Australian Government
Department of Agriculture and Water Resources

AUSTRALIAN Pork

Closing the Loop to Reduce Waste Roadmap for the Australian Pork Industry 2025

Manual

Final Report
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1. Introduction

"Closing the Loop" sets out the pork industries' ambitious aim to move to zero waste and contribute to the circular economy by reducing waste throughout the agri-food sector.

The pig industry is a leader in "Closing the Loop" on waste; both as a user of by-products from other sectors, and as an efficient user of all the resources on the farm to maximise pork production and generating energy and nutrients. This roadmap provides guidance for pork producers, regardless of size, to participate in effective waste management methods to 'Close the Loop'. The pig industry is a 'solutions' industry that can provide services in waste management to other sectors of the economy. The implementation of commercially viable waste management strategies could see piggeries setting a new standard in low waste food production.

There is growing expectation by Australian consumers for all sectors of the economy to demonstrate and report a high standard of environmental, social and governance (ESG) outcomes.

1.1 Closing the loop in the Economy

Waste minimisation is of significance across all Australian jurisdictions, with ambitious targets in place at national, state and regional levels. In addition to government policies, major retailers have also developed programs with the aim of reducing waste. Table 1 provides a summary of the relevant government and enterprise based targets focused on the food sector, which is most relevant to pork because of the link to by-product utilisation.

Table 1. Waste policy summary

Jurisdiction/entity	Relevant targets or programs	Reference
Federal	50% reduction in organic waste to landfill by 2030	National Waste Policy Action Plan 2019
NSW	Reduce organic waste sent to landfill by 50% by 2030	NSW Waste and Sustainable Materials Strategy 2041 – Stage 1: 2021-2027
Queensland	90% of waste is recovered and does not go to landfill by 2050	Waste Management and Resource Recovery Strategy
Victoria	Halve food waste to landfill by 2030	Recycling Victoria: A New Economy
South Australia	Zero avoidable waste to landfill by 2030	Waste Strategy 2020-2025
Western Australia	No more than 15% of waste generated in Perth and Peel regions is landfilled by 2030	Waste Avoidance and Resource Recovery Strategy 2030
Tasmania	Reduce organic waste to landfill by 25% by 2025 and 50% by 2030	Draft Waste Action Plan
Major food retailers	Coles – Together to Zero Waste – divert 85% of waste from landfill by 2025 Woolworths – Sustainability Goal 2 – Zero food waste to landfill by 2025	

APL's closing the loop on waste by 2025 policy position is consistent with other parts of the food supply chain and broader public policy.

1.2 What is Closing the Loop?

Circular systems are the key to closing the loop. Figure 1 shows a transition from a traditional linear economy where materials are used as input to production then waste disposed of at the end of the process; through a recycling economy where a portion of the materials are recycled; through to a truly circular system, where waste products are converted into marketable and useful products.

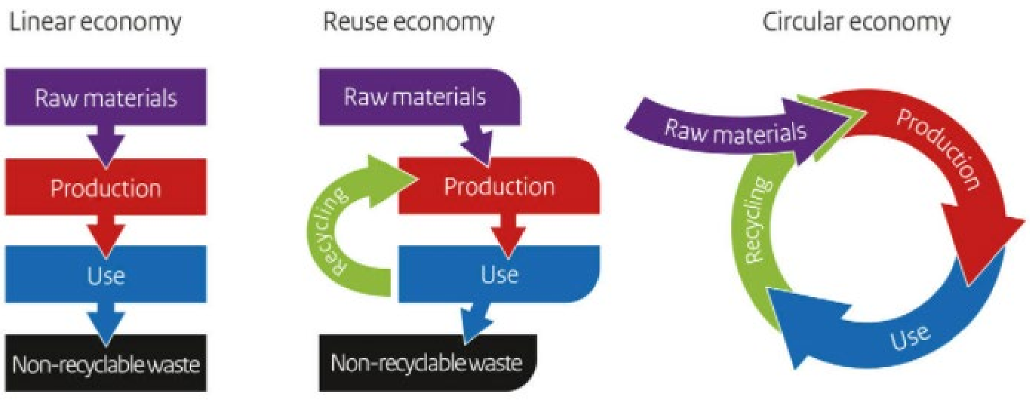

Figure 1. The transition from linear to circular economy (Government of the Netherlands, 2017)

Achieving a circular economy requires a change of thinking: all inputs should be considered to ensure that any waste they generate can be used, and all waste material generated must be considered a potential resource. In the agri-food sector, the pig industry can improve circularity by utilising other "waste" products from the human food supply chain as feed sources for pigs and can also move to circular agricultural systems at the piggery itself.

The waste hierarchy (Figure 2) is relevant in the context of closing the loop for piggery operators as the primary focus should be on waste avoidance and prevention, followed by waste reuse, then recycling and resource recovery of generated waste streams. Waste disposal should be the last alternative, and in an ideal circular system, the aim is for zero waste to require disposal.

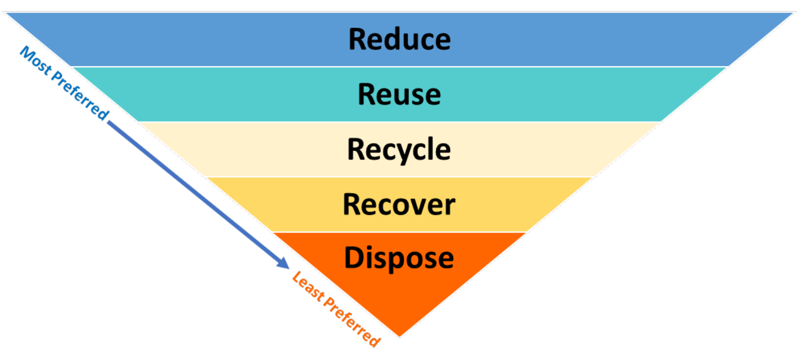

Figure 2. Waste hierarchy (adapted from Australian Government, 2019)

2. What is 'Closing the Loop' for Piggeries?

The pig industry is a leader in circularity in the food sector, but more can be done to harness the opportunities to use by-products from other parts of the economy, and to reduce waste from pig production. While this is obvious to pig farmers, outside the industry there are many competing industries and technologies moving to gain an edge in this field. Some of these are complementary, and some are competitive with the pig industries' goals.

The nature of pig production provides an opportunity to divert food waste for use as feed, which is a preferred option for reuse compared with other competitive processes such as anaerobic digestion for energy recovery or composting. Figure 3 shows the different tiers of the food waste recovery hierarchy based on the benefits gained from waste diversion to the environment, society and the economy. Feeding animals ranks higher than competitive resource recovery alternatives for food waste.

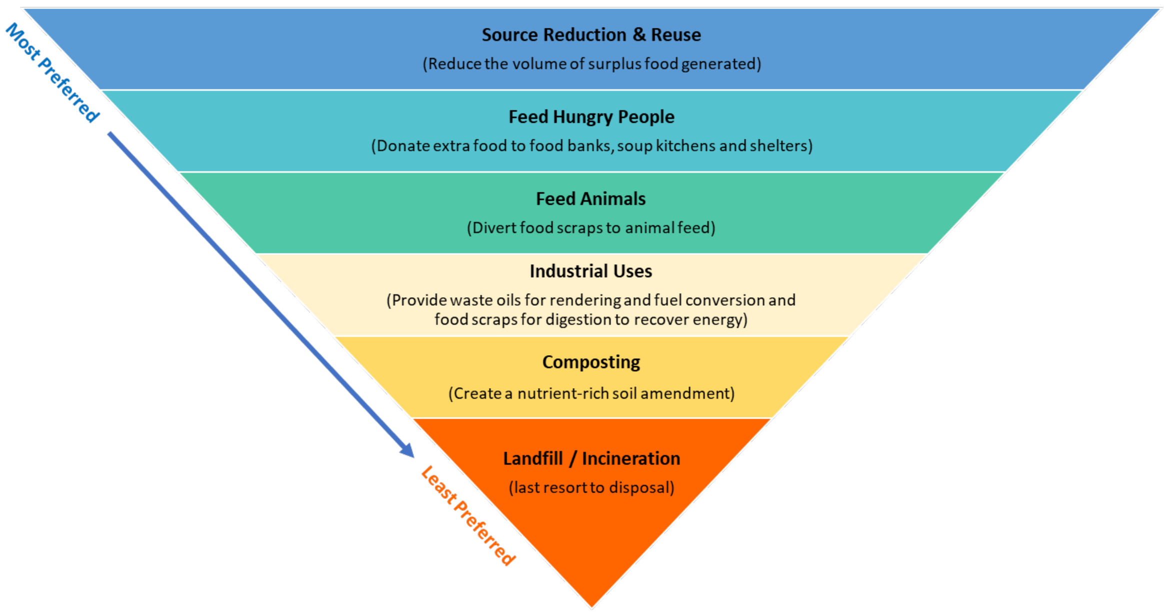

Figure 3. Food waste recovery hierarchy (U.S. EPA, 2021)

There is a strong link between reducing waste and other co-benefits, such as reducing greenhouse gas (GHG) emissions. Using more by-products for pig feed reduces the need for crop production. Using manure to generate energy and provide alternatives to synthetic fertiliser avoids methane emissions, electricity production and impacts from fertiliser manufacture. Nutrient recovery from waste could also potentially generate new revenue streams, and recycled water can reduce fresh water requirements at piggeries. Even carbon dioxide (CO_2) could become a commodity from piggeries if viable uses, such as horticulture, could be effectively established. Considering this array of opportunities, the zero waste roadmap will guide a strategic shift in the pig industry which will also help drive towards low emission pork.

This roadmap is divided into five key areas. In each area the guide shows the process of closing the loop, following steps in the waste hierarchy (Reduce > Reuse > Recycle >Recover). These five areas are:

- **Feed** – minimising inputs, improving production efficiency to minimise wastage, substituting third party food waste products into piggery feed, alternative feed sources

- **Energy** – recovery of residual energy in the effluent system through methane capture from anaerobic digestion, co-digestion of third party waste products to increase methane generation, biomethane production
- **Nutrients** – utilising manure nutrients, nitrogen (N). phosphorus (P) and potassium (K), in raw form, nutrient recovery to create high-value products
- **Water** – minimising water usage through waste reduction and reuse, on-site recycling
- **Solid waste** – minimising consumption and using the highest proportion of recyclable materials on-site, including plastic, cardboard and metal

2.1 Waste Measurement Indicators

To measure progress towards the goal of closing the loop, it is important to measure waste generation rates over time to assess change. Table 2 provides a range of waste indicators for different production systems, allowing an operation to benchmark their current position regarding waste generation and monitor progress towards reducing their waste footprint.

Table 2. Waste indicators for the Australian pork industry

Resource	Description	Units	Indicator	Purpose
Feed	% of ration sourced from residues and by-products	%	Ration ingredients	On-farm/supply chain benchmarking
	Estimated % feed waste in piggery	%	/kg LWG	On farm benchmarking
	Decrease in FCR/HFC in last 12 months		Change in FCR/HFC	On-farm/supply chain benchmarking
	Ration ingredients	%	% of ration using imported ingredients	On-farm/supply chain benchmarking
	Ration ingredients	%	% of ration using locally grown ingredients	On-farm/supply chain benchmarking
Energy	% of energy in manure beneficially used*	%	% of energy in manure beneficially used*	On-farm/supply chain benchmarking
	CO_2 utilisation	%	% CO_2 utilised in a beneficial way*	On-farm/supply chain benchmarking
Nutrients	Effluent / manure utilisation	%	% of N utilised for beneficial purposes*	On-farm/supply chain benchmarking
	Effluent / manure utilisation	%	% of P utilised for beneficial purposes*	On-farm/supply chain benchmarking
	Effluent / manure utilisation	%	% of K utilised for beneficial purposes*	On-farm/supply chain benchmarking
Water	% of effluent water utilised for beneficial purposes*	%	% of effluent water utilised for beneficial purposes*	On-farm/supply chain benchmarking
Solid Waste	kg solid waste excluding manure	kg	/kg LW produced or exported	On-farm benchmarking
	kg of plastic waste	kg	/kg LW produced or exported	On-farm benchmarking

**Beneficial is defined as a positive, good, or advantageous result by the indicated practice. This may be in relation to pasture or crop application of solid waste products or effluent water reuse, where a beneficial application would imply meeting the requirements of the plants in question as to limit nutrient build-up above requirements or possibilities of nutrient leaching or runoff.*

2.2 Baselining and Benchmarking

Collection of reliable waste data across a range of relevant indicators would provide an improved understanding of the current waste generation rates. Understanding the waste volume and streams would then allow opportunities for industry wide recycling to be identified and improve the sharing of knowledge on best practice waste minimisation.

