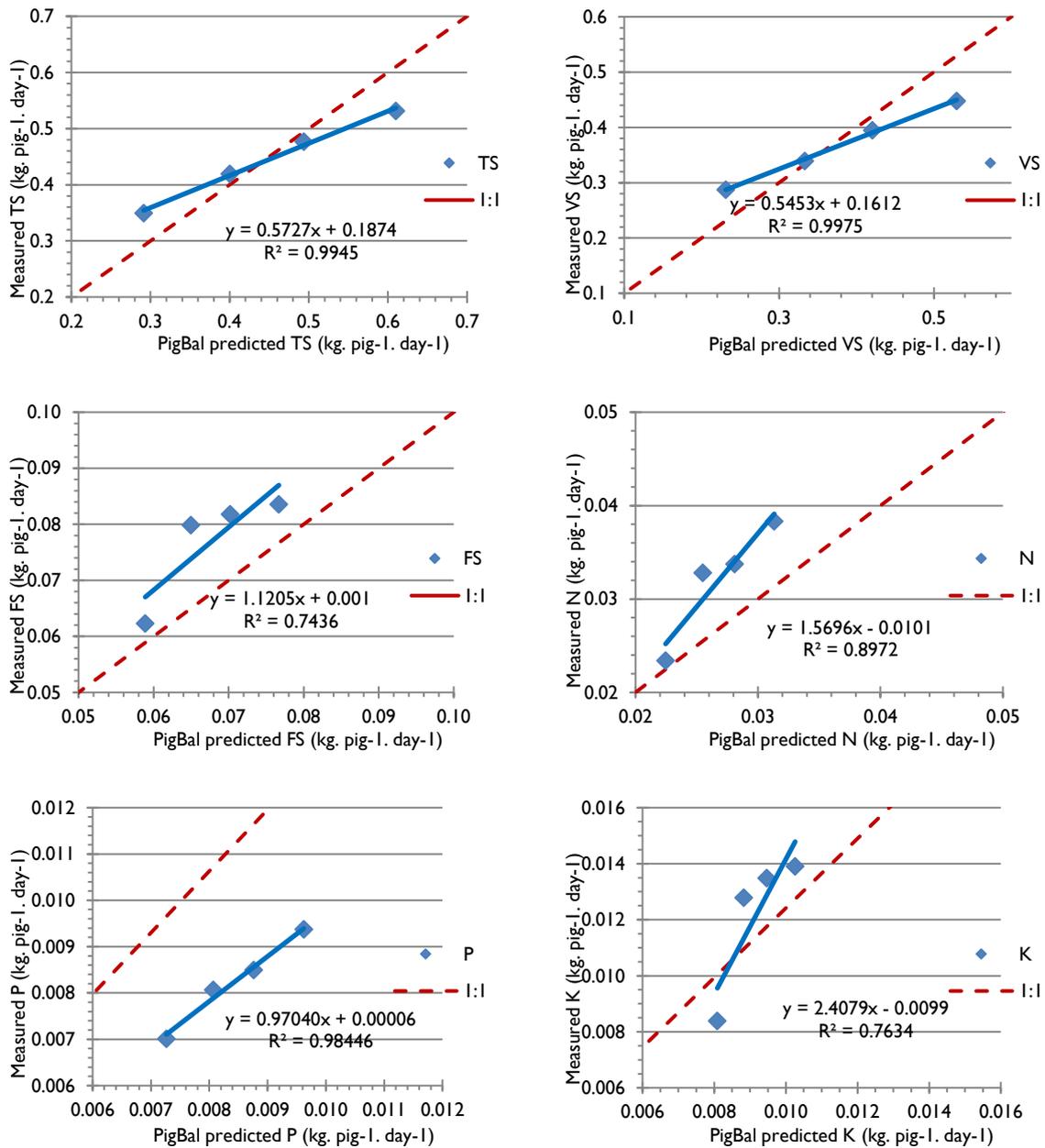
Figure 12 Measured versus predicted (PigBal) plots for the masses of TS, VS, FS, N, P and K in the effluent discharged from the trial shed on the sampling day for the four feed wastage treatments.

The calculated EF and linear regression parameters (R², slope and intercept) are summarised in Table 8 which also includes the P values from the simultaneous F tests for slope = 1 and intercept = 0. In combination with the graphs in Figure 12, these results were used to assess the performance of the PigBal 4 model for predicting key parameters relating to piggery manure production.

Table 8 Modelling efficiency (EF), linear regression parameter values (R², slope and intercept) and simultaneous F test P values used in the validation of PigBal 4 model predictions against measured trial data.

Parameter	EF	R²	Slope	Intercept	P	
TS	0.437	0.994	0.573	0.187	0.010	*
VS	0.270	0.997	0.545	0.161	0.003	*
FS	-0.428	0.744	1.120	0.001	0.180	
N	-0.154	0.897	1.570	-0.010	0.089	
P	0.931	0.984	0.970	0.000	0.226	
K	-1.323	0.763	2.408	-0.010	0.102	

* Slope significantly different from 1 or intercept significantly different from 0 (P < 0.05)

While the R² values are all relatively high, the negative EF values for FS, N and K suggest that the PigBal 4 model gave unsatisfactory predictions of these parameter values. However, the simultaneous F tests indicated that the slopes and intercepts for the TS and VS regression lines were significantly different to 1 and 0 (P<0.05), respectively.

The graphs in Figure 12 indicate that the PigBal 4 model under-predicted the TS and VS values for the lower feed wastage treatments (A and B) while over-predicting the values for the higher feed wastage treatments (C and D). This is inconsistent with the diet ingredient database incorporated in PigBal 4 giving lower concentrations of TS and VS than the measured values, as shown in Table 9.

Table 9 Concentrations of TS, VS, FS, N, P and K in the feed fed to the pigs during the effluent collection period, as measured by laboratory analysis and predicted by the PigBal 4 model.

Parameter	Measured (%)	PigBal 4 (%)
TS	92.62	88.83
VS	88.73	83.97
FS	3.89	4.86
N	2.44	2.69
P	0.51	0.64
K	0.66	0.59

Figures 13 and 14 are bar graphs comparing the solids and nutrient production values published in the National Environmental Guidelines for Piggeries (NEGP, 2nd Edition, Table 9.1, Tucker et al., 2010) with measured values and PigBal 4 estimates. The measured and PigBal data were converted to a per SPU basis by dividing the per pig data by a factor of 1.11, based on the live weight regression equation outlined in the PigBal 4 User Manual (Skerman et al., 2013b) and the mean live weight of 44 kg on the sampling day.

