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AUSTRALIAN Pork

Emission Reduction Opportunities Gap Analysis

Final Report
APL Project 2026/0009

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Integrity Ag
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Executive Summary

The Australian pork industry has achieved a reduction of more than 70% in greenhouse gas (GHG) emissions per kilogram of pork since 1980, primarily through enhanced productivity and the implementation of advanced technologies. The industry has a strong knowledge of baseline emissions, emission sources and potential mitigations. However, mitigation has slowed in the most recent decade because the low-cost options have largely been implemented. While progress historically has been impressive, there are now new expectations for all sectors to contribute to the Nationally Determined Contribution (NDC).

This project, funded by Australian Pork Limited (APL) and supported by the Australian Government through funding from the Carbon Farming Outreach Program, was commissioned to deliver a comprehensive gap analysis of emission reduction opportunities. The aim was to identify knowledge gaps, barriers, enablers, and collaborative opportunities to accelerate on-farm emission reductions. This is a first step to developing new materials that will assist industry deliver emission reductions over the next one to two decades and as such, is a strategic project for industry in the coming years.

Methodology

The analysis combined a thorough literature review with extensive stakeholder engagement, including workshops and producer case studies. The review covered Australian and international research, industry reports, and extension materials. Stakeholder input was gathered from producers, industry representatives, researchers, and government, ensuring the findings reflect both technical evidence and stakeholder insights.

Key Findings

The pork industry has clear technical solutions that can deliver significant abatement for the nation and is well placed to be a leader within agriculture. However, progress has been stalled because of a series of defined barriers. The leading opportunity is expanded adoption of covered anaerobic ponds (CAPs). The key barriers, confirmed though the technical review and consultation, are financial (high capital costs and low returns on investment making it difficult for the industry to invest in capital upgrades), alignment challenges with the ACCU scheme (additionality), uncertainty in optimal design (to maximise biogas yields and minimise construction costs), and shortages of personnel with technical capability.

Other major mitigation opportunities also have significant barriers and / or are associated with core knowledge gaps. Short hydraulic retention time (sHRT) systems, solids separation, and pond additives to reduce methane emissions show promise as lower-cost solutions to CAPs but require more demonstration and policy support. Pond additives would also benefit from further research into optimal dosing rates, their cost-effectiveness, and any regulatory barriers (e.g., potential adverse effects on effluent irrigation). Although fossil energy typically represents a smaller proportion of on-farm emissions relative to manure methane, there are a number of emerging or potential opportunities to generate renewable energy on-farm (e.g., ground-source heat pumps, combined cooling, heating, and power units, displacement of diesel with biomethane) that warrant further investigation and or would benefit from co-funding arrangements to support early adopters which could then act as case studies and demonstration sites. Collaboration with other agricultural sectors (dairy, poultry, grains, feedlot) can accelerate research and adoption, especially in effluent management, feed innovation, and alternative energy generation.

Significant knowledge gaps exist in the measurement and benchmarking of GHG emissions from covered ponds, secondary ponds, and alternative manure management systems. Barriers to technology

adoption include high capital costs, lack of in-house expertise, complex regulatory requirements, and barriers associated with compliance with the ACCU Scheme, which has been and continues to be a key enabler for adoption of some mitigation technology for the sector. There is a shortage of up-to-date, producer-facing resources and case studies, particularly for emerging emission reduction strategies and technologies.

From the industry engagement, key findings included that gaps exist in tools, processes and personnel associated with data capture, benchmarking tools, and tools for quantifying and tracking progress, supporting reporting, and informing investment. Decision support tools that integrate financial and environmental outcomes will enhance adoption by aligning emission reduction with productivity and cost savings.

Recommendations

The project identified over 70 separate recommendations which are documented in the report (see specifically Table 2) and the matrix file. Whilst there are numerous opportunities for collaborative research, extension development, and producer engagement to drive on-farm emission reduction, the main themes of the recommendations are summarised here.

- The need for resources that better integrate the cost-of-production implications associated with on-farm emission reduction (benefits and costs)
- The need to build industry capacity (and available resources) to improve management of CAPs, reduce construction costs through standardised / optimised design
- The need for ongoing research into lower-cost alternatives to CAPs whilst also assessing and where relevant mitigating potential trade-offs (e.g., other environmental risks, management challenges, land requirements)
- The need for more demonstration sites and real-world case studies (including cost-benefit analyses, trade-offs, learnings) of novel and emerging technologies (e.g., sHRT, integrated effluent treatment trains, ground-source heat pumps)
- A desire for a greater focus on what industry are doing right (e.g., as a low margin industry, continually striving for improvements in production efficiency) and what this means financially as well as in terms of GHG emissions
- The need for core research to measure GHG emissions from key emission sources, refine current National Inventory methods, and improve confidence in GHG emission accounting at farm- and product-level.
- The need to foster cross-industry research, development, and solutions (e.g., low emission grain supply chains, centralised food waste processing)
- The need for online tools and resources that better support producers to measure and track their emissions whilst also integrating scenario analysis to help assess the effects of technology adoption or management changes on GHG emissions. A GHG emission specific online database of resources would also be valuable.

Conclusion

This gap analysis provides a clear roadmap for research, extension, and collaboration to drive the next phase of emission reduction in the Australian pork industry. Addressing the identified gaps and barriers—while leveraging enablers and cross-sector partnerships—will be critical to achieving industry and national climate goals.

Table of Contents

Acknowledgements **2**

Executive Summary **3**

1. Background to Research **9**

2. Objectives of the Research Project **10**

3. Introductory Technical Information **11**

3.1 Industry Carbon Account *11*

3.2 Industry Carbon Footprint *11*

3.3 Notable GHG Emission Reduction Research for the Australian Pig Industry *12*

4. Research Methodology **15**

4.1 Literature Review *15*

4.1.1 Development of Matrix 16

4.2 Stakeholder Engagement *16*

4.2.1 Industry Workshop 16

4.2.2 Case Studies 16

4.3 Other Activities *16*

5. Results **18**

5.1 Gap Analysis *18*

5.2 Stakeholder Engagement *30*

1.1.1 Industry Workshop 30

2.1.1 Case Study Workshops 31

6. Discussion **32**

6.1 Covered Ponds *32*

6.2 Other Opportunities to Reduce Emissions from Uncovered Ponds *34*

6.2.1 Short Hydraulic Retention Time 34

6.2.2 Solids Separation 35

6.2.3 Pond Additives 36

6.2.4 Effluent Treatment Train (complimentary technologies) 36

6.3 Energy *36*

6.4 Collaboration Potential *37*

6.5 General Needs for Emission Reduction Resources *37*

6.6 Improving Data Capture *38*

7. Producers **38**

8. Industry **38**

9. Recommendations **40**

10. Intellectual Property **43**

11. Literature Cited **44**

12. Publications Arising **48**

List of Tables

Table 1. Sectoral (Scope 1 & 2) and total attributable emissions (Scope 1, 2 and 3 incl. LU and dLUC) for the Australian pork industry for FY20 and FY22 (from Copley et al. (2024)) 11

Table 2. Summary matrix 19

List of Figures

Figure 1. Changes in GHG emissions (including LU and dLUC) from the production of 1 kg of liveweight pork over the period 1980-2022 (from Wiedemann et al. (2024)) 12

Figure 2. GHG mitigation options for Australian piggeries (from Wiedemann et al. (2021)) 14

1. Background to Research

The Carbon Farming Outreach Program (CFOP) was developed to support Australia's agriculture and land sectors in reducing emissions and to contribute to the Federal Government's target of achieving net zero greenhouse gas (GHG) emissions economy-wide by 2050.