Data collection also allows progress toward waste minimisation targets to be measured and tracked overtime. Accurate measurement would allow the businesses and industry to promote achievements towards national, state, regional and operational levels targets.

3. Feed

Feed is the largest input for a piggery operation. Because of this, there are opportunities for closing the loop through minimising the requirements of traditional inputs and by utilising waste from other industries as pig feed, such as pre-consumer human food chain wastes. Utilising other forms of waste as alternative feed components (for example, black soldier fly larvae) or by-product utilisation may also be viable alternatives for waste reduction. This section outlines options to reduce the waste footprint from feed for a producer.

3.1 Improving FCR

Reducing waste starts with optimising inputs to reduce wastage out of the system. To improve current grain-fed feeding systems requires reduced feed wastage and feed lost into the manure management system. Reducing feed wastage makes economic and environmental sense as it improves productivity and reduces waste nutrients from the manure stream (Table 3).

Table 3. The quantity and related cost of feed wastage in a growing herd (adapted from Carr, 2008)

Age, weeks	Average daily gain, kg/day	FCR	Average daily feed intake, kg/day	Feed usage^, kg		
				+ 2% wastage	+ 15% wastage	+ 30% wastage
4	0.2	1.0	0.2	0.20	0.23	0.26
6	0.4	1.2	0.5	0.51	0.57	0.65
8	0.6	1.4	0.9	0.92	1.03	1.17
10	0.7	1.6	1.1	1.12	1.26	1.43
12	0.7	1.8	1.3	1.33	1.49	1.69
14	0.8	2.4	1.9	1.94	2.18	2.47
16	0.9	2.6	2.5	2.55	2.87	3.25
18	1.00	2.9	2.9	2.96	3.33	3.77
20	1.10	3.0	3.3	3.37	3.79	4.29
22	1.10	3.2	3.5	3.57	4.02	4.55
			Feed cost*, $/pig	**140**	**157**	**178**
			Feed wastage cost*, $/pig	**2.80**	**20.20**	**41.10**

*Based on the average cost of a grower and finisher pelleted diet without freight $0.60/1.00kg feed. ^Sale age is 21 weeks for a dress weight of 76%.

Feed waste can be reduced by over 50% in response to better feed management and feeding systems. Major changes which can reduce wastage include:

- Changing feed type (changing from mash to pellets or liquid food),
- Feed presentation (feeder type), and
- Feed processing (optimising feed particle size for pig growth stage).

Most feeders are manufactured to reduce feed wastage, e.g. creep feeder separations and rounded rims on stainless steel troughs. Minor changes that can greatly reduce feed wastage include optimised feeder adjustment, cleanliness, auger monitoring and feeder pan coverage to reduce spills and overfeeding. For new installations that deliver dry feed, electronic feeding systems that use electronic identification to provide the individual with the pre-set allocated portion will provide the greatest reduction in feed wastage. Liquid feeding systems allow for an even greater reduction in feed wastage, as do wet/dry feeders compared to using conventional dry feeders.

3.1.1 *Feeder type, maintenance and adjustment.*

Gravity fed, circular and modular stainless-steel hoppers allow for regulating feed wastage with manual adjustment of the outlet. The alternative to constant adjustment would be to use mechanical-flow pig feeders activated by feeding events. Feeder adjustment controls the pigs' access to feed and excess feed being presented. Optimum feeder gap settings differ with each growth phase. Stainless steel dry feeders are suggested to be maintained so that feed slightly covers more than half of the feeder pan for grower-finisher pigs up to around 70kg. Beyond this, the feeder gap should be reduced by 30%. Feeders need the be managed properly to work efficiently. A way to reduce feeder wastage is incorporating feeder maintenance procedures into husbandry requirements similar to those listed below:

1. During daily walkthrough's, check for spills or leaks starting from the silo to the feeder.
2. Check feeder pan coverage and feed on the floor and adjust feeder gap as necessary.
3. Repair or replace broken feeders.
4. Reduce "leftover" feed following pig movements, e.g. weaning or sales, by calculating feed delivery with respect to when the pen will be empty.
5. Carefully monitor feed augers to prevent auger over-run.
6. Routinely use a tool to clean corners and under feed gates to dislodge caked feed preventing the raising of the adjustment mechanism.
7. Make required changes to the feeding system to adjust sow feed intake during times of transition.
8. Put lids on feeders. An adult rat will eat 15g/day, and therefore 100 rats will eat 0.5 tonnes of feed annually.
9. Don't allow feeders to overrun as the pigs will prefer freshly delivered feed.
10. Excessive water in wet feeders' spoils feed and obstructs feed intake.

3.2 Utilising Commercial Food Waste

The ability for pigs to digest a diverse range of food without impacting performance makes them the animal most able to consume and subsequently recycle food waste. Pigs are one part of the solution to closing the loop on an estimated 7.3 million tonnes of food wasted in Australia each year (Commonwealth of Australia, 2017).

Of the 7.3 million tonnes of food waste generated each year in Australia, 34% is generated from households, 31% is generated from primary production, 24% from manufacturing and 4% from hospitality and food services. State-wide breakdown of food waste generation is shown in Figure 4 with Victoria generating the largest amount, in line with the concentration of population, agriculture and manufacturing.

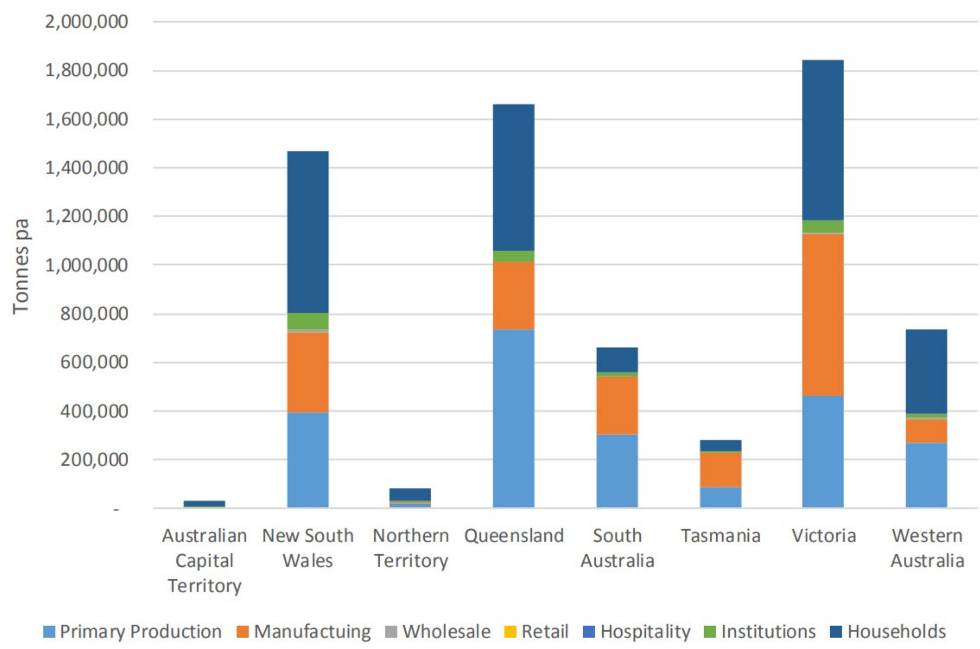

Figure 4. State-wide distribution of food waste in Australia (ARCADIS, 2019)

The term **food waste** refers to fresh produce, foods that are close to, at, or beyond the 'best before' date or large quantities of edible food unused or leftover. The Food and Agriculture Organization (FAO, 2021) defines food waste as safe and nutritious food that has been discarded prior to human consumption.

Food loss refers to any food discarded, incinerated or disposed of along the food supply chain from post-harvest up to, but excluding, the retail level. When a product is a loss or waste from another system, defined as being provided at no cost (FAO, 2021), these products have negligible value and are attributed no environmental burden. Therefore, these products are treated as wastes from their respective industries, with no environmental impacts burdened on the piggery.

Under current laws, swill (food that has been offered for human consumption) and waste meat products are not allowed to be fed to pigs, meaning wastes from primary production and manufacture are the most suitable to be included pig diets.

Primary production waste includes product loss along the supply chain which is damaged or discarded during production, packaging or handling. Surplus product may be a result of a fall in market prices or the inability of the product to meet quality or size specifications. This includes fruit and vegetables, nuts, wine grapes, crops, fisheries, eggs, livestock and milk.

Manufacturing waste is produced from fruit, vegetable and seafood processing and the manufacturing of oil and fat, grain mill and cereal, bakery product, sugar and confectionary, meat and meat product and dairy product.

Around 4 million tonnes of food waste from primary production and manufacturing are generated annually (Table 4).

Table 4. Waste volumes from primary production and manufacturing in Australia (ABARES, 2019; ARCADIS, 2019)

Food supply chain sector	Product	Volume (t/yr)
Primary production	Fruit (citrus, apples, pears and bananas)	228 200
	Vegetables	816 000
	Egg waste	5 000

Manufacturing	Grain	882 000
	Fruit and vegetable packing houses	422 000
	Dairy processing	630 000
	Nuts	82 500
	Wine grapes	224 000
	Seafood	50 080
	Dairy	630 000
Total		**3 969 780**

Currently only 10-20% of commercial pig herds divert food waste from production and manufacturing (Torok et al., 2021), utilising a very small portion of the potentially available 4 million tonnes. There is huge potential to source adequate volumes of allowable food waste to supply commercial piggeries (Table 5). However, logistical barriers which make processing difficult when handling food waste and losses need to be considered.

Table 5. Waste and food loss which can be utilized in pig diets

Waste or food loss	Examples utilised in pig feeding systems
Cereal grains and by-products	Rice pollard, oat bran, wheat dust, hominy, barley offal, malt combining's
Brewing and distilling	Wastes
Oil seed meals	
Milk, milk products and by-products	Milk, ice-cream, whey, cheese, egg waste
Dry meals made from meat	Meat meal
Blood, bone or feathers	Blood and/or bone meals
Non-meat bakery waste	Bread, dough, biscuits, waste
Fruit, vegetable or legume waste	Tinned vegetables, fruit juice
Supermarket waste	
Fish	Waste, fish fingers, oil
Spreads	Mustard meal, Nutella, peanut butter, jam
Staples	Pasta
Pet food	Pet food waste
Confectionary	Soft drink, cordial, syrups, chocolate, lollies, popcorn

3.2.1 Food waste handling and feeding systems

The moisture content in fresh produce and most food waste means these sources have a lower shelf life. To properly manage the use of fresh produce waste it is necessary to ensure selection, transport, processing and sale takes place within an ideal time to ensure freshness and micronutrient content is optimised with transport and storage requirements possibly increasing energy and resource use. Infrastructure and technological solutions are required for acquiring, processing and milling the waste. On-farm processing needs to consider the handling of different products, fluctuating volumes and recycling packaging. There can be additional time required for purchasing and delivery of by-products with seasonal availability in yield. Irregular supply can be difficult to navigate however, there are online apps which enable direct access to pools of surplus food waste. Companies such as Yume Food (yumefood.com.au) trade in surplus wholesale food to minimise food waste.

Additional investment is required for storage and feeding facilities. Dry by-products can be stored in grain bins however, wet waste products require specialised storage to avoid spoilage and shrinkage losses. Waste products may need refrigeration to maintain freshness, which needs to be capable of handling volumes expected to be acquired. Equipment is required for handling and the transportation of waste products, unpackaging and disposal of cartons, containers or plastic wraps which also needs to be clean and maintained. Specialised systems for waste product feeding need equipment for weighing specially formulated rations and the delivery of wet feed. Diverted food waste from landfill may be delivered at no cost. While investigations could be made into the potential to utilise waste heat from biogas operations to heat treat some forms of food waste to further reduce the reliance on expensive and high environmentally impactful feed ingredients such as protein meals.

