

pH: a promising indicator of feed waste in piggery effluent?

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Abstract. Feed waste in pork production sheds can amount to substantial economic losses. No simple methods exist to quantify this waste, which commonly ends up in the effluent stream. Monitoring piggery effluent might offer producers a practical alert solution for feed waste losses. We investigated piggery effluent pH as a potential marker of feed waste, given that most feed substrates and breakdown products are acidic whereas effluent is alkaline. To explore this prospective relationship, we constructed simulated effluent streams comprising faeces, urine and feed. These waste components were acquired from a commercial batch grower shed, at four different times over the 12-week growth cycle. In laboratory settings (25°C) we used the collected wastes to simulate the two stages of typical flushing piggery effluent systems: (1) Faeces + urine + feed waste accumulation in flushing channels, and (2) flush water mixing with these wastes in an effluent collection sump. We repeated the exercise for a one-off sampling event at a sow facility. For all events, at the grower and sow facility, the pH of the simulated effluents yielded exponentially decreasing relationships with increasing feed waste level ($P < 0.05$). For the grower facility we applied each of the four laboratory-derived relationships to the farm's sump effluent pH, which was measured during each of these sampling events. The predicted feed waste levels were commensurate with estimates of feed waste for the same facility derived from alternative, time intensive approaches reported in other studies. Further work is needed to transition the promising results uncovered here into an alert system to help farmers improve profitability and minimise waste.

Additional keywords: agriculture, effluent, feed waste, pH, pig production.

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Introduction

Feed is one of the major input expenses for pork producers (Galanopoulos *et al.* 2006). In Australia, it accounts for 65% of production costs (Skerman *et al.* 2016). Even before feed is ingested by pigs, substantial in-shed losses can occur when feed waste is spilled onto the floor. According to Skerman *et al.* (2016) a 5% increase in feed waste equates to almost \$40 million annually for the Australian industry. Feed waste represents an indicator of mechanical failure of feeders as well as general animal health and behaviour. It also has implications for downstream wastewater treatment because undigested feed has a substantially higher methane-emitting potential than digested manures (El-Mashad and Zhang 2010). According to McGahan *et al.* (2010) a 5% increase in feed waste can cause a 30% increase in the volatile solids content of the effluent stream. Consequently, the presence of even relatively small proportions of feed waste in the effluent stream could result in greater emissions from anaerobic effluent ponds. On the flipside, many producers are adopting bioenergy recovery systems for their treatment ponds and so the presence of feed waste could have important implications here. All of these issues can markedly affect on-farm production, profitability and environmental impact.

There are no simple, robust approaches to quantify feed waste in piggery sheds (Skerman *et al.* 2016). Dunshea *et al.* (2003) and Hofmeyr *et al.* (2005) attempted, with limited

success, to use indigestible markers such as insoluble ash in manure samples. Real-time monitoring of the effluent stream in pig production facilities might offer a responsive means to manage feed waste in pork production sheds; hence, providing an early indication of problems that need to be addressed before serious production losses and expenses are incurred.

Most intensive piggeries in Australia have fully or partially slatted shed floors. The waste products fall through the slats into underlying concrete channels, which are flushed regularly to remove the waste products from the shed, commonly into an effluent collection sump or directly into an anaerobic effluent treatment pond. Beyond Australia, the use of flushing systems to remove waste products from pork production sheds is common practice in Europe, North America and New Zealand (Zahn *et al.* 2001; Ye *et al.* 2007; McGahan *et al.* 2016). As well as collecting faeces and urine, the flush water hoses any feed waste on shed floors and transfers all wastes to the effluent management system. Theoretically, increases in feed waste will be accompanied by an increase in total solids in the effluent stream. However, accurately measuring these changes, which can be subtle and variable in terms of solids concentration changes, is logistically challenging. Targeting compositional differences between the manure (urine and faeces) and the feed waste components of the effluent stream might offer an effective way to quantify feed wastage problems.

Effluent pH may respond to feed waste in pork production sheds. Agricultural feed grains are rich in compounds which exhibit acidic properties, for example, proteins, amino acids, carbohydrates and lipids (Mason *et al.* 1988; Oscarsson *et al.* 1996; Zijlstra *et al.* 1999; Evers and Millar 2002). Domínguez and Cejudo (1999) report that an acid pH is often maintained within the starchy endoplasm of cereal grains in order to facilitate several biochemical conversion processes. Moreover, feed contains a high proportion of readily degradable substrates, which can be rapidly converted to volatile fatty acids (Zhu 2000; El-Mashad and Zhang 2010), hence potentially acidifying the effluent stream. Effluent, by contrast, is typically alkaline owing to hydrolysis of urea in urine by faecal bacteria. Alkaline pH in pig manures has been reported in a host of publications – Velthof *et al.* (2005) documented an average pH of 8.0 for 10 pig manure samples collected from indoor systems in the Netherlands; Huang *et al.* (2006) noted a pH of 8.2 for fresh pig manure analysed from a production facility in Hong Kong; Ye *et al.* (1999) measured a pH of 7.7 for fresh pig manure from a farm in Lechang, China; whereas a pH range of 7.2–8.3 was reported for Danish fattening pig manures by Møller *et al.* (2002). All of these manures were collected from a few hours to days following excretion. Dai and Karring (2014) reported that hydrolysis kinetics for piggery manure are much more rapid than for other livestock manures, because of the presence of uniquely efficient ureolytic faecal bacteria in pig manure. Within less than 24 h, these authors reported almost complete hydrolysis of urea in pig manure samples, coinciding with a final stable alkaline pH of 8.2. Hence, it appears that most piggery manures likely exhibit moderately alkaline pH properties in the shed system even before they are mixed with flush water in the sump stage.

In this study, we investigated prospective relationships between pH and feed waste in effluent streams as a method to estimate the magnitude of feed waste in pig production sheds. Queensland pig production systems were targeted in our predominantly-laboratory based research, which also included a limited field testing component.

Materials and methods

Site description and material collection

Waste materials were collected from a commercial grower pork production facility in the Darling Downs region of Australia, ~150 km west of Brisbane, and a sow facility in the Lockyer Valley, ~75 km west of Brisbane. At the grower facility, materials were collected from a shed housing 1080 animals with average entry and exit liveweights and ages of ~25–30 kg (9–10 weeks) and 100–110 kg (22 weeks). At the sow facility, materials were taken from a mixed parity sow shed with average liveweights of 180 kg. Pig diets are shown in Fig. 1.

