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FINAL REPORT

Food Waste to Pig Feed – Safe & Bio-secure

ENDFOODWASTE COOPERATIVE RESEARCH CENTRE

Australian Government Department of Industry, Science and Resources | Cooperative Research Centres Program

Australasian Pork Research Institute Ltd APRIL

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Panel Review Statement

End Food Waste CRC recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard. The author(s) confirm(s) that this document has been reviewed and approved by the Project Leader and Industry Partner.

This project has also been evaluated by the End Food Waste CRC publication review panel. These reviewers evaluated its:

- Methodology articulated clearly
- Positioning of findings within the current literature
- Acknowledged compliance with food safety standards
- Conclusions against results
- Relevant human and/or animal ethic approvals obtained

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Industry Partner Foreword

The Australasian Pork Research Institute (APRIL) was pleased to be a partner of the End Food Waste project "Food Waste to Pig Feed – Safe & Bio-secure". An important output for the pig industry was the techno-economic analysis (TEA) on the feasibility of utilising food waste for pig feed in five key pig producing regions in Australia for a wet and dry feeding systems compared to a reference pig feed (30% Canola; 70% wheat). The TEA considered capital, operating and transport costs as well as expected revenues which will be invaluable to industry and parties considering investing in the construction of a waste food treatment plant. Of interest is that wet feed production was found to be feasible in all areas investigated, whilst dry feed ingredient production being feasible only on the eastern seaboard. The conservative volume of mixed human food waste reported in this study could reduce the demand for conventional feed ingredients by 6% and subsequently lower feed costs.

Currently, feed accounts for approximately 60% of the cost of raising pigs in Australia and therefore finding cheaper, suitable alternatives to cereal grains which comprise up to 70% of pig diets has been a priority of the industry for a number of years. Australian crop farming is subject to environmental conditions such as drought that produce shortages in grain and increased feed costs, impacting production margins for pork producers. The greater utilisation of food wastes would help reduce the reliance on grain, and provide a cost buffer which will further contribute to the sustainability of the pig industry.

Of interest to the industry are the outcomes of the pilot feeding study in which a processed mixed food waste ingredient at 20% inclusion rate did not adversely impact weaner pig performance nor were there any gut health or impacts on meat quality. This indicates that the treatment processes applied were suitable and provide the basis for regulatory standards that would be required for commercial application.

The study also concluded that the current regulatory framework and legislation in Australia needs to be developed in order for this technology to be commercially applied and maintain Australia's high biosecurity standards.

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Dr Charles Rikard-Bell

Executive Officer, APRIL

31 March 2025

Executive Summary

Currently, livestock species consume over a third of global grain production but could function as efficient bioprocessors for converting unavoidable food waste into valuable animal protein. In establishing a food waste to livestock feed or "EcoFeed" industry, it is imperative to ensure that feed safety is appropriately regulated to prevent adverse animal health, welfare, biosecurity, food safety, economic, market access and food insecurity outcomes. For these reasons, regulatory frameworks in most industrialised countries prohibit feeding of mixed food waste (containing animal product) to livestock. There is a growing body of knowledge showing that if the correct processing and safety measures are implemented, that food waste from retail and food service could be effectively and safety utilised in commercial pig production systems. In Japan a successful food waste to pig feed industry has been developed based on both liquid and dry feeding systems, which is regulated and encouraged under national policy. Furthermore, the Japanese pork industry has not been negatively affected by emergency animal diseases through these feeding practices. If other countries are to establish similar EcoFeed industries, then strategies to mitigate food safety and biosecurity concerns will need to be developed and implemented. Furthermore, legislation, based on scientifically robust research, will be required to incentivise food-waste producers and the livestock industry to actively engage and drive change.

This project aimed to identify the food safety/biosecurity risks and strategies to mitigate these perceived risks in utilising mixed food waste streams into pig feed. It also aimed to determine the techno-economic feasibility of utilising food waste for pig feed in key Australian regional areas and to undertake a pilot pig feeding trial using treated mixed human food waste.

A regional techno-economic analysis (TEA) on the feasibility of utilising mixed human food waste for the pig industry was done in five key pig production areas in Australia (south-eastern Queensland, southern New South Wales, northern and western Victoria, south-eastern South Australia and south-western Western Australia). The TEA considered both wet and dry feeding systems in the production of a feed ingredient as compared with a standard grain-based diet. Approximately, 373,000 tonne/pa of untapped mixed food waste were identified from commercial and industrial sources in identified regional areas. This volume of mixed food waste could support up to six food waste to feed manufacturing facilities. Wet feed production was found to be both technically and economically feasible in all areas investigated, with dry feed ingredient production being feasible only on the eastern seaboard, with NSW having the strongest business case as of 2022. Implementing this opportunity could lead to significant environmental benefits by reducing food waste going to landfill by 5% and lowering demand for conventional feed ingredients by 6%. Such an initiative would have the potential to benefit the Australian pig industry by delivering lower cost pig feed ingredients and insulating them against the price volatility of animal feed traded on the global market. It should be noted that the results are based on the assumptions of the time and may have varied since.

Livestock feed is an integral part of the food chain, and its safety has been recognised as a shared value and a shared responsibility of the livestock industries, feed ingredient producers and manufacturers. Concerns regarding utilisation of food waste in commercial animal feeds are related to whether the feed can satisfy the nutrient requirements to support animal growth and whether the feed contains hazardous microbial or chemical components. A four-week pilot weaner pig feeding trial was undertaken where mixed human supermarket food waste was processed, heat treated and dried into a dry feed ingredient and incorporated into a diet at a 20% inclusion rate. There were no significant differences in the production measurements or faecal amino acid digestibility of pigs fed the food waste containing diet as compared to a commercial weaner diet, demonstrating that food waste diet did not have a negative impact on pig production. Furthermore, minimal impacts were observed on objective meat quality measures, noting that true meat quality can only be assessed by consumer perception. The impact of the food waste containing diet also had no impact on the pig's gut health as determined by the absence of ileal microbiota differences. Further research is required to explore long-term effects of feeding food waste on pig production at a commercial scale. Further research is also required to explore the long-term effects of feeding food waste on pig meat quality, sensory evaluation and consumer acceptability.

An outcome of the project was the peer reviewed publication on the opportunities and challenges of utilising mixed human food waste for the livestock industries which was published in 2021 (Torok et al., 2021). Currently, under the Australian National Food Waste Strategy, only elimination or reduction in the generation of food waste, redirection of safe surplus food to food rescue, relief organisations or repurposing into new food products and diversion of food waste to animal feed, including feeding insects for protein production, will be counted towards reducing food waste by 50% by 2030 (FIAL, 2021). However, Australia currently lacks the legislative framework to support uptake by both the food and livestock industries. Safe implementation would require development of policy and legislative frameworks and further investment into research, new infrastructure for waste handling and feed manufacturing facilities.

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1. Introduction

The gross value of Australian agricultural production is estimated to rise to $88.4 billion in 2024-25 (ABARES, 2024a). Forty-four percent of this is the gross value of production of livestock and livestock products (38.6 billion). The gross value of pig and poultry meat and eggs for 2024-25 is predicted to increase by 5% to $7.4 billion (ABARES, 2024a). Australian pig meat prices are forecast to rise to $4.03/kg carcase weight in 2024-25, up by 3% from $3.91/kg in 2023-24 (ABARES, 2024a). In 2022 and 2023 5.44 million live pigs (representing 436.27 million tonnes meat) and 5.81 million live pigs (representing 466.79 million tonnes meat) were slaughtered in Australia, respectively (ABARES, 2024b).

The Food and Agriculture Organisation (FAO) has estimated that the world will need to produce ~60% more food by 2050 to sustain the global population of 9 billion people, with meat production anticipated to grow by 70% (comprised of growth in cattle by 62%, poultry by 104% and pigs by 35%), aquaculture by 90% and dairy by 55% (FAO, 2012). The United Nations (UN) Intergovernmental Panel on Climate Change has recently outlined adaptation and mitigation response options to land use and the food system in achieving a globally sustainable future (IPCC, 2019). Dietary change, shorter supply chains, reducing food waste, producing more food with less resources and reducing greenhouse gas emissions were identified as the most significant interventions. Global livestock production occupies ~75% of agricultural land, consumes 35% of the world's grain, and produces 14.5% of anthropogenic greenhouse gas emissions (FAO, 2012; zu Ermgassen et al., 2016). Local environmental conditions and geopolitical situations can affect grain production and supply chains, directly impacting livestock production and profitability. For example, strong 2024 production conditions across winter cropping regions in New South Wales, Queensland and Western Australia were forecasted to result in above average production of grains, oilseeds and pulses in these regions (ABARES, 2024a). By contrast, unfavourably dry conditions in spring 2024 reduced production prospects in Victoria, South Australia and southern Western Australia (ABARES, 2024a). In South Australia the estimated grain production for 2024/25 was reduced to 5.3 million tonnes, which is 42% below the five-year average and the lowest total since 2008/09 (PIRSA, 2024).

In the EU, feed costs for monogastric livestock range from 55% to 72% (pigs) and 55% to 75% (poultry) of the total production costs (zu Ermgassen et al. 2016; Georganas et al. 2020). In Australia, feed cost typically accounts for more than 60% of total pig production costs (Australian Pork Limited, 2017). Furthermore, the total feed used per pig sold in Australia ranges from 250-300 kg (average age at sale 19-22 weeks) (Australian Pork Limited, 2017). Although, the cost of feed can be highly variable the average cost is $400/tonne (Australian Pork Limited, 2017). Identifying alternative raw feed materials which are in less demand by competing livestock industries such as poultry, dairy and beef, is key to maintaining a viable pork industry. Most Australian pigs are fed dry meal or pellets, with free access to water (Australian Pork Limited, 2017). Dry feed is easy to store and handle and its contents and consistency can be controlled.

In general, any feed ingredient has nutritive value and can be included in a balanced diet if it is not toxic or harmful to a pig (Australian Pork Limited, 2017), although cost of the ingredient and any other properties which might limit feed intake also need to be considered However, some nutrient sources cannot be fed to pigs under any circumstances. Pigs are considered high risk for the introduction of exotic viral diseases through the illegal feeding of prohibited pig feed or 'swill'. Prohibited pig feed includes any material of placental mammal origin (other than milk and milk by-products, properly rendered meat meal, or tallow) and anything that has come into contact with meat or meat products. It is illegal to feed swill to pigs in all Australian states and territories. Viral diseases such as Foot-and-Mouth Disease (FMD), Classical Swine Fever (CSF), African Swine Fever (ASF) and Transmissible Gastroenteritis (TGE) can be carried and transmitted by feeding prohibited pig feed to pigs. These diseases are emergency animal health diseases exotic to Australia. Incursion of such diseases would have a catastrophic impact on the Australian pork industry.

Australia produces 7.7 million tonnes of food waste annually across the entire production and consumption chain; 310 kg/capita each year (FIAL, 2021). The environmental cost of this food waste is an estimated 7 million tonnes of CO_2 equivalent per annum

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from food waste in the cold food chain and 7.6 million tonnes of CO_2 equivalent per annum from decaying food in landfill, suggesting that total food waste in Australia accounts for ~5% of the national greenhouse gas emissions (Arcadis, 2019).

Additionally, 6.5 million tonnes of food waste is already diverted to animal feed; this is not accounted for in the national food waste baseline (FIAL, 2021). The majority, 96% of this utilised waste, is generated by food manufacturing; largely defined as livestock processing (rendered abattoir waste), fruit and vegetable processing (canning and frozen food production), wine production (grape marc), seafood processing (inedible trimmings), poultry processing (egg waste) and dairy product manufacturing waste (Arcadis, 2019; FIAL, 2021). Other manufacturing food wastes considered in the Australian food waste baseline survey were nut processing, baked product manufacture, beer making, fruit and vegetable pack house, confectionary manufacture, soft drink, cordial and syrup manufacture and grain mill, cereal, pasta and baking mix manufacture (Arcadis, 2019). Of the 7.7 million tonnes of food waste, 32% is attributed to households, 22% to primary production, 17% to manufacturing, 3% to distribution and 26% to wholesale, retail, food services and institutions (FIAL, 2021). Currently, <1% of food waste to animal feed comes from primary production (fruit and vegetables), 2% from distribution and <1% from wholesale/retail (FIAL, 2021).There is significant opportunity for greater utilisation of these food waste sources for animal feed, excluding household waste, if it can been done in an economically viable way, successfully mitigating the risks to animal health and production and establishing a regulated food waste to animal feed industry.