The objectives of the program are to:

- Support farmers and land managers to make decisions to reduce emissions and sequester carbon.
- Build capacity of trusted advisers to deliver independent advice on reducing emissions and sequestering carbon.
- Facilitate access to clear, consistent and culturally appropriate information on carbon farming, low emission technologies and practices.

Other relevant components of this program are the establishment of a 'knowledge bank' to integrate existing training and resources with new tailored resources, and to support Rural Research and Development Corporations (RDCs) to develop commodity-specific information for the knowledge bank to enable faster adoption of lower emission solutions.

The Department of Agriculture, Fisheries and Forestry (DAFF) provided $1.5 million in grants to the RDCs, including Australian Pork Limited (APL), to assist in developing the knowledge bank (DAFF, 2025). APL have funded this project via the grant received from DAFF, and this report delivers the outcomes specified in the Commonwealth Simple Grant Agreement – 2024 for the Activity: *Gap Analysis of Emissions Reduction Information Opportunities Through Manure Management Systems and Feed Inputs for Australian Pork Production*.

2. Objectives of the Research Project

The objectives of this project were to:

1. Identify gaps in available pork specific information for emissions reduction opportunities, including manure management systems and feed inputs.
2. Identify barriers & enablers for technology adoption.
3. Identify opportunities for further collaborative research.
4. Develop case studies of emission reduction screening and planning, considering different manure management systems and geographical differences.
5. Identify opportunities for improved data capture for industry emissions reporting.

3. Introductory Technical Information

3.1 Industry Carbon Account

GHG emissions, including Land Use (LU) and direct Land Use Change (dLUC), for the Australian pork herd were determined for the 2020 and 2022 financial years, (FY20 and FY22) and are reported in Table . Emissions from manure management systems (MMS) contributed 80% of sectoral emissions (Scope 1 and 2) in FY22, with the remainder of the industry carbon account being enteric methane (10%), grid electricity (7%) and other fossil energy related emissions (3%) (Copley et al., 2024). Between FY20 and FY22, sectoral emissions increased by 10% due to industry expansion.

Table 1. Sectoral (Scope 1 & 2) and total attributable emissions (Scope 1, 2 and 3 incl. LU and dLUC) for the Australian pork industry for FY20 and FY22 (from Copley et al. (2024))

	Units	**National Herd FY20**	**National Herd FY22**
Scope 1 - Enteric methane	tonnes CO_2-e	96,199	103,453
Scope 1 - Emissions from MMS	tonnes CO_2-e	767,603	848,959
Scope 1 - Emissions from energy	tonnes CO_2-e	29,684	33,574
Scope 2 - Grid electricity	tonnes CO_2-e	76,735	77,509
Sectoral emissions (Scope 1 and 2)	tonnes CO_2-e	970,221	1,063,495
Scope 3 - Emissions from energy & grid electricity	tonnes CO_2-e	17,422	17,024
Scope 3 - Feed and transport	tonnes CO_2-e	579,422	674,113
Scope 3 - LU & dLUC	tonnes CO_2-e	229,804	161,029
Total attributable emissions (Scope 1, 2 and 3 incl. LU & dLUC)	tonnes CO_2-e	**1,796,869**	**1,915,661**

Scope 1 & 2 emissions accounted for more than half (55%) of the total emissions attributable to pork production. The next greatest source, feed related emissions (incl. LU and dLUC), represented 44% of the total attributable emissions.

3.2 Industry Carbon Footprint

The product carbon footprint of Australian pork production has fallen by 78% since 1980 (Figure 1). This is attributable to improvements in production efficiency and adoption of technology, particularly covered anaerobic ponds (CAPs) which saw emissions from MMS fall from 8.2 kg CO_2-e/kg LW in 1980, to 1.5 kg CO_2-e/kg LW in 2022, equivalent to a reduction of 82% (Wiedemann et al., 2024).

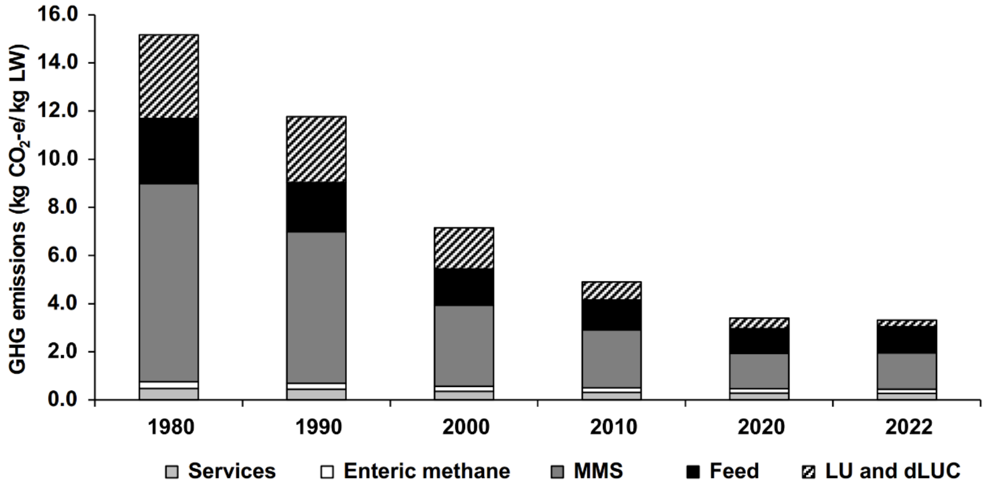

Figure 1. Changes in GHG emissions (including LU and dLUC) from the production of 1 kg of liveweight pork over the period 1980-2022 (from Wiedemann et al. (2024))

3.3 Notable GHG Emission Reduction Research for the Australian Pig Industry

This section summarises previous foundational emission reduction research for the Australian pig industry.

Skerman (2013) monitored the performance of a partially covered pond, with a biogas-fired water heating system and scrubber installed at a Queensland piggery for approximately one year. The study found that biogas generation was sufficient to supply ~64% of the total annual heating energy required for the farrowing shed, resulting in a saving of $31,776 per year in LPG costs (as reported). The study also concluded that the installation of an effective scrubbing device (to remove hydrogen sulphide) could extend the working life of the hot water system (and other components), whilst making the biogas more suitable for a range of productive applications.

Pork CRC Project, *Pathways to Carbon Neutral Pork Production* by Murphy et al. (2013), investigated the technical and practical feasibility of a range of on-farm piggery emission reduction options. Mitigation options were screened by a farmer advisory group, after which a series of CAP-CHP systems were modelled in combination with other strategies, including:

- Low GHG diets: replacement of imported soybean meal with canola meal and Australian soybean meal.
- Low nitrogen diets: reduced crude protein, amino acid supplements & lysine additives.
- Further treatment in a secondary pond: limiting hydraulic retention time (HRT) to 47 days.
- Optimised effluent storage and utilisation: direct irrigation from secondary pond for 70% of year and high nutrient utilisation of effluent from crops, generating an emissions offset by replacing synthetic fertilisers.
- Soil carbon sequestration: land application of effluent or sludge.

