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Nutrient Extraction from Spent Bedding and Pond Sludge

Final Report
APL Project 2011/1015.399

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Summary

Australian Pork Ltd (APL) commissioned FSA Consulting, with The University of Queensland Advanced Water Management Centre (AWMC), to undertake project 2011/1015399 "Nutrient Extraction from Spent Bedding and Pond Sludge". This is the final technical report for that project.

Samples

A total of 12 samples of spent bedding and pond sludge collected from Australian piggeries were analysed as part of the project. There were eight spent bedding samples containing a mix of fresh and aged barley straw, wheat straw and rice hulls-based beddings. There were four samples of pond sludge from uncovered anaerobic ponds. These were collected from sites in northern and southern Australia and it was possible to collect fresh and aged sludge from one pond. All samples were analysed from biochemical methane potential (BMP), metals, solids, chemical oxygen demand (COD), volatile fatty acids (VFA) and nutrients.

Analysis Results

All samples were solids, but varied significantly in organic fraction (as fraction of total solids), with only the fresh bedding samples generally having high organic fraction levels (>70%). The drop in organic fraction between fresh and stockpiled bedding indicates significant destruction of organics during storage. This has serious implications for the viability of anaerobic digestion.

The nutrient levels of all samples of sludge and spent bedding fell within the range of ~0.2-1% nitrogen (N) (0.3-3.5% on a dry basis) and ~0.1-0.5% phosphorus (P) (0.1-2.9% dry basis). All materials had a relatively high zinc content that may pose a concern for reuse in some situations. However, zinc deficiency is one of the most common micronutrient deficiencies for agricultural soils so piggery sludge and spent bedding can be useful in remediating affected soils.

Fresh northern barley bedding had the highest methane production at ~350 L/kg VS followed by fresh southern wheat bedding at ~220 L/kg VS and fresh southern rice hulls bedding ~160 L/kg VS. In Methane production from stockpiled barley straw and wheat straw bedding was significantly lower than methane production from fresh spent bedding. As expected, sludge samples produced the least methane, typically less than 100 mL/g VS. From these results, only fresh beddings have potential for economically-viable anaerobic digestion (in a leach bed process). Rice hulls bedding may be viable depending on the level to which the fresh manure fraction is mobilised.

Hydrolysis rates for all samples were slow at 0.034-0.071 / day for fresh bedding samples; 0.026-0.032/day for spent bedding samples and 0.026-0.031 / day for sludge samples. This is slower than municipal pond sludge, but similar to other agricultural wastes such as beef feedlot manure. Fresh beddings had the fastest degradability, with batch times of ~60 days required for full digestion.

Nitrogen was effectively released in all digested samples (50-80% of nitrogen released). Phosphorus release was far poorer, with only fresh samples achieving reasonable release rates of 30-50%. In general, other samples only released 10-20% of phosphorus. It is likely that phosphorus release would be enhanced in a system with higher waste stream concentration, such as a leach bed.

Advanced Nutrient Recovery Methods

Overall, the analysis results suggest that anaerobic digestion (leach bed process) of fresh barley and wheat straw based beddings and possibly fresh rice hulls bedding, with recovery of phosphorus from leachate is technically feasible. However, it is not expected that stockpiled bedding and pond sludge will be feasible substrates for digestion.

An alternative nutrient recovery method for piggery sludge is acid extraction of nutrients, followed by side-stream recovery of phosphorus, nitrogen and potassium. The cation to phosphate ratio of the material is 2-3, indicating a substantial excess of cations. This suggests that extraction through acid would be technically feasible. This would involve dropping the pH to 2.0, followed by nutrient precipitation as calcium or magnesium oxides. However, the amounts of chemical needed for acid extraction and recovery make nutrient recovery by this method uneconomic.

Incineration is another possibility for nutrient recovery. The pond sludges are too wet to incinerate without co-feeding. However, stockpiled bedding could be directly incinerated with phosphorus recovery from the ash. High nitrogen wastes must be incinerated at high temperatures (>900C) and the resulting ash cannot be directly used as fertiliser. On a large scale, phosphorus could be recovered by acid extraction of the ash. This has both scalability and technical issues (through extraction of metals), and has not been carried forward as an option at this point.

Economic Analysis

While fresh spent beddings (particularly straw-based beddings) are technically suitable for anaerobic digestion with a leach bed system, this research was only able to demonstrate a modest positive economic outcome (12.3 year payback period) for fresh northern barley bedding. This result should also be interpreted with caution as the clean bedding usage at this piggery was very low and not representative of the majority of the industry. Anaerobic digestion was not viable for the remaining spent bedding samples or any of the sludge samples.

Fresh spent bedding is typically up to eight weeks old before it is removed from the shelters. Fresh bedding samples generally have significantly higher methane production that spent bedding samples. Since this significantly influences the economic outcome, it may be worth investigating the performance of litter aged up to two weeks old and up to four weeks old. Practical issues, particularly whether piggery operators would be prepared to clean-out sheds more frequently, would need to be considered.

Both the spent bedding and the sludge are suitable for direct spreading. At this stage this is the recommended reuse method.

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1. Introduction

Australian Pork Ltd (APL) commissioned FSA Consulting, with University of Queensland (AWMC), to undertake project 2011/1015399 "Nutrient Extraction from Spent Bedding and Pond sludge".

Objectives of this project include:

- Objective 1: To determine nutrient extraction rates, nutrient binding issues and nutrient availability for pond sludge and spent bedding.
- Objective 2: To evaluate different techniques for extracting nutrients from pond sludge and spent bedding.
- Objective 3: To provide a preliminary economic assessment of promising technologies for extracting nutrients from pond sludge and spent bedding.
- Objective 4: To provide recommendations for future research into nutrient extraction from pond sludge and spent bedding.

This report represents the final technical report for the project.

2. Samples Collected

As part of this project, FSA Consulting was required to collect ten samples of pond sludge and spent bedding from piggeries. Where practical, these were to include samples from piggeries using different dietary ingredients (e.g. northern versus southern diets) and bedding materials (e.g. barley straw, wheat straw and rice hulls); and pond sludges of different ages and sourced from different systems (e.g. covered versus uncovered ponds).

Samples collected are described throughout this report as:

- young southern pond sludge
- aged southern pond sludge
- northern breeder pond sludge
- northern finisher pond sludge
- fresh southern wheat bedding
- aged southern wheat bedding
- fresh northern barley bedding
- aged northern barley bedding
- fresh southern rice hulls weaner bedding
- aged southern rice hulls weaner bedding
- fresh southern rice hulls grower bedding
- aged southern rice hulls grower bedding

The pond sludge samples represented both southern and northern systems; young and aged material; and breeder and finisher systems. It was hoped that it would be possible to collect samples from a well-established covered pond. However, on-going problems with the pump at the piggery made this impractical. Other covered ponds were not considered representative (too new, only partially covered or research piggery).

The bedding samples represent a very good cross-section of the industry covering: fresh and stockpiled bedding from southern and northern piggeries including with wheat, barley and rice hulls-based material.

3. Sample Characterisation

All samples of spent bedding and pond sludge were characterised using standard methods. Analysis results for total solids (TS), volatile solids (VS) and total chemical oxygen demand (TCOD) are shown inTable 1.

Table 1: Solids analysis and COD of raw samples

Sample Description	TS (g/L)	VS (g/L)	VS/TS (%)	TCOD (g/L)
Young southern pond sludge	237 ±14	138 ±3	58.4	154 ±35
Aged southern pond sludge	300 ±27	134 ±10	44.9	178 ±77
Northern breeder pond sludge	170 ±8	73 ±3	43.2	94 ±7
Northern finisher pond sludge	139 ±7	63 ±3	45.4	98 ±8
Fresh southern wheat bedding	340 ±25	247 ±15	72.8	209 ±13
Aged southern wheat bedding	523 ±48	257 ±41	49.6	216 ±68
Fresh northern barley bedding	368 ±9	290 ±8	78.6	348 ±27
Aged northern barley bedding	562 ±81	230 ±68	42.9	171 ±26
Fresh southern rice hulls weaner bedding	723 ±6	531 ±6	73.4	188 ±55
Aged southern rice hulls weaner bedding	750 ±37	543 ±29	72.4	103 ±25
Fresh southern rice hulls grower bedding	542 ±11	351 ±20	64.7	118 ±5
Aged southern rice hulls grower bedding	592 ±7	281 ±70	47.4	124 ±37

All samples were essentially solid phase, with relatively low organic fractions in the pond sludge (43.2-58.4%) and most of the aged bedding samples (mostly 42.9-49.6%; aged southern rice hulls weaner bedding was 72.4%); and relatively high levels in the fresh bedding samples (74.7-78.6%).This indicates destruction of organics during stockpiling of bedding. Since sludge is a by-product of anaerobic digestion in ponds it is expected to have a relatively low organic fraction.