In 2019, only 10–20% of commercial Australian pig herds were accessing food waste from the production and manufacturing stages of the food supply chain, as indicated by industry nutritionists. This low utilisation rate is thought to be primarily due to a lack of food business to livestock business awareness. Food wastes currently utilised by the pork industry include pet food wastes, dairy products (whey, cheese and ice cream), grain milling wastes (rice pollard, pulse and barley offal, oat bran and hulls, malt combinings, wheat dust and hominy), food industry wastes (flour, dough, biscuits, bakery waste), confectionary, spreads (nutella, peanut butter and jams), canned fruits and juices, vegetable wastes, grape residues, potato wastes, mustard meal, corn steep liquor, fish fingers and batter, soup mix, coffee whitener, glucose syrups and soft drinks, brewing and distilling wastes and egg and hatchery wastes (where allowed by state regulations) (Lane and Hoban, 2017).

Generally, food waste categories reported in animal feeding studies tend to relate to manufacturing co-products or byproducts, food preparation or processing refusals and residuals (bakery goods or out of specification packaged product), or a mixture of food waste from food services and institutions. Manufacturing co-products and by-products are preferred for their economies of scale and predictability of quantity and quality of the by-product materials (Cheng and Lo, 2016). Increasingly, mixed food wastes from retail, food service and households are being investigated as a source of animal feed, and although results are variable, they have been shown to be nutritionally adequate for inclusion into feeds (Cheng and Lo, 2016; Dao et al., 2019; Georganas et al., 2020). The creation of an industrial surplus-food to- pig-feed or 'Ecofeed' industry has set Japan apart from other industrialised countries. Japanese EcoFeed treatment plants operate separately from farm premises and the plants operate to specific biosecurity, treatment, segregation and monitoring requirements, as outlined in Japanese legislation (Luyckx et al., 2019). Ecofeed manufacturers operate under Japanese food safety law (Sugiura et al., 2009). It is noteworthy that FMD outbreaks in both Japan and South Korea in 2010–2011 were not linked to feeding food waste to pigs (zu Ermgassen et al., 2016). Furthermore, Japan has remained ASF free, despite significant global spread since 2016 (OIE, 2020). In Japan and South Korea, it has been shown that pig feed costs have been reduced by 40–60% against standard feed costs. Japan is a global pioneer in this field, recycling 52.5% of manufacturing, retail and catering food waste into animal feed in 2006 (zu Ermgassen et al., 2016). In 2013, all concentrate animal feeds (for pigs, poultry, and ruminants) in Japan were made up of 5.8% of food waste (zu Ermgassen et al., 2016).

The Australasian Pork Research Institute Ltd (APRIL) considers the greater utilisation of food wastes to substitute current feed ingredients to be of high importance for the pork industry.

The objectives of this project were to:

- Identify the food safety/biosecurity risks and strategies to mitigate these perceived risks in utilising food waste streams into feed;
- Determine the techno-economic feasibility of utilising food waste for pig feed in key Australian regional areas; and
- Undertake a pilot pig feeding study using treated mixed human food waste.

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2. Methodology

2.1 Literature review on the opportunities and challenges of utilizing mixed human food waste for the livestock industry.

In 2021 a peer reviewed scientific publication was produced on the opportunities and challenges of utilising human food waste for the livestock industry. The review included available scientific (Web of Science database) and grey literature, including summarisation of the international and Australian regulatory frameworks on the permitted use of human food waste to animal feed.

2.2 Techno-economic analysis into the feasibility of utilising human mixed food waste into pig feed in key regional production areas.

A techno-economic analysis (TAE) was undertaken by Rawtec to investigate the feasibility of utilising mixed human food waste for pig feed in five key Australian regional pig production areas (south-eastern Queensland, southern New South Wales, northern and western Victoria, south-eastern South Australia and south-western Western Australia). Mixed food waste streams from commercial and industrial sources across the five states where pig production is concentrated were considered. Food waste sources such as institutions, accommodation, food services, food retail and food manufacturing were considered. The technical and infrastructure requirements of two technology options were considered: producing a wet pig feed ingredient (slurry) and a dry feed ingredient (meal). In both cases, the ingredient would be transported to feed mills or direct to pig farms and mixed with other ingredients to produce a complete pig feed. Producing a pig feed ingredient rather than a complete feed provides greater flexibility to pig nutritionists to formulate customised feed products, better meeting the diverse needs of pigs at various stages of production.

The high-level cost analysis considered the following in producing both a wet and dry pig feed ingredient:

- Capital costs for setting up a facility (excluding land and buildings);
- Facility operating costs;
- Expected revenues (or gate rates) received at the facility for accepting mixed food waste; and
- Transport costs.

This was compared to the cost of producing a reference diet containing 30% canola and 70% wheat, although it is recognised that the industry feeds a range of diets with different combinations of protein and energy sources.

2.3 Sourcing and processing retail mixed food waste into a pig feed ingredient

Mixed food waste was sourced from an Adelaide metropolitan supermarket over a two-month period during January and February 2024. Waste was collected fresh from back of house in supplied blue waste collection tubs on the day of waste generation. Waste categories collected were fresh produce (fruit and vegetable), pressings from an on-site juice bar (fruit and vegetables), on-site butchery waste (meat trimmings), on-site seafood processing waste (fish frames, skin, guts and crustacean shells), and bakery waste (bread, sandwiches, pizza and biscuits). Waste was transported to the South Australian Research and Development Institute (SARDI), Waite Campus where content was catalogued and weighed. Waste was stored at 4°C in a walk-in cold room until processed, usually within 1-2 days of collection. Treating the mixed food waste was based on the process outlined in the TEA to produce a dry feed ingredient. Waste was macerated using a screw press or industrial mincer, heat treated to an internal temperature of 100°C for at least 30 minutes under pressure in an autoclave, dewatered using a fruit press, dried in drying ovens at 70-80°C until dry to touch (3-4 days), and then milled into a powder (<3 mm particle size). The schematic process used in processing the mixed food waste is shown in Figure 1.

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Figure 1: Process of treating mixed food waste into a dry feed ingredient. The material was initially macerated/shredded and then heat treated, dewatered, dried and milled into a feed ingredient.

2.3.1 Microbial and nutritional analyses of mixed food waste

Microbial analysis was done on macerated mixed food waste (prior to heat treatment) and the dry milled feed ingredient (finished product). The microbial analysis included total viable count of aerobic bacteria (TVC), yeasts and moulds and *Enterobacteriaceae* using various Petrifilm™ methods. To 25g of sample, 225mL of 0.1% peptone water was added and stomached (Bag Mixer; InterScience) for 2 min. The homogenised sample was then serially diluted up to 10^{-6} in 9mL 0.1% peptone water. One mL aliquots of the various dilutions were then evenly dispensed in triplicate onto Petrifilm™ Aerobic Count Plates (ThermoFisher Scientific), Petrifilm™ *Enterobacteriaceae* Count Plates (ThermoFisher Scientific) and Petrifilm™ Yeast and Mold Count Plates (ThermoFisher Scientific) for TVC, *Enterobacteriaceae* and yeast and mould counts, respectively. Inoculated Petrifilms were then incubated at 35±1°C for 24-48hrs for TVC and *Enterobacteriaceae* and at 25±1°C for 120hrs for yeast and mould count. After the respective incubation periods, the Petrifilms were removed from the incubator and characteristic colonies were counted within a countable range of 25-250 colonies on a colony counter (Stuart Scientific). Colony forming units per gram of sample (CFU/g) were calculated from the dilution factors. TVC was used as a general hygiene indicator, *Enterobacteriaceae* were used as an indicator for the presence of potential pathogenic bacteria belonging to this family (e.g. *Salmonella* spp. and *Escherichia coli)* and yeasts and moulds were used as an indicator for the presence of potential mycotoxin producing moulds.

Nutrient analysis was done on each batch of the processed food waste and composite food waste (dry feed ingredient). These analyses included:

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1) Nutritional Informational Panel (NIP); including digestible energy, total fat, protein, carbohydrate, sugars, sodium, saturated fat (only if fatty acid profiling was also undertaken), moisture, ash and fatty acid profile (in some cases) (National Measurement Institute).
2) Standard amino acid screen (18 amino acids); Alanine, Arginine, Aspartic Acid, Glutamic Acid, Glycine, Histidine, Hydroxyproline, Isoleucine, Leucine, Lysine, Methionine, Phenylalanine, Proline, Serine, Taurine, Threonine, Tyrosine and Valine using ultra-performance liquid chromatography photodiode array detection tandem mass spectrometric method (UPLC-PDA-MSMS) with a limit of reporting (LOR) 50 mg/kg per amino acid (National Measurement Institute).

   or

   Amino acid profile (16 amino acids); Alanine, Arginine, Aspartic acid, Glutamic acid, Glycine, Histidine, Isoleucine, Leucine, Lysine, Methionine, Phenylalanine, Proline, Serine, Threonine, Tyrosine and Valine using a liquid hydrolysis method (Australian Proteome Analysis Facility; APAF, Macquarie University SOP AAA-001).
3) Tryptophan using UPLC-PDA-MSMS with a LOR 50 mg/kg per amino acid (National Measurement Institute) or liquid hydrolysis (Australian Proteome Analysis Facility (APAF), Macquarie University SOP AAA-002).
4) Calcium and phosphorus trace elements (National Measurement Institute).

2.4 Pilot pig feeding trial utilising treated mixed human food waste

2.4.1 Feed formulation.

The experimental weaner diets were formulated by David Henman (Rivalea Australia). The composition of the control diet and experimental diet (containing 20% of the processed food waste ingredient) and the nutritional analysis of the diets are shown in Table 1. Crude fat and fibre analysis was done by FeedTest.

Table 1: Weaner diet composition

	Control diet	Food waste diet
Ingredient (% contribution)		
Wheat	68.47	53.17
Canola meal	10.00	10.00
Soya bean meal	17.8	13.35
Food waste ingredient	0.00	20.00
Salt	0.30	0.30
Limestone	0.80	1.60
Dicalcium phosphate	2.00	1.00
DL-methionine	0.05	0.02
Elite pig grower premix	0.20	0.20
Lysine	0.30	0.30
Threonine	0.08	0.05
Nutrient composition		
Crude protein (%)[1]	20.3	20.3
Fat (%)[2]	3.1	6.3
Fibre (%)[2]	2.6	4.0
Ash (%)[1]	7.1	7.1
Digestible Energy (DE) (MJ/kg)[1]	13.8	14.1
Total lysine (%)[1]	1.2	1.2
Standardized ileal digestible lysine[1] (%)	1.0	1.1
Total lysine:DE ratio[1]	0.08	0.08

[1] Calculated chemical composition. [2] Analysed chemical composition.

The amino acid analysis of the diets was done by APAF, Macquarie University and the crude protein analysis was done by CSIRO. The animo acid composition of the control and experimental 20% supplemented food waste diets are shown in Table 2.

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Table 2: Analysed amino acid composition of weaner diets

Amino acid	Control diet (mg/g)	Food waste diet (mg/g)
Histidine	5.4	5.6
Serine	9.4	10.2
Arginine	11.2	12.3
Glycine	8.8	11.6
Aspartic acid	17.1	18.8
Glutamic acid	40.1	41.1
Threonine	8.1	9.3
Alanine	8.0	9.9
Proline	12.8	13.9
Lysine	12.6	14.6
Tyrosine	4.1	5.0
Methionine	2.5	3.3
Valine	9.4	10.6
Isoleucine	8.4	9.4
Leucine	14.2	15.7
Phenylalanine	9.4	10.0
Total crude protein	181.6	201.3

2.4.2 Feeding trial, production characteristics and sample collection

The animal experiment was done in accordance with the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes (NHMRC, 2021). The pig feeding study was undertaken at the South Australian Health and Medical Research Institute (SAHMRI), Gilles Plains Adelaide, and was approved by the SAHMRI animal ethics committee (Animal Ethics Committee Application Number; SAM-23-078).

Thirty-two male weaner Large White x Landrace pigs (mean age 21.5±0.3 days, mean weight 6.39kg; range 4.92–7.64kg) were divided into 8 pens, with 4 pigs per pen. After an approximate 2-week acclimatisation period (including a 6 day transition to the experimental diets) to the facilities and a solid pelleted creep diet, the pigs were randomly assigned to one of two dietary treatments (at approximately 32 days of age): a control diet (standard weaner diet) or a treatment diet (20% food waste ingredient inclusion). Diets were fed as a meal for 28 days. Both diets contained 0.5% titanium dioxide to allow for measuring amino acid digestibility in faecal samples. Pigs were weighed weekly, and feed consumption per pen was recorded.