The shed at the grower facility was fitted with a purpose-built 20 000-L sump, which received effluent from the flushing channels, which run longitudinally beneath the slatted floor. The effluent stream comprised wash-down bore water, supplied from a 22 000-L aboveground holding tank, as well as accumulated faeces, urine and feed waste deposited on the slatted base. Accumulation times between flushing were 1–3 days, which is considered typical for piggery flushing

systems (Tucker *et al.* 2010). The sump takes ~30 min to fill and a further 30 min to evacuate via a submersible pump. From the sump, effluent is directed into the central effluent collection channel and ultimately to the facility's primary holding pond. We targeted a full 12-week grower batch with samples acquired 3, 6, 9 and 12 weeks into the cycle. Faeces and urine were collected directly from animals in the shed with care taken to secure the materials before they contacted the slatted floors. Feed was sampled from the in-shed feeder while flush water was obtained directly from a tank used to supply the wash-down water, in this case bore water, for the shed. At the same time that these wastes were acquired, a sample of the mixed effluent from the sump was also collected, directly following flushing. The flushing interval was 24 h for three of the sampling events; for the other it was 48 h.

The sow facility employs a static pit effluent management system. This facility provided an ideal point of comparison for the results from the grower farm, given the difference in animal type and production practices between the grower and sow facilities. Hence, we simulated a flushing system using faeces, urine and feed from the sow facility with the site water that is used to hose down the sheds. All materials from both facilities were kept chilled on ice and returned to the laboratory for immediate analysis where they were kept frozen before constructing the simulated effluent streams. In addition to the farm samples, we collected batches of unprocessed feed grains, which were representative of the local pig diet profile: wheat, barley and sorghum. These were acquired from a commercial supplier and were ground in a blender for pH measurements.

Feed pH buffer curves

The pH buffering capacity of all farm feed materials, as well as the unprocessed feed grains, was determined following the method outlined by Nelson and Su (2010). Briefly, portions of the feed materials were ground using a domestic processor and 8 g of each material were placed into five screw-cap plastic containers. Forty-mL solutions of varying acid and base strength were then added to these containers. A solution of 0.5 M H₂SO₄ was used for the acid solutions, and 1M NaOH was used for the base solutions. Blank solutions with no feed were also prepared. The containers were shaken end-over-end for 1 h and pH measured in the solution phase.

Simulated effluents

We constructed effluent streams using the materials from the grower and sow facilities to simulate the effect of increasing feed waste on effluent pH. We simulated the two stages of early manure management practices common to piggeries that employ flush systems: (1) faeces + urine + feed waste accumulation in flushing channels, and (2) flush water mixing with these wastes in a sump. For Stage 1, masses of faeces, urine and feed were weighed out into 2-L glass vessels. These unmixed materials were left open to the air at 25°C for 48 h. The chosen temperature represents targeted in-shed conditions at the grower facility (pers. comm., producer, 2017) whereas the flushing interval is typical for Australian systems (Tucker *et al.* 2010). After this time, flush water was added to the wastes and gently mixed for 1 h to simulate the sump phase of the effluent management