While the NEGP states that the solids and nutrient production figures provided in Table 9.1 (NEGP) are based on PigBal modelling (using a previous version of PigBal); it does not specify the level of feed wastage adopted in the modelling.
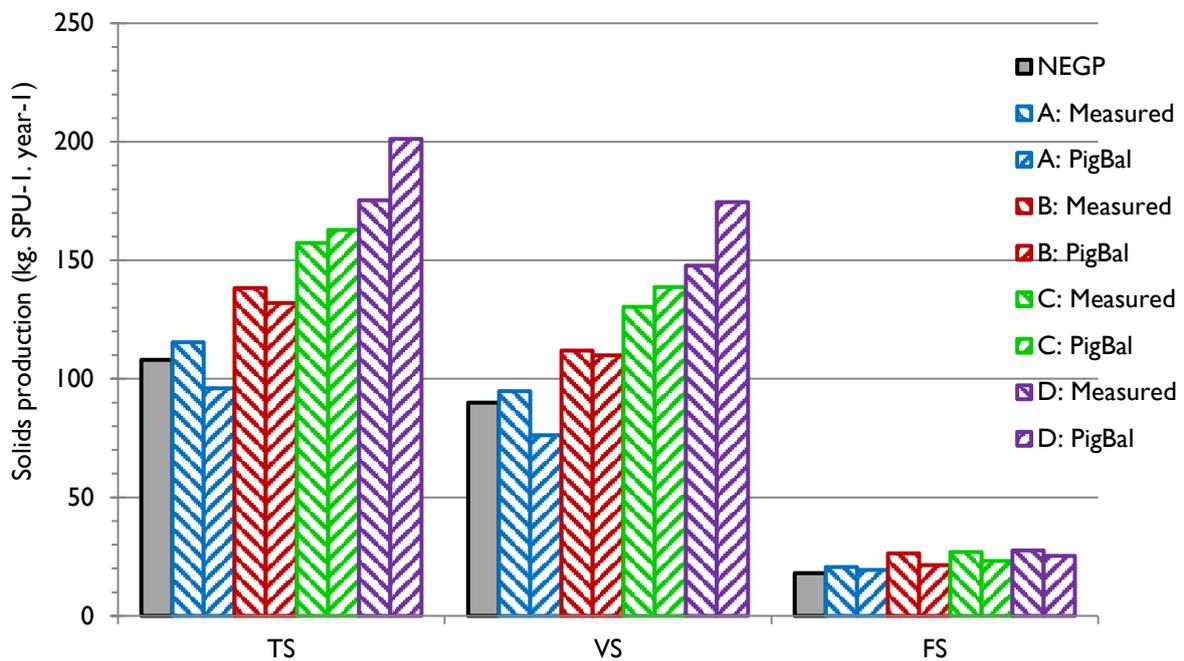
Figure 13 Bar graph comparing solids production published in the NEGP (Tucker et al., 2010) with measured values and PigBal 4 estimates.
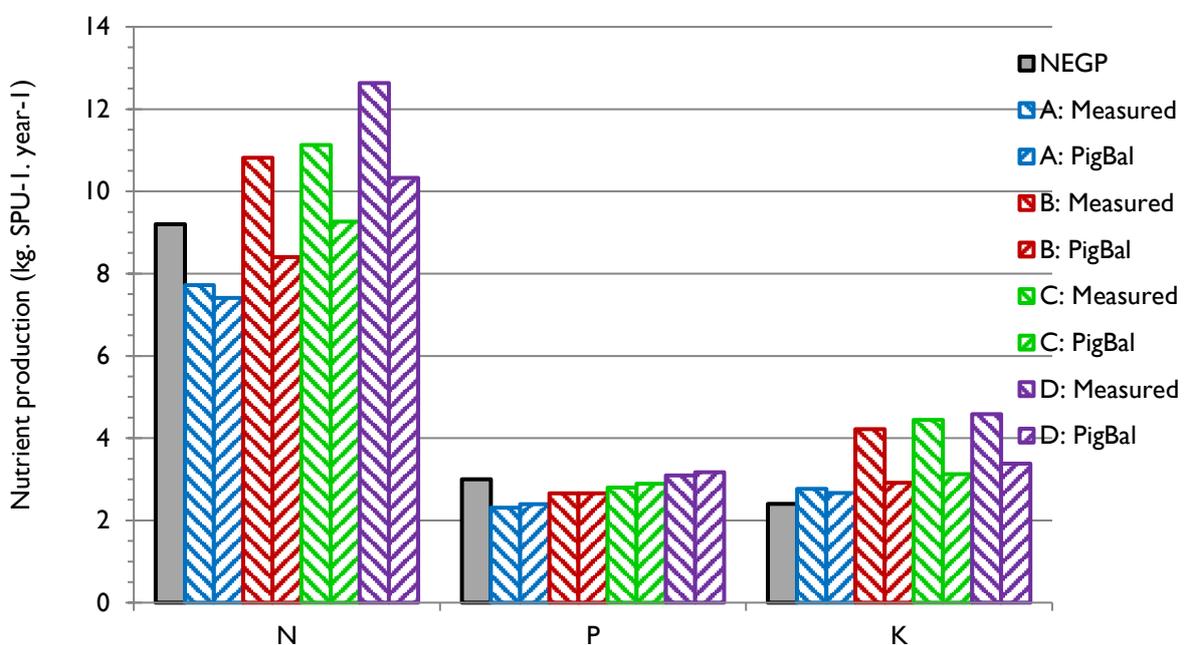
Figure 14 Bar graph comparing nutrient production published in the NEGP (Tucker et al., 2010) with measured values and PigBal 4 estimates.

In general, there appears to be reasonable agreement between the NEGP solids and nutrient production values and the measured and modelled values at the lower levels of feed wastage

(Treatments A and B). McGahan et al. (2010) identified an error in the old (pre-PigBal 4) versions of PigBal which resulted in a 10% underestimation in FS, a 2% overestimation of VS, and 19%, 12% and 14% underestimation of N, P and K, respectively.

While it is difficult to confidently explain the discrepancies between the NEGP, measured and modelled values, the higher levels of K in the measured samples compared to the modelled samples may have resulted from discrepancies between the K concentrations in the diet ingredients, as suggested by the values shown in Table 9.

Table 10 provides comparisons of AUSPIG and PigBal derived predictions for total feed fed, ingested and wasted. The PigBal predictions have used the ADG and FCR values derived from the AUSPIG modelling and the standard growth and feed intake algorithms incorporated in the PigBal model. The results are also shown graphically in Figure 15.

Table 10 Comparison of AUSPIG and PigBal derived predictions for total feed fed, ingested and wasted.