Four days post introduction of experimental diets (control and 20% food waste inclusion) prolonged clinical diarrhoea was observed within all pens, along with the presence of blood in two stool samples in one pen (presumed to belong to two individual pigs). As a result, all pigs were treated with in-feed antibiotics (Tiamulin, 0.2 mg/10 kg body weight) for 7 days. Pigs in pen 7 (a food waste treatment pen), which showed the worst symptoms, received an additional intramuscular injection of 0.5 mL Elevet + Tylosin (200 mg/mL) for 3 days under veterinary supervision. On observation of clinical symptoms pooled feacal samples per pen were collected and sent for a porcine enteric PCR test (ACE Laboratory Services, Victoria, Australia). Target microorganisms for the enteric PCR test were *Salmonella* spp, *Brachyspira hyodysenteriae* (nox), *Brachyspira pilosicoli* and *Lawsonia intercellularis*.

Production data was statistically analysed using RStudio (Version.3). A linear mixed effects model was used to analyse the relationship between weight and treatment (using initial weight as a covariate). The model also accounted for potential random effects due to individual pigs (PigID). Pen and PigID were initially tested for random effects, however, neither contributed significantly to the models fit. Given the biological relevance, PigID was retained as a random effect in the final model.

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```
model_1<- lmer(Weight ~ EntryW + Treatment + (1 | PigID),data = long_data)
```

An additional model was run testing the interaction effect of treatment by timepoint.

```
model_2<- lmer(Weight ~ EntryW + Treatment*TimePoint + (1 | PigID),data = long_data)
```

The significance of the fixed effects was determined using an Analysis of Variance (ANOVA) test using Type III sum of squares methodology within the mixed effects model framework.

```
model_anova_result <- Anova(model,type = "III")
```

Post-hoc analysis was performed to examine the effects of treatment on weight using estimated marginal means and pairwise comparisons.

The treatment by timepoint output (Model_2) was visualised using a plot to display the relationship between treatment and predicted weight.

Average daily feed intake (ADIF) on a pen basis was calculated as the total amount of feed consumed (kg) divided by the number of days over which the consumption is measured. A Mann-Whitney U test was used to assess the differences in ADFI between the control and food waste supplemented groups, as the data were not normally distributed.

```
mann_whitney_result_adfi <- wilcox.test (ADFI ~ Treatment, data = data)
```

Feed conversion ratio (FCR) was calculated as the amount of feed consumed by the pen (in kg) divided by the total amount of weight gained within the pen (in kg) over a given period. A Welch two-sample t-test was used to compare the mean FCR between the control and food waste supplemented groups.

```
welch_t_test <- t.test(Pig_ADG ~ Treatment, data = data)
```

Average daily gain (ADG) was calculated for individual animals as the total amount of weight gained (kg) divided by the number of days over which the weight was measured. A linear model (ANOVA) was used to analyze the effect of treatment on ADG.

```
anova(lm(Pig_ADG ~ Treatment, data = data))
```

A mixed effects model was also tested to account for any random effects due to the pen using the following equation, however the random effect of pen had a variance of 0, suggesting no significant contribution to the model.

```
model <- lmer(Pig_ADG ~ Treatment + (1 | Pen), data = data)
```

In the final week of the experiment (approximately 54 days of age and days 21-28 of the feeding experiment), faecal samples were collected daily from each pen within 2 hours of cleaning. Samples were frozen at -20°C until the end of the experiment, then transported to the SARDI, Pig and Poultry Production Unit, Roseworthy Adelaide for processing. Frozen samples were freeze-dried for 48hrs to remove moisture and stabilise organic material. The dried samples were combined by pen, ground using a mortar and pestle into a homogeneous particle size and stored at room temperature for further analysis (amino acids by APAF, Macquarie University and total nitrogen by CSIRO). Faecal and feed samples were sent to the Sciences Environment and Analytical Laboratories, SARDI West Beach to be tested for titanium dioxide marker I using a colorimetric protocol (Short et al., 1996). The assumption was made that the samples were homogenous and representative of all the animals in the pen. The following equation was used to calculate the digesta for each amino acid measured by pen:

$$\text{Digesta}=1-((\text{Amino acid level in faeces})/(\text{Amino acid level in Diet})*(\text{Diet } TiO_2)/(\text{Faecal } TiO_2))$$

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The treatment effect on amino acid digestibility was tested using one-way ANOVA (RStudio, version 3) with the following equation:

```
model_3<- aov(Amino acid ~factor (Treatment),data=data)
```

On the final day of the experiment all animals were humanely euthanised using an SAHMRI standard operating proceedure , where pigs were sedated, intramuscular injection of Xylazine 100; 1-2mg/kg, followed by an intramuscular injection of Ketamine 100 mg/mL; 6-10 mg/kg) 5-10 minutes later. Humane killing was completed by administering an intracardiac injection of leathabarc (0.5 mL/kg) and vital signs were checked for confirmation of death. Meat and intestinal samples were collected from each animal following slaughter.

2.4.3 Meat quality analysis

A single pork loin fillet (*longissimus lumborum* muscle) was collected from each pig following euthanasia and placed in a zip locked bag and stored on ice until transported back to the SARDI Food Sciences laboratories, Waite Campus, Adelaide, where it was stored at 4^{o}C overnight. The loin was then aged in vacuum -sealed, clear plastic gas impermeable packaging for 6 days at 4^{o}C. A series of meat quality measures were taken. After aging, loins were removed from the packaging, cut into three 3cm sections (muscle fibres running transversely to the direction of cut), placed cut side up on a black polystyrene foam tray and allowed to bloom for 30 minutes. The pH of cut meat loins was measured in duplicate and averaged. Samples were then wrapped with plastic cling film and exposed to continuous simulated retail display (SRD). Temperature and light conditions during SRD were designed to simulate those encountered in retail setting. The SRD was conducted in a cool room with air temperature kept in the range of 2-4°C. An overhead light source consisting of two OSRAM Fluorescent Natura Tubes 36 W and 1800 mm in length (L36W/76) was suspended 85 cm above the samples to provide a light intensity of 1000 Lux, as measured with a Light Meter. Retail colour measurements were taken with a Hunter Lab Mini Scan™ XE Plus with light source set at "D65" with the observer set to 10°. Measurements for L*, a*, b* (where L* measures relative lightness, a* relative redness and b* relative yellowness) were taken at times 0, 4, 8, 11 and 15 days of SRD. Each measurement was repeated after rotating the spectrophotometer 90° in the horizontal plane, to produce the mean of the two measurements. Meat tenderness was measured by cooking loss and mechanical shear force. For cooking loss a ≤ 100 gm of aged loin sample was placed in a water bath (80^{o}C) for 50 min in a sealed heat resistant plastic bag. Samples were allowed to cool for 15 min and cooking loss was calculated as percentage weight loss. Shear force of the cooked meat was determined by the Warner Braztler Shear test using Multitest 2.5 dv (Mecmesin) shear force tester. The parameters were set as follow: diameter - 13 mm, height = 13 mm, area = 132.7223 m^2, grip separation - 13 mm. The minimum trigger force was set to 1. Shear force is the force (measured in newton) required to shear through the meat. All data was statistically analysed using the two sample t test (Excel, Microsoft).

2.4.4 Gut microbial profiling analysis

Approximately a 3 cm ileal gut sample (digesta and tissue) was collected from all pigs at slaughter and frozen at -80^{o}C. Samples were freeze dried and total nucleic acid extracted using a modified SARDI proprietary method. Total nucleic acid was sent to the Australian Genome Research Facility, Brisbane node for PacBio Full Length 16S rRNA (Kinnex) profiling. Each sample was PCR amplified using indexed primers (F27 5'GCATC/barcode/AGRGTTYGATYMTGGCTCAG3' and R1492 5'GCATC/barcode/RGYTACCTTGTTACGACTT3'), pooled and sequenced using PacBio's SMRT Bell sequencing chemistry. Expected output with good quality samples is > 8,000 reads/sample. PacBio HiFi full-length 16S data was quality filtered and "denoised" to high quality amplicon single variants (ASVs) using QIIME2 and DADA2. ASV classification was done using two approaches. A consensus alignment classification (using VSEARCH) against the Genome Taxonomy Database (GTDB r207) was done resulting in high consistency. A naïve Bayesian machine learning based classification (DADA2) using three databases that successively fall over to the next one if a species level match is not found was also done. In order, these databases are the

Genome Taxonomy Database (GTDB r207), the SILVA rRNA database (v138), and the NCBI RefSeq 16S rRNA database supplemented by the Ribosomal Database Project (RDP). This second approach gives better classification for low abundance ASVs.

Primer7 v7.0.20 (Primer-E Ltd) was used to statistically analyse ileal microbial communities. Operational taxonomic unit (OTU) data were standardised by total and fourth root transformed before creating a Bray-Curtis similarity resemblance matrix. One-way analysis of similarity (ANOSIM) was done to test beta diversity (species unique to each treatment) associated with dietary treatment. DIVERSE was used to calculate alpha diversity metrics of total species (S), Brillouin diversity index (H') and Pielou's evenness (J). Treatment associated differences in alpha diversity matrix were analysed using a two sample t-test (Excel, Microsoft).

Non-metric multidimensional scaling (nMDS) on Bray-Curtis similarity data was done to graphically illustrate relationships amongst individual ileal bacterial communities.

3. Results

3.1 Biosecurity challenges of utilizing mixed human food waste for the commercial pork industry

Currently, mixed human food waste containing meat or has come into contact with meat is defined as prohibited pig feed (PPF) or "swill" and is not permitted to be fed to pigs in Australia unless: rendered in accordance with the Australian Standard for the Hygienic Rendering of Animal Products (AS5008:2007, 2007); under jurisdictional permit, cooking processes subject to compliance verification that ensure a core temperature of at least 100^{o}C for a minimum of 30 min, or equivalent; treatment of cooking oil, which has been used for cooking in Australia, in accordance with the 'National Standard for Recycling of Used Cooking Fats and Oils intended for Animal Feeds'; and under jurisdictional permit, any other nationally agreed process approved by Animal Health Committee for which an acceptable risk assessment has been undertaken and that is subject to compliance verification (AHA, 2023). There are also strict biosecurity requirements for imported meat by-products (generated as a result of local human food manufacture) and catering waste from inbound international air and sea travel to not be utilised in animal feed under any circumstance. A summary of international and Australian regulations controlling use of food waste for animal feed is shown in Table 3.

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Table 3: Summary of international and Australian regulations controlling the direct and indirect use of food waste in feed (updated from Torok et al., 2021). RAM - restricted animal material; PPF - prohibited pig feed; PAP - processed animal protein, a feed material produced from category 3 animal by-products, i.e. the part of animals (bones, offal, etc.) coming from non-ruminant animals controlled as fit for human consumption at the point of slaughter.

Permitted	Prohibited	References
Japan/South Korea		
Feeding food waste containing meat to non-ruminants is permitted if heat treated to regulated temperatures by a licensed premise under federal law. Heat treatment in Japan is 90°C for 60 min.	Feeding ruminants animal derived protein is prohibited. In 2019 wet feeding systems utilising human food waste were prohibited for pigs in South Korea following an ASF outbreak	(MAFF, 2003, 2006, 2020; Moon et al., 2023; zu Ermgassen et al., 2016)
Australia		
RAM, defined as meat or blood product from any vertebrate species, may be fed to pigs, poultry or other non-ruminant species if treated by an approved process. Feeding pigs milk and dairy waste, vegetable waste, bakery waste (excluding meat toppings) and eggs (state specific) is permitted. Feeding aquaculture species insect protein is permitted. Feeding pigs insects protein, provided the insects have not been reared on PPF or insects have been rendered, is permitted. Feeding poultry insect protein, with some states specifying that insects should not be reared on PPF or have been rendered, is permitted.	Feeding pigs PPF or swill is prohibited. Feeding ruminants RAM is prohibited.	(AHA, 2019, 2020, 2023; AS5008:2007, 2007). See Table 5 for State regulations and Federal act.
European Union/United Kingdom[b]		
Non-ruminant PAP poultry, porcine and insect) is permitted in fish feed. Porcine PAP may be fed to poultry. Poultry PAP may be fed to pigs. Insect PAP may be fed to fish	Feeding worms/insects animal or human manure is prohibited. Feeding farmed animals (including insects) ruminant protein, kitchen waste, catering waste, and manure is prohibited.	(EC, 2009, 2021b)
USA		
Feeding pigs meat, catering or household waste is permitted if heat treated to regulated temperatures (100°C at sea level for 30 min) by a licensed premise under federal law.	26 USA states prohibit feeding food scraps containing any animal material to pigs and 24 states permit feeding treated human food waste	(USDA, 2009, 2019, 2024)

Jurisdictional regulations do vary amongst Australian states and territories and should be consulted for more nuanced detail. The *Biosecurity Act 2015* and subordinate legislation regulate import of animals and biological materials that may pose a biosecurity risk to Australia (Australian Government, 2024). The various jurisdictional legislation is outlined in Table 4.

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Table 4: Jurisdictional Acts and Regulations controlling animal feed. Current 28th November 2024.

Jurisdiction	Legislation	Reference
New South Wales	Biosecurity Act 2015 No 24	(New South Wales Government, 2024)
Northern Territory	Livestock Act 2008 Livestock Regulations 2009	(Northern Territory Government, 2024a) (Northern Territory Government, 2024b)
Queensland	Biosecurity Act 2014 (Qld)	(Queensland Government, 2024)
South Australia	Livestock Act 1997 Livestock Regulation 2013	(Government of South Australia, 2022) (Government of South Australia, 2020)
Tasmania	Biosecurity Act 2019 Biosecurity Regulations 2022	(Tasmanian Government, 2024a) (Tasmanian Government, 2024b)
Victoria	Livestock Disease Control Act 1994 Livestock Disease Control Regulations 2017	(State Government of Victoria, 2024a) (State Government of Victoria, 2024b)