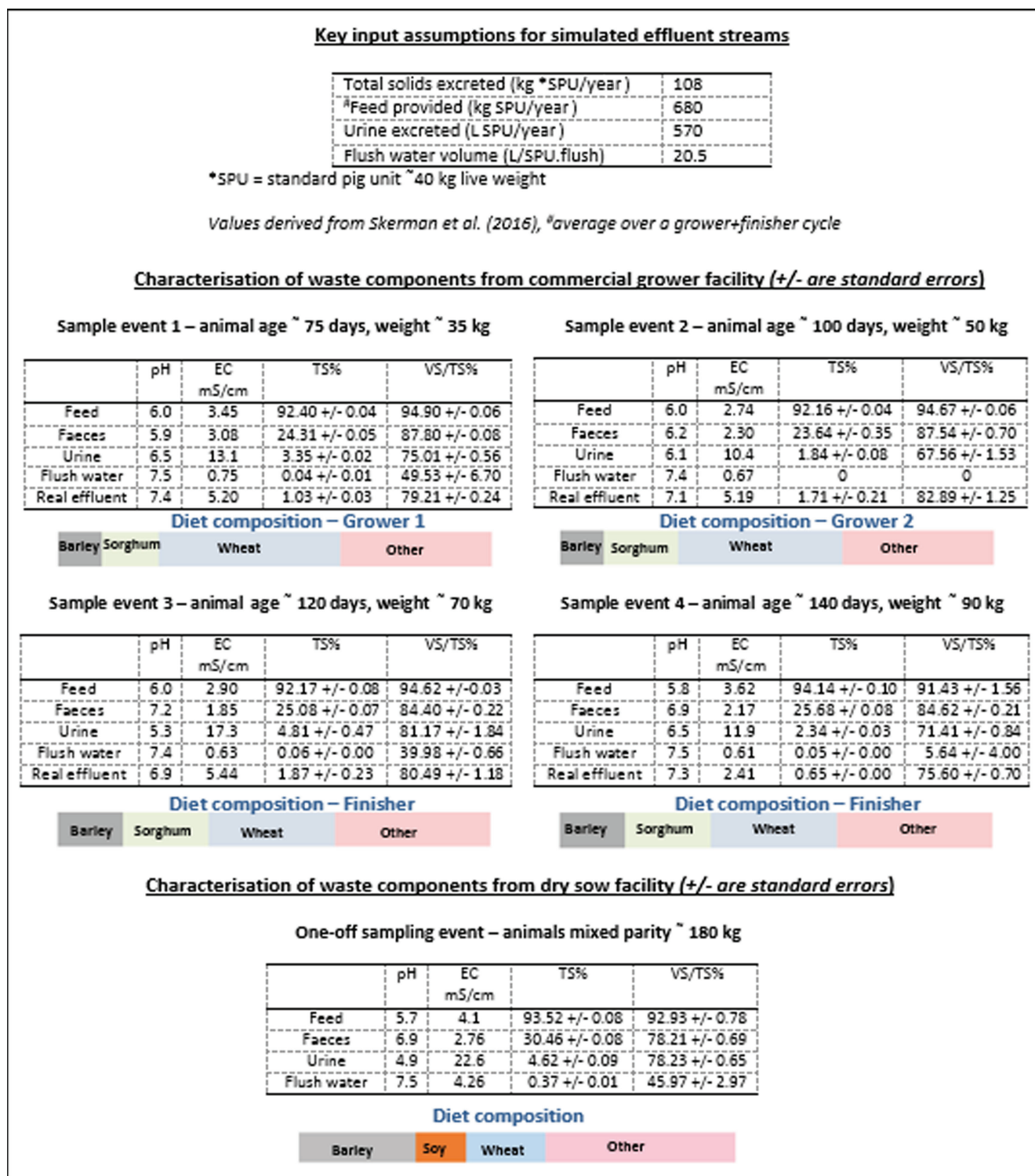


Fig. 1. Key assumptions and material characterisation for constructing simulated effluent streams.

system whereby effluent is typically mixed via the flushing process as well as a mechanical agitator. Effluent pH was immediately measured in each of the vessels, which were subsequently left open to the air for another 48 h. At this time

pH was again measured. The quantities of each material used in the simulated effluents are shown in Table 1.

The ratios of material quantities used were derived from industry data on pig faeces total solids, pig urine volumes and

Table 1. Quantities of waste materials used to construct the simulated effluent streams.

Stream solids content is the total solids content for each treatment. Note, insufficient masses of urine and faeces were collected to construct the 30% feed waste effluent stream for Sample event 4 at the grower facility

		Simulated feed waste (% of feed fed)									
		0	1	1.7	5	7.5	10	15	20	25	30
		<i>Grower facility</i>									
Sample event 1	Feed (g)	0	0.44	0.74	2.21	3.32	4.42	6.64	8.85	11.06	13.28
• Animals ~35 kg, 30 g faeces, 38 mL urine, 500 mL flush water	Stream solids content (%)	1.56	1.64	1.69	1.93	2.11	2.29	2.66	3.02	3.39	3.75
Sample event 2	Feed (g)	0	0.43	0.72	2.16	3.23	4.31	6.47	8.63	10.78	12.94
• Animals ~50 kg, 30 g faeces, 37 mL urine, 500 mL flush water	Stream solids content (%)	1.39	1.46	1.51	1.74	1.92	2.10	2.45	2.81	3.16	3.52
Sample event 3	Feed (g)	0	0.44	0.74	2.21	3.31	4.41	6.62	8.83	11.03	13.24
• Animals ~70 kg, 30 g faeces, 39 mL urine, 500 mL flush water	Stream solids content (%)	1.74	1.81	1.86	2.10	2.28	2.46	2.82	3.19	3.55	3.91
Sample event 4	Feed (g)	0	0.45	0.77	2.30	3.44	4.59	6.89	9.19	11.48	NA
• Animals ~90 kg, 30 g faeces, 40 mL urine, 500 mL flush water	Stream solids content (%)	1.59	1.67	1.72	1.97	2.17	2.36	2.74	3.13	3.51	NA
		<i>Dry sow facility</i>									
• Mixed parity sows, 30 g faeces, 48 mL urine, 500 mL flush water	Feed (g)	0	0.50	0.83	2.5	3.74	4.98	7.47	9.97	12.46	14.95
	Stream solids content (%)	2.29	2.38	2.43	2.71	2.92	3.13	3.55	3.97	4.39	4.80

feed waste approximations all contained in table A1 in the report by Skerman *et al.* (2016). The selected feed waste amounts (0–30%) were chosen to encapsulate typical feed wastage estimated for Australian piggeries – 5–20% (Australian Government 2017) – with additional points tested beyond the lower and upper estimates to fully develop prospective relationships that might be encountered on pig farms. The recipes here were based on a fixed mass of 30 g of faeces (wet weight) for all vessels. The flushing water volumes chosen were designed to simulate a range of typical total solids concentrations for piggery effluent (Tucker *et al.* 2010).

Key assumptions and input values are summarised in Fig. 1. For simplification, the ratios of solids in the faeces, urine and feed were kept constant in this experiment. In reality these ratios likely fluctuate slightly during the growing cycle and changes in feed waste over the course of a grower cycle may in fact be highly variable.

Manure solids loading effect on pH

In order to assess the effect of just the manure solids loading rate on effluent pH – i.e. faeces and urine without feed wastage, we established five × 2-L glass vessels with increasing amounts of faecal and urine solids, at a constant flush water volume. The faeces, urine and flush water were briefly mixed for 5 min and left undisturbed, open to the air for 48 h. The treatments were analysed for their pH and samples were also centrifuged and filtered to <0.45 µm for volatile fatty acid (VFA) and

ethanol analysis. Materials used were from Sample event 3 from the grower facility (described in Table 1 and Fig. 1). The quantities of materials used in this experiment are shown in Table 2.

Hydrolysis kinetics

To assess hydrolysis kinetics in the manure at the shed floor accumulation stage, we added 10 g of faeces and 13 mL of urine into open 12 × 50-mL plastic containers acting as sacrificial replicates. For six of these treatments, 1.47 g of feed was also added. Materials used were from Sample event 3 from the grower facility (described in Table 1 and Fig. 1). The feed added represented ~10% feed wastage, which is considered typical for Australian piggeries (pers. comm., Department of Agriculture and Fisheries Senior Extension Officer, 2017). One of the containers containing no feed and one containing feed were sampled at times: 0 min, 45 min, 105 min, 5 h, 6.5 h, and 22.75 h. The treatments were analysed for pH and ammonium-N (NH₄-N) concentrations.

Feed addition effect on effluent biochemistry

To explore the effects of feed addition on the biochemical conditions of the effluent streams a separate experiment was conducted using five × 2-L glass vessels each with fixed quantities of faeces, urine and flush water but varying amounts of feed. The faeces, urine, flush water and feed were mixed and left undisturbed, open to the air for 48 h. Following this, the

treatments were analysed for their pH and samples were also prepared (centrifuged and filtered to $<0.45 \mu\text{m}$) for VFA and ethanol analysis. Faeces, urine and flush water quantities were fixed at 10 g, 13 mL and 167 mL, respectively, for all vessels. Feed amounts were 0, 0.24, 1.1, 2.2 and 3.7 g for the five vessels corresponding to feed waste levels of 0%, 1.7%, 7.5%, 15% and 25% of feed provided. Again, materials for this experiment were obtained from Sample event 3 from the grower facility described in Table 1 and Fig. 1.