Nutrient levels are shown in Table 2. These include analysis results for total nitrogen (TN), ammonia and ammonium (NHx), total phosphorus (TP) and phosphate (PO_4).

Table 2: Nitrogen and phosphorus levels in raw samples (mg/kg wet weight)

Sample Description	TN (mg/kg)	NHx-N (mg/kg)	TP (mg/kg)	PO_4-P (mg/kg)
Young southern pond sludge	6905	1363	5151	1649
Aged southern pond sludge	5112	1392	5374	1580
Northern breeder pond sludge	5870	2060	4910	1247
Northern finisher pond sludge	5921	2046	4797	2156
Fresh southern wheat bedding	4684	831	2001	1554
Aged southern wheat bedding	7146	683	3713	1621
Fresh northern barley bedding	10,936	1961	4106	2169
Aged northern barley bedding	4490	58	4823	1199
Fresh southern rice hulls weaner bedding	5179	943	1318	713
Aged southern rice hulls weaner bedding	2328	426	811	241
Fresh southern rice hulls grower bedding	2346	164	1408	1329
Aged southern rice hulls grower bedding	3523	124	2213	892

The samples contained ~0.2-1% nitrogen (N) (0.3-3.5% on a dry basis) and ~0.1-0.5% phosphorus (P) (0.1-2.9% dry basis). The ratio of N:P was quite high: 0.9-1.3 for pond sludge samples and 0.9-3.9 for spent bedding samples (higher for fresh samples). In general, 20-80% of the phosphorus was present as phosphates. Phosphate-P levels were mostly higher in fresh samples, suggesting that nutrient recovery is likely to be effective for these materials.

As expected a relatively low proportion of the phosphorus in the sludge was soluble since it is mostly bound with counter ions such as calcium and aluminium.

All materials have significant potential value as fertilisers. It is noted that nitrogen and phosphorus often drop, or remain at the same level through stockpiling (comparing both wet and dry nitrogen and phosphorus contents). We know from both methane potential analysis and from volatile solids (VS) analysis that considerable organics are destroyed during storage. As a consequence, phosphorus and nitrogen would also be lost through nitrification and/or leaching. Indeed, considerable amounts of nitrate (up to 1000 ppm) were found in samples.

Full metals and nitrogen analysis was done by inductively coupled plasma (ICP) analysis. Analysis results for each of the sample types, including wavelengths for each element, are provided in Table 3.

Table 3: Nutrient levels in raw samples (mg/kg wet weight)

Sample Description	Al (396.13)	As (193.696)	B (249.677)	Ba (233.527)	Ca (315.887)	Cd (214.440)	Co (228.616)	Cr (205.560)
Young southern pond sludge	1119	0.00	0.00	26.3	12,581	0.00	1.40	1.85
Aged southern pond sludge	5694	0.00	0.00	32.5	10,962	0.00	2.94	5.99
Northern breeder pond sludge	3506	0.00	0.00	28.4	5923	0.00	2.46	2.43
Northern finisher pond sludge	3020	0.00	0.00	26.7	4853	0.00	3.35	1.81
Fresh southern wheat bedding	1910	0.00	0.00	28.3	5783	0.00	1.47	3.53
Aged southern wheat bedding	3481	0.00	0.00	27.7	4072	0.00	1.76	7.12
Fresh northern barley bedding	285	0.00	0.00	60.4	8054	0.00	2.08	3.38
Aged northern barley bedding	5637	0.00	0.00	52.2	9671	0.00	7.42	10.36
Fresh southern rice hulls weaner bedding	510	0.00	0.00	6.4	1714	0.00	0.98	4.36
Aged southern rice hulls weaner bedding	515	0.00	0.00	6.0	1282	0.00	1.43	5.36
Fresh southern rice hulls grower bedding	1835	0.00	0.00	12.8	2281	0.00	1.12	4.50
Aged southern rice hulls grower bedding	5717	0.00	0.00	37.7	4572	0.05	2.02	7.98

Table 3: Nutrient levels in raw samples (mg/kg wet weight) contd….

Sample Description	Cu (324.752)	Fe (239.562)	Fe (238.204)	K (766.490)	Mg (285.213)	Mn (257.610)	Mo (203.845)	Na (589.592)
Young southern pond sludge	236	1778	1778	575	3452	205.7	2.55	3
Aged southern pond sludge	207	4166	4177	1366	4075	202.9	2.13	0
Northern breeder pond sludge	83	1683	1691	1148	3870	122.7	2.74	1043
Northern finisher pond sludge	146	1927	1934	2087	3800	146.7	2.12	1983
Fresh southern wheat bedding	151	1162	1171	7251	1863	107.9	1.79	1014
Aged southern wheat bedding	99	1949	1958	6385	1961	114.6	1.58	2396
Fresh northern barley bedding	49	562	566	9882	2837	126.1	3.47	3597
Aged northern barley bedding	56	6697	6688	8414	3716	300.8	1.69	1692
Fresh southern rice hulls weaner bedding	23	518	520	4944	758	184.9	1.64	1334
Aged southern rice hulls weaner bedding	27	522	524	1483	339	108.5	1.38	283
Fresh southern rice hulls grower bedding	35	1247	1251	4471	1188	143.1	0.79	1658
Aged southern rice hulls grower bedding	77	4027	4032	5117	2170	219.2	0.91	1671

Table 3: Nutrient levels in raw samples (mg/kg wet weight) contd….

Sample Description	Ni (231.604)	P (213.617)	P (214.914)	Pb (217.000)	S (181.975)	Se (196.026)	Si (251.611)	Zn (206.200)
Young southern pond sludge	3.20	6441	6148	6.62	2884	0.882	2034	738
Aged southern pond sludge	5.73	6933	6650	17.30	2529	0.297	6244	601
Northern breeder pond sludge	2.12	6559	6484	9.49	1529	3.065	4919	953
Northern finisher pond sludge	2.90	6647	6385	10.36	7082	3.012	5241	1145
Fresh southern wheat bedding	2.91	3762	3588	11.55	10747	0.000	4581	665
Aged southern wheat bedding	1.97	2762	2597	6.40	3631	0.195	3515	118
Fresh northern barley bedding	1.61	5952	5765	2.49	1960	1.806	2485	436
Aged northern barley bedding	15.23	6102	5928	15.93	2477	0.000	5284	405
Fresh southern rice hulls weaner bedding	1.86	1875	1784	5.74	942	0.000	2117	569
Aged southern rice hulls weaner bedding	1.44	1048	962	7.35	651	0.000	2032	513
Fresh southern rice hulls grower bedding	2.10	1958	1867	6.80	1049	0.699	2267	48
Aged southern rice hulls grower bedding	4.41	3013	2902	12.71	3859	0.000	2630	98

All elements are within class C biosolids application levels (NSW EPA 1997)except zinc in the pond sludges. Most of the pond sludge samples have zinc levels well above the NSW limit for Class C of 2500 mg Zn/kg (NSW EPA 1997), containing 5600 mg/dry kg (northern breeder pond sludge);6000 mg/dry kg (northern finisher pond sludge); and 3100 mg/dry kg (aged southern pond sludge). The high zinc content of these materials may pose a concern for reuse in some situations. However, zinc deficiency is one of the most common micronutrient deficiencies for agricultural soils and sludge reuse can help in remediating affected soils. Hence, soil zinc levels and crop sensitivity should be considered when reusing these materials.