The project also described variations in payback periods and financial viability, reiterating that covering ponds and making changes to effluent management could be cost effective for a portion of industry, but that modifying diets was likely to result in an increase in cost-of-production for all producers. Overall, the project highlighted key barriers and enablers to adopting modelled mitigation options on-farm and laid the foundation for further research on emission reduction options for industry.

In 2013, the Bioenergy Support Program (BSP) was formed by the Pork CRC to promote and support the uptake of biogas across the Australian and New Zealand pork sectors. Learnings at the demonstration piggeries were instrumental to enable the BSP and APL to work with the federal government and refine a Carbon Farming Initiative (CFI) Method (Tait, 2016).

The PigGas Extension Project calculated baseline GHG emissions for 55 piggeries, which at the time, accounted for about 24% of Australia's pork production (APL, 2025). For each site, mitigation opportunities were considered, with GHG emissions reported under both the baseline and mitigation scenarios. Mitigation opportunities included covered anaerobic ponds, energy generation from biogas, feed waste reduction, strategic use of deep litter, solids separation, renewable electricity generation from solar, more efficient feeders, daily effluent spreading, and desludging and removal from site (Kruger, 2015). Emission reduction potential varied significantly. One piggery had the opportunity to reduce emissions by 84%, while another had no viable options for reducing site emissions (Kruger, 2015). This highlights an ongoing challenge (not unique to pig production), where highly efficient production systems have addressed and implemented all feasible direct mitigations but still face unavoidable biological emissions (e.g., manure related emissions, enteric methane).

A study comparing methane, nitrous oxide, and ammonia produced from deep litter housing (with or without stockpiling) to conventional housing with uncovered effluent ponds found that GHG emissions were 66% to 80% lower in the deep litter system than the conventional system (Phillips et al., 2016). This research confirms that litter-based systems offer a lower-emission alternative to conventional housing with uncovered anaerobic ponds.

McGahan et al. (2016) measured methane, nitrous oxide, and ammonia emissions from a short HRT (sHRT) tank and a conventional (long-HRT) uncovered anaerobic pond. GHG emissions were found to be 79% lower from the sHRT system than the uncovered pond. This confirmed (in the Australian context) that sHRT systems are a technically feasible lower-emission manure management system. Subsequently, a producer-facing guide was developed to demonstrate how sHRT systems could be implemented across a variety of production systems and climates (McGahan, 2024c). Key advantages of sHRT over CAPs outlined in the guide include lower capital investment and less nitrogen loss, effectively increasing the value of effluent. Conversely, this can be a disadvantage as more land area is required for irrigation. A major challenge is that optimal performance of sHRT systems may be limited to specific climatic zones in Australia.

In 2018, only two emission reduction methods related to piggery manure management (both involving methane destruction) were eligible for registered Australian Carbon Credit Unit (ACCU) projects under the Clean Energy Regulator (CER). Watson et al. (2018) developed technical material to support the creation of additional Emission Reduction Fund – ERF (now ACCU Scheme Project) methods, including sHRT effluent systems and deep litter housing, when used in preference to conventional housing with long-HRT effluent treatment. The technical specifications for solids separation and sHRT systems were developed for the *Animal Effluent Method,* with solids separation being included in a 2019 update of the method.

The *Low Carbon Emission Roadmap for the Australian Pork Industry* was developed by Wiedemann et al. (2021) in response to growing pressure to reduce GHG emissions from agriculture, reviewing a long-list of potential mitigation strategies (see Figure 2). In addition to a producer-facing manual and roadmap document, the project outputs included an R&D Report for APL. This report provided an extensive and detailed list of recommendations for research, development, extension and adoption opportunities to drive emission reduction in the Australian pork industry, covering the following topics:

- Baselining, target setting and industry data.
- Short-term mitigation strategies.
- Blue sky mitigation options.
- Carbon storage.

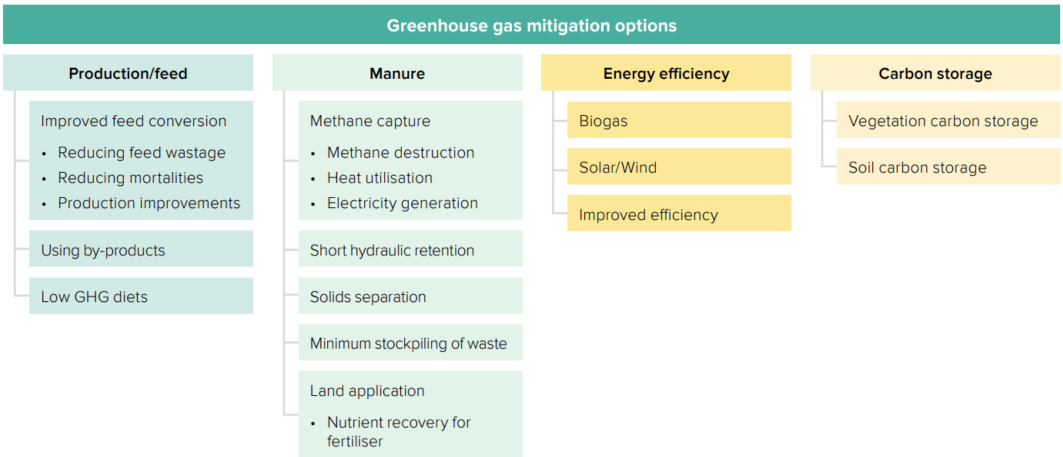

Figure 2. GHG mitigation options for Australian piggeries (from Wiedemann et al. (2021))

This project laid a strong foundation for the current DAFF-funded project by creating a central reference of emission reduction strategies for the pork industry.

In addition to the selection of past research described above, the Australian pork industry continues to investigate GHG mitigation opportunities. Recent research by Townsend & Simmons (2025), for example, assessed the feasibility and cost of formulating lower GHG diets through ingredient selection. The study found that the emission reduction potential of low GHG pig diets may be 5-15% without prohibitive increases in diet costs. Alternative available feed ingredients with lower emission intensities or changed dietary specifications were required to achieve larger reductions. In addition, George et al. (2025b) investigated the efficacy of methane abatement in uncovered effluent ponds from some commonly used coagulant-flocculants, where ferric-sulphate was found to reduce methane by 52.9%.

4. Research Methodology

This project involved two core components of work undertaken concurrently: a literature review (which formed the basis of the gap analysis) and stakeholder engagement (to supplement the gap analysis with on-ground experiences of knowledge gaps, barriers, and potential enablers identified by producers and industry stakeholders).

In the context of this project, a 'gap' refers to missing, insufficient, or incomplete publicly available information, resources, research, or guidance needed for effective decision-making, technology adoption, or practice change in emissions reduction. A gap is:

- An absence or shortfall in commodity-specific information, such as research findings, case studies, technical guides, or data, that producers, advisers, or industry stakeholders need to reduce emissions (e.g., no publicly available costings on a technology).
- A lack of clarity, consistency, or accessibility in existing resources, which may hinder adoption (e.g., studies or resources with conflicting or differing findings or recommendations).
- An area where further research, extension, collaboration, or resource development is required (e.g., an unknown or an assumption that requires validating or updating through research).