Materials analyses

Total solids of the materials were determined by oven-drying at 65°C overnight, to try to minimise ammonium and VFA loss, which can be substantial at the conventionally chosen temperature of 105°C for manure drying (Derikx *et al.* 1994; Vedrenne *et al.* 2008). Volatile solids (VS) were measured after ashing the samples in a crucible at 550°C for 4 h. Total solids and VS were analysed in triplicate for all samples. pH and electrical conductivity, EC, of the feed materials and faeces were determined following 1:5 dilution in deionised water and shaking end-over-end for 1 h. pH and EC of the urine, simulated effluent streams and real effluent were measured by directly inserting the probes into the liquid materials. pH was measured using an ECOTEST pH2 Probe (Eutech Instruments, Vernon Hills, Oakton, IL, USA) calibrated before each measurement event using pH 4 and pH 7 buffer solutions. Electrical conductivity was measured using an Orion Probe (Model 130) calibrated using a $273 \mu\text{S}/\text{cm}$ solution.

Ammonium-N concentrations were measured on 2M KCl extracts by titration using 0.01M HCl following steam distillation using MgO (Sparks 1996). Volatile fatty acids and ethanol were measured by gas chromatography (Agilent Technologies, Model 7890A, Santa Clara, CA, USA) with a flame ionisation detector and a polar capillary column (DB-FFAP) on filtered samples (Millex-GP Syringe Filter Unit SLGP033RS, Darmstadt, Germany) and addition of an internal standard (1000 ppm stock of six VFA) and 1% formic acid.

Statistical analyses

Regression analysis was used to resolve key interactions investigated in this study: notably relationships between: (1) pH buffering capacity and acid/base additions to the feed materials; (2) feed waste and pH in the simulated effluent streams; (3) VFA content, pH and manure solids content in the simulated manure streams; (4) VFA content, ethanol and pH and feed waste in the simulated effluent streams; and (5) hydrolysis kinetics in the simulated effluent streams.

Table 2. Quantities of waste materials used to construct simulated manure effluent streams of varying manure solids content

Vessel	Faeces (g)	Urine (mL)	Flush water (mL)	Solids (%)
1	5	6.5	167	0.94
2	10	13.0	167	1.73
3	15	19.6	167	2.43
4	20	26.1	167	3.07
5	25	32.6	167	3.65

A logistic regression function was fitted to the pH buffering capacity curves shown in Eqn 1:

$$f(X) = A + C/(1 + e^{-B\{X - M\}}) \quad (1)$$

An exponential regression function (Eqn 2) was fitted to the observed relationships between feed waste and pH in the simulated effluent streams. The parameter estimates from this function were applied to approximate feed waste at the commercial facility using the pH values of the real effluent samples. For this specific application, the parameters of Eqn 2 are $f(X) = \text{feed waste}\%$; $A = \text{feed waste}\%$ asymptote value; B and $r = \text{function constants}$ and $\times = \text{pH}$. All regression analyses were performed using GENSTAT (2013).

$$f(X) = A + B[R^X] \quad (2)$$

Mean, lower and upper 95% confidence level relationships between pH and feed waste for the combined four sampling events conducted at the grower facility were calculated in Microsoft Excel 2010.

Results and discussion

pH buffering capacity of feeds

The results of the feed pH buffering capacity tests are shown in Fig. 2. Modelled curves for all feeds are derived from the logistic function in Eqn 1 ($P < 0.05$). The initial pH values for all feed materials assessed were in the acidic range (Fig. 2). The buffering capacity of the processed feed materials was greater than for the unprocessed grains. This indicates that these piggery feeds are able to resist, at least to some extent, the ambient pH of the flush stream used in the effluent management system. At a practical level this is encouraging because it suggests that the inherently acidic properties of the feed materials are likely to exert a pH 'signature' on the alkaline effluent stream.

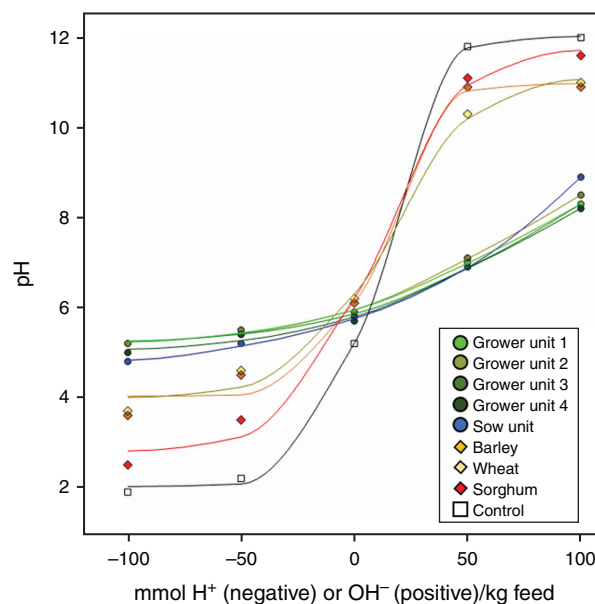


Fig. 2. pH buffer curves for the tested feed materials.