The only other concern with respect to direct spreading of sludge is the relatively high levels of iron (7500-14,000 mg/dry kg) and aluminium (~5000-21,000 mg/dry kg). Elevated iron and aluminium levels may decrease plant availability of phosphorus (Pritchard et al. 2010). Hence, soils of reuse areas should be analysed to confirm that these elements are not in excess. Annual monitoring should be used to confirm that these nutrients do not reach excessive levels.

4. Biological Methane Potential

To assess potential for anaerobic digestion, raw methane production, degradability and nutrient release were determined for all samples.

4.1. Raw Methane Production

Biological methane potential (BMP) was assessed using the method described by Angelidaki *et al., (2009)*. Methanogenic inoculum used in the tests was collected from digesters at Luggage Point waste water treatment plant (WWTP). All samples were tested in triplicate, with triplicate blanks (inoculum but no sample) also used. Methane production from the blanks was subtracted from the cumulative methane production curves to correct for residual methane potential in the inoculum. Cumulative methane production from the raw samples is shown in Figure 1–Figure 5. Fresh northern barley bedding had the highest methane production, followed by fresh southern wheat bedding, with southern rice hulls lower again. The pond sludge samples produced the least methane, typically at less than 100 mL / g VS.

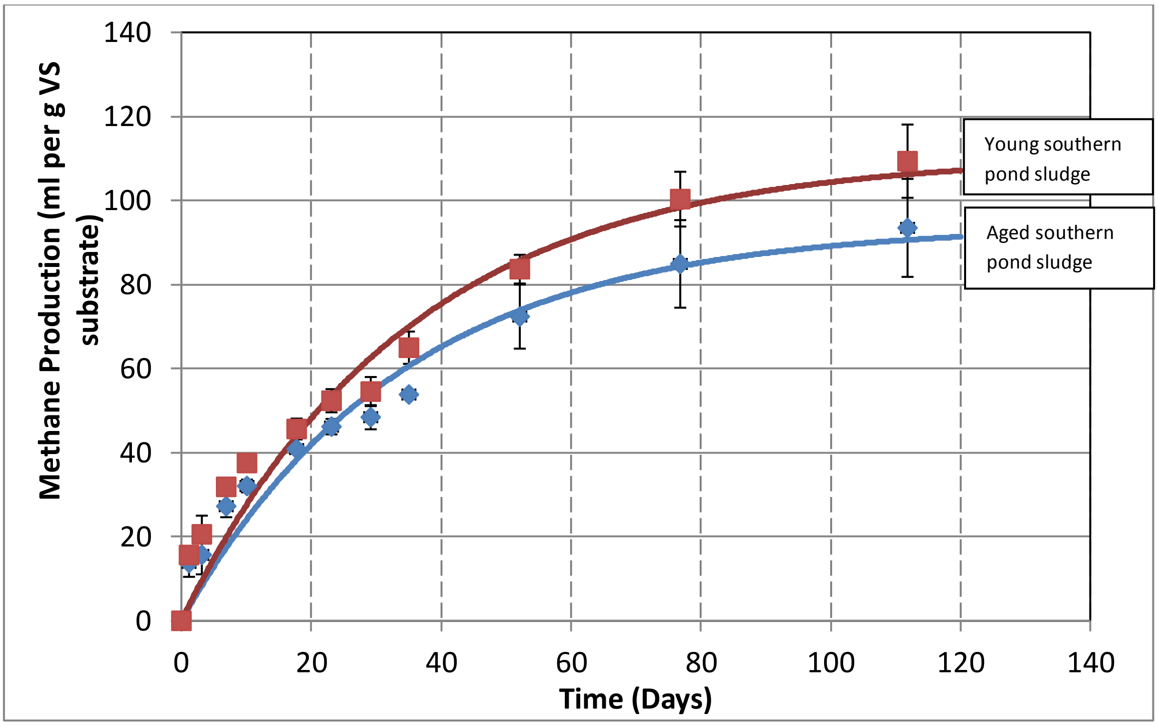

Figure 1: Cumulative methane production (BMP) for southern pond sludge samples

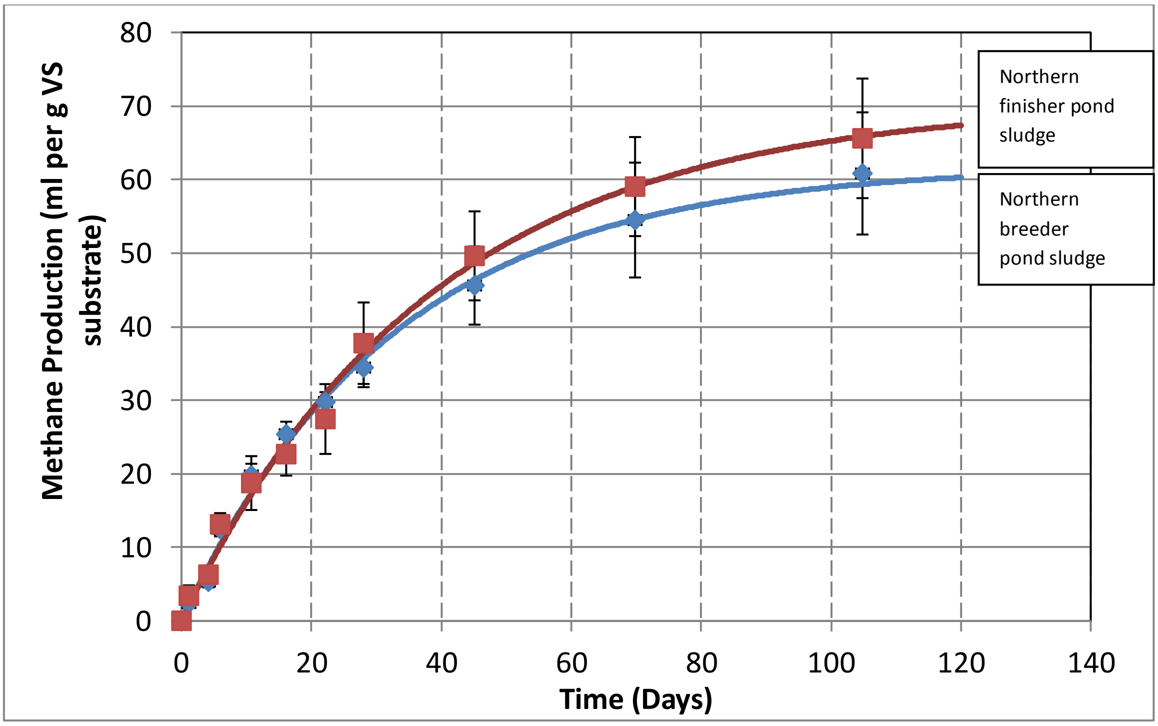

Figure 2: Cumulative methane production (BMP) for northern pond sludge samples

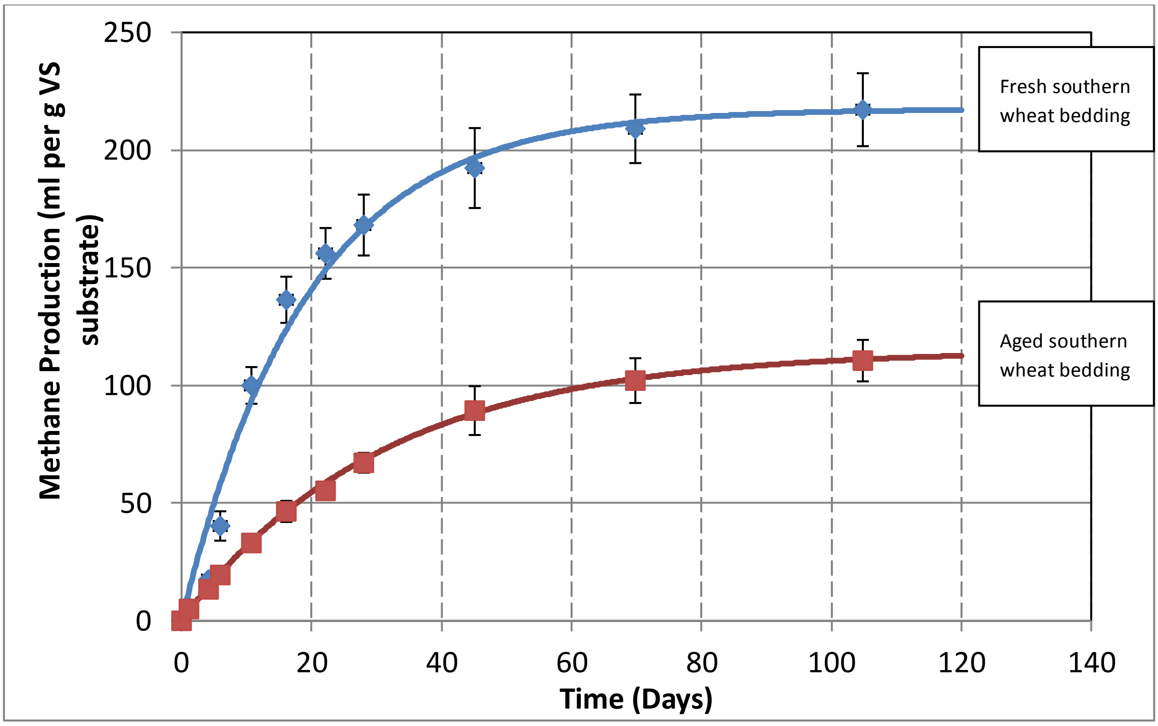

Figure 3: Cumulative methane production (BMP) for southern wheat bedding samples

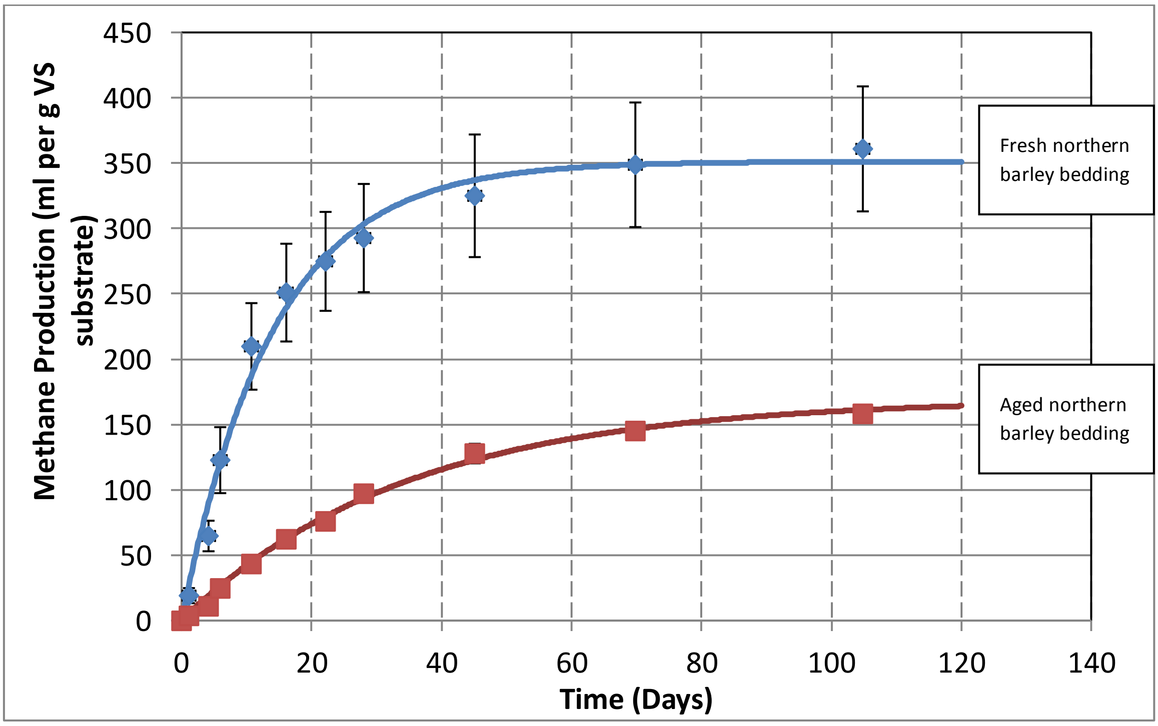

Figure 4: Cumulative methane production (BMP) for northern barley bedding samples

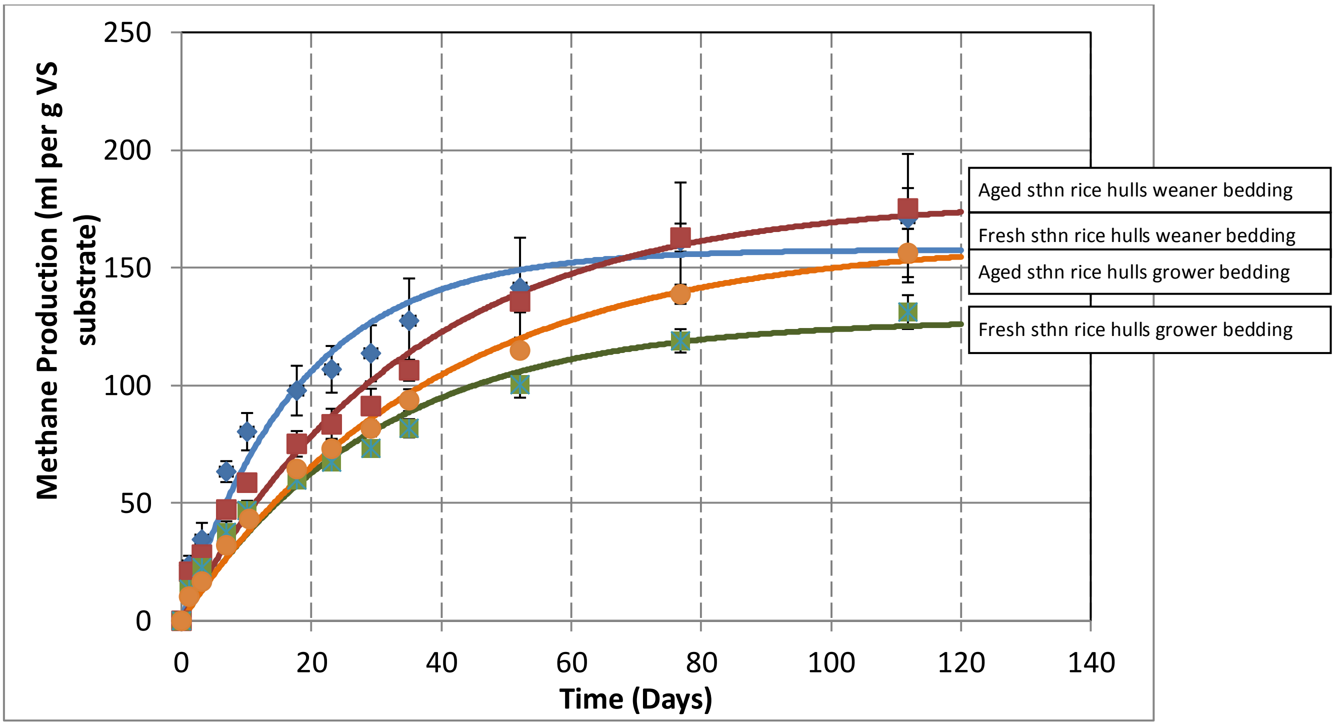

Figure 5: Cumulative methane production (BMP) for southern rice hulls bedding samples

4.2. Degradability Analysis

The methane production curve for each set of tests was fitted to a first order kinetic model (implemented in AQUASIM 2.1d) to model the methane potential (on a VS fed basis), and estimate hydrolysis rate (speed of degradation). The results are shown in Table 4. All fits were based on the average of triplicate BMP tests for each sample. Errors represent the 95% standard error on the fitted parameter.