Western Australia	Biosecurity & Agriculture Management Act 2007 Biosecurity & Agriculture Management Regulations 2013	(Government of Western Australia, 2024) (Government of Western Australia, 2022)

The peer reviewed scientific publication “Human food waste to animal feed: opportunities and challenges” was published in 2021 in the journal *Animal Production Science* (Torok et al., 2021). The publication reviewed the following topics:

- Global food waste and environmental implications.
- Potential for food waste utilisation in animal feed.
    - Production and manufacturing food waste;
    - Mixed food waste;
    - Indirect use of food waste via insects.
- Food safety and biosecurity hurdles.
- International regulations on food waste in animal feed.
- Enabling a food waste to animal feed industry to support waste reduction targets.

3.2 Techno-economic feasibility of utilising mixed human food waste as a feed ingredient for the pork industry.

In 2022 it was estimated that there was 373,000 tonne/pa of mixed food waste available for, commercial and industrial sources across New South Wales, Victoria, South Australia, Western Australia and Queensland (Rawtec, 2022). These are ‘untapped’ sources of food materials currently going to waste destinations from sources like institutions, accommodation, food services, food retail, and food manufacturing. This represents only a fraction of the total food waste volumes generated from these sources in Australia for the following reasons:

- practical limitations, such as low collection densities (and high collection costs) in regional areas;
- competition for food waste volumes from other facilities (such as composters);
- availability of low cost/zero cost management options already in place such as feeding untreated, low risk surplus primary production and food manufacturing food waste to livestock.

The Food Recovery Hierarchy was also considered when estimating potential volumes of food waste. Materials going to higher value uses, such as upcycling and food rescue, and existing animal feed destinations, were excluded from the analysis.

The technical process considered for the transforming mixed food waste into a pig feed ingredient are shown in Figure 2. The wet feed process involved receival, decontamination, shredding, heat treatment, and acidification. The dry feed process was an extension of the wet feed process, with additional steps of dewatering and drying included to reduce moisture content of the product and form a dry meal. The acidification step was not included in the dry feed ingredient process as stability was achieved through a reduction in moisture rather than through acidification. Both the wet and dry feed processes included heat treatment to mitigate any biosecurity risks. The heat treatment considered was at least 100°C core temperature for a minimum of 30 minutes in accordance with the Australian Standard for the Hygienic Rendering of Animal Products (AS5008:2007, 2007).

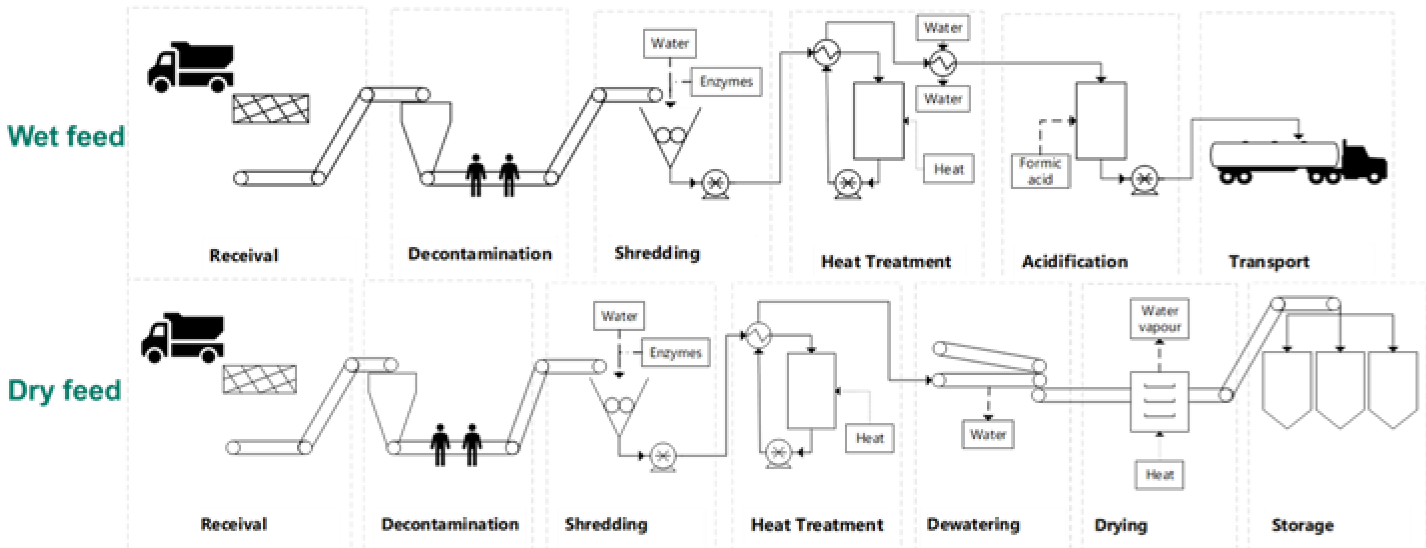

Figure 2: Processes considered for producing a wet and dry pig feed in the techno-economic analysis.

Turning mixed food waste into a wet pig feed ingredient was potentially cost-competitive with a reference pig feed (30% canola and 70% wheat) in all Australian states assessed. These facilities could collectively satisfy 6% of demand for grain used for pig feed (a conventional dry feed) across states. The viability was stronger in states with high food waste volumes (such as New South Wales, Queensland and Victoria), as greater economies of scale could be achieved. The viability was lowest in South Australia due to lower economies of scale combined with lower gate rates (driven by highly competitive markets for source separated food waste). Most pig farms currently use a dry feed system and would need to invest in wet feed infrastructure to utilise this approach. The additional costs of on-farm infrastructure are excluded in the cost estimates.

Turning mixed food waste into a dry pig feed ingredient involves higher capital and operating costs. A large amount of energy is needed for dewatering and drying. Despite these higher costs, the process was potentially still cost-competitive with conventional animal feed ingredients in New South Wales, Queensland and Victoria. It was deemed not currently viable in South Australia and Western Australia. Similar to wet feed, the viability was stronger in locations that can attract a higher gate rate ($/tonne incoming food waste) and that have higher food waste volumes leading to economies of scale. Gate rate calculations were based on the individual states waste levies. This is the levy which must be paid for all wastes (by the generator) that are received at permissioned landfills. A key purpose of the waste levy is to help reduce waste by encourage waste generators to look for ways to reduce the amount of waste they generate and send to landfill. The TEA showed that in areas where the production of a dry feed

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ingredient was not currently economically viable, this could easily change with the introduction of higher waste levies in those states.

If all potentially available mixed food waste material identified in the TEA were captured and converted into pig feed, this would represent a 5% reduction in Australia's food waste volumes, achieving 10% of the national reduction target. The untapped mixed food waste identified would support six food waste to feed manufacture facilities, including two 20,000 tonne/pa, one 60,000 tonne/pa and three 80,000 tonne/pa plants in the various states. In practice, it is expected this would take several years to secure required food waste volumes. However, policy changes and other supporting mechanisms could be introduced to support market development. The business case in NSW is the strongest, where the government is introducing mandated source separation of food waste by large commercial and industrial generators by 2025.

3.3 Microbial and nutritional quality of mixed retail food waste

A total of 1,144kg of mixed food waste was collected over 13 occasions in January and February 2024. This mixed food waste was processed over 11 occasions into a total of 178kg of dry feed ingredient (140kg sieved to <2.8mm). The estimated water content of the wet mixed food waste collected ranged from 73-91%. The minimum and maximum percentage composition from each of the various food waste categories are shown in Table 5, along with the composition of the final aggregated waste used in the dry feed ingredient.

Table 5: Composition of wet mixed food waste.

Wet mixed food waste categories	Minimum composition	Maximum composition	Final composition
Fruit/vegetables	38.7%	85.6%	53.6%
Juice bar pressings	0%	32.4%	12.2%
Bakery products	0%	34.9%	6.1%
Meat trimmings/fat	0%	17.6%	4.9%
Seafood processing waste	4.5%	45.4%	22.8%

Some examples of the categories of collected mixed food waste are shown in Figure 3.

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Figure 3: Examples of mixed food waste categories processed.

The processed finished feed ingredient batches prior to aggregation are shown in Figure 4.

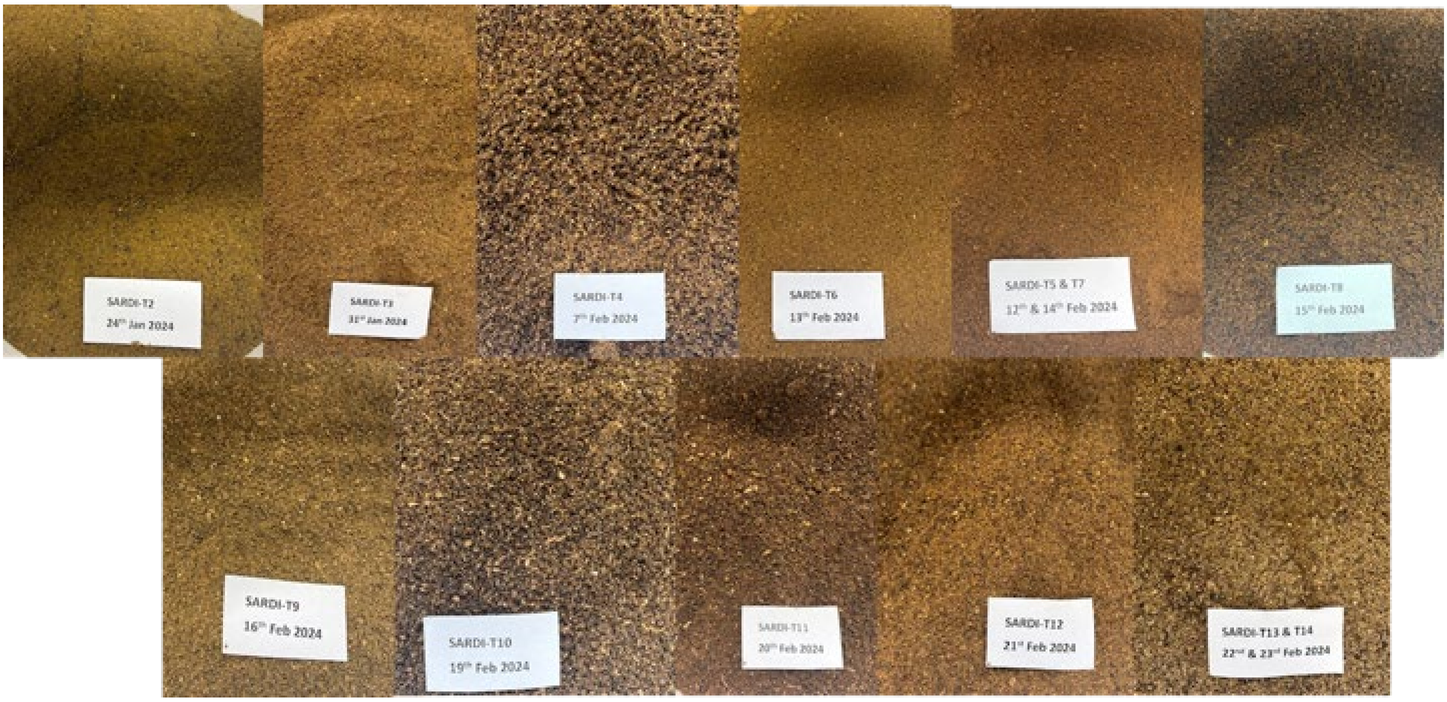

Figure 4: Visual appearance of each batch of processed dry feed ingredient.

The TVC, *Enterobacteriaceae* and yeast and moulds microbial analyses for the macerated (raw) and finished (heat treated, dried and milled) dry feed ingredient and shown in Figure 5.

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The microbial load of raw food waste dropped significantly following processing into a dry feed ingredient. TVC dropped on average $\log_{10}$ 3.9 CFU/g, *Enterobacteriaceae* dropped $\log_{10}$ 5.6 CFU/g and yeast and moulds dropped $\log_{10}$ 6.7 CFU/g. Yeast and mould would be expected to remain low post processing due to the dry nature (Table 6) of the material and *Enterobacteriaceae* would also expect to remain low unless contaminated from the environment, usually from a faecal source. The TVC were significantly reduced following processing, however the levels observed are not concerning as TVC measure all environmental aerobic bacteria, including those which are not harmful.

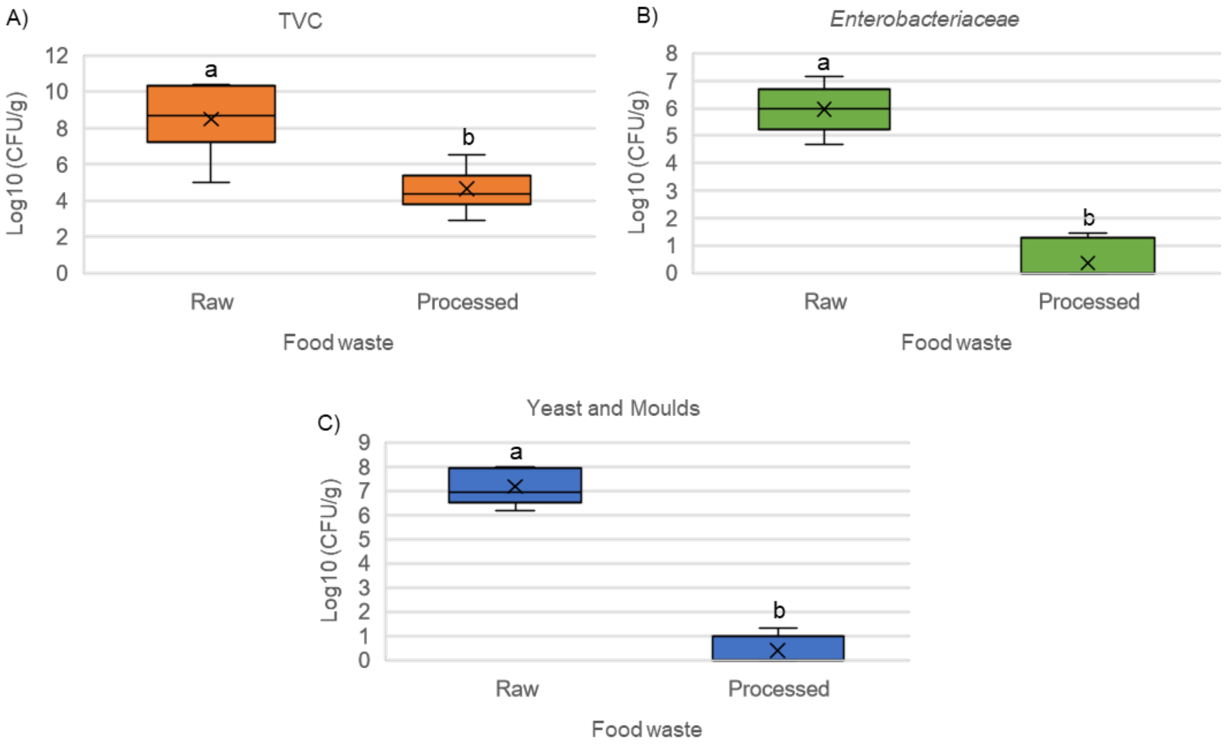

Figure 5: Microbial load of fresh and processed food waste. A) TVC, B) Enterobacteriaceae, C) Yeast and moulds. Treatments with different superscripts are significantly (P<0.0001) different.

Phosphorous and calcium levels varied amongst the 11 batches of processed dry feed ingredient. The range in phosphorus was 4,800-32,200 mg/kg (mean ± SEM; 13,777 ± 3,284) and the range in calcium was 3,560-63,200 mg/kg (mean ± SEM; 25,406 ± 6,797). The final composite food waste feed ingredient had a calcium level of 23,600 mg/kg and a phosphorus level of 12,900 mg/kg giving a Ca:P ratio of 1.8:1.

The minimum and maximum levels for sodium, various nutrients, moisture and energy observed amongst the various batches of process dry feed ingredient are shown in Table 6. The composition observed in the final composite dry feed ingredient used in the feeding trial is also shown. Fructose, glucose, sucrose and maltose were the main sugars observed in the treated food waste ingredient. In the composite food waste ingredient fructose and glucose represented 51% and 25% of the sugars, respectively. In the composite food waste ingredient saturated fats represented 42% of the total fat composition (Table 6).

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Table 6: Nutrient analysis (as is) of dry feed ingredient

Nutrient analysis	Minimum	Maximum	Final
Sodium (mg/100g)	90	670	427
Total sugar (g/100g)	<1	21	5.5
Moisture (g/100g)	2	6.3	4
Total fat (g/100g)	5.4	35	14.8
Saturated fat (g/100g)*	1.5	12	6.2
Protein (g/100g)	6.8	43.2	26.1
Ash (g/100g)	3.7	20.6	9.4
Carbohydrate (g/100g)	6	80	46
Energy (kJ/100g)	1,580	2,090	1,770

* Saturated fat analysis was only done on six of the 11 processed batches and the composite feed ingredient.

The fat composition of the composite food waste ingredient is shown in Table 7. Palmitic acid was the most prevalent (22%) saturated fatty acid observed in the food waste ingredient followed by stearic acid (13%). Oleic acid was the most prevalent mono-unsaturated fatty acid observed at 35%. The poly-unsaturated:mono-unsaturated:saturated fatty acid ratio was 0.3:1:1.

Table 7: Fat composition of composite food waste ingredient used in feeding trial

Fats	Level in final processed feed ingredient (g/100g)
Mono trans	0.2
Mono-unsaturated	6.2
Omega 3	0.9
Omega 6	1.1
Poly trans	<0.1