In the context of this project a 'barrier' is any factor, condition, or circumstance that impedes, restricts, or slows the adoption of technologies, practices, or systems aimed at reducing emissions. A barrier is:

- An obstacle that prevents or makes it difficult for producers, advisers, or industry stakeholders to access, implement, or benefit from emissions reduction opportunities (e.g., red tape or high levels of administration).
- A challenge that may be technical, financial, regulatory, informational, cultural, or practical in nature (e.g., high capital costs).
- Something that must be identified and addressed through research, extension, collaboration, or resource development (e.g., no standardised design or methods).

In the context of this project an 'enabler' is any factor, condition, resource, or mechanism that facilitates, supports, or accelerates the adoption of technologies, practices, or systems aimed at reducing emissions. Enablers may include, but are not limited to:

- Policy and regulatory frameworks that support innovation and adoption.
- Technical solutions that make implementation feasible.
- Financial incentives or resources that reduce the cost or risk of adoption.
- Information, training, and extension services that build capacity and awareness.
- Collaborative networks that connect stakeholders and share best practices.

4.1 Literature Review

A review of existing literature was undertaken, considering both Australian and international pig research, as well as research for other animal industries relevant to pork production (e.g., feed-related mitigation strategies, effluent, manure, and by-product management).

The scope of the literature review covered journal publications, other industry-funded research and extension materials (e.g., APL, Pork CRC projects), including Final Reports, R&D Reports, User Manuals, Case Studies, and grey literature from privately-funded projects.

A range of emission reduction opportunities for pork production (commercially available, proven, technically feasible, and blue-sky) were considered.

4.1.1 Development of Matrix

A review matrix was created to structure the literature review and allow identification of gaps. Each literature source was assessed against selected categories to identify gaps, barriers, enablers, research needs and collaborative opportunities with other industries.

4.2 Stakeholder Engagement

Extensive stakeholder engagement was conducted, and the findings integrated into the matrix, the recommendations of this report, and the other project deliverables.

4.2.1 Industry Workshop

An online workshop was held on the 8th of September 2025, to collaboratively identify and expand on the details from the literature review. Key areas of industry input were in relation to knowledge, resource, and research gaps, barriers to adoption, and potential enablers.

The attendees included key pork industry stakeholders (e.g., producers of various scales, and manure management systems) government representatives, researchers, and consultants. Meeting minutes and materials were provided to APL following the workshop.

4.2.2 Case Studies

Four producer case studies were developed to demonstrate how emission reduction principles could be applied at the farm level, and to identify knowledge gaps, barriers to implementation, and potential enablers. Two rounds of meetings were held with each of the two medium-large producer groups, and one-hour meetings were held with the two small-medium producers. These workshops ensured representation of producers across different scales, regions and levels of interest in emission reduction were considered and included in the case studies. The producers were at different stages of understanding on-farm (and value chain) emissions, and had undertaken varying levels of GHG emission assessment and on-farm emission reduction investigation.

4.3 Other Activities

Engagement was also undertaken with stakeholders from other agricultural industries to identify and discuss potential collaboration opportunities. Insights around collaborative opportunities were drawn from the following:

- MLA Project No. L.GNT.2501 – Integrated Approaches to Building On-Farm Emissions Knowledge – Gap Analysis (including stakeholder consultation process).
- Participation in cross-industry / RDC gap analysis workshops to identify horizontal collaboration opportunities (7 October and 13 November 2025).

- Ad-hoc engagement with various stakeholders (primary producers, processors/value chain representatives, RDCs, and researchers) in the egg, chicken meat, dairy, feedlot, sugar, and grains sectors.

5. Results

This chapter outlines the results of the gap analysis (presented as a matrix) and summarises key findings from the stakeholder consultation process.

5.1 Gap Analysis

Table 2 provides a summary of the gap analysis of emission reduction technologies in the Australian pork industry, drawing on the literature review and insights from the stakeholder engagement. The complete matrix has been provided as a separate file.

Table 2. Knowledge gaps matrix

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
Enteric methane (Scope 1)			
Probiotics in feed (e.g., *Bacillus* spp.)	Lack of publicly available, Australian specific research and resources on the topic. Uncertainty regarding implication for pig performance and least-cost diet formulation.	Trials in Australian context to verify pig performance and assess emission reduction potential from certain Bacillus strains and doses. Trials should also assess cost-of-production implications.	Dairy, feedlot, poultry
Low fibre diet	Lack of publicly available, Australian specific research and resources on the topic. Uncertainty regarding implication for pig performance and least-cost diet formulation.	Ongoing research to investigate emission reduction potential (e.g., verify no adverse pig performance implications) and assess cost-of-production implications.	None identified (specific to digestive system)
Anti-methanogenic feed additives	Lack of publicly available, Australian specific research and resources on the topic. Uncertainty regarding implication for pig performance and least-cost diet formulation.	Australian specific research needed for anti-methanogenic additives – pig performance and cost-of-production.	None identified (specific to digestive system)
Manure methane (Scope 1)			
Covered anaerobic ponds / digesters	10% methane leakage is an IPCC default assumption adopted in Australian NIR with no research to verify this in Australian context. Difficult to quantify emissions if/when pond covers tear. Whether the pond is heated and/or stirred may have bearing on biogas yield. Similarly, there may be seasonal variation in biogas generation in some climates. High variability in costs. Some systems can run in excess of $20 million CAPEX. Earthworks and lining can be high-cost activities/sources. The limited number of service providers for covered ponds/digesters may compound this problem, and the slow rate at which new ponds are built. Retrofitting (covering) existing ponds can be difficult - often a whole new pond system is needed. Several producers with covered systems also indicated that they had little in-house knowledge to design or operate the systems (hence, outsource, driving up operating costs) and likewise have limited insights into what the reported performance of the	Measure GHG emissions from secondary ponds. Updated benchmarking needed, covering a variety of systems (covered ponds, engineered digesters, heated and stirred vs no etc) on farms in different regions and at different scales of production, reporting: biogas yield (incl. vs maximum theoretical yield), CAPEX, OEPX, age of system. Need minimum viable standardised design based on this - e.g., is heating or stirring worth it? Develop extension materials for site-specific viability, compatibility with other systems (e.g., deep litter), boosting biogas production safely, materials to support producers manage and operate their own systems. Develop business case for build-own-operate-maintain (BOOM) model (could be cross-industry to attract large investors).	Dairy, feedlot, abattoir, poultry

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
	pond compares with the optimum. In certain jurisdictions, disposal of digestate can also be costly and complex - Victoria, for example, class this as industrial waste. Where renewable energy (electricity, heat) is generated from biogas, hydrogen sulphide (H2S) must be managed appropriately. More generally, producers indicate that for so long as the systems remain extremely high capital cost, it is only by generating and selling ACCUs that they can recover the CAPEX in a reasonable (~7 year) payback period, with the remaining crediting period then supporting the design and construction of the next covered pond. Newness and additionality requirements of the ACCU Scheme are increasingly difficult to meet.		
Short hydraulic retention time	Previous studies have found that emissions were higher in summer than winter for sHRT systems. This may suggest that the emission reduction potential varies regionally (though this is consistent with the MCFs of uncovered systems). Requires large land area for irrigation. May be residual methanogenic bacteria in storage tanks.	Demonstration site, with updated cost-benefit analysis considering management challenges (effluent disposal).	Dairy, feedlot, abattoir
Solids separation	GHG emission abatement efficiency differs between various types of solid separation systems (screw press separator vs baleen filter screen). Should reduce odour from effluent pond but benefit may be marginal. Cost and time associated with treatment/disposal of separated solids, where some jurisdictions may have different requirements. May not go well with CAP heat/energy systems as producers want to maximise biogas for energy/heat outputs. Lack of registered ACCU projects may be methodological - i.e., that proponents would need to measure and weigh separated	Need quantified benefits under Australian conditions to determine the most cost-effective systems e.g. trafficable sedimentation basins and other more traditional forms of solids separation, investigate methane capture and reuse from solids.	Dairy, feedlot, abattoir