Table 4: Preliminary degradability parameters of bedding and pond sludge samples

Sample Site	Methane Potential (L /kg VS):	Hydrolysis rate (per day):
Young southern pond sludge	111 ±17	0.029 ±0.01
Aged southern pond sludge	94 ±14	0.029 ±0.01
Northern breeder pond sludge	62 ±4	0.031 ±0.005
Northern finisher pond sludge	70 ±5	0.026 ±0.004
Fresh southern wheat bedding	217 ±16	0.052 ±0.01
Aged southern wheat bedding	115 ±3	0.032 ±0.002
Fresh northern barley bedding	351 ±17	0.071 ±0.01
Aged northern barley bedding	162 ±10	0.026 ±0.003
Fresh southern rice hulls weaner bedding	158 ±14	0.056 ±0.014
Aged southern rice hulls weaner bedding	179 ±20	0.029 ±0.007
Fresh southern rice hulls grower bedding	128 ±15	0.034 ±0.009
Aged southern rice hulls grower bedding	162 ±10	0.026 ±0.002

The BMP information is also required to determine whether an anaerobic digestion process is likely to be economically and technically feasible or not. In general, samples with a methane potential>200 L/kg will result in a feasible anaerobic digestion process. Therefore, of all the samples analysed, only the fresh southern wheat bedding and the fresh northern barley straw beddings appear feasible for digestion. However, if a leach bed process were used, fresh southern rice hull beddings may also be feasible depending on whether the degradable fraction of the manure could be readily mobilised.

4.3. Nutrient Release

Phosphate and ammonia analysis on all digestate samples indicates that nitrogen is generally released in proportion, or excess to digestion (50-80% of the added nitrogen is released as ammonia), while phosphate is largely retained as a precipitate. In general, only 10-20% of the phosphorus is released as phosphate, which is consistent with previous analysis. The key exception is fresh beddings, where 30-50% of the phosphorus is released through anaerobic digestion and is available for precipitation.

5. Potential for Nutrient Extraction

The analysis results (nitrogen and phosphorus contents, metals, and methane potential) support anaerobic digestion (leach bed) of fresh beddings only. Straw based beddings are likely to be readily digested. The feasibility of rice hulls beddings will depend on how readily the degradable manure fraction is mobilised, and this type of bedding should undergo a leach test in the future. The sludge and stockpiled bedding samples have relatively high nitrogen and phosphorus contents and direct spreading of this material is likely to be the best way to use the nutrients in these.

5.1. Anaerobic Digestion Using a Leach Bed Process

Anaerobic digestion is a biological conversion process that in the absence of a major electron acceptor, converts organic material to the most reduced form and most oxidised form of carbon (methane and carbon-dioxide respectively). It is one of the most promising nutrient release techniques, and provides other advantages such as destruction of pathogenic and parasitic organisms, production of methane, low biomass production, better process stability and lower treatment cost(Quan et al. 2010). Digestate from anaerobic digestion is often rich in ammonium and phosphate that can be recovered via crystallisation. Recovered products such as struvite ($MgNH_4PO_4.6H_2O$) and calcium phosphates have potential as marketable fertilisers from waste streams (Gaterell et al. 2000).

Anaerobic digestion of pond sludge and spent bedding is considerably complicated by high solids concentrations. Standard liquid digestion processes operate at <5%, while the TS contents of the fresh bedding samples analysed for this project were 36.8%-72.3%. Issues are not only related to mixing and organic loading(Metcalf & Eddy Inc. 2003), but also to ammonia inhibition (Webb & Hawkes 1985). Large amounts of water would be required to digest the spent bedding to achieve the required input concentration of <10%. A combination of a leach bed with high-rate anaerobic digester (generally upflow-anaerobic pond sludge blanket (UASB)), and combined side-stream ammonia removal has been effectively applied for diluted manure and bedding (Rao et al. (2008), Yetilmezsoy & Sakar(2008)). A generalised schematic for such a process is shown in Figure 6. The leach bed would be loaded and unloaded in a batch-wise fashion. The digestion process would last for about two months and makeup water would be added to the waste stream both initially and continuously throughout the batch. Leachate from this process would be continually fed to the methanogenic digester.

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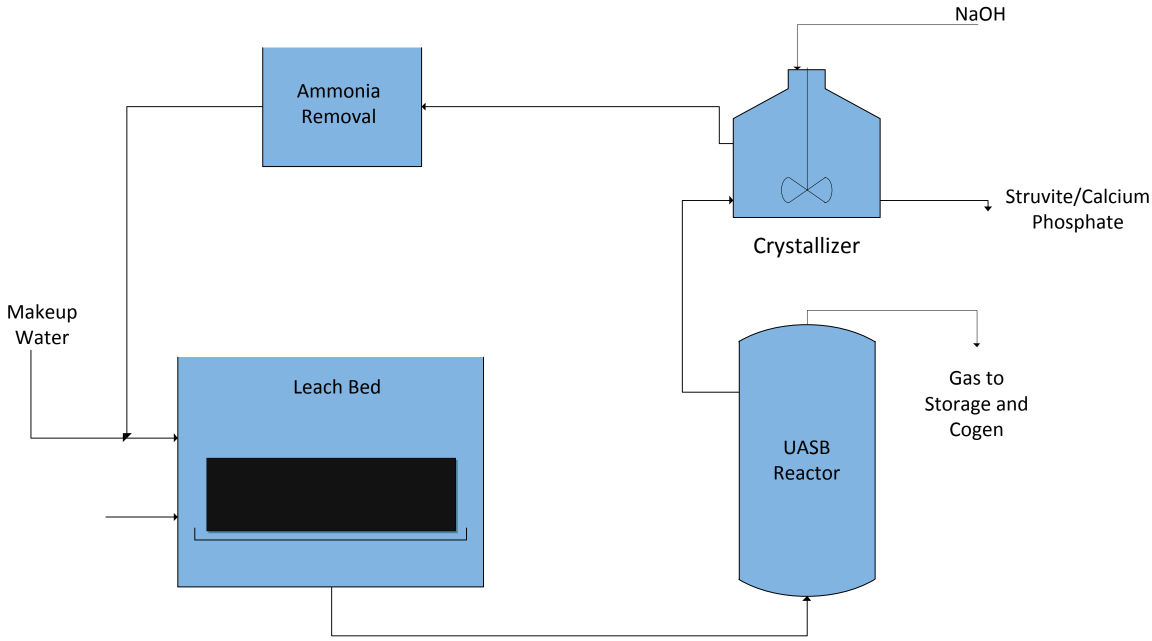

Figure 6: Leach bed system (anaerobic digestion and crystallisation)

5.2. *Nutrient Recovery from Anaerobic Digestion and Crystallisation*

Based on work undertaken for the recent Grains Research and Development Corporation Project "Fertiliser from Wastes: Phase I" (Tucker et al. 2011), the typical nutrient recovery rates as fertiliser (struvite) from crystallisation processes are:

- 31.5-40.5% N (say 36%)
- 63-81% P (say 72%)
- <1% K (not considered in the economic analysis).

Struvite has six molecules of water embedded in the crystalline form which accounts for 44% of the wet weight.

5.3. *Alternative Nutrient Extraction and Recovery Methods*

Nutrients could also be recovered through acid extraction (at pH 2.0), followed by recovery of mainly phosphorus by calcium phosphate precipitation. The molar cation (Al, Fe, Mg, Ca) to phosphate ratio is 2-3, which indicates a substantial excess of cations. It should be noted that several of the streams, including northern finisher pond sludge have high sulfur (anion) levels. In any case, the molar cation:phosphate levels are consistent with those of waste streams investigated as part of a GRDC Fertiliser from Waste: Phase I project, in which acid-phosphate extraction was investigated successfully(Mehta & Batstone D. 2010). This indicates that extraction through acid would be technically feasible. This would involve dropping the pH of the material to 2.0, followed by precipitation with calcium or magnesium oxides to generate a calcium or magnesium phosphate product. However, research undertaken as part of the GRDC Fertiliser from Waste: Phase I project showed that materials with comparable phosphorus levels (0.2-1%N, 0.1-0.5%P) needed such large amounts of chemical for nutrient extraction and recovery that the process is uneconomic and direct application is a more feasible option(Mehta & Batstone D. 2010).