Poly-unsaturated	2.1
Trans	0.3

The amino acid profiles of the processed dry food waste ingredient also varied amongst the 11 processed batches. The minimum and maximum levels observed for each amino acid are shown in Figure 6, along with the actual levels observed in the composite feed ingredient used to formulate the experimental pig feed diet in section 2.4.1.

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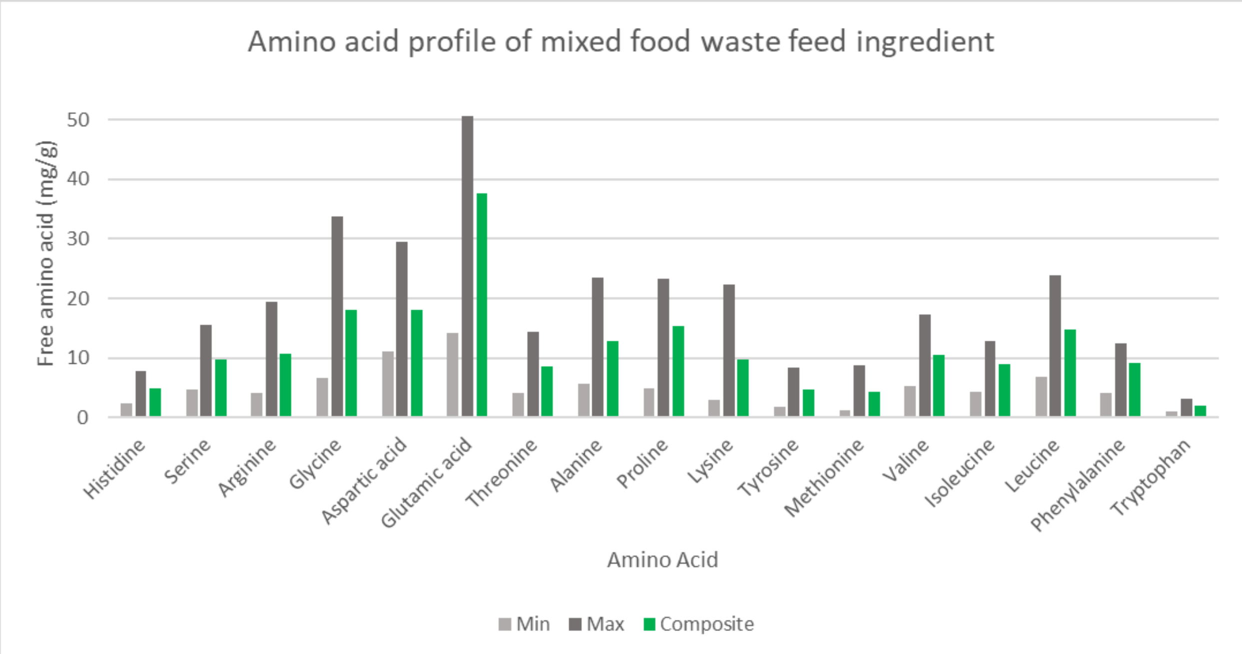

Figure 6: Amino acid profiles of processed feed ingredient from mixed supermarket food waste.

3.4 Animal production characteristics of pigs fed treated mixed human food waste

Piglet performance measures are shown in Table 8. The enteric PCR tests done on all pen faecal samples when piglets were exhibiting diarrhoea at 5 weeks of age showed that *Salmonella* spp, *Brachyspira hyodysenteriae* (nox), *Brachyspira pilosicoli* and *Lawsonia intercellularis* were not detected.

Table 8: Mean ± SEM for weaner performance measure by dietary treatment

Production measures	Control diet	Food waste diet	*P* value
Average daily gain (ADG) kg/d	0.482 ± 0.029	0.506 ± 0.031	0.575
Average daily feed intake (ADFI) kg/d	0.996 ± 0.056	0.956 ± 0.049	0.886
Feed Conversion Ratio (FCR)	1.88 ± 0.08	1.75 ± 0.07	0.253

Dietary treatment was not significantly different for both models (Model_1 *P=0.824*, Model_2 *P=0.917*) and the interaction effect of treatment by timepoint (each time the pigs were weighed) was also not significant (*P=0.91*). Both timepoint and entry weight were significantly different (P<0.001). Figure 7 shows the mean weight (kg) at each timepoint for the two dietary treatment groups over the course of the feeding trial. Final weaner weight was not significantly different between the two dietary treatment groups (control 24.60 ± 1.00 kg and food waste 24.64 ± 0.07 kg). ADG, ADFI and FCR were not significantly difference between the two dietary groups (Table 8).

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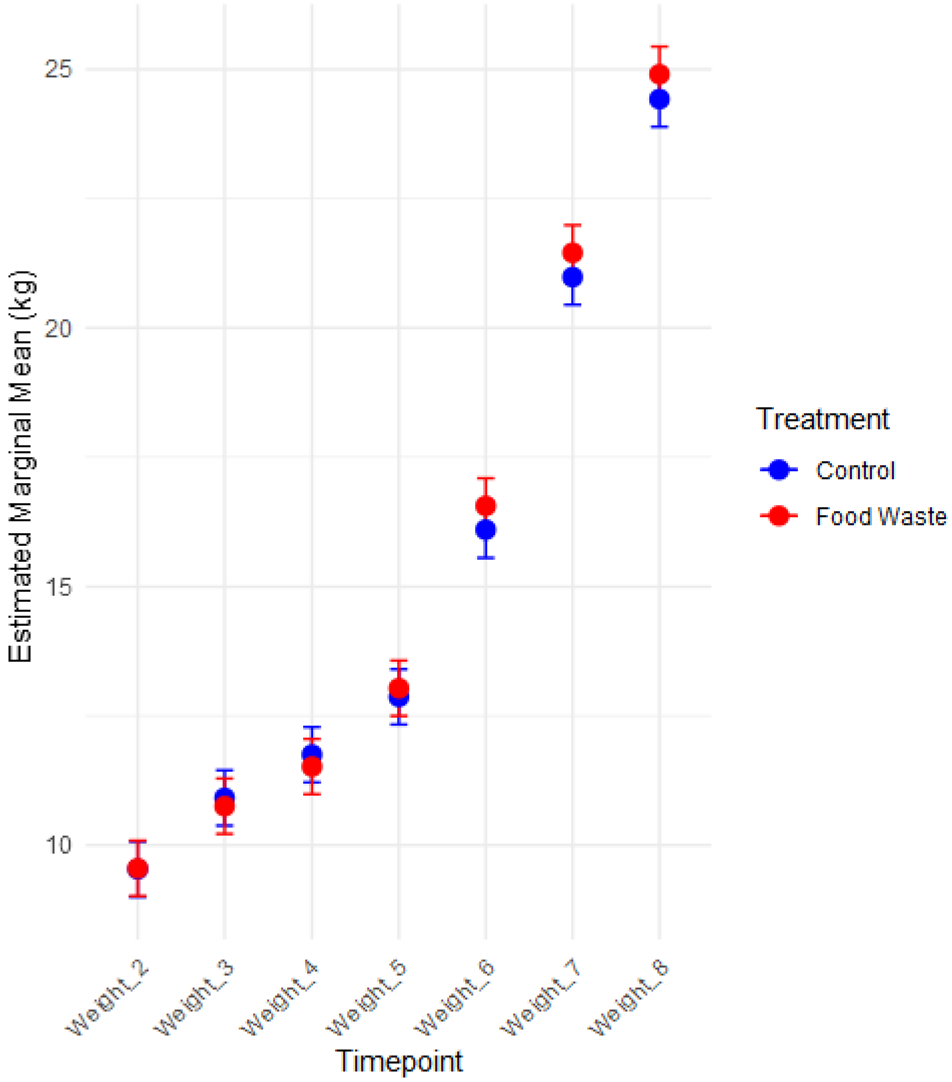

Figure 7: Mean weight (kg) at each timepoint interval for control (blue) and food waste (red) experimental groups Weight 2 = 28 days, Weight 3 = 33 days, Weight 4 =36 days, Weight 5 = 40 days, Weight 6 = 48 days, Weight 7 = 55 days, and Weight 8 = 61 days of age.

Faecal amino acid digestibility was not significantly different for piglets on the control as compared with the 20% inclusion food waste diets for any of the 17 amino acids tested (Table 9).

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Table 9: Amino acid digestibility coefficients of weaner pigs fed diets with and without a treated mixed food waste ingredient. Cont=control diet, FW= 20% inclusion food waste diet.

Amino Acid	Amino Acid digestibility coefficients			*P*
	Cont	FW	SEM	
Histidine	0.800	0.780	0.008	0.260
Serine	0.769	0.750	0.008	0.283
Arginine	0.812	0.804	0.007	0.586
Glycine	0.689	0.721	0.011	0.205
Aspartic acid	0.697	0.683	0.012	0.590
Glutamic acid	0.847	0.827	0.006	0.133
Threonine	0.687	0.690	0.011	0.878
Alanine	0.599	0.629	0.014	0.327
Proline	0.840	0.821	0.006	0.142
Lysine	0.716	0.733	0.011	0.465
Tyrosine	0.662	0.687	0.013	0.377
Methionine	0.632	0.689	0.017	0.143
Valine	0.671	0.669	0.012	0.928
Isoleucine	0.688	0.678	0.011	0.677
Leucine	0.732	0.722	0.009	0.628
Phenyl alanine	0.753	0.735	0.008	0.319
Total N	0.670	0.663	0.014	0.808

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3.5 Meat quality

The loin pH (day 7) was significantly higher for the control group (pH=5.92) as compared with the food waste treatment (pH=5.75) group (*P=0.026*) (Figure 8).

The loin cooking loss (day 7) was significantly higher for the food waste group (66.5%) as compared with the control (64.4%) group (*P=0.048*) (Figure 9).

There was no significant difference (*P=0.494*) in loin shear force measures between pigs fed a control or food waste supplemented diet (Figure 10).

There were no significant (*P>0.05*) differences in loin SRD between pigs fed a control or food waste supplement diet at t=0, 4 and 15 days. At t=8 and 11 days there were significant differences in a* (*P=0.009*) and b* (*P<0.0001*) respectively only. The L*a*b* results are shown in Figure 11.

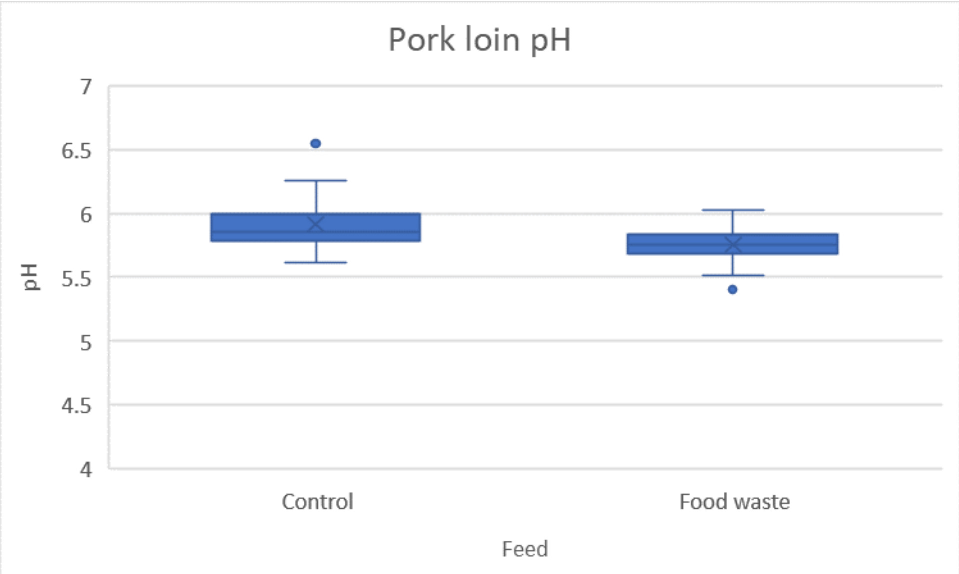

Figure 8: Pork loin pH of pigs fed a control and 20% supplemented food waste diet.

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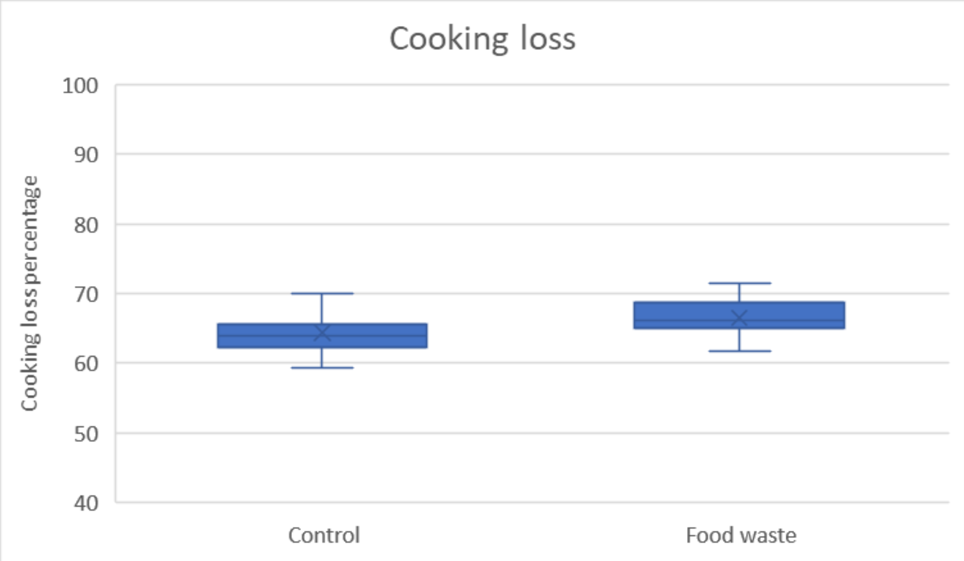

Figure 9: Pork loin cooking loss of pigs fed a control and 20% supplemented food waste diet.

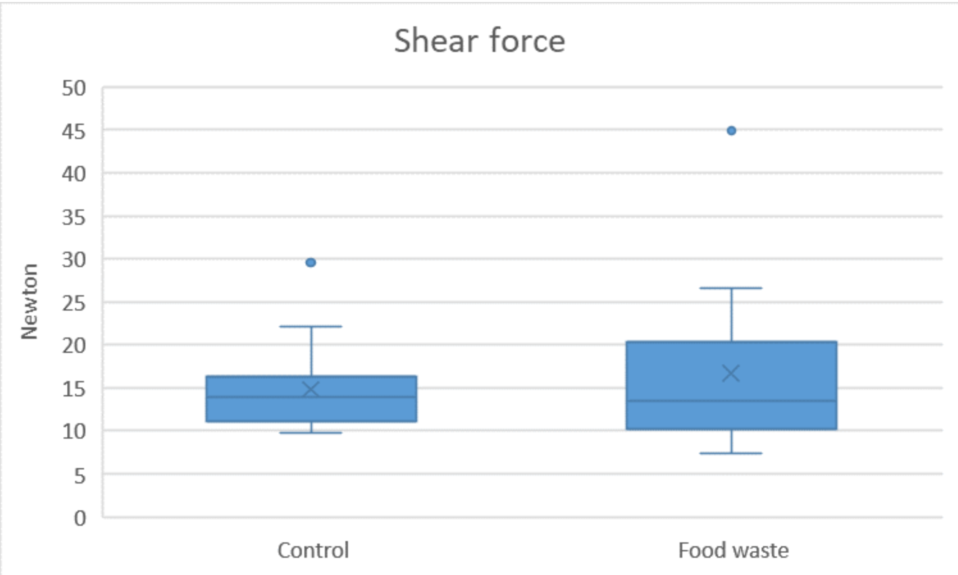

Figure 10: Pork loin shear force of pigs fed a control and 20% supplemented food waste diet.

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Figure 11: SRD of pork loin. Cont=control diet, FW=food waste diet, t=time in days exposed to SRD.

3.6 Ileal microbiota

There was no significant difference between the ileal bacterial communities of pigs fed the control or 20% food waste supplemented diet. Both alpha and beta diversity was investigated at the level of phyla, class, order, family and genus. There were also no significant differences in ileal bacterial communities amongst pigs in different pens for phyla, class and order. However, there were significant difference in ileal bacteria associated with pens at the family (R=0.176, *P=0.018*) and genus levels (R=0.189, *P=0.011*). In the pairwise comparison there were only significant differences observed between pen 1 as compared with pens 2, 3, 6, 7 or 8. There were no significant difference in any of the other pairwise pen comparisons. The non-metric MDS of ileal genera identified by diet and pen are shown in Figure 12.

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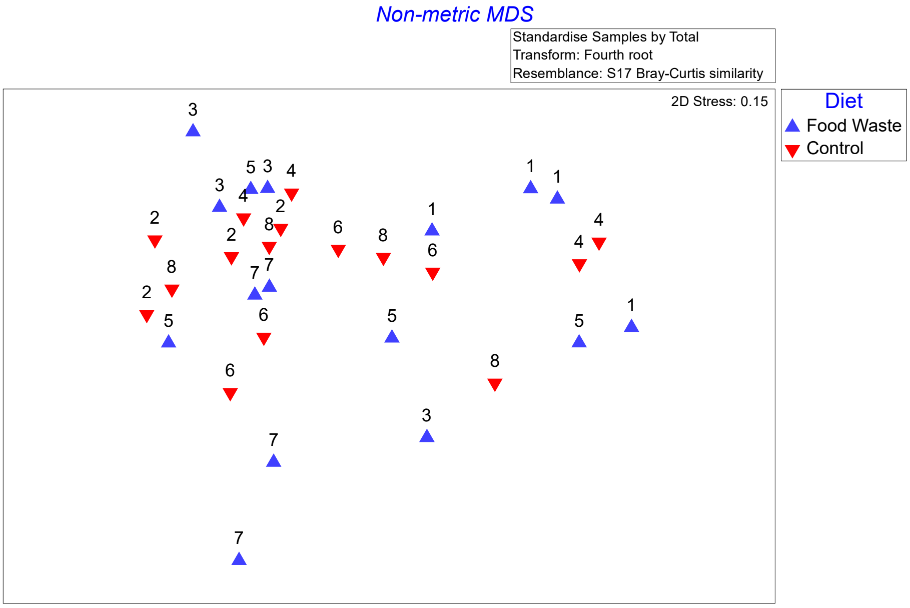

Figure 12: Non-metric multidimensional scaling ordination of ileal genera identified by dietary treatment (blue triangle = 20% food waste supplemented diet and inverted red triangle = control diet) and pen number (1-8)

The major bacterial phyla found in the ilea were Firmicutes, Campylobacterota, Proteobacteria and Bacteroidetes regardless of diet (Figure 13).

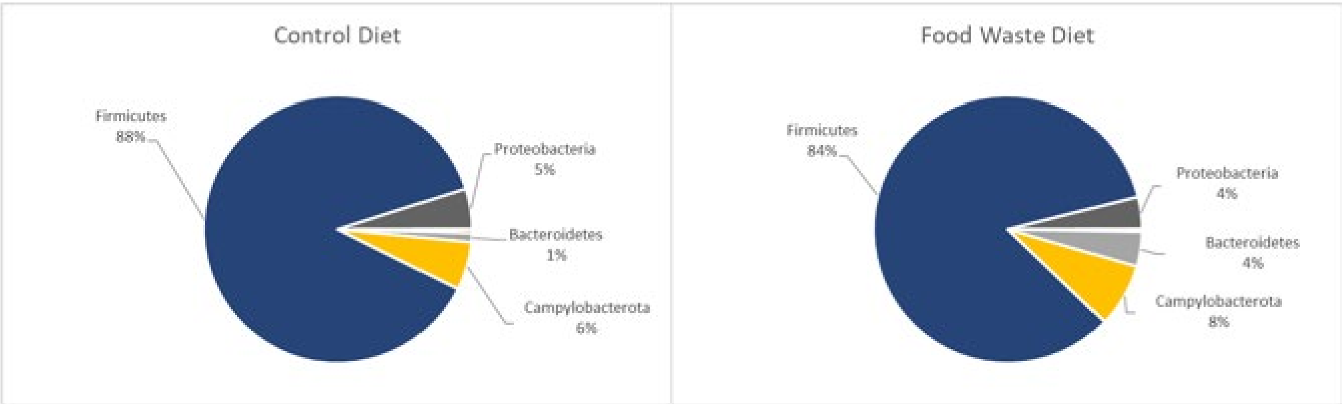

Figure 13: Ileal bacterial phyla of pigs fed a control and 20% food waste supplemented diet.

Lactobacillaceae, *Clostridiaceae* and *Peptostrepococcaceae* were the dominant families observed in the ilea. Other observed families are shown in Figure 14.

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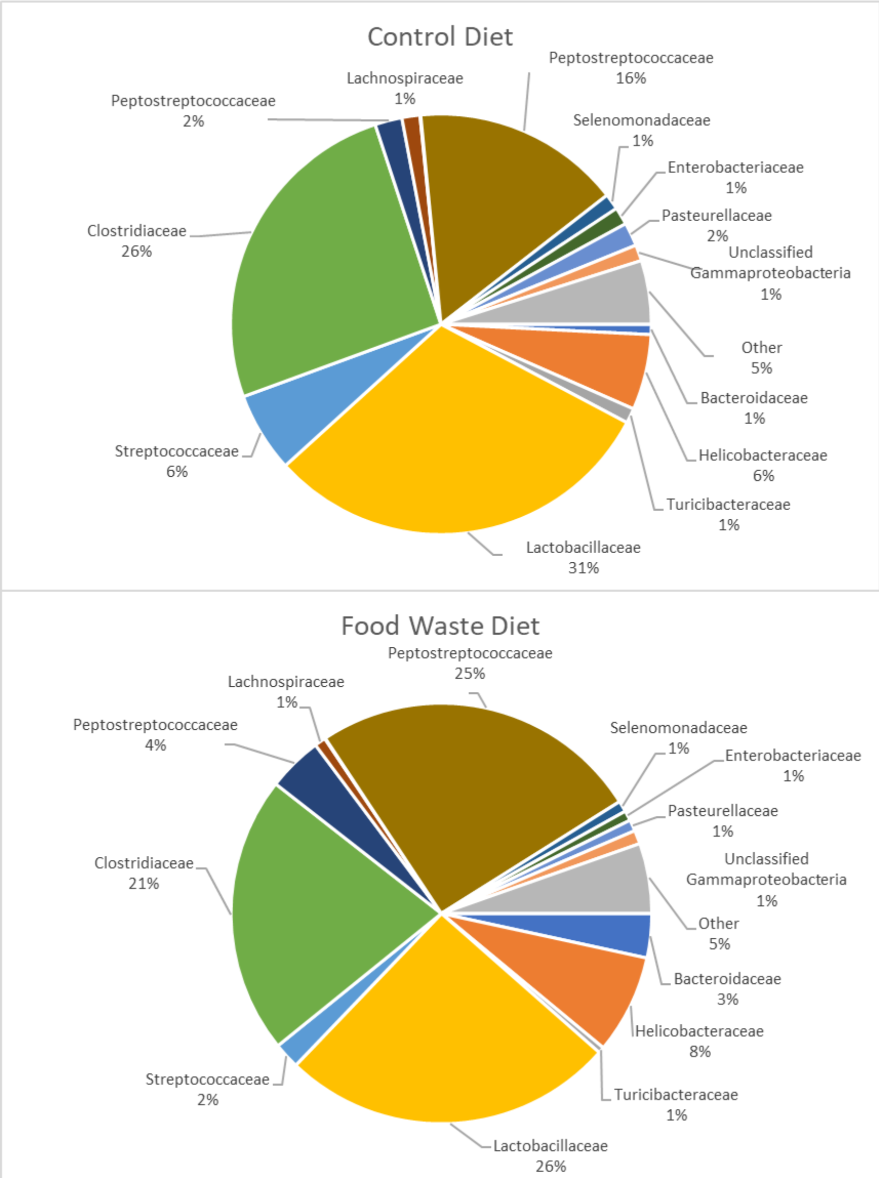

Figure 14: Ileal bacterial families in pigs fed a control and 20% food waste supplemented diet

Bacterial genera contributing to the top 50% of bacterial abundance were *Lactobacillus*, *Clostridium*, *Terrisporobacter*, *Romboutsia*, *Streptococcus* and *Limosilactobacillus*.

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4. Discussion

Globally, nations are supportive of working towards the United Nations Sustainable Development Goal 12.3 of 'by 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses' (FAO, 2020). The Food and Agriculture Organisation has recommended increased feeding of unavoidable food waste to livestock, suggesting regulatory frameworks be reviewed 'to consider the sanitary and technical requirements for including [. . .] waste from households or the food service industry into livestock feed rations' (FAO, 2017). It should be noted that the European Union has recently lifted feed bans in line with becoming a more circular bioeconomy and reduction of waste. In 2021 the European Union regulation re-authorising the use of porcine processes animal protein (PAP) in poultry feed, avian PAP in pig feed, insect PAP in pig and poultry feed and ruminant gelatine in non-ruminant feed was established (EC, 2021a). In Australia, actions to be undertaken to reduce food waste are laid out in the 'National Food Waste Strategy', 'A Roadmap for Reducing Australia's Food Waste by Half by 2030' and the 'National Waste Policy' (Australian Government, 2018; Commonwealth of Australia, 2017; FIAL, 2019). The National Waste Action Plan has created targets and actions to implement the 2018 National Waste Policy, which, in relation to food waste reduction, includes the following: establish a voluntary commitment program; develop and publish a National Food Waste Implementation Plan; halve the amount of organic waste sent to landfill by 2030; report on options to increase the recovery of organics from all waste streams; provide support to develop infrastructure solutions to process organic waste; and make comprehensive, economy-wide and timely data publicly available to support better consumer, investment and policy decisions. Currently, under the Australian National Food Waste Strategy, only elimination or reduction in the generation of food waste, redirection of safe surplus food to food rescue or relief organisations or repurposing into new food products and diversion of food waste to animal feed, including feeding insects for protein production, will be counted towards reducing food waste by 50% by 2030 (FIAL, 2021). However, Australia currently lacks the legislative framework to support uptake by both the food and livestock industries. Safe implementation would also require further investment into research, new infrastructure for waste handling and feed manufacturing facilities or development of emerging industries.

It is imperative that proper treatment of mixed human food waste and appropriate regulatory and management measures are in place if this is to be considered viable for the Australian livestock and feed manufacturing industries. Failure to do so would expose the Australian livestock industry to severe financial and reputational damage. The successful and safe implementation of a regulated EcoFeed industry has been evidenced in Japan and South Korea for decades where its establishment has been supported by regulatory policy and government funding to establish infrastructure. In 2001, Japan introduced the "Promotion of Utilisation of Recyclable Food Waste Act", which resulted in increased food waste recycling, including the recycling into Ecofeed (Sugiura et al., 2009). The law regulates the collection, transport and storage of food wastes and Ecofeed products. Furthermore, in 2007 the law was amended to make animal feed the preferred use of food wastes, above that of composting or incineration, and stipulating that companies that produce food waste purchase Ecofeed reared pork in preference to conventionally reared pork (Takata et al., 2012). The Ecofeed industry has also received financial support under the 'Grant to Create a Strong Agricultural Industry' (US$194 million) and 'Urgent Plan to Increase Ecofeed Production' (US$750 000) with certification introduced in March 2009 (zu Ermgassen et al., 2016). In 2011, certification of products from livestock reared on Ecofeed was also introduced (zu Ermgassen et al., 2016).