Two options exist to handle the use of commercial food waste:

1) On-site liquid feeding system.
2) Off-site centralised processing plant.

Liquid feeding systems can be used to mix high moisture ingredients into a liquid feed, remix dry diets with water or feed a liquid ingredient along with the dry diet. Although capital costs of installing a liquid feeding system are high, installation costs are comparable to dry feeding systems. Therefore, the conversion of existing dry feeding units to liquid feeding systems can be costly, although liquid feeding systems can utilise current stainless-steel feeders and troughs. Liquid feeding involves mixing the stored on-farm high moisture ingredients with water and proper ratios of vitamins and minerals into a slurry which is pumped via feed lines to the troughs or feeders. A second option which reduces costs, and less equipment is to use current water lines to provide a mix of dry feed with any amount of liquid ingredient e.g. whey, along with a complete diet through existing feed lines.

To avoid risks associated with procurement, supply, depackaging and contamination, **centralised processing plants** would be recommended to divert food waste and produce pig feed. In 2001, a Food Recycling Law was introduced in Japan which started to target businesses which produced over 100t of food waste/year and the sector began to demonstrate innovative processes for utilising food waste in on-site processing plants. Food waste is collected and manufactured in licensed, well-regulated treatment plants to produce feed alternatives. The product is marketed and sold as 'Ecofeed' to piggeries at half the cost of conventional diets. The Japan Food Ecology Center converts around 39 t/day of food waste into liquid feed using computerised formulation technology. Pre-sorted rice, bread, noodles, cooking scraps, delicatessen, vegetable and fruit waste are transported in bins to the factory. On arrival, each individual barcoded bin is weighed to enable computerised diet formulation. Food waste is then sorted to remove contamination (e.g. plastics) and broken up using high pressure hoses. Sterilisation occurs at 80-90˚C and the waste is then fermented with lactic acid bacteria for 6-8 hours. Feed diets are transported in tank trucks to its destination. The resultant, high-quality pork is then sold and branded as 'superior', 'delicious' and 'flavourful'.

In Australia, while this area is well understood by industry leaders there would be a much greater uptake if barriers were known and could be overcome. An Australian Pork Limited funded report summarised the practicality and regulatory requirements of utilising food waste as a feed source for pigs (Lane & Hoban, 2017). The introduction of feeding food waste would require support from producers, the public and policymakers. By investing in infrastructure for on-site processing or a centralised processing plant there's a need to:

a) investigate packaging options to reduce waste,

b) explore the possibility to produce bioenergy,

c) optimise procurement, forecasting and planning and,

d) develop operational guidelines, certification, and rating systems for handling of waste.

Food waste reuse opportunities which currently do not require regulatory approval include (ARCADIS, 2019; Lane & Hoban, 2017):

- Whey from the manufacture of dairy products
- Fruit and vegetable losses or surplus from primary production
- Establishment of a centralised processing plant to process food waste into feed (adhering to swill feeding legislation)

There are a number important considerations with regard to herd health that are required when considering the incorporation of food waste into diets, and any new introductions and changes should be undertaken under the guidance of a pig nutritionist. Regular analysis should be undertaken for nutritional content of each source of food waste to ensure continuity of supply quality. Strict compliance to the swill feeding legislation and sterilisation of products is mandatory to meet with current biosecurity regulations.

3.3 Utilising By-products

Loss of quality by- and co-products occurs during the production, processing and distribution of food through the supply chain. For example, bran, germ and hulls are by-products wasted in the milling of wheat to flour and the processing of certain crops. The incorporation of these losses utilises waste of unusable products otherwise disposed. The two categories of feed products, based on the production system they are sourced from are:

- Co-products: generated from another production system as a secondary product attributed a proportion of the 'environmental burden' of the production system where they arose e.g. canola meal, meat meal and tallow.
- By-products: low or high value by-products from other production systems e.g. whey and some yeast products. Where the value is negligible and demand is low, it is reasonable to assume that no environmental burden is associated with these products.

By-products and co-products suitable for use in pig diets are summarised in Table 6.

Table 6. Examples of by-products and co-products suitable for formulating into pig diets

Dairy	Grain milling	Animal	Vegetable	Sugar production
Whey	Millrun	Animal fat (tallow)	Dried potato meal, slices, flakes	Cane molasses
Dried buttermilk	Wheat bran	Blood meal		
Dried skim milk	Wheat pollard	Meat and bone meal		
	Rice hulls	Hydrolysed animal hair		
	Rice bran			
	Rice pollard			
	Biscuit meal			
	Brewers grain			
	Dried Distillers Grain			
	Hominy meal			

Utilisation of high-quality by-products is done successfully at some piggeries in Australia. In Canada, energy and protein-rich dried distillers' grains are recovered in large volumes from the increased production of biofuels and used in cattle, pigs and poultry diets. The use of potato waste from two major potato processors are utilised in pig diets. In the Netherlands common contributors to pig diets from the waste stream are steamed potato peelings, slurry wasted from the extraction of starch from wheat and whey from the production of cheese.

It is important to note that the use of by-products in pig diets requires delivery through a liquid feeding system. Liquid feed systems have clearly demonstrated positive impacts on feed wastage, feed intakes and subsequent pig performance. Recovering by-products from the human food manufacturing industry can also allow piggery operators to save money, as by-products often represent a less expensive source of nutrients than traditional feeds.

3.4 Alternative Feed Sources

The use of alternative feed sources in pig diets can utilise waste from one system and reduce the use of grains/protein sources and associated waste along the supply chain. Insect meal has been recognised as a cost-effective and sustainable alternative to reducing protein meals in pig diets. Most insect species are a nutrient-dense source of protein and fatty acids with their amino acid composition providing high-quality protein. The black soldier fly larvae (BSFL) is the most promising candidate in place of high-protein feeds. The environmental impact associated with farming the BSFL is considered small in comparison to grains, with limited use of land and water. Farmed in manure or food waste, the BSFL recover residual nutrients and in turn the larvae are used as a source of protein in livestock diets. There is substantial evidence in the benefits of the BSFL in manure bioconversion, although issues have been raised around the increased energy. However, piggeries producing heat from CHP generators could utilise excess or waste heat to offset some of this requirement. Additionally, an opportunity arises to use waste CO_2 stripped from biogas or the exhaust from CHP/flaring to kill the reared insects or larva, providing a use for this waste stream.

Although currently in Australia all insect farmers are of small scale or in the startup phase, the sector is receiving significant interest and investment due to the potential of closing the loop on waste whilst producing protein for use in livestock feed. The prospect of insect meal being used in pig diets is still not clear, although State-wide regulations indicate growing insects on plant material does meet swill feeding legislation, further policies are required to finalise regulations (Nolet 2020). There is ongoing Government and private research investigating the development of insect farming to service the pork industry.

Alternative waste utilisation includes duckweed and algae. There is the potential for the use of duckweed as a wastewater treatment option and an alternative protein supplement in diets. Duckweed could either be dried and fed back into the piggery as a feed additive or be fed straight as a high moisture and protein supplement. Other alternatives include the production of micro and macroalgae for a similar purpose to duckweed and for the treatment of anaerobically digested pig effluent. With high production and nutritional value (e.g. carbohydrate and crude protein), micro and macro algae could be an alternative for effluent water polishing where duckweed may be unsuitable). Further, algae production could be supplied to biodiesel production operations as an additional source of revenue for piggeries. For the adoption of alternative waste utilisation, extensive foundational research and development of guidelines and legal frameworks is required.

3.5 Considerations when Introducing Feed Substitutes

Before introducing new dietary ingredients to a commercial piggery operation, the following considerations should be addressed:

1. Check state government guidelines with regard to regulations for alternative feed for pigs.
2. Is it considered swill? Meat or meat products or any food that has been in contact with meat is prohibited. Do not use food waste from households or restaurants. For more information go to farmbiosecurity.com.au
3. Check the supply for continuity considering swine digestive processes need time to adjust.
4. Are there storage and packaging requirements to consider and what is the shelf life?
5. What is the cost benefit, are there added costs associated with transportation and storage?
6. What is the moisture content e.g. brewers grains and vegetable by-products must be stored to minimise leaching.

7. Conduct a nutrient analysis and check variation in the nutrient content.
8. Consider contamination and toxins as feeding excess phosphorus must comply with nutrient management and waste plans while cottonseed and grain screenings can harbour mycotoxins.

Due to current biosecurity regulations in Australia, utilising by-products and waste for pig feed is restricted to pre-consumer products. Across all states and cities, there is an increase in post-consumer organic waste via kerbside collection. This has resulted in a highly consistent supply of post-consumer food waste. This waste stream is not permitted to be utilised in the piggery waste stream. To be used the waste must undergo an intermediate processing, such as the utilising the organic waste first as an insect feed source, then using insects to produce pig feed. Heat treatment of post-consumer waste is not currently an approved method of treatment in Australia, and this is an area of significant potential. Thermal processing of waste is commonly used internationally and proven effective in countries like Japan to utilise 35 – 43% of food waste through animal feed.

4. Energy

4.1 Methane Capture

Regardless of how efficient a piggery is at minimising feed waste and improving FCR, a proportion of the energy in feed will pass through the pig into the effluent treatment system. In traditional effluent treatment systems, this is converted through a biological process in the anaerobic effluent ponds, and energy is released to the atmosphere as methane gas. Methane has an energy density of 55.65 MJ per kilogram, and enough is generally released at most piggeries to power the whole piggery and sell excess power to the electricity grid. This is closing the energy loop at the piggery. Capture and reuse of methane for energy production a viable process at conventional piggery sites, and it is a common practice in many parts of the world, , utilising the inherent energy value contained within the piggery effluent stream. In 2018, it was estimated 13.5% of total Australian pork production had adopted biogas systems (Skerman & Tait, 2018). Methane capture systems can range from simple covered pond designs, to advanced, in-ground digester or above ground, tank based systems. The process for all systems works by capturing the biogas resource generated from the anerobic digestion of effluent which can be burnt to generate electricity and/or heat. If this methane was not captured, the gas is lost to the atmosphere, which is considered a wasted resource as well as contributing to the greenhouse gas emissions from the operation. An additional benefit from biogas capture systems is potential odour reduction. Australian Pork have developed a Code of Practice for On-farm Biogas Production and Use (Piggeries) (APL, 2015) which provides guidance for the establishment an on-farm biogas system and is important reference when considering for the safe design, construction, operation and maintenance of biogas systems.

Covered anaerobic ponds (CAPs) are designed in much the same way as uncovered anaerobic ponds, however a high quality geo-membrane cover is used to capture the methane gas that is produced. CAPs are designed with a hydraulic retention time (HRT) of 40-50 days (less than uncovered anaerobic ponds) and a variable sludge accumulation period between 6 months and several years.

Engineered digestors are custom built inground ponds or above ground tanks that typically have heating and mixing to assist in maximising the biogas generation. Conditions within the digestor are managed to maximise biogas production. The yield of biogas and the resulting methane composition produced from a CAP or digester is highly dependent on various factors such as the biogas potential of feedstock, design of anaerobic system, inoculum, nature of substrate, pH, temperature, loading rate, HRT, carbon to nitrogen ratio, volatile fatty acids content, and other trace gases, which all influence the biogas production (Dhevagi et al., 1992)(Dhevagi et al., 1992). Several options exist to utilise captured biogas, with each described below.

- **Heat Utilisation:** Methane can be used in a boiler to produce heat and hot water for the piggery. A typical boiler has an efficiency of about 90%. The heat produced can be used to offset the annual gas usage of the site leading to reductions in the energy expenditure of the piggery. Because of the large volumes of gas, heat generation may be well beyond the requirements of the piggery.
- **Electricity Generation:** The methane gas captured can be combusted in a generator to produce electricity. The power generation units which are suitable for use in the Australian piggery industry are spark-type gas engines and micro-turbines (Murphy et al., 2012). Methane can be converted to electricity on-site using these engines, which can be assumed to operate with efficiencies of 25-40%.
- **Combined Heat and Power (CHP):** CHP generation is another energy recovery option. A variety of reciprocating engines can be used, including spark ignition and compression ignition engines. Methane is burnt in a reciprocating gas engine to drive an alternator to produce electrical energy. Simultaneously the heat energy exhausted by the engine and the coolant system is recovered, usually in the form of hot water (80 – 90°C). The conversion of methane gas into electrical energy is approximately 25-40%; while an additional 45-55% can be recovered as heat energy.