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
	solids (requiring a weighbridge and annual calibration, increasing CAPEX and OPEX).		
Hydrothermal decarbonisation	Some emission reduction would occur outside the piggery boundary (e.g., displaced peat in horticultural production). No quantified Australian studies assessing GHG emissions from this process vs uncovered effluent ponds. Requires energy inputs (heat and pressure).	Australian research needed in pig industry (some research in paunch in abattoirs).	Dairy, feedlot, abattoir
Supported straw / geomembrane pond covers	GHG emission reduction potential unknown. Covers may degrade quickly and require frequent replacement, increasing costs. Straw costs can be high in drought.	Investigate effectiveness at decreasing methane; detailed costings (geomembrane covers (incl. replacement frequency), cost and availability of straw).	Dairy, feedlot
Natural pond crust	Effect of Australia's hot and dry conditions on GHG emissions unknown. May increases N_2O emission. Performance and buoyancy of thick crust during heavy rainfall is unclear. Pond may need to be dewatered and crust/sludge manually removed with earthmoving equipment.	Investigate effectiveness at reducing GHG emissions.	Dairy, feedlot, abattoir
Chemical additives to modify pH	Research into dosing rates, emission reduction potential is ongoing. Safety of additives, potential constraints around reuse/disposal unknown.	Ongoing research to investigate emission reduction potential and ensure additives do not exacerbate odour or negatively impact crops/soils where effluent is applied.	Dairy, feedlot, abattoir
Biological additives (e.g., Bacillus)	Variability in emission reduction potential due to dosage, microbial community composition, slurry characteristics, environmental conditions.	Ongoing research to investigate emission reduction potential and ensure additives do not exacerbate odour or negatively impact crops/soils where effluent is applied.	Dairy, feedlot, abattoir
Deep litter system (as opposed to uncovered conventional)	Deep litter shed design sub-optimal in certain climates (e.g., QLD). May be a higher operating cost / labour requirement than indoor, flushed systems.	Measurement of CH_4 (and N_2O) emissions in deep litter systems needed (NIR uses average of international literature for CH_4).	

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
Outdoor system (as opposed to uncovered conventional)	Risks of nutrient leaching into soil and groundwater. Requires more land. Reduced FCR from outdoor systems can reduce productivity. Increased labour costs in outdoor piggeries.	Quantification of N_2O emissions (NIR uses IPCC value). Field level assessment of nutrient loss rates.	
Reduced stockpiling & composting time	Emission reduction potential will vary based on content of material in question (VS etc.). Current method in NIR does not consider timeframe as input (mass-flow based).	Investigate pathogen risks of shorter storage/processing time; investigate GHG emissions from different storage/processing times.	Poultry, feedlot, dairy
Avoid stockpiling or composting (spread immediately)	Quantification of emission reduction dependent on material composition. Questionable as to whether emissions are actually avoided or shifted down treatment train to field-level. May be heightened risk to biosecurity of farms where applied, also some jurisdictions restrict uncomposted (raw) sale (if attempting to sell off-farm unprocessed). Storage may be preferred (align with cropping cycle) and end-users may prefer composted product (reduced bulk, more stable).	Quantify emission reduction potential in case study scenarios (consider manure composition, displaced fertiliser etc). Conduct a desktop-based assessment of whether there is actual benefit (GHG reduction) associated with avoided processing.	Poultry, feedlot, dairy
Black soldier fly (BSF) larvae on manure	No quantified studies of emissions from process. Unclear as to availability (and cost) of larvae volume required to process manure / spent bedding at piggeries. Some heavy metals found in Australian study. Storage area needed and time for full processing may be long. Lack of clear regulatory framework re insect farming; some jurisdictions may restrict use of leavings and larvae where these are associated with manure and/or animal products. Rearing conditions and larval factors believed to be important for pathogen control but are poorly understood.	Conduct BCA. Conduct LCA to determine if BSF tech could be included in GHG abatement technology. Explore other benefits (e.g., extraction of high-cost oils).	Poultry
Manure nitrous oxide - direct (Scope 1) and indirect (Scope 3)			

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
Reduced stockpiling & composting time	As per previous.	As per previous.	Poultry, feedlot, dairy
Covered stockpile	Not assessed previously for bedding from deep litter piggeries. May be heightened pathogen risks (risk of botulism).	Measure emissions from covered vs uncovered stockpiles; benefit-cost of cover replacement.	Poultry, feedlot, dairy
Sorbers	Emission reduction potential largely dependent on the type of sorber used and environmental conditions. Very large amounts of sorber required to achieve statistically significant GHG reductions, hence, high input costs to achieve emission reduction. Uncertain effects on soil where sorbers are applied (especially in large amounts year after year).	Investigate cost-effective sorbers which can be applied at lower rates for meaningful emission reduction.	Poultry, feedlot, dairy
Nitrification inhibitors	Difficult to quantify benefit, effectiveness will vary with soil type and season.	Field-level trials to measure emission reduction potential, and benefit-cost (including of any enhanced nitrogen use efficiency).	Poultry, feedlot, dairy
Avoid stockpiling or composting (spread immediately)	As per previous.	As per previous.	Poultry, feedlot, dairy
Black soldier fly (BSF) larvae on manure	As per previous.	As per previous.	Poultry, feedlot, dairy
Reduced stocking rate and duration	N_2O emissions are elevated by high N levels in soil over extended periods of time, particularly if these periods include frequent wetting and drying cycles.	Further research into emission factors for outdoor production. Assess emissions under various stocking rates and durations.	
Reduce crude protein in diet	Diets typically formulated on least-cost basis, anything that deviates from that will increase cost-of-production. Diets	Ongoing research to investigate emission reduction potential (e.g., verify no adverse pig performance implications) and assess cost-of-production implications.	Poultry