Treatment		A	B	C	D
ADG [birth to 100 kg live weight]	g/pig/day	660	660	660	660
Age at 100 kg live weight	days	149	149	149	149
Age at 100 kg live weight	weeks	21.33	21.33	21.33	21.33
FCR [birth to 100 kg live weight]		2.06	2.21	2.34	2.51
AUSPIG					
Total feed fed	kg/pig	203	218	231	247
Total feed ingested	kg/pig	203	203	203	203
Total feed wasted	kg/pig	0	15	28	44
Feed wastage	%	0.0%	6.9%	12.1%	17.8%
PigBal					
Total feed fed	kg/pig	220	237	251	268
Total feed ingested	kg/pig	220	220	220	220
Total feed wasted	kg/pig	0	16	30	48
Feed wastage	%	-7.9%	-1.0%	4.2%	9.9%
Feed wastage difference	%	7.9%	7.9%	7.9%	7.9%

The standard live weight and feed intake curves incorporated in the PigBal model have resulted in the total feed intake (from birth to 100 kg live weight) predicted by the PigBal model being 8.6% higher than the AUSPIG predictions. This has resulted in a 7.9% discrepancy between the feed wastage predictions, using the AUSPIG generated FCR and ADG values in the PigBal model.
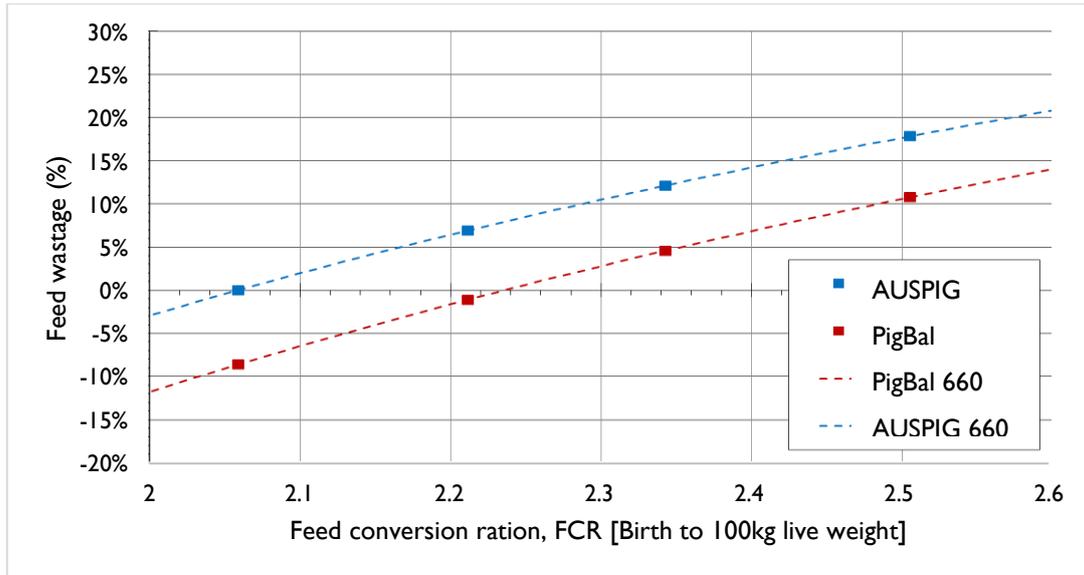
Figure 15 Feed wastage versus FCR at an ADG value of 660 g/day [birth to 100 kg live weight] for data derived from both the AUSPIG and PigBal model outputs.

6. Discussion

The level of feed wastage in the raw effluent (Treatment B) collected from the trial shed on the sampling day was calculated at 4.2%, based on the TS mass balance approach (using measured TS concentrations), and 6.9%, based on the AUSPIG modelling results. These results suggest that the actual feed wastage in the shed on the sampling day may have been approximately 5%, which is considered to be the approximate practical minimum value achievable in commercial piggeries. A visual inspection of the piggery shed on the sampling day suggested a high level of management with virtually no visible spilled feed on the shed floor. The feeders all appeared to be in good working order. These observations support the results of the feed wastage calculations.

As anticipated, the analysis results confirmed that increasing levels of feed wastage resulted in incrementally increasing concentrations of TS, VS, COD, most nutrients and VFAs in the four treatment samples. However, the measured increases in TS and VS were lower than the values predicted by McGahan et al. (2010) based on previous PigBal modelling.

Increased methane yields were also observed with increasing feed wastage. In uncovered anaerobic ponds, this result implies potentially serious increases in greenhouse gas (GHG) emissions; however, if these emissions are collected in a covered anaerobic pond or digester, the resulting additional energy could be used to offset on-farm electricity and heating costs. A simple economic analysis suggested that the piggery energy cost savings would be insufficient to compensate for the increased feed costs associated with higher levels of feed wastage.

Some Australian piggeries employ a form of co-digestion as a lower cost option to boost biogas production and energy generation potential. This practice involves deliberately adding low cost by-products (often with relatively high methane potential) to their covered anaerobic lagoons or digesters to increase biogas production above the levels achievable with the piggery effluent base loading. In some cases, the by-products are used in pig diet formulations and any excess can be used for co-digestion. This approach can be an economically viable method for generating additional on-farm energy, without wasting more costly feed ingredients, provided the biogas system can cope with the increased loading.

Comparison of the measured and modelled manure production with the NEGP values shows reasonable agreement at the lower feed wastage levels (Treatments A and B); however, modelling efficiency (EF) values for the measured versus modelled data from this study were generally lower than the values reported by Skerman et al. (2015) for a more controlled experiment carried out in metabolic pens, with no feed wastage. The exception to this outcome was the higher EF value (0.93) determined for P in this study.

A wide range of factors may have influenced the results of this study, including the following:
- The initial on-farm effluent sampling may not have produced a truly representative sample of the shed effluent.
- Some of the assumptions made in deriving the original recipes for mixing the components included in the four waste feed treatments may not have been accurate.
- The sub-sampling carried out in the laboratories may not have produced truly representative sub-samples of the shed effluent.

- Losses in TS, VS and N (and transformations of N) in the effluent and waste feed temporarily stored in the shed flushing channels and sump prior to sampling may have influenced the measured values.
- The relatively high ambient temperature on the sampling day may have accelerated the rate of fermentation of the organic matter in the waste stream.
- Comparisons between the experimental results for the four treatments may have been influenced by the addition of fresh feed to the treatments C and D samples, whereas the treatment B sample only contained potentially degraded feed.
- Similarly, treatment A contained fresh faeces and urine while treatments B, C and D contained potentially degraded faeces and urine.
- The volumes of fresh flushing water and the trickle flow from the shed prior to flushing were not measured accurately, relying on some estimated volumes.

The impact of several of these factors on the experimental results could have been minimised by using only fresh feed, faeces and urine in preparing the samples for the various treatments.

Over the past decade, several new piggeries have been constructed with pull-plug effluent management systems. In these systems, the effluent is typically held in the pull-plug pits for periods of six weeks prior to release into pre-treatment systems or anaerobic ponds. During this time, breakdown and transformation of the organic matter, possibly resulting in gaseous losses, may significantly alter the composition of the effluent. Consequently, the results of this present study may not be applicable to pull-plug piggeries.

7.   Implications & Recommendations

The availability of a relatively simple tool to assist in assessing and managing feed wastage could have a major impact on the profitability of the pork industry. On a national scale, a 5% improvement in feed wastage could save the industry from wasting 82,000 t feed/yr., with an annual value of approximately $38 M.