- **Biomethane Production:** Biomethane is produced from biogas by removing the carbon dioxide and any other contaminants to produce a high quality renewable methane gas (equivalent to natural gas) and carbon dioxide. Options exist for piggeries with a methane capture system and excess biogas to either sell the biogas to a commercial processer to produce biomethane and bio-carbon dioxide, or to process on-site to produce biomethane. Evaluation of biomethane production for large piggery operation by Tait et. al. (2021) indicate that the commercial value of biogas may make this a viable option for large scale producers.

4.2 Co-digestion

The capital investment associated with the construction of a methane capture and reuse system is significant for a piggery operation, and one method which assists in maximising the return on investment as well as assisting in closing the loop on waste is co-digestion. Anaerobic co-digestions is the treatment of two (or more) separate waste streams through an anerobic digestor in order to increase the methane generation from a system. A comprehensive review of the opportunities associated with co-digestion in the pig industry was undertaken by CRC 4C-109: Enhanced methane production from pig manure in covered lagoons and digesters (Tait et al., 2017). The key outcomes of this report and relevant updates are provided in the below section.

There are two methods that can be used to increase methane production from anaerobic digestion including:

- Digesting pig manure simultaneously with of waste products of higher biochemical methane potential; and/or
- Increasing the total amount of waste digested, therefore increasing methane production.

A range of waste products, by-products and co-products products from agricultural, industrial and municipal sources are potentially suitable for co-digestion (Table 7). The biochemical methane potential of a material is a measure of the methane and carbon dioxide produced during anaerobic digestion and provides an indication of the likely benefit to a methane capture system. Table 7 shows the biochemical methane potential of piggery waste and several other potential co-digestion material. It should be noted that these rates are determined in laboratory conditions and significant variations may results from site specific factors. Some co-products may also increase methane production when combined with others.

Table 7. Methane potential and other relevant characteristics of potential co-digestion materials (Tait et al., 2017)

Waste type	Dry matter (%)	Volatile solids (VS,% of dry matter)	Biochemicial methane potential (L CH_4/kg VS)	Reference
Piggery shed effluent	1.7-6	64-84	150-640	(a), (c), (f)
Apple pulp, apple waste			306,317	(a), (b)
Alcohol*	40	95	400	
Banana Peels			289	(a)
Beef feedlot manure (fresh)	20-22	79-88	230-360	(e)
Brewers spent grains	20	90	330	
Fruit wastes	15-20	75	250-500	(c)
Fish Waste			390	(b)
Glucose			335	(b)

Stomach intestinal content, Cattle	12	80	400	(d)
Stomach intestinal content, Pigs	12	90	460	(d)
Concentrated whey protein (20-25%)	5	90	330	

a)(Lesteur et al., 2010); (b)(Raposo et al., 2011); (c) (Al Seadi et al., 2013); (d)(Tait et al., 2009); (e)(Gopalan et al., 2013); (f)(Gopalan et al., 2012)

Anaerobic co-digestion is only successful when the organic loading rates of solid material does not exceed the capacity of the digester. Although the use of anaerobic co-digestion can successfully reuse, reduce and recover waste, implementation requires careful consideration and consultation with professional staff. Generally, co-digestion in a CAP is generally suitable for wastes with low solids content, while a mixed liquid digester is more suitable for wastes with higher solids.

Based on costings undertaken by Tait et al (2017) the expected return financial return from co-digesting a range of products is shown in Table 8.

Table 8. Financial benefit estimate for biogas produced per tonne of co-substrate co-digested (Tait et al., 2017)

Substrate	Methane Yield (m3 per tonne dry matter)	Volatile solids Destruction (%)	Energy Value ($ per tonne dry matter)
Fat oil and grease	900	80	$200
Glycerol	460	100	$106
Paunch	250	60	$58
Feedlot Manure	200	40	$44

Basis for calculation:
1. Energy content of methane 34 MJ/m3
2. Conversion to electricity: 0.35
3. Electricity value: 3.6 MJ = 1 kW.h and 1kW.h = $0.07

4.3 Relevant Funding Opportunities

The use of methane for energy generation has the co-benefit of reducing GHG emissions associated with the loss of methane to the environment. As a result, methane capture projects can generate revenue through the carbon market. The carbon market is regulated by the Clean Energy Regulator (CER) which administers national carbon markets for:

- The Emissions Reduction Fund (ERF), which supplies Australian carbon credit units.
- The Renewable Energy Target, which creates tradable large-scale renewable energy certificates (LGCs) and small-scale technology certificates (STCs).

The ERF is a voluntary program that provides financial incentives for companies to adopt approved methodologies to reduce emissions, or by removing carbon dioxide from the atmosphere and sequestering carbon in soil or vegetation.

The Renewable Energy Target consists of two schemes: the Large-scale Renewable Energy Target (LRET) that provides incentives for large-scale renewable energy power stations and the Small-scale Renewable Energy Scheme (SRES) that creates incentives to install small-scale renewable energy systems. Demand for renewable energy certificates is set in legislation each year. However, there is increasing demand from businesses and other levels of government for LGCs to offset emissions.

The following sections detail how the ERFs and the Renewable Energy Target are applicable to pork production.

4.3.1 Emission reduction funds for piggeries

Under the ERF, the rules for estimating emission reductions are termed methodology determination (methods). These standards define how to gain carbon credits for reductions and the reporting requirements of projects. These methods are required to ensure reductions are valid and verifiable strategies, and the methods applicable to pig production are outlined in the below sections.

Animal effluent method

This method provides an opportunity for revenue generation through the crediting of ACCUs for emission reduction through the capture and destruction of GHG emissions from animal effluent systems.

An ***emissions destruction*** project is where effluent in treated in an anaerobic digester/s that generates and captures methane. The captured methane must then be destroyed via a combustion device (i.e. flare, boiler generator). The method is flexible in that allows ***ineligible*** material to be added in an emissions destruction facility, provided it is less than 10% of the total material. Ineligible material is generally other organic effluent which is non-animal effluent derived and utilised to boost methane production through co-digestion.

The net abatement amount of CO_2-e for a project under the Animal effluent method is the quantity of methane emissions destroyed or avoided because of the project, minus GHG emissions from the use of electricity and fuel used to operate the any equipment to run the project. This method may be particularly advantageous to a pork producer if they could receive (e.g. get paid a gate-fee) for waste from other industries (whey, canned fruit, bread etc.). This material could be used in rations to reduce costs and lower the carbon footprint of the operation. Material that was not used for the pigs could be co-digested, and the captured methane used to generate electricity and/or heat energy.

Biomethane method

Under the ERF scheme, the biomethane method will provide an opportunity utilising waste or agriculturally generated biomethane as a natural gas substitute. As last updated on 2 October 2021, this new method is in the draft development and technical and expert consultation phase of the ERF approval process with the CER, and is expected to be released for public consultation in early November 2021.

4.3.2 Renewable energy target

Large scale renewable energy credits (LGSs) can be acquired from the Clean Energy Regulator for eligible power generators. Within a piggery operation power generation from a CAP or anerobic digestor would, in most cases, be eligible for LGCs. LGCs are allocated on a basis of one unit per megawatt hour (MWh) of eligible electricity generated.

LGCs can be sold through the open market. The trading price of LGCs is variable and has decreased significantly over the last five years. For the 2016-2017 period the price generally remained above $70. Since this time the decrease in value has been notable, with the current spot price as of 20 October 2021 being $42.10. The variability in commercial return would need to be factored into any capital investment feasibility study for the development of a reusable power generation system at any piggery.

5. Nutrients

5.1 Manure By-products

Piggery by-products contain significant quantities of nitrogen, phosphorus, potassium, trace elements and carbon which are valuable commodities in agricultural production. Due to the intensive nature of the most piggery operations, the management of manure is a significant factor in production. Depending on the production system, nutrient rich manure by-product streams may include:

- Effluent
- Separated Solids
- Sludge
- Spent Litter

Typical nutrient and carbon generation from two common production systems for a 1,000 sow farrow to finish operations with a wheat and barley based diet are shown in Table 9. The Piggery Manure and Effluent Reuse Guideline (Tucker, 2015) details the steps involved with determining the value contained within the nutrient in effluent and solid waste. As shown in Table 9, significant commercial value is contained within the manure by-products.

Table 9. Nutrient excretion rates for 1,000 sow farrow to finish piggery (Source: Pigbal v4, 2015)

	Total Nitrogen#	**Total Phosphorus**	**Total Potassium**	**Total Organic Carbon**
Conventional	259 kg/day	90 kg/day	88 kg/day	2,190 kg/day
	94 tonnes/year	33 tonnes/year	32 tonnes/year	800 tonnes/year
- Value*	$147,000	$129,000	$46,000	
Conventional bred and deep litter grown	254 kg/day	107 kg/day	107 kg/day	3,330 kg/day
	93 tonnes/year	39 tonnes/year	39 tonnes/year	1,210 tonnes/year
- Value*	$146,000	$152,000	$57,000	

 # Assumes 30% loss of nitrogen through volatilisation

**Based on fertiliser values of $720/tonne of urea, $780/tonne of triple superphosphate and $710/tonne of muriate of potash. (October 2021 prices)*

Based on typical fertiliser application rates for broadacre farming of 100kg of nitrogen and 20kg of phosphorus, a 1,000 sow conventional operation could provide enough nitrogen for 945 ha and phosphorus for 1,650 ha of broadacre farmland each year.

5.2 Current Nutrient Usage

Typical wastewater treatment at conventional Australian piggeries involves effluent to be treated though a pond system to reduce the organic loading, nitrogen and carbon concentrations to levels that allow a reduction in odour and nutrient levels for practical irrigation application. Solid wastes (including sludge, separated solids and spent litter) are generally either stockpiled or composted and then periodically spreading to land on farm, exported from site for direct land application or used as input into a soil blending/compost process at a third party site.

Current practice in the Australian pig industry varies from farm to farm, with a high level of use of piggery manure by-products through irrigation or for soil application occurring at some sites, while others operate closed systems where effluent is lost through evaporation and nutrient lost to the atmosphere and retained in the sludge in effluent ponds. Accurate data is not currently available on the level of nutrient usage across the Australian pig industry.

On-site manure use leads to a reduction in waste, particularly if crops (grain/straw) produced on-site can be utilised back through the piggery production cycle. Manure reuse on-site can minimise waste associated with transport of fertiliser, raw materials inputs as well as minimise impacts associated (e.g. GHG emissions) with the production of inorganic fertiliser.

Although the nutrients in effluent are a valuable resource, regulatory and operational issues associated with the transport and spreading of high volume, low strength effluent can make the cost and process onerous for some piggery operators. While on-site treatment and storage of effluent and manure solids improves the operational management of application, the process does result in a loss of significant amounts of nitrogen to the atmosphere which could be considered a wasted resource. Opportunities exist for the recovery and reuse of the maximum amount of nutrients (further discussed in Section 5.4).

5.3 Mortalities Use

Management of mortalities is a part of all piggery operations, with the preferred methods for disposal as recommended by Tucker (2015) shown in Figure 5.

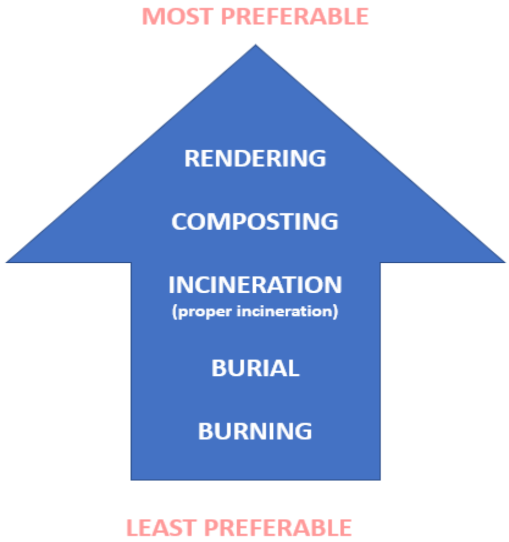

Figure 5. Mortalities management hierarchy (modified from 2015)

Based on average mortality rates of 11% for pre-weaning, 5% for post weaning, 10% for breeder and between 0.5% and 1.6% for grower pigs, the total mass of mortalities expected from a 1000 sow farrow to finish piggery is 85 tonnes. Within the 85 tonnes to total nutrient composition is inherent nutrient and organic carbon value is summarised in Table 10.