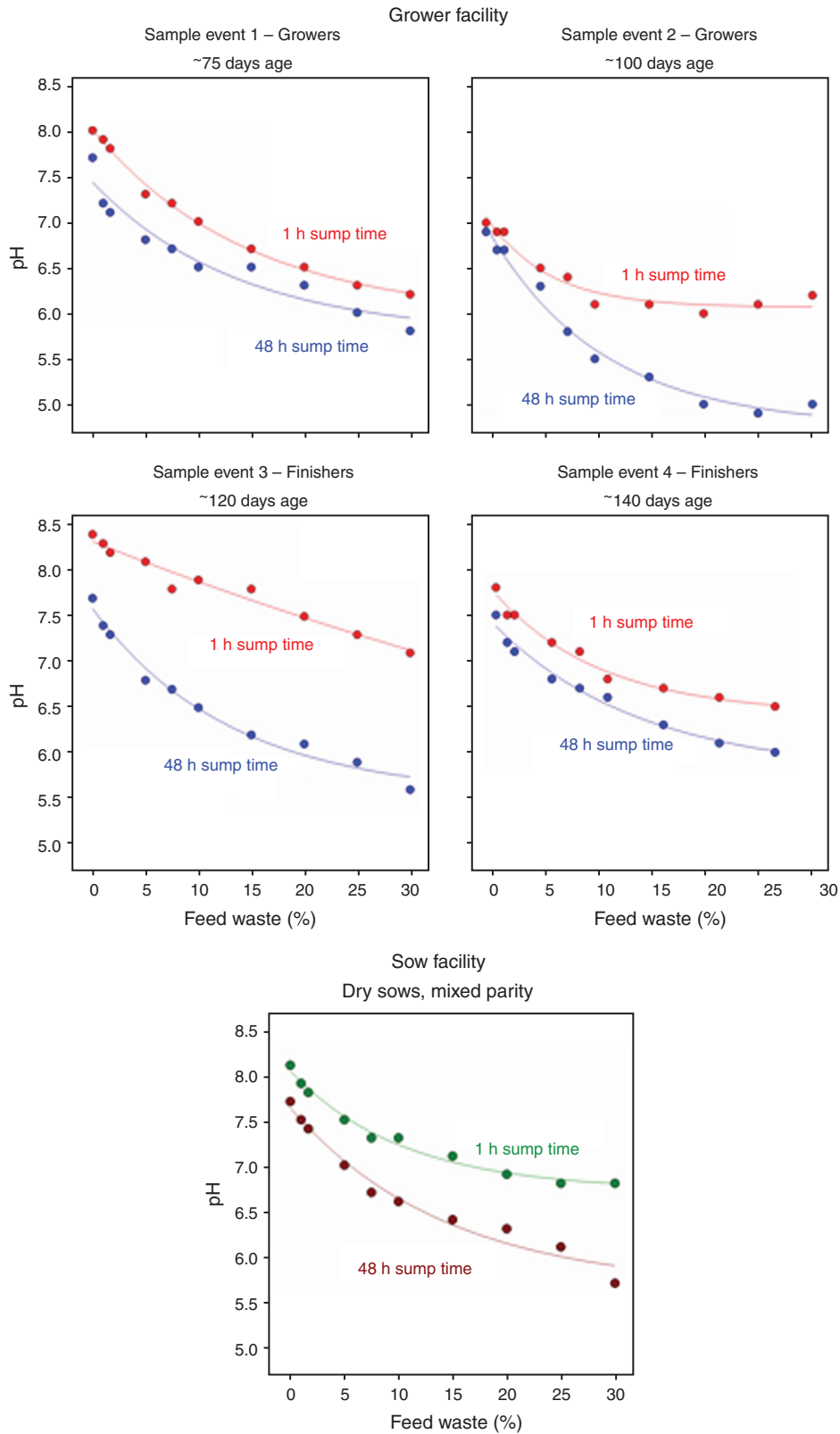


Fig. 3. Relationships between feed waste and pH for the simulated effluent streams for each of the four sample events conducted during a full grower cycle and for the sow facility.

Effect of feed waste on simulated effluent pH

The impact of feed waste on pH in the simulated effluent streams is shown in Fig. 3. Strong nonlinear relationships were evident between feed waste and pH for all four sampling events at the grower facility as well as for the one-off event at the sow facility.

The pH-feed waste relationships were well fitted ($P < 0.05$) to the exponential function shown in Eqn 2. The magnitude of the relationship was variable between sampling events and facilities, likely relating to differences in animal physiology and diet composition during the grower cycle as well as between the grower pigs and the sows. No broadly obvious patterns were evident for the relationships between diet composition, pH and feed waste quantity across the grower cycle; although we are currently exploring the potential for intricate relationships between these parameters (see final section).

We observed a clear decrease in effluent pH with increasing sump time for the simulated streams across all sample events (Fig. 3). pH levels ranged from 6.9 to 8.4 in the simulated effluent streams with no feed waste to 4.9–7.1 in the streams with the maximum feed waste level investigated (30%). The raw wastes used to construct the simulated effluent streams clearly underwent hydrolysis during the experiment as confirmed by the consistently higher pH in the effluent streams with no feed waste (Fig. 3) compared with the pH values of the fresh faeces and urine samples (Fig. 1).

Mechanisms of pH changes

Our hypothesis underpinning this research is that increasing feed waste in the effluent stream triggers a corresponding decrease in the effluent's pH, as the acidity of the feed substrate buffers the alkaline pH of manure (faeces and urine). This is supported by the feed pH buffering results in Fig. 2. Moreover, we observed a clear relationship between pH and feed waste quantity (Fig. 3). Despite this, the observed trends might be attributable to additional biological mechanisms that are not directly related to feed pH, including: (1) simply varying solids levels in the effluent; (2) suppression of hydrolysis in manure by the presence of feed; and (3) changes in effluent biochemistry caused by varying feed quantities.

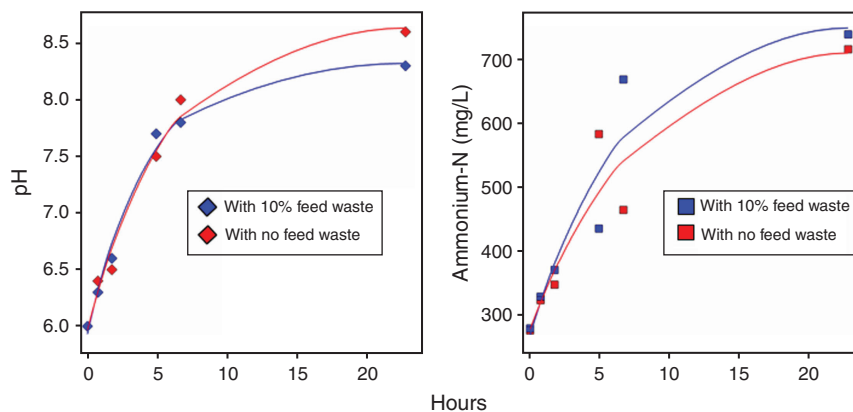


Fig. 5. Kinetics of pH and $\text{NH}_4\text{-N}$ concentration changes in simulated shed floor deposited manure (faeces and urine with and without spilled feed).