Phosphorus could also be recovered by incineration followed by extraction (nitrogen is volatilised during incineration. While the pond sludges are too wet to incinerate without co-feeding, spent, stockpiled bedding could be directly incinerated, with phosphorus subsequently recovered from the ash.

Phosphorus is non-volatile, and is preserved in incineration ash. To maintain the phosphorus in a plant-available form, incineration temperature must be kept low (<700°C) (Thygesen et al. 2011). This retains all metal contaminants and the levels of metals such as zinc, copper, lead and mercury can render ash unusable especially if co-incinerated with municipal solid waste. Another consideration is the greenhouse gas emissions from this process. To minimise nitrous oxide (N_2O) emissions from incineration of nitrogen-rich wastes such as these, the incineration temperature must be maintained at >900°C (Gutierrez et al. 2005), which produces an ash that is unsuitable for direct use as a phosphorus fertiliser. Acid extraction could be applied to the ash to recover the phosphorus however this is expensive. In addition, acid extraction will generally leach metal contaminants. Alkali extraction is ineffective where there are calcium or magnesium precipitates (such as here). At a large scale, phosphorus recovery only could be applied via acid extraction of incineration ash. Given the scale requirements and technical issues, this has not been carried forward in this evaluation.

6. Amount and Value of Nutrients in Untreated Fresh Bedding

Table 5 shows the calculation of spent bedding per SPU for each of the piggeries that provided bedding. The piggery that provided the fresh northern barley sample had very low bedding material usage compared with the other piggeries and with industry best practice.

Table 5: Estimation of manure production (kg/SPU/yr)

Sample Description	Manure TS (kg/ SPU/yr) *	Bedding Material TS (kg/SPU/yr) #	Total Incoming TS (kg/SPU/yr)	Total Outgoing TS (kg/SPU/yr) ^	TS Content of Spent Bedding (%)+	Wet Mass of Spent Bedding (kg/SPU/yr)
Fresh southern wheat bedding	108	287	395	296	34.0	872
Fresh northern barley bedding	108	60	168	126	36.8	342
Fresh southern rice hulls weaner bedding	108	432	540	405	72.3	560
Fresh southern rice hulls grower bedding	108	548	656	492	54.2	908

* a grower pig (1 SPU) produces some 108 kg TS/hd/yr (Tucker et al. 2010).

bedding usage estimated based on data provided by piggery managers. Fresh southern wheat bedding: weaners (2-9 weeks) with 800/shed using 15 t/batch & growers and finishers (10-22 weeks) using 84 t bedding / 800 pigs/ batch; fresh northern barley bedding: grow-out unit with pigs aged 10 to 22 weeks (av 1 pig = 1.3 SPU), 144 pigs in sheds using an average of 2 X 70 kg bales/wk; fresh southern rice hulls weaner bedding: 500 weaners aged 2-9 weeks / shed using 18 t/batch; and fresh southern rice hulls grower bedding: 700 growers aged 10-15 weeks/shed using 48 t/batch. Bedding TS content assumed to be: 92% for rice hulls, 91% for barley straw, 89% for wheat straw) (based on (National Research Council 1984).

^ assuming 25% of incoming TS is lost through decomposition in the shelter

+ The TS content of the various finished beddings is provided in Table 1.

Table 6 shows the estimated quantity of nitrogen and phosphorus in each type of fresh bedding from a 10,000 SPU piggery. The concentration of nitrogen and phosphorus in each of the fresh bedding samples collected is shown in Table 2.

Table 6 also shows the fertiliser (nitrogen and phosphorus) value of these nutrients assuming a nitrogen value of $1380/t and a phosphorus value of $3480/t. (Note: These values were derived from fertiliser prices obtained 1 March 2011, ex Brisbane and including delivery to the Darling Downs for 1 t bags of $615/t for urea which has a nitrogen content of 46%; and an MAP cost of $885/t and a phosphorus content of 21.9% (N value of $560/t deducted to give $3480/t. Fertiliser prices fluctuate throughout and between years e.g. in January 2012 urea was priced at around $500/t at port (Marshall 2012a) but by early May 2012 it was up to around $600/t at port (Marshall 2012b). Consequently these values are considered reasonable to use here.

A typical sale price for spent bedding is around $12/t.

Table 6: Mass of nitrogen and phosphorus in fresh bedding produced annually by a 10,000 SPU unit and the fertiliser value of these nutrients

Sample Description	N (t/yr)	P (t/yr)	N ($/yr)	P ($/yr)	Total ($/yr)	Total ($/t of bedding)
Fresh southern wheat bedding	40.8	17.4	$56,300	$60,700	$117,000	$13.43
Fresh northern barley bedding	37.4	14.0	$51,600	$48,900	$100,500	$29.38
Fresh southern rice hulls weaner bedding	29.0	7.4	$40,000	$25,700	$65,700	$11.73
Fresh southern rice hulls grower bedding	21.3	12.8	$29,400	$44,500	$73,900	$8.14

7. Economic Analysis

A detailed economic analysis for anaerobic digestion and crystallisation of piggery spent bedding for a 10,000 standard pig unit (SPU) piggery is given below. This was prepared using a spreadsheet developed and made available by Dr Damien Batstone of AWMC, UQ. Dr Batstone also reality-checked the output.

The analysis considers the value of the untreated spent bedding; the capital and operating costs of anaerobic digestion; and the value of the fertiliser that could be recovered, along with additional income generated through electrical power sales, renewable energy incentives and Australian Carbon Credit Units (ACCUs).

7.1. Assumptions

For the purpose of this study, we assume the following apply to anaerobic digestion of each waste stream:

- The quantity of material for treatment is estimated to be:
  - fresh southern wheat bedding 8716 t TS/yr
  - fresh northern barley bedding 3420 t TS/yr
  - fresh southern rice hulls weaner bedding 5600 t TS/yr
  - fresh southern rice hulls grower bedding 9080 t TS/yr

Table 5 shows the calculation of spent bedding per SPU. The wet mass was then converted to a total mass per 10,000 SPU.

- The nitrogen and phosphorus content of the spent bedding is given in Table 2.
- 65% of the nitrogen in the bedding is released as ammonia.
- 40% of the phosphorus in the bedding is released through anaerobic digestion and is available for precipitation.
- Nitrogen and phosphorus recovered as mineral fertiliser ($MgNH_4PO_4$) are valued at the market price for nutrients in commercial inorganic fertilisers.
- Co-generation conversion efficiency to electricity is 35%. Conversion efficiency to heat is 55%. There is no cost for disposal of organic waste streams.

7.2. Raw Material Value

Table 6 provided the fertiliser value of fresh spent bedding based on the nitrogen and phosphorus content and fertiliser prices for these elements However, at the present time, spent piggery bedding can only be sold for around $12/t (wet) and this is the value used in the economic analysis. We have assumed that the anaerobic digestion plant operates on-farm and consequently there are no transportation costs to be added to the raw material value.

7.3. Capital Costs

For this study, capital costs include the cost of purchasing the anaerobic digestion and crystallisation equipment. It was assumed that land on-site is available for this use and so there is no cost allowance for land purchases.

The capital costs for the leach bed and UASB digesters were scaled based on the capacity of each component (see Figure 7 and Figure 8). Minimum rates of $300/m^3 for a leach bed digester and $500/m^3 for a UASB digester were applied. This costing was provided by UQ.