The opportunities and challenged of utilising food waste for livestock and associated regulatory frameworks have been reviewed internationally and within Australia (Luyckx, 2018; Luyckx et al., 2019; Torok et al., 2021). In Australia, feeding restricted animal material (RAM), defined as meat or blood products from any vertebrate animal or bird including meat meal, bone meal, bone flour, poultry meal, fish meal, and also feather meal or any part of an animal, to ruminants is prohibited and feed containing RAM needs to be identified (AHA, 2020). The ban was introduced by the Australian livestock and stock feed industries and was legislated in all states and territories of Australia in 1997. RAM-containing stock foods are permitted to be fed to pigs, poultry and other non-ruminant species as long as they have been treated by an approved process, including the following: rendering according to the Australian Standard for the Hygienic Rendering of Animal Products (AS5008:2007, 2007); under jurisdictional permit, cooking processes subject to compliance verification that ensure a core temperature of at least 100°C for a minimum of 30 min, or equivalent; treatment of cooking oil, which has been used for cooking in Australia, in accordance with the 'National Standard for Recycling of Used Cooking Fats and Oils intended for Animal Feeds'; and under jurisdictional permit, any other nationally agreed process approved by Animal Health Committee for which an acceptable risk assessment has been undertaken and that is subject to compliance verification (AHA, 2023). Animal materials are the highest-risk ingredient in mixed food waste, but the Australian rendering industry already has the technical know-how in terms of treatment and biosecurity to turn such materials into safe non-ruminant feed. As has been suggested for the European Union (Luyckx et al., 2019), the legislation and technical requirements applicable to the rendering industry should form the basis for the legislative framework for a mixed food waste to feed industry.

Research should focus on adapting treatment parameters (heat, time, pressure) for RAM so that they are adequate for mixed food waste within this legislative framework. It should be noted that there are still some Australian biosecurity risks to be addressed for repurposing mixed food waste into pig feed. Namely, the biosecurity risk posed by imported food products, in particular imported pig meat waste. In Australia, pig meat imported for further cooking destined for human consumption or storage at an Approved Arrangement is under biosecurity control and requires generated waste products to be disposed of as biosecurity waste. The waste to pig feed pathway could pose a diversion risk for this biosecurity material and would need to be managed. While many imported food products and ingredients do not pose an animal biosecurity risk, they may have become cross-contaminated with animal material during harvesting, processing or transport. Therefore, the active risk management being considered for food waste to pig feed (i.e. heat treatment at 100°C for at least 30 minutes used in our TEA) needs to include an ongoing assurance and verification program. A further biosecurity risk could be failure in the application of heat treatments, which have caused disease outbreaks overseas. This risk could also be addressed through assurance and verification programs but could also consider the application of additional heat processing or repeat processing for under processed waste. The processed food waste to pig feed ingredient is still Restricted Animal Material would require labelled according to the relevant state or territory law to mitigate the risk of diversion to ruminants.

Prior to 2021 the Japanese heat treatment requirement for EcoFeed production was 70°C for 30 min (MAFF, 2006), which was considered sufficient for the deactivation of African Swine Fever Virus (ASFV). In 2019 the World Organisation for Animal Health (OIE) acknowledged that ASFV may behave differently in swill and recommending a higher heat treatment of 90°C for at least 60 min, with continuous stirring or 121°C for at least 10 min at an absolute pressure of 3 bar (OIE, 2019). This increased heat treatment of 90°C for 60 min was legislated in Japan in 2020 and implemented in 2021 (MAFF, 2020). Our heat treatment of the mixed food waste was a minimum internal temperature of 100°C, but could reach up to 121°C, for a minimum of 30 minutes in line with Australian Health Australia (AHA, 2023). It should be noted that our heat treatment of mixed human food waste for the pilot pig feeding trial was also done under pressure of 100-200 kPa (1-2 bar), although, our heat treatment met and exceeded the Australian requirement it may not be equivalent to the OIE recommendation. The microbial load of raw food waste dropped significantly following processing into a dry feed ingredient. TVC dropped on average $\log_{10}$ 3.9 CFU/g, *Enterobacteriaceae* dropped $\log_{10}$ 5.6 CFU/g and yeast and moulds dropped $\log_{10}$ 6.7 CFU/g. Following processing the average yeast and mould, and *Enterobacteriaceae* in the milled feed ingredient was 4.6 CFU/g and 6.4 CFU/g, respectively.

The techno-economic analysis of turning mixed food waste into a pig feed ingredient in wet or dry feeding systems in five key regional Australian pig production areas showed it was viable, based on assumption of the time (Rawtec, 2022). It was cost competitive as compared with a standard grain-based reference diet in all locations (wet feed process) or in New South Wales, Victoria and Queensland (dry feed process). It is important to recognise that diets of different composition (and hence cost) are fed in Australia, therefore, outcomes may be different. The viability of these systems was stronger on the eastern seaboard where there are higher gate rates for food waste combined with larger volumes of potentially available material. Implementing this opportunity could lead to significant environmental benefits by reducing food waste going to landfill and lowering demand for conventional grain-based feed ingredients. The initiative has the potential to benefit the Australian pig industry by delivering lower cost pig feed ingredients and buffering industry against grain price volatility. A cooperative model could be setup to run these feed manufacturing facilities, which would secure feed ingredients and associated benefits for the pig industry. Introducing such an initiative is not without its challenges. There is significant competition for mixed food waste volumes, and there are practical challenges limiting the ability to secure food waste volumes. In practice, it is expected to take several years to build volumes required. The business case in New South Wales is the strongest, where the government is introducing mandated source separation of food waste by large commercial and industrial generators in 2025. A range of other policy measures could be considered by states to support the establishment of facilities turning mixed food waste into pig feed ingredients.

The treated and processed mixed food waste ingredient in this study was shown to have good nutritive value. Results pooled from 23 trials in the literature of consumption-stage food waste for livestock feed showed the mean and coefficients of variation (CV) for major nutritional parameters; 21.7% (CV 25.0%) dry matter, 19.2% (CV 24.5%) crude protein, 6.2% (CV 44.1%) crude fibre, 21.5% (CV 33.3%) ether extract lipids, 38.6% (24.5%) nitrogen-free extract carbohydrates and Ca:P ratio of 2.3:1 (CV 77.8%) (Dao et al., 2019). In Japan, dehydration (heating, fermentation and fry cooking) treatment of mixed food waste is preferred (Lane and Hoban, 2017). Despite fluctuations in the nutritional content of individual food waste products, collection and combination from a variety of waste sources results in dehydrated feed products with a consistent nutritional composition (Kawahima, 2004). The certified nutritive value of dried food waste for monogastric production in Japan is 23.4% crude protein, 9.7% ether extract, 4.5% crude fibre, 83.1% total digestible nutrient value and a dietary energy of 15.33 MJ/kg dry matter (Kawahima, 2004). To be EcoFeed certified, animal feeds must contain more than 20% food waste with at least 5% of the entire feed made up by promoted food wastes (noodle debris, plate scraps, waste oil and coffee grounds). Our composite mixed food waste ingredient had 26.1% crude protein, 46% total carbohydrate, 14.8% total fat, Ca:P ratio of 1.8:1 and dietary energy 17.70 MJ/kg. The pilot weaner feeding study incorporated 20% of this processed food waste ingredient in the diet.

Japanese dehydration temperatures used to treat mixed food waste for EcoFeed have ranged from 70°C to 230°C, with higher temperatures conferring greater security of sterilisation, but also a greater risk of denaturing proteins which reduces nutritive value (Kawahima, 2004). The Maillard reaction is an integral and unavoidable part of feed manufacturing. It has been repeatedly demonstrated that thermal over-processing of high-protein materials reduces lysine bioavailability, depending on temperature levels and the duration of heat application (Mavromichalis, 2015). Destruction of lysine is accomplished in two ways. Firstly, lysine is bound to sugars, forming early-Maillard reaction products. At this stage lysine is still detectable in chemical assays but no longer bioavailable. Secondly, the formation of late-Maillard reaction products, such as melanoides, reduces the amount of chemically analysed lysine (Mavromichalis, 2015). Although the amino acid levels in the 20% food waste supplemented weaner feed was higher than in the control diet, it is unknown to what extent bioactive lysine was impacted as a result of the sterilisation and drying of the mixed food waste. Reactive lysine was not measured in this study although it should be noted that there were no significant impacts of the food waste supplemented diet on weaner production.