This study indicated that the current version of the PigBal 4 model did not accurately predict the feed wastage levels suggested by AUSPIG modelling, primarily because the standard live weight gain and feed ingestion curves incorporated in PigBal 4 resulted in higher feed consumption estimates compared to the AUSPIG predictions. To achieve a higher level of consistency between AUSPIG and PigBal 4 feed wastage estimates, further comprehensive AUSPIG simulations are recommended to provide revised growth curves and feed intake data for derivation of revised algorithms for inclusion in PigBal 4.

The existing PigBal diet ingredient database should also be reviewed to improve consistency between measured and modelled feed composition.

The experiment described in this report should be repeated using only mixtures of fresh feed, faeces, urine, and flushing water to prepare several samples simulating piggery shed effluent having a range of feed wastage levels. This approach would eliminate some of the potential differential losses resulting from the use of a mixture of fresh and aged sample ingredients in this trial. It would also be desirable to collect and analyse several sets of samples, corresponding to the different diets fed to a batch of pigs over the wean-to-finish growth cycle.

The above recommendations would assist in revising PigBal to provide a relatively simple tool which can be used confidently for assessing and managing feed wastage across the Australian pig production industry.

8. Intellectual Property

No commercially significant intellectual property is expected to arise from this research.

9. Technical Summary

The commercial grower piggery located in southern Queensland where the raw effluent, faeces, urine, feed and flushing water were sampled for this project, is ideally suited for this purpose because the below-ground sump at the end of the trial shed has sufficient capacity to hold and agitate the entire flush from half of the shed. It is also serviced by an automated feeder which accurately weighs the mass of feed delivered to each pen. Furthermore, the pigs accommodated in the trial shed are grown out in batches, from approximately 9 to 22 weeks of age. This piggery also employs high standards of management, representing current best management practices observed within the Australian pork industry.

The methods used in this project for sampling raw effluent, faeces, urine, feed and flushing water from the trial shed, and for preparing samples simulating shed effluent having a range of feed wastage levels, have been applied in the more recently commenced APL Project 2015/052 'Development of a novel sensor technology to improve effluent management decisions in the pork industry'. Based on the experience and findings of this project, it is anticipated that all future sample preparation for the more recent project will use pre-determined mixtures of freshly sampled faeces, urine, feed and flushing water. It is anticipated that most of the planned field trials for the more recent project will be carried out at the same commercial grower piggery. The ongoing collection of data from this site will assist in gaining a detailed understanding of the piggery operation and production performance.

This project saw the first use of the AMPTS II apparatus which was recently purchased for use at the DAF Toowoomba laboratory. Consistently decreasing methane production results, across the three replicates (in the chronological order of sub-sampling) for each of the four treatments, suggest that there is a need to review the sub-sampling procedure before this apparatus is used again for further research. While there was reasonable agreement between the UQ AWMC and DAF AMPTS II BMP results, the UQ AWMC results (Table 5 and Figures 6 and 7) are considered to be more reliable due to their lower variability.

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11. Publications Arising

No publications have arisen from this research to date. The authors may seek approval from APL to publish a Journal or Conference paper at a later date.

12. Appendix

Table A1 Values used in determining original sample recipe.

Parameter	Units	Simulated 0% FW	Raw effluent	Raw effluent + 5% FW	Raw effluent + 10% FW
Treatment		A	B	C	D
Pigs	pigs. side⁻¹	535	535	535	535
Shed flushing interval	days	1	1	1	1
ADG (birth to 100 kg lwt)	g lwt. day⁻¹	632	632	632	632
Pig age in	weeks	13.0	13.0	13.0	13.0
Pig age out	weeks	13.1	13.1	13.1	13.1
Pig live weight in	kg. pig⁻¹	45.3	45.3	45.3	45.3
Pig live weight out	kg. pig⁻¹	46.1	46.1	46.1	46.1
SPU factor (LWT regression)	SPU. pig⁻¹	1.14	1.14	1.14	1.14
No of SPUs	SPU	608	608	608	608
TS excreted (NEGP)	kg TS. SPU⁻¹.	108	108	108	108
TS excreted	kg. day⁻¹	179.69	179.69		
Assumed feed wastage	%	0%	2%	7%	12%
Feed ingested (as fed)	kg. pig⁻¹. day⁻¹	1.79	1.79	1.79	1.79
Feed ingested (as fed)	kg. day⁻¹	955	955	955	955
Feed wasted (as fed)	kg. day⁻¹	0	19	72	130
Feed fed (as fed)	kg. day⁻¹	955	975	1,027	1,085
Feed density (Letsche et al, 2009)	kg. m⁻³	600	600	600	600
Waste feed volume	L. day⁻¹	0	32	120	217
Feed moisture content	%	11.3%	11.3%	11.3%	11.3%
Waste feed DM	kg. day⁻¹	0	17	64	116
Waste feed moisture	L. day⁻¹	0	2	8	15
Pig age (100 kg lwt)	weeks	22.3	22.3	22.3	22.3
Total feed intake (birth - 100 kg lwt)	kg. pig⁻¹	231	231	231	231
Total feed wasted (birth - 100 kg lwt)	kg. pig⁻¹	0	5	17	32
Total feed fed (birth - 100 kg lwt)	kg. pig⁻¹	231	236	249	263
FCR (birth - 100 kg)		2.35	2.39	2.52	2.66
TS excreted + waste feed	kg. day⁻¹	179.69	196.98	243.46	295.23
Shed TS loss	%	2.0%	2.0%	2.0%	2.0%
Shed TS loss	kg. day⁻¹	3.59	3.94	4.87	5.90
TS excreted + waste feed (after losses)	kg. day⁻¹	176.10	193.04	238.59	289.32
Faeces moisture content (ASAE 2003)	%	76%	76%	76%	76%
Faeces moisture excreted	L. day⁻¹	569	569	569	569
Faeces excreted	kg. day⁻¹	749	749	749	749
Faeces density fresh (ASAE 2003)	kg. m⁻³	981	981	981	981
Faeces volume fresh	L. day⁻¹	763	763	763	763
Urine excreted (ASAE 2003)	L. SPU⁻¹. day⁻¹	1.56	1.56	1.56	1.56
Urine excreted	L. day⁻¹	948	948	948	948
Flushing volume	L. side⁻¹	11,000	11,000	11,000	11,000
Total shed effluent volume	L. flush⁻¹	12,711	12,744	12,831	12,928

Shed effluent TS conc	%		1.39%	1.51%	1.86%	2.24%

Table A2 Concentrations of various parameters recorded in the UQ analyses of(a) effluent treatments A – D and urine samples and (b) feed samples.