Table 10. Mortalities composition (Source: Pigbal v4, 2015)

	Total Nitrogen#	Total Phosphorus	Total Potassium	Total Organic Carbon
Mortalities	2.18 tonnes/year	0.4 tonnes/year	0.2 tonnes/year	13.3 tonnes/year

Both composting and rendering of mortalities assist in closing the loop on waste, as a significant portion of the nutrient and material contained within the pigs is recovered and can then be reused. Incineration, burial and burning are not preferred as they result in a loss of almost all resources contained within the bodies to the environment.

An alternation method of resource recovery for mortalities is to utilise dead pigs through co-digestion. Anaerobic co-digestion of pig carcasses and effluent can increase biogas and methane yields by 6% (Tápparo et al., 2020). For carcass co-digestion to be effective, the system must be designed and constructed to specifically to manage mortalities, and bodies processed as required by the system prior to digestion.

5.4 Nutrient Recovery Technologies

While some piggery by-products are utilised through agriculture, a significant portion of the nutrients are wasted through loss to the atmosphere (nitrogen) and/or retained indefinitely in closed system wastewater treatment systems. Opportunities exist to improve recovery of the resources contained in manure by-products through the production of high nutrient value added products. These would provide an alternative to commercial fertiliser products. These options are likely to increase in financial viability as the price of synthetic fertiliser increases.

Synthetic fertiliser production is an energy intensive process that uses a number of finite resources in the production process, including phosphorus. Phosphorus is a non-renewable resource that is widespread in soil and in living organisms but is relatively scarce in concentrated forms, with only a few countries having commercial reserves. Prediction on when phosphorus resources will become scarce vary significantly, but it is logical to expect that as phosphorus prices increase the opportunity for nutrient recovery from resources such as pig manure will become increasingly viable (Murphy et al., 2016).

Opportunities exist for the pig industry in this context because unlike most other industries, piggery sites often accumulate phosphorus over multiple years of production, rather than exporting most or all of it off-site annually, such as in intensive beef and poultry industries. This may give piggeries the unique advantage of marketing a high concentration phosphorus and potassium manure product such as pond sludge, but the supply would be restricted due to the long production interval between pond de-sludging.

The aim of traditional piggery effluent treatment systems is to reduce the organic loading and nitrogen concentrations to levels suitable for irrigation and to manage odour. This is achieved through the loss of methane, ammonia, and carbon dioxide to the atmosphere, resulting in a reduced concentration of carbon and nitrogen in the effluent. Converse to traditional systems, nutrient recovery aims to minimise losses and concentrate nutrients to form a product with suitable nutrient value to be a viable alternative to synthetic fertiliser.

Technologies to recover nitrogen, phosphorus, and potassium have undergone rapid development in recent years, primarily due to increased fertiliser prices and the strict discharge limits on nutrients. Within effluent, the macro plant nutrients of nitrogen, phosphorus and potassium are in the highest demand, resulting in potential opportunities for nutrient recovery technologies to be employed.

Nutrient recovery technologies can be divided into three categories:

- Nutrient accumulation - includes biological mechanisms such as enhanced biological phosphorus removal (EBPR) and physiochemical mechanisms such as adsorption/ion exchange.
- Nutrient release - occurs through anaerobic digestion in anaerobic pond or engineered digesters
- Nutrient extraction - liquid-gas stripping, crystallization and chemical precipitation.

The following sections provide an overview of current nutrient recovery technologies suitable for the pig industry.

5.4.1 Enhanced Biological Phosphorus Removal (EBPR)

The EBPR treatment process is an activated sludge process tailored for phosphorus removal that is suitable to be implemented either before or after anaerobic digestion Lin et al. (2015). The process involves the environment constantly alternating between anaerobic and aerobic, to enable phosphate accumulating organisms (PAOs) to store large quantities of phosphorus. The main product from this process is a phosphate-rich sludge (5-7% phosphorus), which can be separated from the effluent stream by settling. After settling, the nutrients in the sludge can be released and recovered using extraction methods such as chemical coagulation and crystallisation. For piggery effluent, phosphate recovery efficiency ranges between 95% (Bortone et al., 1992) and 97.8% (Obaja et al., 2005), while nitrogen recovery efficiency is 83% (Bortone et al., 1992) to 99.8% (Obaja et al., 2005). Operating conditions are carried out at a pH of 6.5 to 8.0, with a hydraulic retention time of 30 minutes.

5.4.2 Chemical coagulation/flocculation

Chemical accumulation of nutrients involves coagulation and flocculation, where nutrients are precipitated as solids and separated from the effluent using sedimentation. The most common coagulants are aluminium or iron-based coagulants, e.g. aluminium chloride and ferric chloride. Chemical accumulation is useful for wastewater that has large proportions of the nutrients in a dissolved form.

The nitrogen and phosphorus recovery efficiency is greater than 90% for this technology. This process is also effective for removing pathogens, viruses, arsenic, fluoride and organic matter. Operating conditions are carried out at a pH of 6.0 to 11.0, temperature of 25-40°C, with a hydraulic retention time of less than one hour. The level of pre-treatment required is low. The product from this process is sludge at 1-3% P (Mehta et al., 2015).

5.4.3 Chemical precipitation/crystallisation

Struvite is a crystal of magnesium ammonium phosphate. Struvite precipitation is currently the most commercially adopted technology for phosphorus recovery from wastewater; for use as a slow-release fertiliser. Struvite is a durable white crystalline granule, with good nutrient (nitrogen and phosphorus) density and superior storage, handling, transport and application characteristics, when compared with compost or biosolids.

Struvite formation requires three soluble ions in the solution (magnesium, ammonium and phosphate) to react, forming precipitates with a low solubility. Magnesium salts such as magnesium chloride are used to cause a phase change process in the effluent, which converts dissolved components into a particulate compound, which can easily be separated from the liquid effluent. Struvite crystallisation recovers both nitrogen and phosphorus from nutrient rich streams. Reactors have been run in both batch (Adnan et al., 2003) and continuous mode (Rahman et al., 2011) for piggery wastewater and achieved similar levels of nutrient recovery. Anaerobic digestion significantly increases the amount of available magnesium ions in the effluent (Moody et al., 2009), increasing the suitability of the treatment post anerobic digestion. This reduces costs associated with purchasing magnesium salt for the process. However, a large proportion of the total phosphorus in effluent is tied up in a fine suspended calcium-phosphate solid, which is unavailable for struvite production. Therefore, it can be beneficial to use technologies such as EBPR to produce a phosphate rich sludge, prior to struvite production.

Operating conditions are carried out at a pH of 8.0 to 9.0, with a hydraulic retention time less than one hour. Solids retention time needs to be relatively long at greater than 10 days to allow for crystal formation. Typically, struvite contains 12% P and 5% N with minimal heavy metal or biological contamination (Mehta et al., 2015). Figure 6 shows struvite crystals formed from pond wastewater.

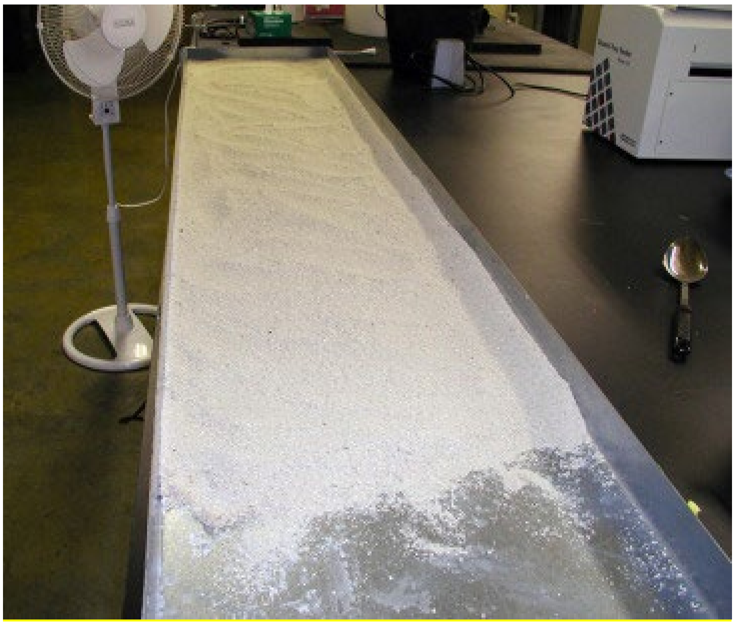

Figure 6. Struvite crystal produced from pond wastewater (Westerman et al., 2009)

5.4.4 Liquid-gas stripping

Air stripping in combination with absorption, can be used to remove and recover ammonia from piggery effluent. Gas–liquid ammonia stripping is a physiochemical process, which involves the mass transfer of ammonia from the liquid phase to the gas phase. Dissolved ammonia is contacted with air (extraction gas) in a gas-stripping tower. This process transfers the ammonia from the effluent stream into the air. The ammonia can then be absorbed from the air into a strong acid solution e.g. sulphuric acid, generating an ammonium-salt in solution, which can be crystallised and sold as a fertiliser (Figure 7).

Pre-treatment of the effluent feed generally involves pH and temperature adjustments. However, Bonmati and Flotats (2003) found that for digested piggery effluent, ammonia removal efficiencies above 96% can be achieved without pH adjustment, if temperature is maintained between 60 and 70°C.

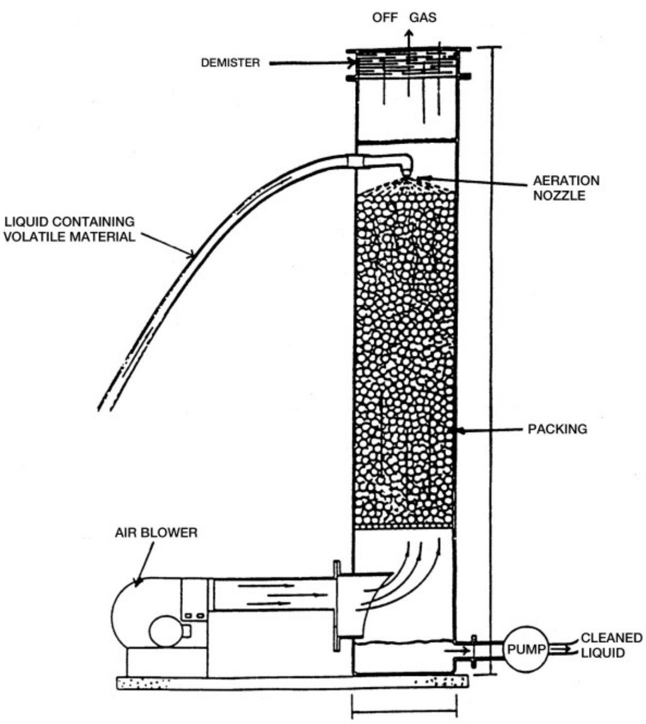

Figure 7. Ammonia stripper (Huang and Shang 2006)

5.4.5 Adsorption/Ion-exchange

Adsorption/ion exchange works by exchanging ions from the effluent, to the charged surfaces of sorbent materials. The sorbent attracts nutrients, such as nitrogen, phosphorus and potassium from the effluent, by chemical and physical processes, which cause them to adhere to its surface. Adsorption/ion-exchange is a hybrid nutrient accumulation/recovery technology, as the spent sorbent media is nutrient rich and can be used directly as a fertiliser in agriculture.

The total solids concentrations in the input stream should be less than 2,000 mg/L for treatment using this technology (Mehta et al., 2015). Tucker (2015) reports total solids (TS) concentrations of anaerobically treated piggery effluent, ranging from 1,100 to 44,300 mg/L. It should be noted that a typical value could not be provided due to the range of design, management, diets, water use and climate encountered in Australian piggeries. Therefore, it is recommended that a solid-liquid separation step is used to reduce the solids concentration of the effluent prior to this accumulation/recovery process.