First, we investigated if the observed pH changes were simply attributable to varying solids concentrations in the effluent streams. An increased supply of organic solids in the effluent stream would certainly enhance the quantity of substrate for microbial communities, which could trigger numerous acid-generating biological pathways including respiration (aerobic and anaerobic conditions), glycolysis (aerobic and anaerobic conditions), fermentation (aerobic and anaerobic conditions) and acetogenesis (anaerobic conditions). Indeed, pig manures contain a diverse bacterial community, which likely influence pH: Zhu (2000) reported that almost 50% of the bacteria in pig faeces comprise *Eubacteria* and *Lactobacillus*, which are known VFA producers and fermenters, respectively.

Figure 4 shows pH levels and VFA concentrations in simulated effluent streams with increasing manure solids concentrations but with no feed waste. There was a linear increase ($P < 0.05$) in VFA concentrations with increasing manure solid content (Fig. 4). However, although the VFA content increased with increasing manure solids, the pH did not show a corresponding decrease. Indeed, pH remained relatively constant irrespective of manure solids content (Fig. 4).

The positive relationship between VFA and manure solids content may signify stimulation of acetogenesis in the effluent,

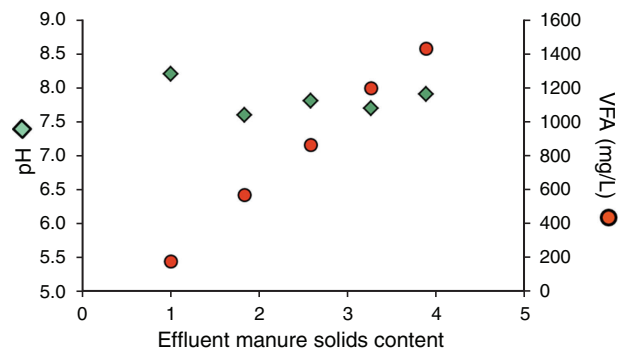


Fig. 4. pH and volatile fatty acid concentrations in simulated effluent streams comprising increasing quantities of manure solids.

as rapid VFA production in stored effluent has been noted by Paul and Beauchamp (1989). Alternatively, the observed relationship may simply reflect the initial VFA content of the faeces combined with the steadily increasing faeces amounts added to the treatments. Sutton *et al.* (1999) and Conn *et al.* (2007) note that short-chain VFA formation can occur very rapidly in freshly excreted pig manures. In any case, it is clear that simply changing the manure solids content of the effluent stream does not exert an obvious influence on effluent pH. Importantly, this reveals that the inherent properties of the feed substrates themselves are responsible for triggering the observed pH changes in the simulated effluent streams, seen in Fig. 3.

To evaluate if the presence of feed waste affects manure pH during the flushing channel accumulation phase (i.e. before mixing with flushing water), we investigated the impact of feed waste on manure hydrolysis rates (Fig. 5). For the two scenarios, i.e. with feed waste and with no feed waste, the rate of pH increase with time was well fitted ($P < 0.05$) to the exponential function shown in Eqn 2. The maximum pH predicted for the manure with no feed was 8.6, compared with a maximum predicted pH of 8.3 for the manure containing feed waste. These results demonstrate that feed waste exerts a pH decrease in the manure during the accumulation phase before mixing with flush water. Equation 2 also adequately defined the rate of $\text{NH}_4\text{-N}$ production ($P < 0.05$, Fig. 5). From these data, it is obvious that the addition of feed does not suppress hydrolysis in the manure, with maximum predicted $\text{NH}_4\text{-N}$ concentrations of 735 mg/L for manure with no feed and 768 mg/L for manure with feed waste.

To further investigate potential mechanisms of effluent pH decreases caused by feed waste we evaluated a series of simulated effluent streams, with varying feed levels, for their biochemical properties (Fig. 6). The effluents had been left to settle for 48 h, representing upper sump retention times at the commercial grower facility.

Figure 6a shows that the pH decrease with increasing feed waste amount was associated with a corresponding increase in VFA concentration, with both relationships well described ($P < 0.05$) by the exponential function in Eqn 2. A corresponding increase in the proportion of acetic acid formation was also observed (Fig. 6a). This indicates stimulation of acetogenesis with increasing feed waste content in the effluent streams.

We also measured ethanol concentrations, a by-product of glycolysis and fermentation, which are acid-generating biological processes. Ethanol concentrations showed a linear, albeit near-significant ($P = 0.08$), increase with increasing feed waste levels. This result indicates that the presence of feed waste in the effluent stream might stimulate glycolysis and fermentation.

The biochemical analysis of the simulated effluent streams suggests that biological processes likely influence ongoing pH decreases in the simulated streams over time. Overall, we are uncertain of the precise contributions from each possible mechanism underpinning the observed pH changes in the effluent as a function of feed waste. Indeed, these processes are likely to be varied and nuanced, with several simultaneous chemical and biological processes likely influencing the results.

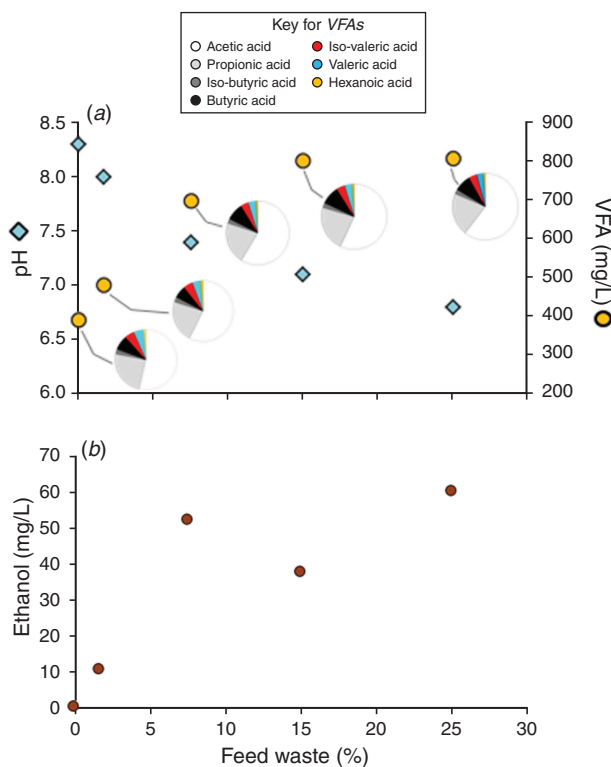


Fig. 6. (a) pH and volatile fatty acid (VFA) concentrations, and composition; and (b) ethanol concentrations in response to increasing feed waste content in simulated effluent streams.