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
	must also be carefully formulated to ensure that there is no adverse effect on productivity.		
Fossil energy - Scope 1, 2 and 3			
Improved energy efficiency	Emission reduction potential will be site-specific (e.g., vary with age of infrastructure, frequency of maintenance etc).	Updated case-studies and cost-benefit analyses.	
Electricity from solar and wind power	Grid electricity emissions will decline in line with the National Renewable Energy Target. This means that the emission reduction benefit from adopting on-site renewable electricity generation will be most pronounced in the short-term, i.e., producers who take a passive approach (no adoption) will still see a reduction in Scope 2 emissions in the longer-term. There may, however, be energy security or financial benefits from adoption on-site generation.	Case-studies (actual or desktop) and cost-benefit analyses.	
Electricity & heat from biogas	Generators and boilers can operate at varying levels of efficiency. In addition, the composition of the biogas can have a significant effect on the efficiency of the generator. A scrubber to remove hydrogen sulphide may be required. Best use of biogas (electricity vs heat energy) may be site/system specific - energy potential is with grower pigs but heat energy demand is with the breeder (farrowing) unit.	Updated case-studies and cost-benefit analyses.	Dairy, poultry
Replace diesel transport engines with methane	Likely most viable on sites with CAPs and owner-operated trucking over a regular route with a fixed distance (e.g., farm to abattoir). Specific engine (e.g., correctly sized tank) required in truck. Compressing methane can be expensive. Piggery biogas would also need to be cleaned (remove H_2S).	On-farm trial/demonstration site. Case study writeup and cost-benefit analysis. Investigation of opportunities to reduce costs associated with upgrading (compressing) the methane on-farm.	Dairy, abattoir, feedlot (covered housing), transport
Green CO_2 from biogas	CO_2 gas not used at piggeries. Would need to be captured and transported (sold) to alternative user. Cost of	Trial at abattoir with covered pond.	Abattoir

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
	upgrading (separating CO_2 from CH_4 and other impurities) may be prohibitively expensive/impractical at farm-level.	Evaluate feasibility of transporting CO_2 from farm to end-user (and whether ROI is possible).	
Trigeneration – cooling from biogas heat	Benefits of trigeneration likely confined to selected piggeries (e.g., where heat energy from biogas is wasted in summer, or where climate is warm enough that significant energy is required to reduce shed temperatures as pigs grow). Previous studies have indicated that capital and installation costs of absorption chillers may not be cost-effective.	Expanded desktop pre-feasibility (benefit-cost, energy demand/profile) to evaluate whether trigeneration is cost-effective for a given piggery.	Abattoir, dairy, feedlot (covered housing)
Optimised insulation	Insulation decisions are typically made in the design phase (not retrofitting), hence emission reduction potential is difficult to assess as they are more likely to be 'avoided' emissions.	Case studies of energy demand (and GHG emissions) from well-insulated sheds vs other.	Poultry
Renewable diesel	Emission reduction potential (vs regular diesel) is not yet verified. Can currently only pre-order (i.e., not available at fuel stations).	Research required at federal level to verify emission reductions and improve availability. Thereafter, assess cost to user vs regular diesel.	Poultry, feedlot, dairy
Electrification	Emission reduction potential likely to increase over time (as grid electricity decarbonises in line with National Renewable Energy Target). Gas prices in Australia are typically lower than in many other countries, making the payback period here far longer (based on current pricing) than quoted for overseas. May not be financially viable to replace existing systems in warm climates (e.g., with low heating demand).	Case studies (different farm types and climatic regions) and benefit-cost analyses .	Poultry
Green Gas (e.g., low emission renewable gas)	Unless purchase is of certified carbon neutral gas, exact emission reduction potential may vary.	Investigate cost effectiveness and emission reduction potential.	
Ground source heat pump	Viability may be site-specific (geothermal energy potential) and heat energy demand (e.g., to generate ROI). Earthworks can be very expensive and system can be	Perform case-study on piggery known to current utilise the system. Model cost-benefit for other operations.	Poultry

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
	difficult to integrate into existing farm (without halting production).		
Upstream feed production (Scope 3 incl. LU, LUC)			
Low carbon/carbon neutral cereal grains	Integrity of carbon neutral claim may vary depending on certifying agency and methodology. Bulk commodity market means traceability may be poor, i.e., may need to separate physical good and emission reduction benefit (as in style of renewable energy certificates etc).	Cross collaboration with grains sector and other intensive animal industries to increase availability of low carbon/carbon neutral grain at a viable price point.	Grains. poultry, dairy, feedlot
Algae (alternative feed ingredient)	No Australian research to quantify/compare carbon footprint of algae versus traditional feed ingredients, or inclusion rates.	Investigate feasibility of producing algae on piggery effluent ponds and use as a feed ingredient (e.g., regulatory constraints).	
Diverted food waste in feed	Feeding diverted food waste better suited to some systems (e.g., liquid feeders). Where ingredients and availability are fluid, regular reformulations may be needed. Transport distances (and costs) from source to mill may be prohibitive.	Case-study of product carbon footprint (and cost of feed) with and without diverted food waste inclusions. Factsheets on what these are, where they can be sourced from, challenges or considerations when including, implication for cost of feed. Investigation of feasibility of centralised collection / processing (stabilisation) - e.g., in peri-urban areas (closer to sources of diverted food waste) to make sourcing and transport to mills easier.	Poultry
Insect meal (alternative protein)	Very limited research into the carbon footprint of insect meal vs other protein sources. Processing of larvae into meal may be energy intensive. Availability and volume of insect meal is uncertain. Some jurisdictions may prohibit inclusion if insects were fed certain substances (e.g., restricted animal material - RAM).	Undertake literature review of insect options and environmental benefits and trade-offs, analysing 'whole of system' benefits in an LCA, alongside a BCA.	Poultry
By-products in feed	If diet digestibility is reduced as a result of their inclusion, manure-related emissions may be slightly higher.	Case-study of product carbon footprint (and cost of feed) with and without by-product inclusions. Factsheets on what these are, where they can be sourced from, challenges or considerations when including, implication for cost of feed.	Poultry, dairy, feedlot

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
Replacement of high-impact imported soybean meal with certified soy or locally produced soy	Very limited information is available on land use and direct land use change emissions associated with soybean meal. Where this is available, it is typically dated and assessed using high-level statistics at a national level (i.e., not farm or region-specific). In addition, there is a high degree of uncertainty as to the extent to which the general market for imported soybean meal in Australia is exposed to deforestation (e.g., in Brazil, as Argentina is a major source region). Hence, certified deforestation-free soybean meal may not actually result in a reduction in attributable LU, LUC emissions.	Detailed investigation and review of certification schemes to assess whether LUC emissions from other land conversion (excl. deforestation) can credibly be said to be avoided. Review the risk of exposure to land transformation and soil carbon loss in each import market for soy. Track land transformation using GIS at a national scale.	Poultry
Optimised sourcing of Australian cereal grains	Previous estimates by these authors have been based on National Greenhouse Accounts (previously AEGIS) data and ABS data. NGA only reports to a state-level for LU, LUC emissions meaning that any soil carbon losses are average across the State production. In reality, this will vary farm-to-farm. Likewise, the NGA data also indicates that cropland in some states (e.g., WA) may be a carbon sink. Out of conservativeness (and in accordance with best practice), this was assumed to be zero (in equilibrium) as it could not be verified on a farm-basis.	Review available certification schemes and methods and assess against case study farms to verify that no soil carbon losses are occurring. Develop supply chain case studies (tracking cropping through to feed mill) outlining avoided LU, LUC emissions and associated cost for the product. Refine / improve NGA disaggregation to report emissions on a regional basis. Develop regional grain benchmarks (incl. LU and dLUC).	Grains, poultry, dairy, feedlot
All sources (Scope 1, 2 and 3)			
Optimise turn-off weight	Emission reduction potential is complex to estimate - need actual production information to assess this. Must be evaluated on a system basis (e.g., carcass specifications often set by customer) - some farms will be growing out pigs to an above optimum weight (from a feed efficiency perspective) but this is based on customer requirements. Ability to achieve this is largely outside the control of a given pig producer.	Develop case studies (GHG emissions, inputs, cost-of-production) associated with different turn-off weights. Engage with customers around how alternative market specifications might contribute to their goals to reduce their value chain emissions.	