(a)

Parameter	A	B	C	D	SEM	Urine
TS (%)	1.51 [a]	1.81 [b]	2.06 [c]	2.29 [d]	0.04	1.88 ± 0.07
VS (%)	1.24 [a]	1.46 [b]	1.70 [c]	1.93 [d]	0.03	1.40 ± 0.09
FS (%)	0.27 [a]	0.34 [b]	0.35 [b]	0.36 [b]	0.01	0.48 ± 0.04
tCOD (g/L)	22.2 [a]	26.7 [b]	31.4 [c]	35.8 [d]	0.73	9.20 ± 1.24
sCOD (g/L)	3.20 [a]	5.42 [b]	6.44 [c]	7.32 [d]	0.06	8.29 ± 0.21
TKN (mg/L)	1,010 [a]	1,415 [b]	1,455 [b]	1,652 [c]	19	996 ± 53
NH_4-N (mg/L)	262.7 [a]	644.2 [b]	671.8 [c]	706.1 [d]	6.4	453 ± 7
TKP (mg/L)	302.4 [a]	347.8 [b]	366.2 [b]	404.2 [c]	7.9	855 ± 80
PO_4-P (mg/L)	26.5 [a]	123.6 [b]	173.2 [c]	231.3 [d]	1.7	354 ± 5
K (mg/L)	361.6 [a]	551.5 [b]	581.5 [c]	599.7 [d]	1.8	1,861 ± 25
tVFA (mg/L)	726 [a]	2,409 [b]	2,644 [c]	2,809 [d]	50	51.3 ± 4.9

[abcd] Means in a row with different superscripts differ significantly ($P<0.05$).

(b)

Parameter	Feed
TS (%)	92.62 ± 1.56
VS (%)	88.73 ± 2.93
FS (%)	3.89 ± 2.28
tCOD (g/g sample)	0.72 ± 0.12
sCOD (g/g sample)	0.14 ± 0.01
TKN (mg/g sample)	24.44 ± 2.14
NH_4-N (mg/g sample)	0.08 ± 0.07
TKP (mg/g sample)	5.14 ± 0.70
PO_4-P (mg/g sample)	1.91 ± 0.00
K (mg/g sample)	6.58 ± 0.30
tVFA (mg/g sample)	5.82 ± 1.18

Table A3. Concentrations of total and volatile solids parameters recorded in the DAF analyses of effluent treatments A – D and feed and faeces samples.

Parameter	A	B	C	D	Feed	Faeces
TS (%)	1.63 ± 0.36	2.13 ± 0.23	2.41 ± 0.17	2.60 ± 0.29	92.82 ± 0.97	27.57 ± 1.08
VS (%)	1.34 ± 0.33	1.78 ± 0.21	2.05 ± 0.16	2.23 ± 0.29	88.13 ± 0.65	22.83 ± 0.79

Table A4 Concentrations of volatile fatty acids (VFA) (ppm) in (a) effluent treatments A – D and (b) feed and urine samples.

(a)

Volatile fatty acid	A	B	C	D
Acetic acid	368.37 ± 26.80	1,290.65 ± 155.56	1,399.06 ± 111.89	1,480.15 ± 138.95
Propionic acid	160.66 ± 14.41	447.56 ± 47.21	497.30 ± 36.62	539.00 ± 48.14
iso-Butyric acid	17.22 ± 1.41	56.77 ± 6.04	57.36 ± 3.93	58.42 ± 7.68
Butyric acid	107.69 ± 6.13	393.33 ± 39.87	454.07 ± 34.23	486.70 ± 46.07
iso-Valeric acid	28.42 ±1.47	89.14 ± 9.13	90.94 ± 6.30	92.71 ± 8.33
Valeric acid	38.04 ± 4.07	104.01 ± 9.52	116.01 ± 7.54	122.51 ± 9.81
Hexanoic acid	5.34 ± 1.25	27.56 ± 1.03	29.39 ± 2.39	29.81 ± 3.22
tVFA	725.74 ± 51.84	2,409.04 ± 268.12	2,644.13 ± 202.34	2,809.29 ± 261.27

(b)

Volatile fatty acid	Feed	Urine
Acetic acid	22.77 ± 3.33	46.57 ± 8.75
Propionic acid	0.00 ± 0.00	43.75 ± 7.31
iso-Butyric acid	0.00 ± 0.00	0.00 ± 0.00
Butyric acid	11.49 ± 1.46	13.93 ± 7.63
iso-Valeric acid	0.00 ± 0.00	0.85 ± 3.66
Valeric acid	15.71 ± 1.16	44.47 ± 6.52
Hexanoic acid	1.31 ± 5.62	0.00 ± 0.00
tVFA	51.27 ± 4.86	149.57 ± 30.26

Table A5 Concentrations of various elements (ppm) in (a) effluent treatments A – D and (b) feed, urine and drinking/flushing water samples.

(a)

Element	A	B	C	D
Al	3.08 ± 0.50	3.83 ± 0.92	4.16 ± 0.44	4.76 ± 0.42
As	0.04 ± 0.03	0.11 ± 0.16	0.13 ± 0.18	0.18 ± 0.17
B	0.17 ± 0.01	0.42 ± 0.01	0.44 ± 0.01	0.45 ± 0.01
Ba	0.93 ± 0.02	0.96 ± 0.06	0.99 ± 0.10	1.03 ± 0.02
Ca	353.58 ± 12.19	319.25 ± 10.45	364.02 ± 48.49	396.75 ± 11.56
Cd	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Co	0.07 ± 0.01	0.08 ± 0.01	0.08 ± 0.01	0.08 ± 0.00
Cr	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.01	0.01 ± 0.01
Cu	10.93 ± 0.20	13.08 ± 0.60	13.16 ± 0.67	13.88 ± 0.39
Fe	23.77 ± 1.36	26.93 ± 2.14	27.66 ± 2.21	30.07 ± 0.77
K	361.61 ± 7.57	551.46 ± 9.34	581.50 ± 1.39	599.72 ± 9.91
Mg	209.59 ± 1.21	226.06 ± 3.25	236.01 ± 9.64	244.38 ± 6.13
Mn	8.90 ± 0.60	8.12 ± 0.25	8.66 ± 0.49	9.13 ± 0.27
Mo	0.08 ± 0.03	0.14 ± 0.06	0.14 ± 0.01	0.15 ± 0.01
Na	129.18 ± 1.28	199.55 ± 3.11	205.29 ± 0.54	204.87 ± 2.88
Ni	0.08 ± 0.01	0.11 ± 0.01	0.09 ± 0.02	0.10 ± 0.02
P	339.42 ± 4.21	379.39 ± 8.25	411.96 ± 17.01	439.34 ± 6.96
Pb	0.04 ± 0.15	0.00 ± 0.00	0.03 ± 0.05	0.00 ± 0.00
S	96.25 ± 1.97	143.77 ± 6.49	150.79 ± 9.89	159.73 ± 2.15
Se	0.02 ± 0.09	0.04 ± 0.06	0.06 ± 0.12	0.07 ± 0.08
Zn	26.45 ± 0.26	20.02 ± 0.41	20.58 ± 0.76	21.39 ± 1.33

(b)