This supports the research outcomes by Paul and Beauchamp (1989). Although their study did not focus on feed waste influences on pH, they nonetheless established an intricate balance between VFA and manure pH for a range of livestock slurries.

In Fig. 7 we present a simplified schematic depiction of the key processes potentially affecting effluent pH, from the time that manure is deposited and accumulates on the shed floor through to its mixing with flush water and storage in the sump. Encouragingly, despite the potential complexities controlling effluent pH over time we observed the same generalised patterns in pH response to feed waste over the entire grower cycle as well as the sow facility.

Field testing of model results

We used the relationships in Fig. 3, to attempt to quantify feed waste levels in the effluent stream at the studied facility. It was not possible to conduct this exercise for the sow facility because it does not employ a regular flush effluent management system.

For the grower facility, four stages in a cycle were sampled and real effluent samples were acquired from the studied shed at each of these stages. Applying the pH values from the real effluent samples to the exponential function described in Eqn 2 enabled an estimate of feed wastage to be calculated for each sample event. For Sample events 1, 2 and 4, the relationships from the 1-h sump simulation data were used, given that the effluent from the trial shed was held in the sump for 1 h during

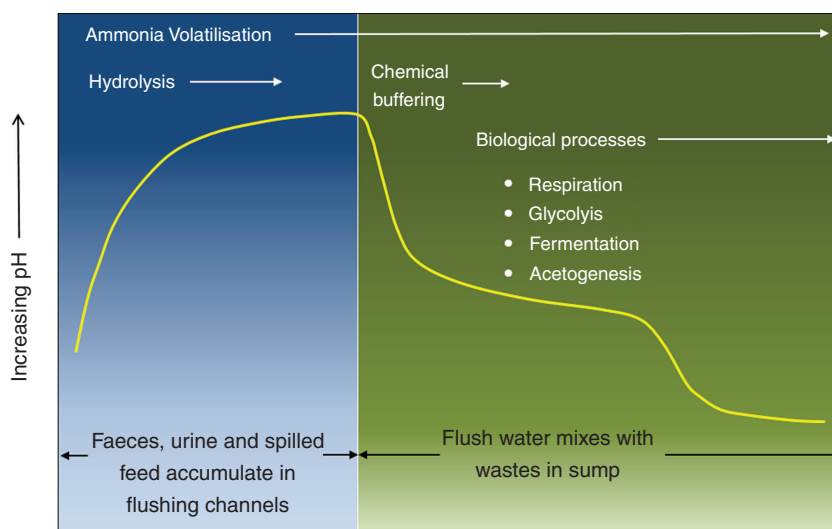


Fig. 7. Simplified schematic showing the range of processes potentially affecting the pH (yellow line) of effluent containing spilled feed.

each of those events. For Sample event 3, the 48-h sump simulation data were used instead because the shed’s effluent had been held in the sump for 2 days before that particular time.

In Fig. 8 we plot the estimates feed waste content in the trial shed effluent for each of the four sample events. We compare our predictions with those yielded by approaches involving nutrient modelling – using the AUSPIG model – and solids mass balance calculations, conducted on effluent from the same trial shed during a grower stage approximately 3 months before this study (Skerman *et al.* 2016). The AUSPIG model has been widely used and published for a variety of animal production assessments (Black *et al.* 1993a, 1993b; Banhazi *et al.* 2008; Moore *et al.* 2013). The solids mass balance approach was conducted on a section of one of the grower sheds with inputs tightly controlled and measured during that exercise (Skerman *et al.* 2016). The feed waste estimates given by Skerman *et al.* (2016) pertain to a different life cycle stage sampled compared with our work. The animals were ~45 kg weight in the study by Skerman *et al.* (2016), which sits between Sample events 1 and 2 assessed here.

Apart from Sample event 2, when the animals had been in the shed for 6 weeks, the predictions from the pH approach used here matched closely with the estimates given by Skerman *et al.* (2016). The average feed waste estimate of ~5% determined by AUSPIG and solids mass balances in the report by Skerman *et al.* (2016) is also considered to be broadly accurate according to the facility owners. The clearly erroneous prediction for Sample event 2, which produced a negative feed waste result, might be due to unrepresentative samples of faeces and urine collected during that event. We attempted to collect these materials from as many animals in the shed as possible during the permitted access time, but this was limited to between 5 and 10 animals for each event. The starting pH for the simulated effluent streams for Sample event 2 was quite low (7.0). Albeit lacking supporting evidence, this could indicate the presence of a substantial quantity of undigested feed in the faeces collected at that time.

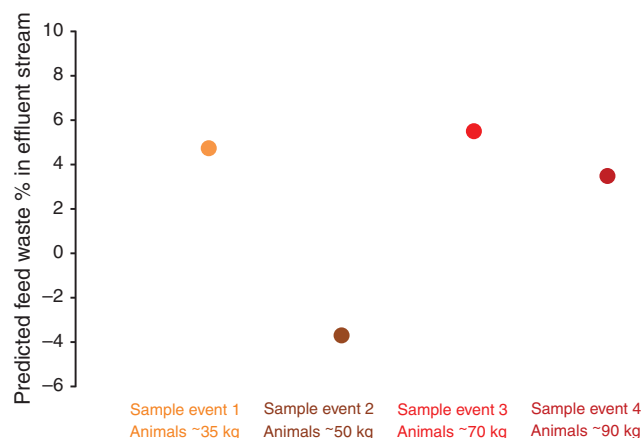


Fig. 8. Predicted feed waste quantities in real effluent collected from the trial shed for the four different sampling events, determined using models from the simulated effluent stream data and pH readings in the real effluent. For comparison, Skerman *et al.* (2016) estimated feed wastage of 4.2% (using a solids mass balance approach) and 6.9% (using the AUSPIG model) for the same shed during a grower stage ~3 months before our work.