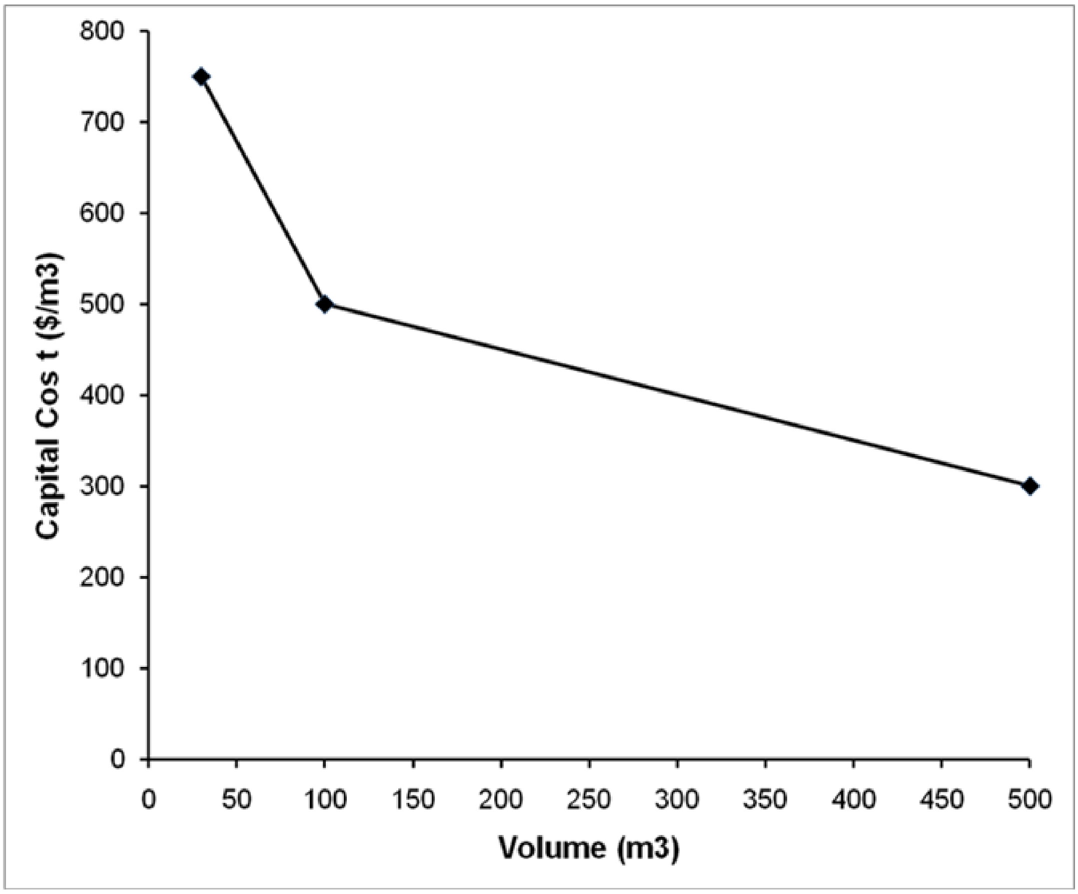

Figure 7: Capital cost basis for leach bed

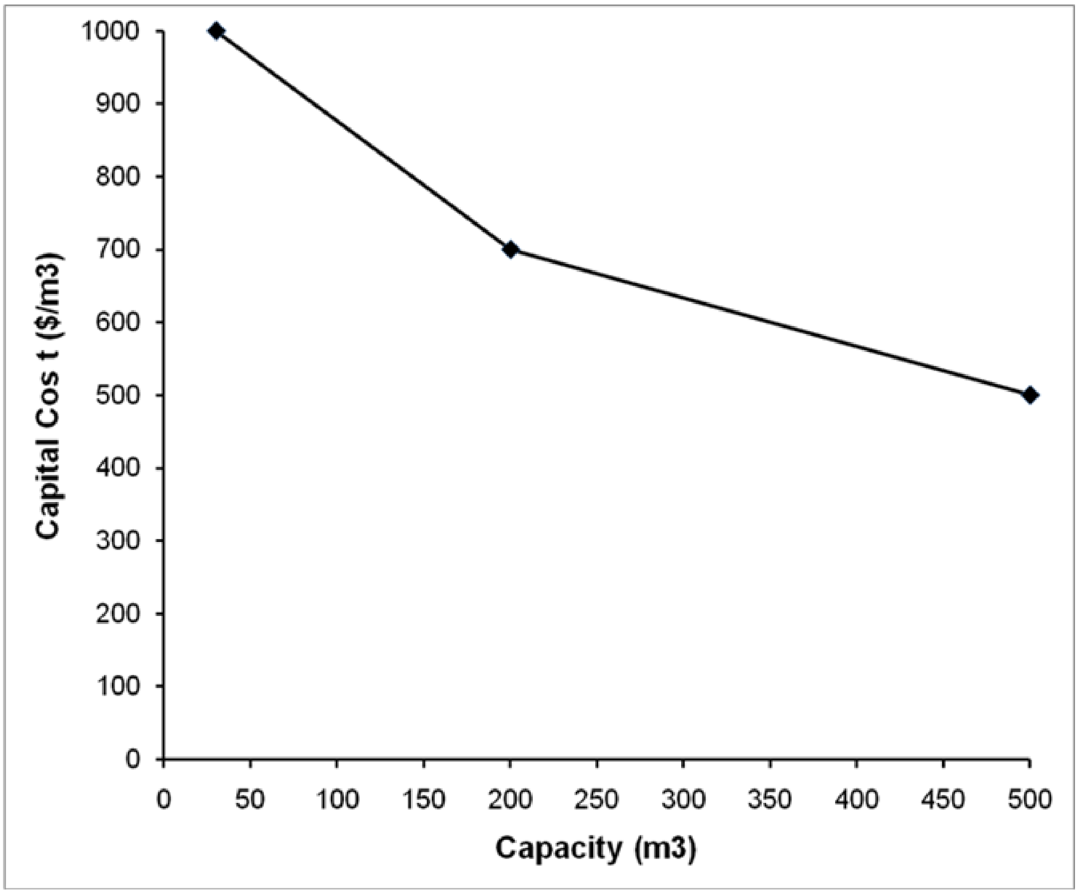

Figure 8: Capital cost basis for UASB

The capital costing basis for various leach bed system components is provided in Table 7. Cost estimates for pumps, piping, foundations, gas piping electrical equipment and the crystallisation equipment were based on the actual cost of a 500 kL digestion plant and scaled linearly according to capacity.

Table 7: Capital cost basis for components of leach bed-UASB system

Equipment	Units	Cost ($)
Pumps and instrumentation	$/500 kL digestion volume	40,000
Cogeneration Unit	$/kWh	1,000
Engineering	% of total installed capital cost	10

Table 8 provides the capital costing details for the plant for each type of spent bedding.

Table 8: Capital costing for the digester system for each type of spent bedding

Item	Fresh southern wheat bedding	Fresh northern barley bedding	Fresh southern rice hulls weaner bedding	Fresh southern rice hulls grower bedding
Batch digester	$297,000	$123,000	$217,000	$361,000
Methanogenic digester	$87,000	$98,000	$132,000	$89,000
Pumps	$22,800	$17,400	$21,600	$25,000
Piping	$7,600	$5,800	$7,200	$8,300
Foundation	$15,200	$11,600	$14,400	$16,700
Gas piping	$3,800	$2,900	$3,600	$4,200
Electrical and installation	$4,600	$3,500	$4,300	$5,000
Crystallisation and sidestream	$68,000	$52,000	$65,000	$75,000
Cogeneration engine	$49,000	$55,000	$85,000	$50,000
Engineering	$56,000	$37,000	$55,000	$63,000
Total	$611,000	$406,000	$606,000	$698,000

7.4. Plant Operating Costs

Anaerobic digestion plants require low levels of operational labour attendance, so operational labour costs are typically low. The technology is automatically monitored and protected using computer control systems. The risk of explosion or fire is low. Hence the costing does not include continual attendance.

Table 9 shows the basis for determining costs for equipment maintenance, chemical addition and wastewater treatment for the leach bed anaerobic digestion systems. These operating costs are based on real data for a 500 kL digestion plant with scaling corrections. A three point linear relationship was used to scale operating costs to plant size (D Batstone, AWMC UQ, pers. comm. 16 March 2011).