Element	Feed	Urine	Flushing/drinking water
Al	0.04 ± 0.00	0.00 ± 0.00	0.03 ± 0.01
As	0.00 ± 0.00	0.05 ± 0.11	0.00 ± 0.00
B	0.00 ± 0.00	1.80 ± 0.06	0.03 ± 0.00
Ba	0.01 ± 0.00	0.01 ± 0.00	0.06 ± 0.01
Ca	7.20 ± 3.52	75.86 ± 1.65	42.47 ± 0.52
Cd	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Co	0.00 ± 0.00	0.06 ± 0.01	0.00 ± 0.00
Cr	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Cu	0.08 ± 0.03	0.03 ± 0.01	0.14 ± 0.01
Fe	0.38 ± 0.10	0.12 ± 0.07	0.00 ± 0.00
K	6.58 ± 0.30	1,860.62 ± 25.20	0.92 ± 0.13
Mg	1.97 ± 0.11	96.73 ± 1.81	31.82 ± 0.48
Mn	0.10 ± 0.04	0.00 ± 0.00	0.00 ± 0.00
Mo	0.00 ± 0.00	0.24 ± 0.12	0.00 ± 0.00
Na	0.88 ± 0.51	230.61 ± 2.72	77.40 ± 1.22
Ni	0.00 ± 0.00	0.01 ± 0.01	0.00 ± 0.00
P	5.18 ± 1.63	370.80 ± 4.03	0.00 ± 0.00
Pb	0.01 ± 0.02	0.00 ± 0.00	0.02 ± 0.01
S	2.14 ± 0.03	302.55 ± 4.96	1.66 ± 0.05
Se	0.00 ± 0.00	0.09 ± 0.14	0.00 ± 0.00
Zn	0.11 ± 0.01	0.39 ± 0.01	0.01 ± 0.00

Table A6 Biochemical methane potential (BMP) analysis results calculated using the DAF AMPTS II analysis method.

Biochemical methane potential (NmL CH$_4$ / g VS)					
Treatment	A	B	C	D	SEM
DAF AMPTS II	319 [a]	357 [b]	348 [ab]	375 [b]	10.5

[ab] Means in a row with different superscripts differ significantly (P<0.05).

Table A7 Cumulative mean CH$_4$ volume from substrate, per g VS (NmL/g VS), determined using the DAF AMPTS II analysis method.

| Day	A	B	C	D
0	0	0	0	0
1	54	60	67	74
2	82	86	88	92
3	116	111	107	108
4	151	136	126	124
5	179	162	148	143
6	202	194	172	170
7	221	227	199	195
8	237	250	231	220
9	252	269	255	247
10	264	285	276	269
11	273	296	289	289
12	280	305	297	306
13	287	313	302	320
14	292	321	307	329
15	297	327	314	334
16	301	332	321	339
17	305	336	327	343
18	307	339	331	348
19	309	341	335	352
20	311	343	337	355
21	313	345	339	359
22	314	346	340	361
23	316	348	341	363
24	317	349	342	365
25	317	350	343	366
26	318	351	343	368
27	318	353	344	369
28	318	354	345	370
29	319	355	346	372
30	319	356	347	373
31	319	356	347	373
32	319	356	348	374
33	319	357	348	374
34	319	357	348	375
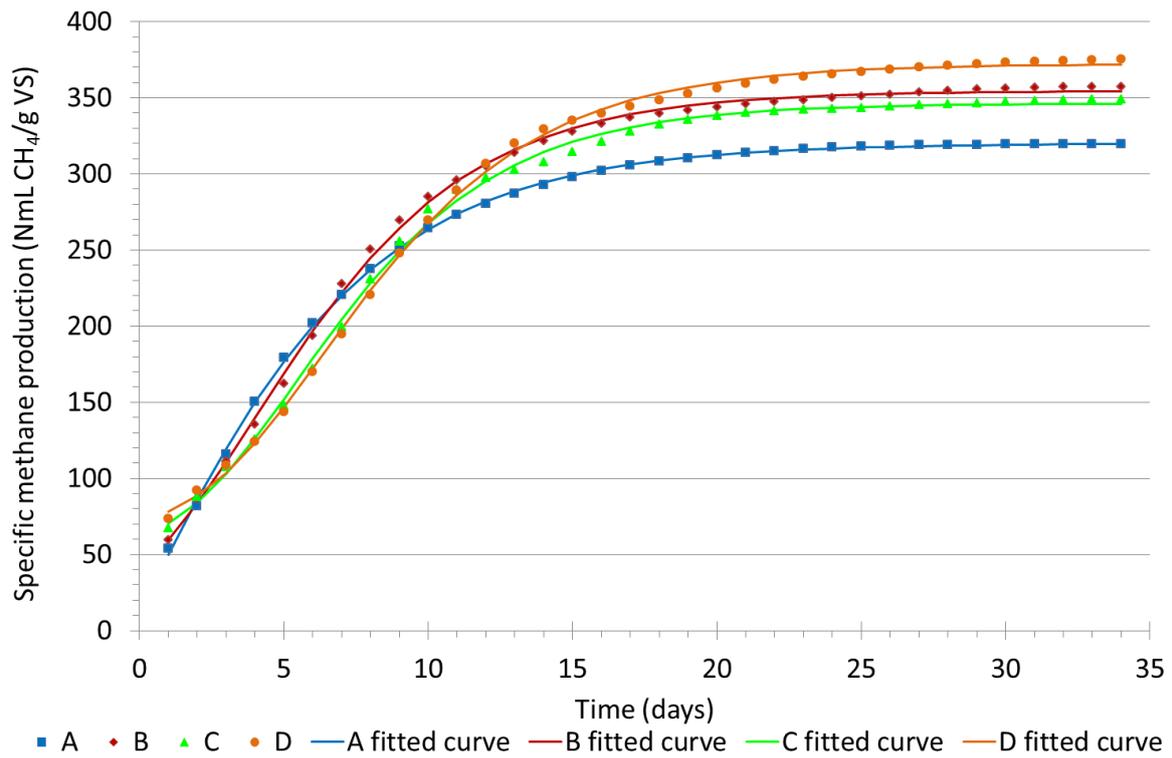
Figure A1 Cumulative specific methane production from the four treatment substrates determined from the DAF AMPTS II analysis results. Gompertz curves have been fitted to the raw data.
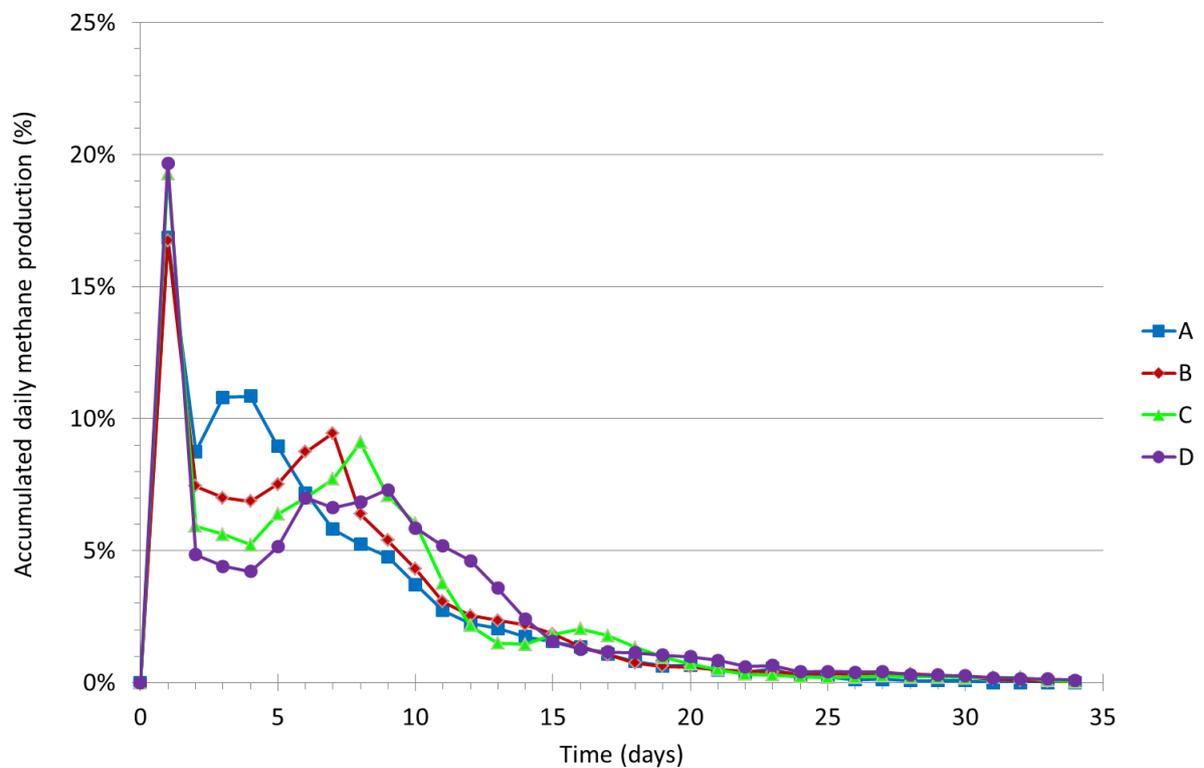
Figure A2 Daily methane production as a percentage of the total methane production for the four treatments, as determined from the DAF AMPTS II analysis results.