For concentrated waste streams such as piggery effluent, typically red mud, metal oxide/hydroxide, and zirconium sorbents are used for phosphorus recovery, while modified zeolite and clinoptilolite are used for nitrogen and potassium recovery. Operating conditions are carried out at a pH less than 8.0, with a hydraulic retention time less than one hour. Solid-liquid separation is a required pre-treatment stage prior to adsorption/ion-exchange.

5.4.6 Settling systems

A large proportion of the solids found in effluent will settle out if left to settle in a pond, either with or without provision of additives to the effluent stream. This is a low-cost means of reducing the total solids and nutrient content of the liquid component of the wastewater prior to irrigation. Phosphorus will generally remain in the sludge until removed through periodic desludging, while a portion of the nitrogen will remain dissolved in the effluent and a portion lost to the atmosphere. Nutrient removal rates from the liquid effluent in settling systems are as high as 95% for phosphorus and 23% for nitrogen.

5.4.7 *Summary of nutrient recovery technologies*

The advantages and disadvantages of a range of nutrient recovery methods that are suitable for piggery effluent are summarised in Table 11, with the technology associated with each method briefly detailed in the following sections.

Table 11. Advantages and disadvantages of nutrient removal technologies

Nutrient Removal Technology	Advantages	Disadvantages
Enhanced Biological Phosphorus Removal	• Can be cost effective for agricultural waste streams (Mehta et al. 2015) • Phosphorus recovery 95-98% and nitrogen recovery up to 83-99% (Obaja et al., 2005). • High reduction in oxygen demand also achieved during the process	• End-product is a wet sludge (5-7% P) which has operationally can be difficult to use as fertiliser replacement.
Chemical coagulation/flocculation	• Nitrogen and phosphorus recovery greater than 90% • Pathogens, viruses, arsenic, fluoride and organic matter also removed. • Low capital costs • Ease of operation • Flexibility to varying conditions	• High operational costs • Increased salinity in the treated effluent (due to Cl^-, SO_4^{2-}), an • Increase in the volume of sludge produced, • Reduction in the bioavailability of the chemically bound P in the sludge, and • Inhibitory effects on anaerobic digestion following coagulation
Chemical Precipitation/Crystallisation	• Currently the most commercially adopted method of phosphorus recovery • Produces a high stability nutrient dense product • Suitable for nutrient recovery post anaerobic digestion	• Operating costs can be high due to magnesium salt inputs
Liquid-Gas Stripping	• 96% ammonia recovery • Relatively low management cost requirements	• High capital and annual input chemical costs. • No removal of phosphorus
Adsorption/Ion-Exchange	• Ability to generate high P accumulation and low P concentrations in the treated effluent. • No additional sludge apart from the spent adsorptive media is created, and the • pH is not affected by the process.	• Relatively high cost of the adsorptive media • High volume required for complete adsorption (Mehta et al., 2015)
Settling systems	• Low capital and operating costs. • Proven technology • Periodic removal of nutrient sludge does not allow for ongoing supply.	• Nitrogen remains largely remains dissolved in solution. • End-product is a wet sludge which has operationally can be difficult to remove from ponds and use as fertiliser replacement. • Periodic removal of nutrient sludge does not allow for ongoing supply. • Large area footprint required for long on-site retention time of liquid.

6. Water

6.1 Minimising Potable Water Use

Water is both the most important nutrient for pigs and the most valuable natural resource (after land) in Australia. Clean water at piggeries is required not only for drinking but also shed cleaning and summer cooling. A comprehensive assessment of the full supply chain freshwater consumption was undertaken by Watson et al. (2018). Direct water consumption (freshwater used utilised within the piggery operations) ranged from 4.1 to 56.2 L/kg LW. The significant differences in water usage were influenced by:

- Production type
- Climate
- Shed design (sheds with evaporative cooling used much higher quantities of water and deep litter sheds used less water than conventional sheds)
- Drinker system maintenance and wastage rates
- Proportion of freshwater used in recycling in conventional sheds

Total direct freshwater consumption has reduced from over 90L/kg LW to less than 20L/kg LW between 1980 to 2020 for conventional piggery operations, see Figure 8 (Watson et al., 2018). Historic decline in piggery water consumption is linked to the change in percentage of flushing water supplied by recycled effluent (5% in 1980 to 80% in 2020) (Watson et al., 2018) and continual improvements in on-farm water use efficiency.

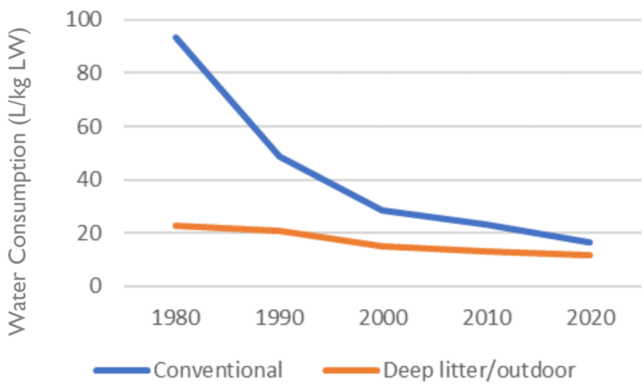

Figure 8. Trends in direct freshwater consumption for Australian pork production (Watson et al., 2018)

It is common for effluent treated through a pond system to be used for flushing through a conventional piggery. This is an effective way to minimise the potable water usage and regulatory approval is not required for this reuse. It should be noted that ongoing, very high recycling rates can negatively impact on the effectiveness of wastewater treatment ponds due to the escalation of certain contaminants (ie. Ammonia, salts and volatile fatty acids) which can inhibit biological wastewater treatment processes.

Although there is some scope to further reduce direct freshwater usage through improvements in efficiency, maintenance and FCR, the most promising opportunities come from water treatment.

6.2 Water Recycling

Advanced water treatment plants (AWTPs) are becoming more common in Australian meat supply chains. However, there is low uptake at a farm-scale compared with processing plants. Technologies available within AWTP processes include:

- Membrane Filtration – including microfiltration, ultrafiltration, nanofiltration and reverse osmosis
- Disinfection treatments- including ultraviolet (UV) light and oxidative disinfection

At present, there are knowledge gaps around the commercial viability at the farm scale of these technologies. Different technologies are available for the treatment and recycling of effluent, with the method adopted highly dependent on the intended final use of the treated wastewater. Different water quality standards, regulatory approvals and monitoring requirements are applicable for different uses. Potential use options for recycled water include:

- Hose down and cleaning water
- High volume irrigation water
- Cooling water
- Stock drinking water.

Piggery wastewater typically contains high levels of nutrients, salts, heavy metals and pathogens which limits use without undergoing treatment. Contaminant concentrations vary significantly between operations depending on a range of factors including housing design, treatment system (ie. solids separation) and effluent reuse rates through flushing. Table 12 provides a summary of the concentrations of a range of parameters in piggery effluent in Australia.

Table 12. Typical piggery effluent quality (Source: Tucker, 2015)

Parameter	Units	Range for Pond Effuent*
Total Solids	mg/L	1,100–49,500
Volatile Solids	mg/L	480–5690
pH	mg/L	7.0–8.0
Total Nitrogen (or TKN)	mg/L	158–955
Ammonium- Nitrogen	mg/L	25–243
Total Phosphorus	mg/L	19.3–850
Ortho Phosphorus	mg/L	2.4–77.9
Potassium	mg/L	128–784
Sulphur	mg/L	22
Sulphate	mg/L	13.3–87.2
Copper	mg/L	0.00–2.43
Iron	mg/L	0.09–1.61
Manganese	mg/L	0.00–0.05
Zinc	mg/L	0.16–1.27
Calcium	mg/L	7.3–41.2
Magneisum	mg/L	6.6–72.3
Sodium	mg/L	41–1132
Cholride	mg/L	3.6–34.4
Electrical Conductivity	dS/m	2.5–11.7

** Results a combination of raw and pond effluent for piggeries in NSW, Queensland and WA*

The sections below outline a number of available treatment methodologies which are applicable to the treatment of piggery effluent.

6.2.1 Membrane filtration

Membrane filtration is a physical separation method with the ability to separate contaminants in a waste stream based on the different sizes and characteristics of the molecules. Membrane filtration technologies such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) are suitable for heavy metal removal due to their high efficiency, ease of operation and limited space requirements. Contaminants in particulate form greater than 0.1 µm in size (suitable for micro or ultrafiltration) or in soluble form (suitable for nanofiltration or reverse osmosis), can be selectively removed using these membrane technologies. Toxic heavy metals of particular concern in treatment of wastewaters include lead, zinc, copper, mercury, nickel, cadmium, and chromium, as these limit the reuse opportunities within a piggery (Fu & Wang, 2011).

UF is the considered the most suitable technology for heavy metal removal, and has a pore size range of 0.001-0.05µm (Masse et al., 2007). A review of heavy metal removal efficiencies from UF suggested a high level of removal can be achieved as shown in Table 13 (Fu & Wang, 2011). In addition to heavy metals, UF can remove bacteria, protozoa, endotoxins, proteins and carbohydrates very efficiently.

Table 13. Summary of UF heavy metal removal efficiencies

Heavy Metal	Removal efficiency (%)	Reference
Chromium	82-100	Korus and Loska (2009)
Arsenic	19	Ferella et al. (2007)
Lead	>99	Ferella et al. (Ferella et al., 2007)
Cadmium	92-99	Huang et al. (2010), Landaburu-Aguirre et al. (2010)
Copper	94-99.5	Molinari et al. (2008), Camarillo et al. (2012)
Nickel	98.6-100	Danis and Aydiner (2009), Molinari et al. (Molinari et al., 2008)
Zinc	92-99	Huang et al. (Huang et al., 2010), Landaburu-Aguirre et al. (Landaburu-Aguirre et al., 2010)

Reverse osmosis technology can also be successfully used for the reduction of heavy metal and pathogen concentrations of effluent. In addition, RO has a very high effectiveness in removing viruses. One of the additional advantages of RO is that it is an established desalination technology. The process is used to reduce the sodium content of wastewater. In brackish waters, salt rejection ranges between 95 and 99% and water recovery can be as high as 75-90% (Greenlee et al., 2009). As well as desalination, RO can remove dissolved constituents from wastewater that is not possible with UF.

Pre-treatment before RO is an important step because of the sensitivity of RO membranes to suspended solids and organics in natural waters. These impurities can lead to fouling of the membranes, which can significantly compromise the membranes' performance and increase operating costs. The frequency of membrane cleaning and replacement will be an important factor in calculating the operating cost of the system. Another drawback of RO systems is the generation of a brine waste stream, which is concentrated in salts, and produced as part of the process. This product can have a negative environmental impact and needs to be disposed of correctly to ensure it does not cause damage

6.2.2 Disinfection treatments

Piggery effluent contains a range of pathogens, including bacteria, viruses, and protozoa. Disinfection treatments such as ultraviolet (UV) light and oxidative disinfection are used to remove pathogens from water, following extensive pre-treatment. These are termed disinfection processes and inactivate the pathogens.

Oxidative disinfection reacts with the organic structure of the pathogen. Typical oxidants such as chlorine gas or hypochlorite salts are used (termed chlorination), however ozone can be used in a process called ozonation. Chlorination is very effective against enteric bacteria, such as E.Coli, however is not as effective for other bacterial species. This means that if E.Coli is used as an indicator of disinfection efficiency, the sensitivities of different pathogens needs to be taken into account. Ozonation is typically more effective against bacteria and viruses than chlorination.

UV treatments disrupt the pathogen's genetic material and restricts replication. It is a physical process, which involves passing a film of treated effluent within close proximity of a UV source. Some of the major advantages of UV disinfection are that it does not add to the toxicity of the wastewater, it is rapid and it is a cost effective process. In addition, it is highly effective for protozoa, bacteria and most viruses.

Treatment efficiency of these technologies is widely measured using the log removal value (LRV):

$$LRV = log_{10}(C_{in}/C_{out})$$

Where C_{in} is influent pathogen concentration and C_{out} is effluent pathogen concentration. For a given pathogen, LRV 2 means 99% removal, while LRV 4 means 99.99% removal.

To determine the treatment efficiency of the different technologies, the concept of disinfectant concentration (C) and contact time (T) is integral. The product of these (CT) can be used to determine the LRV of different pathogens (Stanfield et al., 2003) with the results summarised in Table 14.