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
Reduce feed waste	Difficult to quantify benefit - reduction in Scope 1 will be more pronounced in conventional systems, lesser in deep litter and outdoor. Would also reduce Scope 3 emissions.	Methods to quantify feed waste at farm-level are needed to better predict emissions from waste streams. Current APL research looking at EMMAs device to reduce feed waste (in conventional systems) through faster management response to issues. Study and develop extension materials around other strategies - e.g., optimal feeder spacing.	
Increase productivity (e.g., feed conversion ratio, pigs sold/sow/yr)	Emission reduction potential is complex to estimate - need actual production information to assess this. Ability to achieve this is largely outside the control of a given pig producer. May be small gains in production efficiency through improved management on some farms but otherwise will be largely down to genetics.	Develop producer-facing fact sheets which place productivity improvements in financial and GHG emission context.	
Precision feeding (phase feeding)	Emission reduction potential must be assessed on case-by-case basis - e.g., complex relationship between ingredients, digestibility, protein, and pig growth.	Continue to investigate least-cost formulations, effect on N and VS excretion, feed intake, and pig growth.	
Genetic improvements (e.g., feed efficiency, growth rate, survivability, litter size)	Difficult to estimate how much new genotypes/ongoing incremental genetic advances will contribute to emission reduction. May yield product-based improvements but total emissions may increase if total production expands. Ability to achieve this is largely outside the control of a given pig producer.	Conduct LCA of different genotypes to compare product carbon footprint. Continue to benchmark and track industry performance to assist producers in understanding how long-term genetic improvement has influenced their current product carbon footprint (i.e., what was their starting point?)	
Closed loop farm	Emission reduction potential (if any) from utilising by-products on-farm will vary farm-to-farm - e.g., baseline emissions, what (if anything) is being displaced, carbon storage potential (and storage timeframe) of soils, soil N mineralisation.	Updated case-studies and cost-benefit analyses. Assess nutrient production (N, P, K, C) in by-products vs nutrient demands (by region) - identify manure sheds etc.	
Removals			
Tree planting	Storage potential depends on a variety of factors (tree type, soil type, rainfall etc). General hesitancy to 'lock up' land	Case study examples of carbon sequestration rates for different scenarios / regions. Develop low-cost methods to estimate	All agriculture

Mitigation Strategy / Opportunity	Barriers to adoption / Gaps in knowledge	Research Needs / Enablers	Potential collaboration
	with trees - may only be an option for small tracts of land unlikely to ever yield a productive use for the pig producer. May also be concerns around insurance (fire risk etc).	small volumes of carbon storage on-farm (e.g., in vegetative buffers).	
Building on-farm soil carbon through application of manure and effluent	Soil carbon storage potential depends on a variety of factors (soil type, climate, rainfall etc). Also uncertainty re permanency of soil carbon from these organic sources.	Case study examples of soil carbon storage for different scenarios / regions. Develop low-cost methods to estimate small volumes of carbon storage on-farm (e.g., in outdoor areas).	Poultry, feedlot, dairy, grains

5.2 Stakeholder Engagement

5.2.1 Industry Workshop

The knowledge gaps, barriers to adoption, and enablers identified in the industry workshop have been integrated into the gap analysis matrix and are not repeated here. Briefly, the key themes/points of discussion were:

- Barriers, gaps and enablers to further adoption of covered anaerobic ponds:
  - Capital costs
  - Lack of in-house/local skillsets to operate
  - Costs and administrative burdens associated with ACCU projects
  - Ability to generate and sell credits fundamental to achieving viable payback period
  - Minimum/standardised design requirements (e.g., benefits of stirring and/or heating vs without)
  - Support to install CAPs across the industry
  - Benchmarking resources – evaluate biogas yield against other systems/designs, theoretical maximum
  - Renewable energy/gas credits.
- Barriers, gaps and enablers to adoption of other options to reduce pond emissions:
  - Impacts/regulatory constraints of disposal of effluent with pH modification or additives
  - Costs associated with alternative feeding systems to reduce feed waste
  - Alternative means of reducing feed waste (or predicting feed waste)
  - Diet formulations that reduce VS and nitrogen flows.
- Barriers, gaps and enablers to reduction of manure-related emissions in deep litter and outdoor systems:
  - Regulatory requirements – e.g., to compost material before it can be removed from site, uncertainties around nutrient loss rates
  - Inconsistent/episodic local demand for spent bedding
  - Perceptions of spent bedding as a low value product (and hence low willingness to pay) by end-users
  - Assessment of optimal rotation times for outdoor pig production
  - Reassess value of spent bedding, identify optimal end-users, and market accordingly
  - Cost-effective means of measuring soil carbon levels – range areas, areas with successive application of spent bedding.
- Barriers, gaps and enablers to achieving further emission reduction through productivity gains:
  - Customer requirements (e.g., carcass specifications) deviating from the environmentally-optimal slaughter weight
  - Clear quantification of productivity gains (e.g., improvement in FCR etc) and impact on product carbon footprint (by housing/manure management system)
  - Review/case studies of industry-leading farms (e.g., farms that low emitters) to identify what practices or strategies support this.
- Barriers, gaps and enablers to achieving further emission reduction through diet formulation:

    - Inconsistency in supply, quality and volume of diverted food waste, and long transport distances from source to mill
    - Potential biosecurity risks with using diverted food waste
    - Challenges associated with moisture content of diverted food waste
    - Focus on optimising feed to achieve other outcomes (e.g., reduced phosphorous excretion)
    - Lack of research/resources around what feed additives might reduce enteric methane emissions or VS and N excretion
    - Regional grain benchmarks outlining differences in emission intensity of feed grains due to production differences
    - Ongoing research into viable alternatives to high emission imported soybean meal
    - Review of credibility behind low-emission feedstock claims/certification schemes.
- Barriers, gaps and enablers to achieving further energy-related emission reduction:
    - Location – limited capacity for increased electricity consumption (e.g., as a result of electrification of heating) when located at the "end of line" electricity network (associated with power quality issues, disruptions).
    - Complexity – more than one backup system required when not connected to the grid
    - Range of current electric vehicles – distance of farms from abattoirs usually too great for effective use of electric trucks
    - Range of compressed gas trucks – high cost to compress methane, replace fuel system, and also distance of farms from abattoirs requires large amount of energy
    - Case studies (and benefit-cost analyses) of electrification, ground source heat pumps, electricity from biogas – use on-site vs sell into market.
- Barriers, gaps and enablers to achieving carbon removals on-farm:
    - Resource requirements associated with tree planting – land, water (particularly for establishment), and labour
    - Fire risks
    - Assessment of increases in long-term soil carbon from spent bedding application and in range areas
    - Techno-economic analysis of pyrolysis of spent bedding – through to field application – consider soil carbon
    - Case studies/producer facing resourcing around carbon removal on-farm.

5.2.2 Case Study Workshops

The deidentified case studies have been provided as separate outputs. The discussion points and outcomes are not repeated here.

6. Discussion

As outlined in the matrix, there are numerous emission reduction opportunities for pork production, and each option comes with its own barriers, knowledge gaps, and potential enablers.