Table A8 Cumulative mean CH₄ from substrate per g VS (NmL/g VS) determined from UQ manual BMP analyses.

Day	A	B	C	D	Feed
0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
1.0	89.6 ± 3.0	88.5 ± 5.8	88.5 ± 16.9	88.0 ± 4.6	84.5 ± 6.6
2.1	127.2 ± 21.0	145.5 ± 9.7	152.3 ± 1.8	148.3 ± 2.2	148.2 ± 5.0
3.0	165.3 ± 20.2	189.8 ± 5.5	193.9 ± 2.5	197.2 ± 1.1	184.2 ± 9.0
5.1	202.0 ± 24.5	231.2 ± 7.6	243.3 ± 3.4	248.3 ± 9.2	217.2 ± 12.7
9.1	234.4 ± 24.0	268.5 ± 9.0	284.6 ± 9.1	297.8 ± 11.1	230.8 ± 17.6
13.0	253.3 ± 24.0	292.2 ± 11.7	310.2 ± 9.3	326.6 ± 9.1	243.9 ± 18.5
17.9	266.7 ± 22.9	308.4 ± 12.9	330.8 ± 11.4	351.9 ± 8.6	254.4 ± 17.1
27.0	275.9 ± 23.2	320.4 ± 16.1	346.7 ± 10.4	370.2 ± 8.6	260.4 ± 19.6
34.2	281.8 ± 26.6	324.3 ± 20.7	356.7 ± 10.8	378.4 ± 8.9	266.1 ± 19.1
41.3	283.8 ± 27.7	327.5 ± 18.8	360.6 ± 10.7	383.1 ± 9.8	267.1 ± 18.8
50.3	284.6 ± 28.3	326.6 ± 15.6	360.9 ± 8.4	383.3 ± 9.2	264.0 ± 18.6

Table A9 Details of the Grower 2 diet fed to the pigs in the trial shed prior to the sampling day.

Diet ingredient	Percentage of mass (as-fed)
Barley 11	10.00
Wheat 11	51.48
Mill Run 15% Crude Protein	17.50
Soybean Meal 46% CP Solvent	1.60
Canola Meal 37 Solvent	12.00
Blood Meal 90 – Ring Dried	0.50
Meat Meal 50	2.50
Vegetable oil	2.40
Limestone - fine	1.00
L-Lysine HCL	0.43
DL Methionine	0.07
L Threonine	0.105
Tryptophan	0.015
Salt	0.20
Grower Premix	0.20

Table A10 AUSPIG model summary of grower performance output.

Age	Live weight	Live Weight Gain			Live P2	FCR	
		Current	From birth	Average to date		Current	Average to date
(days)	(kg)	(g/d)	(g/d)	(g/d)	(mm)		
23	6.2	3	204	3	1.0	72.22	72.22
25	6.9	349	215	229	1.2	1.44	1.71
28	8.0	375	230	297	1.7	1.50	1.58
31	9.1	358	243	319	2.2	1.56	1.56
34	10.1	351	252	327	2.6	1.61	1.57
37	11.2	350	260	332	3.0	1.65	1.59
39	11.9	423	266	338	3.2	1.55	1.59
40	12.4	429	270	343	3.3	1.55	1.58
43	13.7	427	281	355	3.7	1.61	1.59
46	14.9	427	290	364	3.9	1.66	1.59
49	16.2	430	298	371	4.2	1.71	1.61
50	16.8	590	304	379	4.3	1.53	1.60
52	18.0	591	315	393	4.6	1.59	1.60
55	19.8	609	331	412	4.9	1.65	1.60
58	21.7	621	345	429	5.1	1.69	1.61
61	23.5	633	359	445	5.4	1.74	1.62
64	25.5	649	372	459	5.6	1.92	1.64
67	27.4	670	385	472	5.9	1.99	1.67
70	29.5	687	397	485	6.1	2.04	1.71
73	31.6	704	409	498	6.3	2.08	1.74
76	33.7	720	421	510	6.5	2.12	1.76
79	35.9	736	433	522	6.7	2.16	1.79
82	38.2	752	444	533	6.8	2.20	1.82
85	40.5	768	455	544	7.0	2.23	1.85
88	42.8	784	466	554	7.2	2.27	1.87
91	45.2	801	477	565	7.4	2.30	1.90
94	47.6	817	487	575	7.5	2.33	1.92
97	50.1	833	498	585	7.7	2.37	1.95
100	52.6	849	508	595	7.9	2.40	1.97
103	55.2	864	518	605	8.0	2.43	2.00
106	57.8	880	528	615	8.2	2.46	2.02
109	60.5	895	538	624	8.4	2.49	2.04
112	63.2	910	548	633	8.6	2.52	2.06
115	66.0	920	557	643	8.7	2.65	2.09
118	68.8	939	567	652	8.9	2.64	2.11
121	71.6	953	577	661	9.1	2.67	2.14
124	74.5	966	586	670	9.2	2.70	2.16
126	76.5	976	592	676	9.3	2.70	2.17
127	77.4	985	595	679	9.4	2.70	2.18
130	80.4	992	604	687	9.6	2.73	2.20
133	83.4	1,003	613	696	9.7	2.76	2.22
136	86.4	1,014	621	704	9.9	2.79	2.25
139	89.5	1,024	630	712	10.1	2.82	2.27
142	92.6	1,033	638	720	10.2	2.85	2.29
145	95.7	1,042	647	728	10.4	2.88	2.31
147	97.8	1,047	652	733	10.5	2.90	2.32

Table A11 AUSPIG model grower pig feed offered and energy intake.