Table 14. Summary of disinfection treatment pathogen removal efficiencies

	Units	**Inactivation: 2-log**
Virus		CT Value
Chlorination	mg*min/l	3
Ozonation	mg*min/l	0.5
UV	mW*s/cm^2	21
Bacteria		CT Value
Chlorination	mg*min/l	0.02-200
Ozonation	mg*min/l	0.5
UV[A]	mW*s/cm^2	20 (E. Coli) 30 (Salmonella)
Protozoa		CT Value
Chlorination	mg*min/l	15
Ozonation	mg*min/l	0.7-1.3
UV[B]	mW*s/cm^2	5.8 (Cryptosporidium) 5.2 (Giardia)

[A] *This CT value is for a 4-log reduction*
[B] *2012 – health Canada, Canadian drinking water guidelines*

The disinfection of effluent using chlorine and ozone can result in the formation of by-products that negatively affect the environment. Therefore, it may be advantageous to use processes which do not increase effluent discharge toxicity, such as UV. However, it is important to ensure that the wastewater is treated with UV immediately prior to use in the piggery, as UV does not have any residual disinfection capabilities.

6.3 Regulatory Requirements

Depending on the end use of the recycled water, and the relevant State government regulations a water recycling scheme may require approval from the state government agency. Generally, approval is required if there is an opportunity for human contact (ie. hose down water) to ensure protection of the environment and public health .

7. Solid Waste

Solid waste generation is an important and easily measurable waste stream, and is often an important key metric in supply chain waste assessments. Solid waste can be categorised as:

- Recyclable – recycling is the process of converting waste into a reusable material.
- Compostable – composting natural materials into a nutrient-rich substrate.
- Biodegradable – any material that can be decomposed by bacteria and micro-organisms and can return to nature.

In March 2021 the Australian Government took action to work with industry to phase out problematic and single-use plastics and released the National Plastics Plan. Products for industry-led phase outs which impacts the pig industry include expanded polystyrene recycling (EPS) loose fill packaging used for product protection in freight e.g. peanut shaped loose foam packaging and EPS moulded packaging used for product protection of electronics e.g. ultrasound machine. This initial phase out of certain plastics does not impact the pork industry greatly but should initiate a move in the industry to start focusing on reducing waste.

Most waste can be recycled if the correct method of disposal is followed (see Table 15).). Typically agricultural waste has a low recycling rate. As shown in Table 6, almost all of the waste streams from a piggery have the capacity for recycling. Some operational changes, such as bundling of like wastes together, allows for a greater range of products to be recycled.

Most construction waste can be recycled by specialised construction disposal companies which accept all waste and sell the recycled product. For example, concrete can be recycled by being crushed and refined through a filtration process and sold as crushed concrete or concrete aggregate. Correct disposal of waste through specialised waste facilities allows the opportunity to further close the loop on waste as various recycling facilities capture the methane generated from the breakdown of organic waste to create Processed Engineered Fuel, a renewable energy substitute for coal and gas.

Table 15. Correct method of waste disposal for solid waste

Category	Recyclable	Method of disposal
Metal (e.g. feeders, gates, crates)	✓	Scrap metal company offers collection or use of a collection bin free of charge. The dealer pays for the scrap metal (copper, aluminium, stainless steel, lead, steel, brass) by weight
Concrete (e.g. slatted flooring)	✓	Can be disposed of to a concrete recycling facility, free of charge
Expanded polystyrene (e.g. eskies)	✓	Dropoff at an EPS collection facility
Rigid plastic (e.g. penguin feeders, slatted flooring, feeders)	✓	Plastics recyclers offer pickup, drop-off or a collection bin
Rubber (e.g. matting)	✓	Rubber tyre recycling and disposal service offer pickup
PVC (e.g. polypipe)	✓	Needs to be free from contamination and in sufficient, ongoing quantities to warrant feeding offcuts into production processes. Alternatively, use a construction waste company for disposal.
Paper and cardboard	✓	Recycle in curb side or industrial specific recycling bin
Glass (e.g. medicine & vaccination bottles, coffee jars/tins)	✓	Remove the plastic or metal lids and dispose of in general waste. Bottles can then be disposed of in the recycling bin. No need to remove paper labels.

Chemical drums	☑	Cleaned containers recycled through the Drummuster program
Plastic AI straws	☑	AI straws may be recycled if they are collected and tied into bundles or packaged into containers of the same type of plastic. Once repackaged, the straws can be processed through the normal plastics recycling.
Feed bags (woven polypropylene)	☑	Feed bags may either be returned to the producer for reuse, or recycled through the REDcycle system. The REDcycle system does require bags to be cut into A3 sized pieces which will require additional processing by producer.
Cling film pallet wrapping	☑	Pallet wrap can be recycled if bundled. Once bundled then the wrap can be recycled through the REDcycle system.
Baling twine	☑	Baling twine can be recycled if bundled together into clean bundles. Once bundled, the straws can be processed through the normal plastics recycling.
Sharps bin	☒	*Place all needles and syringes in a sharps disposal container. Syringes are not recyclable. Collection company will dispose of in a thermal treatment facility.*

In summary, the following can be disposed in roadside or industrial recycling bins:

- Paper and cardboard
- Medicine and vaccination bottles (with lids removed)

While scrap metal companies pay for collection of scrap metal such as:

- Farrowing crates
- Gates and panels
- Silos
- Feeders e.g. *Ad libitum* sow feeder
- Nuts and bolts
- Steel off-cuts
- Old machinery and milling equipment
- Wire

Long-term options to reduce wastes include:

- Going paperless – utilising electronic data recording
- Removing the single-use of eskies - businesses are using thick cardboard as an alternative which is strong enough to protect the product and costs the same to use. For thermal insulation, leak proof hard plastic tubs can be used and returned at each collection time to be reused e.g. veterinary industry.
- Locally sourced moulded fibre tray, paper tray with fresh seal film in place of plastic meat trays.

8. Partnerships and Funding

Considering the proliferation of policies and targets in waste management, significant resources have been allocated to assist industry in achieving the waste reduction goals. The following sections outlines a number funding sources that are available to the pig industry to assist with the innovation and implementation of on-ground waste reduction strategies.

It must be recognised that the waste sector is becoming competitive, and the use of food waste as pig feed is only one competing option: – others include compost, anaerobic digestion for energy recovery and feedstock for insect production. These pathways are lower on the waste hierarchy than reuse for animal feed, and therefore from a policy perspective, animal feed is preferred due to greater environmental and financial outcomes. However, if the pig industry is not able to offer commercial and scalable solutions, other alternatives will dominate the food waste sector and develop long-term agreements for supply that effectively locks the pig industry out of the opportunity.

8.1 Government Funding

Australian Renewable Energy Agency (ARENA)

ARENA is a federal government agency that operates a number of programs to support projects that advance renewable energy technology along the innovation chain. ARENA projects are generally large in scale and APL may be best placed to develop an industry wide project scope to maximise renewable energy from the pig industry which would assist in meeting both the GHG and waste minimisation objected of the industry. Further information can be found at https://arena.gov.au/funding/

Queensland

Funding opportunities are listed on the State Development, Infrastructure, Local Government and Planning website. Funds were available for Biofutures projects. The Queensland Biofutures 10 Year Roadmap and Action Plan (DSDMIP, 2016) considered animal feed from waste, but the focus was on biofuels, bioplastics and biochemicals.

Victoria

Sustainability Victoria regularly offer grants, funding or investment incentives for recycling and reducing waste (Sustainability Victoria, 2021). For example, Dairy Australia in collaboration with Fight Food Waste Australia Limited, Australian Dairy Products Federation and Dairy Manufacturers Sustainability Council are recipients of a Business Support Fund to devise a food waste action plan aimed to quantify volumes of waste and develop solutions to reduce waste in processing and households.

Tasmania

The Hobart waste management strategy (City of Hobart, 2016) aims to achieve zero waste to landfill by 2030. This strategy includes the introduction of a kerbside food waste bin, pending appropriate receival infrastructure and facilities are identified. An action to implement the strategy includes investigating sites and technologies for food organics diversion.

New South Wales

NSW has invested in waste reduction programs in recent years. The Bin Trim program provided free help and support to NSW businesses to maximise recycling of solid wastes and minimise waste to landfill. The program includes funding opportunities.

Western Australia

The diversion of food waste from landfill to animal feed could assist with each of these targets. Kerbside recovery of food and garden waste streams is a priority for 2025 and will be assisted by local governments' financial contributions. Consistent household collection systems and improved messaging will foster clean and consistent organic waste streams, though these are not available for use as a feed for pigs. This could be used as an insect substrate or energy feedstock. Directing food waste streams to animal feed was not considered in the 2030 strategy document or the position Statement on Food Organics Garden Organics (FOGO) Collection Systems

The WA Waste Authority website lists various programs aligned with the 2030 plan, some of which include funding opportunities.

South Australia

Green Industries SA offers funding for businesses to assess materials and e-source efficiency, waste management and/or options to support a more sustainable and circular economy. Examples include funding for plastic recycling bins and signage as well as funding for food salvaging and refrigeration.

8.2 Cooperative Research Centres (CRCs)

The Fight Food Waste Cooperative Research Centre has funding until 2022 for small to medium-sized enterprises to focus on (1) testing new and novel food processing, packaging and agricultural technologies, (2) identifying valuable products and transform into new commercial opportunities, and (3) identify technology opportunities and processes to enhance food and agricultural waste reduction. The CRC is representative of widespread interest in waste management and the funding available to conduct research, development, and extension in this area. A collaboration with the Department of Primary Industries and Regions (PIRSA), South Australian Research and Development Institute (SARDI) and University of Adelaide supported by the Fight Food Waste CRC and Australasian Pork Research Institute Ltd (APRIL) aims to (1) identify food safety and biosecurity risks, (2) identify waste streams with the least variability and, (3) determine the economic feasibility of using food waste for pig feed. The timeline for the current food waste to pig feed project is 2021 – 2023.

Other CRCs of potential relevance include the Future Food Systems CRC, which began in 2019. It is focused on agri-food industry development, resilience, and sustainability. Its broader aims include synergies between the agri-food sector and other sectors such as renewable energy (and health and tourism), which presents an overlap with the strengths of the pork industry. The Food Agility CRC is focused on business challenges related to data and digital technology. It may have application-specific relevant to the pork industry.

8.3 Retailers

Major retailers in the food sector have defined strategies in waste management. Because of their scale and the fact that they deal with pre-consumer waste, the supermarkets are a key, relevant stakeholder.

Woolworths

1. Woolworths Stock Feed for Farmers Program
    - The Woolworths website explains they donate food (surplus fruit and veg, produce off-cuts, and surplus bakery items) to farmers (including commercial farmers) for animal feed or composting. They partner with 600 farmers and are seeking to expand this program. Donating food to farmers is prioritised behind donating feed to people in need.

- The default unit of food waste is a 240 L bin, so special arrangements may be required to obtain commercial quantities of food waste. The website includes a link to an application form that is submitted to the State Administration Manager, and respondents are encouraged to speak to a store manager for access to surplus food regularly.
- Woolworths partnered with the Fight Food Waste Cooperative Research Centre to develop a food waste reduction roadmap which includes diverting waste to local farmers for animal feed. The timeline for the current Woolworths roadmap for food waste reduction is 2019 – 2023.

<u>Coles</u>

1. The Coles Group prioritises the distribution of surplus food to people in need. Donating to farmers (amongst other recipients) is secondary.

   The policies of supermarket chains like Coles and Woolworths are driven by their consumers – increasing public awareness of food waste is likely to increase supermarket engagement in food waste flows.

9. Closed Loop Farm

Technology currently exists to develop a wholistic and large scale demonstration site to show how food waste, pig systems and energy recover can function effectively. This site could be established with the ambition of demonstrating positive energy production (export of energy), low-cost pork production, with feed totally supplied via by-products.

The full cascading system of food waste recovery could be demonstrated, as per the hierarchy shown in Figure 3.

This site would:

1. Conduct research on maximising value from waste food from manufacturers, retailers and municipalities via:
    a. Developing new processes for handling of difficult waste streams (mixed) and how to separate these to maximise value as feed.
    b. Developing heat treatment for products that currently can't be fed legally, and developing the regulatory processes to legally feed these products.
    c. Develop ideal feeding strategies and diet formulation.