Table 9: Operating cost basis for leach bed-UASB system

Item	Units	Scalable Cost
Equipment maintenance	% of digestion cost	2
Cogeneration maintenance	% of cogeneration cost	5
Chemical addition (MgO)	$/t	800
Wastewater treatment	$/kL	4

It is assumed that 0.3 of a full time equivalent staff would be required to operate the leach bed-UASB system. A full time salary was $62,400.

A breakdown of estimated costs is provided in Table 10.

Table 10: Annual operating costs for the digester system for a 10,000 SPU piggery digester system for each type of spent bedding

Item	Fresh southern wheat bedding	Fresh northern barley bedding	Fresh southern rice hulls weaner bedding	Fresh southern rice hulls grower bedding
Operator salaries	$12,000	$9,600	$12,600	$13,900
Vessel and pipe maintenance	$8,000	$5,200	$8,800	$10,200
Cogenerator maintenance	$4,300	$2,800	$2,500	$2,500
Pump and mixing energy	$3,200	$2,500	$3,300	$3,700
Chemical MgO	$7,400	$6,000	$2,200	$5,400
Cost of wastewater treatment	$40,000	$15,700	$23,800	$36,000
Value of spent bedding	$105,000	$41,000	$67,000	$100,000
Total	$180,000	$83,000	$120,000	$171,500

7.5. Income

Each nutrient release technology produces a range of potential revenue streams. These can include:

- Fertiliser-type products
- Power
- Renewable energy credits (RECs)
- Australian Carbon Credit Units (ACCUs)

The following values were assumed for the macro-nutrients based on prices obtained 1 March 2011, ex Brisbane and including delivery to the Darling Downs for 1 t bags:

- N: $1337/t based on a urea cost of $615/t and N content of 46% = $1337 / t N
- P: $3480/t based on a MAP cost of $885/t and a P content of 21.9% = $4040 /t less N value ($560) = $3480/t

A very valuable co-product of the nutrient extraction processes is electrical power. This can be used to offset power costs from the reticulated mains supply and a value of $0.1/kWh was used for the economic analysis. If electrical power were sold to the grid then the realisable value would be closer to $0.035/kWh (AEMO 2011). The thermal energy generated by the cogeneration plant is significant and could potentially be used to run a water heater at a facility. However this has not been factored into the economic analysis. Revenue generated from thermal energy is difficult to realise unless there is a demand located adjacent to the source e.g. heating farrowing sheds. Hence, it may not be useful at all piggeries and its inclusion may result in unrealistically attractive results.

Renewable energy credits (RECs) can be applied to power generated by the process. The value for RECS is continually changing. For this analysis, a value of $0.035/KWh was used (NGES 2011).

Anaerobic digestion of wastes produced onsite will allow piggery owners to generate additional revenue through the receipt of Australian Carbon Credit Units (ACCUs). For this analysis, it is assumed that ACCUs generate income of $15/tonne $CO_{2\text{-equivalent}}$. One tonne of methane is equivalent to 21 t of $CO_{2\text{-equivalent}}$.

Table 11 summarises the values assumed for the main revenue streams considered in this study.

Table 11: Annual income stream values for economic analysis for a 10,000 SPU piggery digester system for each type of spent bedding

Parameter	Units	Scalable Cost
Electrical power	\$/kWh	0.1[1]
Heat energy	\$/kW	0
RECs credits	\$/kW	0.035[2]
ACCUs	\$/t $CO_{2\text{-equivalent}}$	15[3]
N	\$/kg	1.33[4]
P	\$/kg	3.48[4]

Sources : 1 Assumed value for energy cost
2 (NGES 2011)
3 Government-set carbon price is \$23/t $CO_{2\text{-equivalent}}$ but current reports are that the market value will be significantly lower
4 Market value of fertiliser ex Brisbane for Darling Downs delivery)

Nutrient values for the waste streams were calculated from the quantity of macro-nutrients present in each untreated waste stream multiplied by a dollar value for the nutrients that was derived from their value in commercial inorganic fertilisers. *They do not represent the value that could be realistically expected from selling the spent bedding in its raw form.* The current sale values for spent bedding are considerably lower than the 'fertiliser' values for the macro-nutrients. The value of nutrients has fluctuated greatly in the past few years. Despite variations in price however, there is a long term trend towards increasing nutrient values for nitrogen and potassium. It is also noted that the nutrient content within spent bedding is variable and may be lower than used in the estimates here. It is important to note that spent bedding also contain considerable amounts of other important nutrients such as sulfur, calcium and the trace elements zinc and copper. While these are valuable in themselves, they are also typically present in, or are added to fertiliser products based on macro-nutrients and usually command only a modest premium. For example, single superphosphate contains calcium and sulfur, whilst zinc can be purchased in a blend with mono-ammonium phosphate (MAP). For this reason they are not valued separately in the waste stream valuations determined in this section.

Income streams for the digestion process for each type of spent bedding are provided in Table 12.

Table 12: Annual income streams for a 10,000 SPU piggery digester system for each type of spent bedding

Item	Fresh southern wheat bedding	Fresh northern barley bedding	Fresh southern rice hulls weaner bedding	Fresh southern rice hulls grower bedding
Cogenerated electricity	$74,000	$48,000	$43,000	$44,000
RECS	$26,000	$17,000	$15,000	$15,200
ACCUs	$43,000	$28,000	$25,000	$25,000
Nitrogen	$4,200	$3,400	$1,300	$3,100
Phosphorus	$24,300	$19,600	$7,300	$17,800
Total income	$172,000	$116,000	$92,000	$105,000

7.6. Economic Analysis

The economic analysis estimates the payback period as the number of years of annual gross income required to pay-back the debt of capital cost using "at present" values.

Table 13 shows the annual income, operating costs and gross return for piggery spent bedding digested anaerobically, along with an estimated payback period.

Table 13: Annual income, operating costs and economic performance for a 10,000 SPU piggery digester system for each type of spent bedding

Item	Fresh southern wheat bedding	Fresh northern barley bedding	Fresh southern rice hulls weaner bedding	Fresh southern rice hulls grower bedding
Income				
Total income	$172,000	$116,000	$92,000	$105,000
Total operating cost	$180,000	$83,000	$120,000	$171,000
Annual gross return	($8,000)	$33,000	($28,00)	($66,000)
Capital cost	$611,000	$406,000	$606,000	$698,000
Payback period on capital investment	N/A - loss	12.3 years	N/A – loss	N/A - loss

Only one of the spent bedding materials tested produced a positive payback period for anaerobic digestion using the scale and method described in this research. Fresh northern barley bedding produced a fair payback period of 12.3 years. However, it is important to note that this spent bedding is atypical of the broader industry due to the very low levels of clean bedding material used at this piggery. This meant that there was less material for treatment so a smaller system with a lower capital cost was needed. This material also had a significantly higher methane production rate than the other materials tested, possibly due to the high ratio of manure to bedding material.

8. Conclusions

While fresh spent beddings (particularly straw-based beddings) are technically suitable for anaerobic digestion using a leach bed system, this research could only demonstrate a fair economic performance for one type of bedding. The fresh northern barley bedding produced a payback period of 12.3 years. However, the sample tested came from a piggery with very low clean bedding usage compared to the majority of the industry meaning the ratio of manure to bedding was unusually high.

Nor were pond sludge and stockpiled beddings feasible for anaerobic digestion. Direct spreading of these is recommended. They would be particularly beneficial on zinc-deficient soils.

Other nutrient extraction techniques are unsuitable due to: the relatively low nutrient concentration making direct acid extraction uneconomic; the high relative nitrogen concentration requiring high-temperature incineration which produces an ash that is unsuitable for direct use as a fertiliser; and the high cost of acid extraction from the ash making the process uneconomic (alkali extraction is not an option due to the high magnesium and calcium levels).

Bedding is typically up to eight weeks old before it is removed from the shelters. As shown in section 4.1, fresh bedding samples generally have significantly higher methane production that spent bedding samples. Since this significantly influences the economic outcome, it may be worth investigating the performance of litter aged up to two weeks old and up to four weeks old. Practical issues, particularly whether piggery operators would be prepared to clean-out sheds more frequently, would need to be considered.

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