Live weight	Diet	Feeding Regime	Feed Offered	Feed Waste	Cumulative Feed Offered	DE Intake
(kg)			(kg/d)	(kg/d)	(kg)	(MJ/d)
6.2	CREEP	0.70*ADLIB	0.19	0.02	0.19	2.53
7.6	CREEP	0.70*ADLIB	0.55	0.07	2.25	7.21
9.4	CREEP	0.70*ADLIB	0.56	0.07	5.04	7.40
11.2	CREEP	0.70*ADLIB	0.58	0.07	7.89	7.63
11.9	STARTER	0.80*ADLIB	0.66	0.07	9.12	8.87
13.2	STARTER	0.80*ADLIB	0.68	0.07	11.14	9.20
15.4	STARTER	0.80*ADLIB	0.72	0.08	14.64	9.71
16.8	WEANER	1.00*ADLIB	0.90	0.06	17.00	12.56
18.0	WEANER	1.00*ADLIB	0.94	0.07	18.86	13.11
21.0	WEANER	1.00*ADLIB	1.03	0.07	23.87	14.45
24.2	WEANER	1.00*ADLIB	1.12	0.08	29.29	15.60
25.5	GROWER 1	1.01*ADLIB	1.25	0.09	31.67	16.23
27.4	GROWER 1	1.01*ADLIB	1.33	0.09	35.59	17.40
30.9	GROWER 1	1.01*ADLIB	1.44	0.10	42.59	18.81
34.5	GROWER 1	1.01*ADLIB	1.55	0.11	50.12	20.17
38.2	GROWER 1	1.01*ADLIB	1.65	0.11	58.17	21.54
42.0	GROWER 1	1.01*ADLIB	1.76	0.12	66.75	22.91
45.2	GROWER 1	1.01*ADLIB	1.84	0.13	73.99	24.02
46.0	GROWER 1	1.01*ADLIB	1.86	0.13	75.85	24.29
50.1	GROWER 1	1.01*ADLIB	1.97	0.14	85.49	25.70
54.3	GROWER 1	1.01*ADLIB	2.08	0.14	95.67	27.10
58.7	GROWER 1	1.01*ADLIB	2.19	0.15	106.40	28.52
63.2	GROWER 1	1.01*ADLIB	2.30	0.16	117.66	29.92
66.0	FINISHR 1M	1.01*ADLIB	2.44	0.17	124.75	30.76
67.8	FINISHR 1M	1.01*ADLIB	2.46	0.17	129.68	31.06
72.6	FINISHR 1M	1.01*ADLIB	2.56	0.18	142.29	32.37
76.5	MALE PAYLN	1.01*ADLIB	2.64	0.18	152.75	33.43
77.4	MALE PAYLN	1.01*ADLIB	2.66	0.18	155.41	33.66
82.4	MALE PAYLN	1.01*ADLIB	2.75	0.19	168.95	34.83
87.5	MALE PAYLN	1.01*ADLIB	2.85	0.20	183.00	36.10
92.6	MALE PAYLN	1.01*ADLIB	2.94	0.20	197.53	37.30
97.8	MALE PAYLN	1.01*ADLIB	3.03	0.21	212.52	38.42

Table A12 Details of calculations assessing the economic impact of increased biogas energy production resulting from increased feed wastage, based on the experimental results.

Treatment	Units	A	B	C	D	Extrap.
Feed wastage	%	0.0%	4.2%	9.4%	15.2%	20.0%
Bo, Ultimate methane yield	NL CH_4. kg VS^{-1}	285	326	362	383	386
VS conc	%	1.26%	1.43%	1.63%	1.86%	2.05%
VS production	kg VS. pig^{-1}. day^{-1}	0.292	0.331	0.379	0.432	0.476
VS production	kg VS. SPU^{-1}. day^{-1}	0.263	0.298	0.342	0.390	0.430
VS after screening	kg VS. SPU^{-1}. day^{-1}	0.198	0.224	0.256	0.292	0.322
CH_4 production	NL CH_4. SPU^{-1}. day^-	56.31	72.90	92.73	111.99	124.38
CH_4 production	Nm^3 CH_4. SPU^{-1}. yr^-	20.57	26.63	33.87	40.90	45.43
CH_4 elec energy	kWh. SPU^{-1}. yr^{-1}	61	79	101	122	136
CH_4 thermal energy	kWh. SPU^{-1}. yr^{-1}	102	132	168	203	226
Elec energy cost saving	$. SPU^{-1}. yr^{-1}	15.34	19.86	25.26	30.51	33.88
Thermal energy cost saving	$. SPU^{-1}. yr^{-1}	11.46	14.83	18.87	22.79	25.31
Elec energy cost saving	$. yr^{-1}	153,409	198,590	252,624	305,066	338,822
Thermal energy cost saving	$. yr^{-1}	114,591	148,340	188,701	227,874	253,088
Additional elec energy saving	$. yr^{-1}	-45,181	0	54,033	106,476	140,232
Additional thermal energy	$. yr^{-1}	-33,749	0	40,361	79,534	104,748
Total energy savings	$. yr^{-1}	-78,930	0	94,395	186,010	244,980
Feed consumption	t. yr^{-1}	5,747	6,000	6,313	6,660	6,947
Additional feed cost	$. yr^{-1}	-118,232	0	146,549	308,650	443,368
Total saving / loss	$. yr^{-1}	39,301	0	-52,154	-122,640	-198,388

Table A11 Summary of assumptions made in carrying out the above economic analysis.

Total Eff Vol	L	12,405
No of pigs	pigs	535
SPU factor	SPU. pig^{-1}	1.11
No of SPU	SPU	593
Screening VS removal	%	25%
Piggery capacity	sows	1,000
Piggery capacity	SPU	10,000
CH_4 energy	MJ. Nm^3 CH_4^{-1}	35.8
CH_4 energy	kWh. Nm^3 CH_4^{-1}	9.94
CHP elec efficiency	%	30%
CHP thermal efficiency	%	50%
Electrical energy value	$. kWh^{-1}	0.25
LPG energy value	MJ. m^{-3} (liquid)	25,704
LPG energy value	kWh. m^{-3} (liquid)	7,140
Average LPG cost	$. L^{-1}	0.80
LPG thermal energy value	$. kWh^{-1}	0.11
Feed consumption	t. yr^{-1}	6,000
Feed cost	$. t^{-1}	468