No significant differences were observed in weaner weight gain and faecal amino acid digestibility between pigs fed a control and 20% food waste supplemented diet for 28 days. Not all amino acids within a raw material are necessarily available to the pig, and in this regard, ileal digestibility of amino acids is a better indicator than faecal digestibility. Ileal digestibility was not able to be done in this study. Moreover, factors including fibre (content and type), processing methods, and anti-nutritional factors can limit the availability of amino acids to the pig (Australian Pork Limited, 2017). The higher fibre level of the food waste supplemented diet, thermal treatment of the food waste ingredient and potential anti-nutritive facts present in the food waste stream, did not appear to have an impact on weaner performance at a 20% inclusion level. Nevertheless, there were some differences observed in the

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calculated versus analysed levels of some dietary components, but collectively, the mixed food waste product showed promise in being incorporated into a diet. Although there was a 0.3 MJ difference in the calculated digestible energy content of the diets, this made no difference given the lack of contrast in production between the two diets.

Several objective measures were undertaken to investigate meat quality of pigs fed the control commercial weaner diet and the 20% supplemented food waste diet. Shear force and cooking loss are both pseudo measure of meat tenderness. While there were no significant differences associated with shear force measures in this study, the pigs fed the food waste supplemented diet had a significantly higher cooking loss than the control diet fed pigs, which may indicate that their meat is less tender.

Meat pH is also a measure of meat quality. Post slaughter, muscle glycogen is broken down to produce lactic acid instead of supplying energy. This lactic acid lowers the muscle's pH and increases its acidity. Approximately 24 hrs after a healthy, well-fed, rested pig has been slaughtered, with minimal stress, the pH of muscle declines from pH 7.2 in the live animal to between pH 5.5–5.8 (Australian Pork Limited, 2017). The extent and rate of acid production can have an impact on meat colour, texture, tenderness, juiciness, flavour, water-holding capacity and shelf-life. Meat with low glycogen stores have a high pH causing it to be dark and less stable in colour. High pH (6.0 or higher) meat will spoil quicker than meat with a pH of 5.3 to 5.7. Furthermore, high initial levels of bacterial contamination on the surface of the meat will reduce the storage life because spoilage numbers of bacteria are reached sooner. The pork loins from pigs fed food waste had a significantly lower pH (5.8) than pigs fed the control (5.9) diet, indicating potentially better meat quality of the food waste fed pigs. However, it should be noted that our pH measurement was taken at day 7 post-euthanasia as opposed to 24 hrs post-slaughter which is normal industry practice. The loin sample collection was also not done under the same conditions as would be standard in an abattoir due to the experimental nature of the feeding trial. Despite a significant difference in loin pH overserved, there were minimum differences observed in SRD, a pseudo measure for shelf life. At day 8 and 11 of the SRD there were only significant differences in a* (redness) and b* (yellowness), respectively between loins from pigs fed a food waste supplemented diet and the control weaner diet. While objective meat quality measurements provide valuable insights, sensory evaluation by humans remains essential for assessing overall eating quality. Flavour, tenderness and juiciness are the main qualities influencing a consumer's experience of pork (Australian Pork Limited, 2017).

The firmness or softness of fat tissue is influenced by the fatty acid composition, principally the proportion of saturated and unsaturated fat acids present (Australian Pork Limited, 2017). Changing the type and quantity of oil in the feed can alter the fatty acid composition in pig fat and muscle tissues. When manipulating the fatty acid profile of pork fat, a 4-6 week period is required on the necessary diet to observe the profile changes (Australian Pork Limited, 2017). Whilst increasing the polyunsaturated: saturated fatty acid ratios in meat for human health reasons has attracted interest, this can reduce the shelf stability of the product. Off-flavours are most apparent in pigs fed unsaturated oils (e.g. canola oil), and there is more risk of rancid meat and off-flavours when large amounts of fish oil are used (Australian Pork Limited, 2017). The processed food waste ingredient used in the feeding trial had a poly-unsaturated:mono-unsaturated:saturated fatty acid ratio of 0.3:1:1 with the dominant fatty acids being palmitic (22%), stearic (13%), oleic (35%), omega 3 (6.3%) and omega 6 (7.5%). The impact of this on flavour profile was not investigated in the current study.

There were no significant differences in ileal microbiota associated with dietary treatment of weaners. It should be noted that all pigs were treated with oral antibiotics at day 4 of the experiment due to diarrhoea. This would have impacted the gut microbiota of all pigs, however, following withdrawal of antibiotics pigs received their allocated dietary treatment for a further 2 weeks which should have enabled the impact of dietary treatment to be observed. Significant differences in ileal bacteria associated with pens at the family and genus levels were observed between pen 1 as compared with pens 2, 3, 6, 7 or 8; no other significant pairwise pen differences were observed. This observation may have been impacted by pen configuration in the research facility but was not associated with dietary treatment.

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5. Conclusions & Recommendations

The techno-economic feasibility of utilising mixed food waste for the pig industry has been demonstrated in five key production regions for wet and dry feeding systems. However, regulatory frameworks would need to be developed to ensure safe production of such a feed ingredient to maintain Australia's high biosecurity standards, and assumptions used in this initial assessment would have to be retested in any future assessments. The processing (heat treatment) of the mixed food waste significantly reduced the microbial load in the finished feed ingredient, reducing *Enterobacteriaceae,* and yeasts and moulds to <10 CFU/g each. Feeding a processed mixed food waste ingredient at 20% inclusion did not adversely impact performance in a pilot feeding study. Objective meat quality and gut health paraments were also not negatively impacted.

To further utilise findings of this research the following is recommended:

- Gain a better understanding for the appetite of industry to engage further in exploring an EcoFeed type industry.
- Science based regulatory frameworks need to be developed to enable the food and livestock industries to engage more easily in becoming more sustainable.
- Further research is required to explore long-term effects of feeding food waste on pig production at a commercial scale.
- Further research is required to explore long-term effects of feeding food waste on pig meat quality, sensory evaluation and consumer acceptability.

6. Impact and Ongoing Monitoring

Impacts of the project will only be realised if regulatory frameworks are developed to enable utilisation of food mixed waste by the pig industry in a safe and bio-secure manner. This may include financial support for the establishment of certified infrastructure to transform mixed food waste into a safe feed ingredient. Ongoing monitoring is beyond the scope of this project. We have demonstrated both the technical and economic feasibility of utilising mixed food waste into pig feed at a high level, but have also highlighted the challenges, knowledge gaps and need for more research.

If an Australian EcoFeed industry were to be established for the pig industry the potential impacts would be:

- Food waste reduction: A reduction of 373,000 tonne/pa of mixed food waste from commercial and industrial sources. If all this material was utilised it would represent a 5% reduction in Australia's food waste volumes, achieving 10% of the national reduction target (50% reduction by 2030).
- Industry profitability gained: Production of mixed food waste to a pig feed ingredient was cost competitive with a reference diet comprising 70% wheat and 30% canola in wet feeding systems in all pig production regions investigated and in dry feeding systems in New South Wales, Victoria and Queensland.
- Greenhouse gas emission savings: Overall significant greenhouse gas emissions savings would be expected from food waste not rotting in landfill, reduced emissions from grain production and transport, and reduced emission from land use changes required to produce more grain for the livestock industry. The latter two are significant greenhouse gas emission inputs for pig meat production (Poore and Nemecek, 2018). We estimated, based on assumptions at the time, that the mixed food waste volumes identified would satisfy 6% of the demand for grains used for pig feed in Australia. It is acknowledged that there would be greenhouse gases produced in the thermal processing of mixed food waste required to turn it into a safe pig feed ingredient. It has been estimated that by using half of the surplus food from the EU retail, manufacturing and catering sector (equivalent to 14 million tonnes) to replace pig feed, it would result in an estimated

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greenhouse gas emission reduction of 5.8 million tonnes of CO_2 equivalent per year (Luyckx et al., 2019). This estimate was based on current pig farming and waste handling conditions in France and the UK, but did consider the environmental cost of heat treatment necessary to render feed safe. Furthermore, it has been estimated that feeding food waste to the global population of pigs reared in intensive production systems would increase nitrogen-use efficiency, reduce nitrogen losses at the production stage, and achieve savings of 31 million tonnes of soybeans and 20 million tonnes grain, equivalent to 16 million hectares of land use (Uwizeye et al., 2019).

- Circular economy jobs created: New jobs would be created for staff managing and operating the established EcoFeed facilities. It is estimated that 6 facilities could be supported in Australia, each capable of processing 20,000 to 80,000 tonnes of mixed food waste per annum.

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