2. Demonstrate alternative options for residual waste food – insect production for animal feed.
    a. This field is expanding, and the site could act as a demonstration and proof-of-concept testing ground for new options as they become available. Integrating this into a system which already maximises waste food and manure would be more insightful that operating in isolation.

3. Demonstrate energy recovery technology.
    a. Optimising biogas yield and quality
    b. Value recovery from CO_2
    c. Biomethane generation
    d. Energy recovery from manure and mixed biomass (i.e. energy generation with all biomass not suitable for feeding to pigs)
    e. Heat recovery and utilisation (for example, rendering)

4. Demonstrate nutrient recovery technology.
    a. Bolt-on technologies for P removal (i.e. based on struvite)
    b. Bolt-on technologies for N removal (i.e. ammonia stripping).
    c. System optimisation and cost reduction of nutrient removal.

With these core aspects in place, a system to evaluate environmental and economic potential for new technologies could be established to provide guidance for research and adoption. This would be a strategic investment for the industry. Provided a suitable, existing piggery was available, development of this type of facility may require $25M funding. It would suit a university or possibly a large scale private enterprise.

10. References

ABARES. (2019). *Australian vegetable-growing farms: an economic survey.*

Adnan, A., Koch, F., & Mavinic, D. (2003). Pilot-scale study of phosphorus recovery through struvite crystallisation-II: applying in-reactor supersaturation ratio as a process control parameter. *Journal of Environmental Engineering Science*, 2, 473–483.

Al Seadi, T., Drosg, B., Fuchs, W., Rutz, D., Janssen, R. (2013). *Biogas digestate quality and utilization. in: The biogas handbook : science, production and applications* (O. A. Wellinger, J. Murphy, D. Baxter (ed.)). Woodhead Publishing.

APL. (2015). *Code of practice for on-farm biogas production and use at piggeries. APL Project 2011/1013.423.*

ARCADIS. (2019). *National Food Waste Baseline* (Issue March). https://www.environment.gov.au/system/files/pages/25e36a8c-3a9c-487c-a9cb-66ec15ba61d0/files/national-food-waste-baseline-final-assessment.pdf

Australian Government. (2019). *National Waste Policy Action Plan 2019*. Australian Government. www.environment.gov.au/protection/waste-resource-recovery/publications/national-waste-policy-action-plan

Bonmatí, A., & Flotats, X. (2003). Air stripping of ammonia from pig slurry: characterisation and feasibility as a pre-or post-treatment to mesophilic anaerobic digestion. *Waste Management*, *23*(3), 261–272.

Bortone, G., Gemelli, S., Rambaldi, A., & Tilche, A. (1992). Nitrification, denitrification and biological phosphate removal in sequencing batch reactors treating piggery wastewater. *Water Science and Technology*, *26*(5–6), 977–985.

Camarillo, R., Pérez, Á., Cañizares, P., & de Lucas, A. (2012). Removal of heavy metal ions by polymer enhanced ultrafiltration: batch process modeling and thermodynamics of complexation reactions. *Desalination*, *286*, 193–199.

Carr, J. (2008). *Management Practices to Reduce Expensive Feed Wastage.* . The Pig Site (Online).

City of Hobart. (2016). *A Strategy to Achieve Zero Waste to Landfill by 2030*. City of Hobart.

Commonwealth of Australia. (2017). *National Food Waste Strategy: Halving Australia's food waste by 2030*. Commonwealth of Australia, Department of the Environment and Energy.

Danis, U., & Aydiner, C. (2009). Investigation of process performance and fouling mechanisms in micellar-enhanced ultrafiltration of nickel-contaminated waters. *Journal of Hazardous Materials*, *162*(2–3), 577–587.

Dhevagi, P., Ramasamy, K., & Oblisami, G. (1992). In Biological Nitrogen Fixation and Biogas Technology. *Tamil Nadu Agricultural Unveristy, Coimbatore*, 149–153.

DSDMIP. (2016). *Queensland Biofutures 10-Year Roadmap and Action Plan*. Department of State Development, Manufacturing, Infrastructure and Planning (DSDMIP). http://www.statedevelopment.qld.gov.au/resources/plan/biofutures/biofutures-10yr-roadmap-actionplan.pdf

FAO. (2021). *Livestock Primary*. Food and Agriculture Organisation (FAO) of the United Nations. http://www.fao.org/faostat/en/#data/QL/visualize

Ferella, F., Prisciandaro, M., & De Michelis, I. (2007). Removal of heavy metals by surfactant-enhanced ultrafiltration from wastewaters. *Desalination*, *207*(1–3), 125–133.

Fu, F., & Wang, Q. (2011). Removal of heavy metal ions from wastewaters: A review. *Journal of Environmental Management*, *92*(3), 407–418.

Gopalan, P., Jensen, P. D., & Batstone, D. J. (2012). Anaerobic digestion of swine effluent : Impact of production stages. *Biomass and Bioenergy*, *48*, 121–129. https://doi.org/10.1016/j.biombioe.2012.11.012

Gopalan, P., Jensen, P. D., & Batstone, D. J. (2013). *Biochemical Methane Potential of Beef Feedlot Manure: Impact of Manure Age and Storage*. *4*. https://doi.org/10.2134/jeq2012.0457

Government of the Netherlands. (2017). *From a linear to a circular economy*. National Agreement on the Circular Economy.

Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B., & Moulin, P. (2009). Reverse osmosis desalination: Water sources, technology, and today's challenges. *Water Research*, *43*(9), 2317–2348. https://doi.org/10.1016/J.WATRES.2009.03.010

Huang, J., Zeng, G., Zhou, C., Li, X., Shi, L., & He, S. (2010). Adsorption of surfactant micelles and Cd2+/Zn2+ in micellar-enhanced ultrafiltration. *Journal of Hazardous Materials*, *183*(1–3), 287–293.

Korus, I., & Loska, K. (2009). Removal of Cr (III) and Cr (VI) ions from aqueous solutions by means of polyelectrolyte-enhanced ultrafiltration. *Desalination*, *247*(1–3), 390–395.

Landaburu-Aguirre, J., Pongrácz, E., Perämäki, P., & Keiski, R. (2010). Micellar-enhanced ultrafiltration for the removal of cadmium and zinc: use of response surface methodology to improve understanding of process performance and optimisation. *Journal of Hazardous Materials*, *180*(1–3), 524–534.

Lane, J., & Hoban, S. (2017). *To investigate the practicalities and regulatory requirements of utilising food waste as a feed source for pigs*.

Lesteur, M., Bellon-Maurel, V., Gonzalez, C., Latrille, E., Roger, J.M., Junqua, G., Steyer, J. P. (2010). Alternative methods for determining anaerobic biodegradability: A review. Process Biochemistry. *Process Biochemistry*, *45*(4), 431–440.

Lin, H., Gan, J., Rajendran, A., Reis, C., & Hu, B. (2015). Phosphorus removal and recovery from digestate after biogas production. In *Biofuels-status and perspective*. IntechOpen & Department of Bioproducts and Biosystems Engineering, University of Minnesota.

Masse, L., Massé, D., & Pellerin, Y. (2007). The use of membranes for the treatment of manure: A critical literature review. *Biosystems Engineering*, *98*(4), 371–380.

Mehta, C., Khunjar, W., Nguyen, V., Tait, S., & Batstone, D. (2015). Technologies to recover nutrients from waste streams: a critical review. *Critical Reviews in Environmental Science and Technology*, *45*(4), 385–427.

Molinari, R., Poerio, T., & Argurio, P. (2008). Selective separation of copper (II) and nickel (II) from aqueous media using the complexation–ultrafiltration process. *Chemosphere*, *70*(3), 341–348.

Moody, L., Burns, R., & Stalder, K. (2009). Effect of anaerobic digestion on manure characteristics for phosphorus precipitation from swine waste. *Applied Engineering in Agriculture*, *25*(1), 97–102.

Murphy, C, Wiedemann, S., & McGahan, E. (2016). *Alternative/Integrated Wastewater Treatment - Closing the Loop. APL Project No. 2015/055*. Australian Pork Limited (APL).

Murphy, Caoilinn, McGahan, E., & Wiedemann, S. (2012). *Assessment of Treatment Technologies and Strategies to Mitigate GHG Emissions* (Issue June). Australian Pork Limited (APL).

Nolet, S. (2020). *Catalysing a $10m Australian Insect Industry*. https://www.agrifutures.com.au/product/catalysing-australian-insectindustry/

Obaja, D., Mace, S., & Mata-Alvarez, J. (2005). Biological nutrient removal by a sequencing batch reactor (SBR) using an internal organic carbon source in digested piggery wastewater. *Bioresource Technology*, *96*(1), 7–14.

Rahman, M., Liu, Y., Kwag, J., & Ra, C. (2011). Recovery of struvite from animal wastewater and its nutrient leaching loss in soil. *Journal of Hazardous Materials*, *186*(2–3), 2026–2030.

Raposo, F., Fernandez-Cegri, V., De la Rubia, M.A., Borja, R., Beline, F., Cavinato, C., Demirer, G., Fernandez, B., Fernandez-Polanco, M., Frigon, J.C., Ganesh, R., Kaparaju, P., Koubova, J., Mendez, R., Menin, G., Peene, A., Scherer, P., Torrijos, M., U, V. (2011). Biochemical methane potential 75 (BMP) of solid organic substrates: evaluation of anaerobic biodegradability using data from an international interlaboratory study. *Journal of Chemical Technology and Biotechnology*, *86*(8), 1088–1098.

Skerman, A., & Tait, S. (2018). *Bioenergy Support Program - DAF Transition. Final Report: Pork CRC Project 4C-116*.

Skerman, A., Wilis, S., Mcgahan, E., & Marquardt, B. (2015). *PigBal 4. A Model for Estimating Piggery Waste Production*. Department of Agriculture, Fisheries and Forestry (DAFF).

Stanfield, G., Lechevallier, M., & Snozzi, M. (2003). Treatment efficiency. *Assessing Microbial Safety of Drinking Water*, 159.

Sustainability Victoria. (2021). *Grants and Funding*.

Tait, S., Tamis, J., Edgerton, B., Batstone, D. J. (2009). Anaerobic digestion of spent bedding from deep litter piggery housing. *Bioresource Technology*, *100*(7), 2210–2218.

Tait, S., Astals, S., Yap, S. D., Jensen, P., & Batstone, D. (2017). *Enhanced methane production from pig manure in covered lagoons and digesters. Final Report: Pork CRC 4C-109*.

Tait, S., Harris, P. W., & McCabe, B. K. (2021). Biogas recovery by anaerobic digestion of Australian agro-industry waste: A review. *Journal of Cleaner Production*, *299*, 126876. https://doi.org/10.1016/j.jclepro.2021.126876

Tápparo, D. C., Viancelli, A., Amaral, A. C. do, Fongaro, G., Steinmetz, R. L. R., Magri, M. E., Barardi, C. R. M., & Kunz, A. (2020). Sanitary effectiveness and biogas yield by anaerobic co-digestion of swine carcasses and manure. *Environmental Technology*, *41*(6), 682–690. https://doi.org/10.1080/09593330.2018.1508256

Torok, V. A., Luyckx, K., & Lapidge, S. (2021). Human food waste to animal feed: Opportunities and challenges. *Animal Production Science*, *2012*(Fao 2011). https://doi.org/10.1071/AN20631

Tucker, R. (2015). *Piggery Manure and Effluent Management and Reuse Guidelines*. Australian Pork Limited (APL).

U.S. EPA. (2021). *Sustainable Management of Food, Food Recovery Hierarchy*. United States Envrionmental Protection Agency. https://www.epa.gov/sustainable-management-food/food-recovery-hierarchy

Watson, K., Wiedemann, S., Biggs, L., & McGahan, E. (2018). *Trends in environmental impacts from the pork industry*.

Westerman, P., Zering, K., & Rashash, D. (2009). Struvite crystallizer for recovering phosphorous from lagoon and digester liquid. *Unpublished Article. NC State University Collaborative Extension Program, USA. The Article Is Available in: Http://Www. Bae. Ncsu. Edu/Programs/Extension/Manure/Lagoon/Ag-724w_ Struvite_crystallizer. Pdf*.