Limitations and recommendations

The results obtained in this work are promising. Moreover, the close relationship between pH and feed waste in effluent observed in this study might apply across many production sites given that: (1) urine hydrolysis in pig effluent is a generic process, thus, triggering an alkaline starting pH in the effluent stream; (2) feed substrates in the pork industry are generally acidic, at least for the grains commonly used in warmer, northern production systems in Australia; and (3) feed has a much higher bioenergy value than digested manures, thus potentially leading to rapid VFA production and associated pH decrease. However, given that our study is region-specific and that a reasonably wide variation was observed within our datasets, we are clearly a long way from being able to deploy a pH sensor into

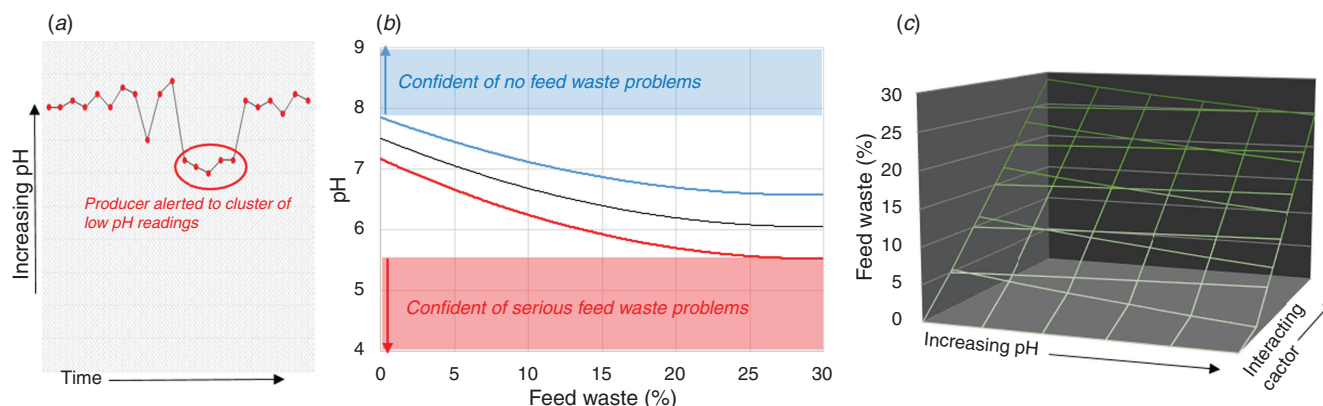


Fig. 9. Ways that pH data in piggery effluent streams could be used to alert producers on spilled feed problems: (a) scanning for anomalous pH decreases in a site's effluent stream; (b) using site-specific data to construct confidence models on feed waste levels. Here data from the grower cycle shown with mean (black), lower 95% confidence interval (red) and upper 95% confidence level (blue) trends plotted for relationships between pH and feed waste; and (c) schematic depiction of how information on factors that interact with pH, in this case volatile solids, could be modelled to predict relationships between pH and feed waste levels in effluent streams.

a pig farm's effluent stream to accurately obtain an estimate of the site's in-shed feed waste. Nonetheless, with further work the relationships identified in this research could be used to notify producers of feed waste problems. We highlight a few such approaches in Fig. 9.

At the most uncomplicated level, our results indicate that scanning a piggery effluent stream for anomalous pH decreases could be useful in alerting farmers to potential feed waste and animal behaviour problems (Fig. 9a). Deploying a sensor in the effluent stream and recording pH over a protracted period of time will help build an effluent pH profile for a given site, thus, enabling anomalies to be identified. Alternatively, farm-specific models relating pH responses to feed waste in effluent could be further developed, similar to the work conducted here but with additional datasets compiled over multiple cycles and at different times of year encompassing seasonal variation (Fig. 9b). Finally, it may be possible to develop process-based models, which can predict feed waste levels in effluent for a specific piggery (Fig. 9c). Potentially, these models could be sufficiently developed to the extent that they are applicable to any given production site. In order to further develop such models, it will be necessary to gain an improved understanding of the mechanisms underpinning the observed relationships between effluent pH and feed waste level.

Understanding how differences in effluent management practices and environmental conditions across sites affects the pH feed waste relationships in effluent is also critically needed to formulate effective predictive models. We already know from the present study that factors such as effluent storage time in the sump exerts a strong influence on the relationship between pH and feed waste. Temperature is likely to be another important parameter in this regard. Yuan *et al.* (2011) reported that VFA production can decrease by 40% over a temperature decrease from 25°C to 14°C. Chu *et al.* (2014) revealed that fermentation of livestock manure is temperature-dependent with activity increasing up to 35°C and then decreasing at higher temperatures.

Moreover, this study involved the use of bore water as the flushing stream whereas in reality many producers use recycled effluent to flush sheds. Encouragingly, many secondary ponds

on piggery farms exhibit alkaline pH values of 8 or higher (Tucker *et al.* 2010), likely due to the combination of relatively high ammonium concentrations and high amounts of algae, which scrub CO₂ in the secondary pond (Green *et al.* 1996; Tadesse *et al.* 2004). In the study at the grower facility, the recycled effluent pH was measured at 8.0, which holds promise for contrasting against the acidic 'signature' of any feed waste added to that effluent stream. Currently, we are working on developing predictive models relating pH with other effluent factors including ammonium, diet composition, temperature, and volatile solids, to quantify in-shed feed waste.

Conclusions

- pH showed a decreasing non-linear relationship ($P < 0.05$) with feed waste quantity in simulated effluent streams comprising wastes from a commercial grower pig facility as well as a sow facility.
- The mechanisms driving the observed relationships appear to be complex, involving a combination of chemical and biological processes.
- Applying the observed relationships to the grower facility's actual effluent pH, which was measured during the four sampling events, yielded feed waste predictions broadly commensurate with estimates of feed waste for the same facility derived from alternative time intensive approaches.
- Our research highlights a promising approach for quantifying feed waste in pig production sheds, but further work is needed to develop a precise predictive alert system for farmers.

Conflicts of interest

The authors declare no conflicts of interest.

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