The following sections highlight the current major priorities for research, extension and adoption of emission reduction opportunities for the Australian pork industry. This is not an exhaustive list, and readers should refer to the matrix for details on other mitigation opportunities. These priorities were selected based on the significance of the targeted emission sources and the potential for adoption, as well as the level of interest by the industry at this time.

The key focus areas are: overcoming barriers associated with adoption of covered anaerobic ponds, investigating alternative technologies/overcoming barriers to existing options to reduce emissions from uncovered ponds, and exploring opportunities to generate renewable energy on-farm to reduce production costs.

6.1 Covered Ponds

Methodological Gaps: In 2022, just under 20% of manure in the Australian pig industry was treated in covered anerobic ponds (Copley et al., 2024), a significant increase on the 0.4% in 1990 (Wiedemann et al., 2024). Despite the significant role that CAPs now perform in the pork industry (as well as the dairy and meat processing sectors), and their potential to further reduce GHG emissions, only limited studies have been conducted in methane leakage from CAP/digesters in Australia (e.g., Reinelt et al., 2022). In the absence of sufficient verified country-specific research, the National Inventory Report - NIR (2025c) uses the IPCC default assumption of 10% methane leakage. It remains unverified in the Australian context whether methane leakage occurs at this rate (or at all) from piggery CAPs/digesters. In practice, this leakage can happen through torn covers or at cover seals and anchors, welds, and similar points. Regular maintenance may help reduce this risk (Reinelt et al., 2022). It is also unclear whether certain designs leak less (or not at all). A well-maintained engineered digester, for example, is unlikely to leak (particularly in the early years of operation). A variety of designs should be studied to assess methane leakage and an update to the inventory considered (as needed) to improve the accuracy of industry/piggery GHG emission estimates.

Another area of uncertainty is the extent to which GHG emissions arise from secondary ponds (and subsequent ponds) in the treatment train following a CAP. These uncertainties have been described in detail by McGahan & Copley (2025) for APL and are not repeated in full here. Briefly, the NIR (2025c) methodology states that, for waste from CAPs/digesters to secondary (uncovered) ponds, 75% of volatile solids (VS) are assumed to be reduced in the primary system via gaseous loss and deposition to sludge. In contrast, Wiedemann et al. (2014), (in a technical review of the NIR methods) recommended that the assumed proportion of VS to the secondary pond be set at 20% (effectively an average based on Kruger et al. (1995) and Heubeck & Craggs (2010)). Therefore, the assumption used in the NIR is more conservative (i.e., assumes a greater proportion of VS flows to the secondary pond). Nevertheless, the reference studies considered in the development of this assumption are 15 to 30 years old. Given the advancements in design and management of the primary manure management system (MMS), the assumption (and reference studies) may over-estimate/not reflect current conditions. Hence, research is needed to determine the VS reduction in CAPs/digesters.

Another key area of uncertainty regarding CAPs is the methane potential of the VS in secondary ponds. Associated methodological gaps have been described in detail by McGahan & Copley (2025) for APL and are not repeated here in full. In summary, the VS entering the secondary pond should have a lower methane potential than the VS flushed from the sheds. A portion of the VS that enter the secondary pond are partially digested, and another portion fully digested (e.g., from waste feed). A certain percentage of the VS will degrade very slowly and remain in the pond (dead cells), as noted by McGahan et al. (2014). The VS:TS ratios of piggery sludge from covered ponds ranges from 0.55 to 0.67, indicating the degree of VS breakdown that has occurred (McGahan et al., 2014). Sludge from covered ponds is well degraded with only the highly-indigestible lignin and similar components left in the liquid component (McGahan et al., 2014). This supports an assumption that VS in secondary ponds have a low methane potential.

The approach and assumptions for secondary pond emissions are not clearly described in the NIR as this (system-specific detail) goes beyond its purpose (to fulfil Australia's annual national inventory reporting obligation under the United Nations Framework Convention on Climate Change). It is recommended that the NIR be upgraded to disaggregate between primary and secondary manure management systems and improve GHG emission estimates from Australian piggeries. To measure and verify the methane potential for secondary ponds, data from a range of covered ponds/digesters to uncovered secondary pond systems should be collected and analysed.

Practical Challenges: Although CAPs are a relatively mature technology, there are considerable practical challenges to their design, construction, and operation. Capital costs (particularly when design and construction are outsourced to a provider, i.e., not done in-house) are considerable, with costs known to exceed $20 million in some cases. In addition to lining, earthworks can be a major cost centre, as retrofitting existing ponds is often impractical, requiring full reconstruction, particularly at piggeries with multiple production units and ponds. Producers indicated that the limited number of service providers (limited competition) may be a factor that keeps costs high. A shortage of in-house knowledge (described further in the following section) extends to a lack of understanding (and available resources) around the minimum viable design requirements for an efficient covered pond system. This may result in some systems being 'over-engineered' with limited to no benefit (additional biogas generation) and hence producers pay for additional infrastructure (e.g., stirrers, heaters) that will never generate a return. Standardised designs and competitive tendering have been proposed to reduce costs (capital, construction) and accelerate adoption. Updated benefit-cost analyses (e.g., for a benchmark group of existing systems) and collective procurement strategies could help identify least-cost models.

Desludging covered ponds is particularly challenging as the cover cannot be removed during the operational phase. Available methods include: in-situ desludging (solids pumped out via a pipeline once they settle), suspension removal (agitators prevent solids from settling meaning they are then removed in the effluent flow from the CAP), and life-time accumulation (solids only removed when the pond is decommissioned) (McGahan et al., 2014). These options all present different trade-offs for consideration (precise design of piping, high nutrient load in effluent leaving the pond, and an increased pond size to accommodate the large sludge volume). Research has indicated that the methane potential of sludge from CAPs is low, meaning that frequent removal and treatment may not be a large source of GHG emissions but that less frequency (i.e., two-yearly) removal may optimise methane recovery in the CAP (Tait et al., 2017).

Regulatory requirements can also add another layer of complexity to operation of CAPs/digesters. In Victoria, for example, digestate is classified as industrial waste (EPA Victoria, 2021) meaning that there are significant additional compliance requirements associated with any storage, transport, or land application.

Operational & Knowledge Barriers: Producers report a lack of in-house expertise to design and operate CAPs, leading to reliance on external contractors and exacerbating already high operating costs. Benchmarking is an essential resource to assess system performance, yet publicly available (and up to date) industry-wide data is scarce. APL have previously developed biogas resources including a Code of Practice (APL, 2015), and a numerous pre-feasibility case studies have been published (e.g., McGahan et al., 2013; Skerman & Tait, 2018). However, these resources, do not provide benchmarks and comparisons for biogas yield from existing CAPs. Producers stated that this comparative benchmarking exercise (particularly where it also compared CAPEX, OEPX, system design, and summarised any key learnings or challenges) would be a highly valuable resource to support producers build capacity and in-house knowledge. Whilst this information remains spread across various resources (e.g., APL, 2015; Birchall, 2010; McGahan et al., 2013; Skerman et al., 2015; Skerman & Tait, 2018; Tait & McCabe, 2020b), it is difficult for potential users to navigate.

Policy Implications: The ability to generate and sell ACCU units through the ACCU Scheme remains the cornerstone for financial feasibility of CAPs, with credits enabling payback within ~7 years (according to some producers). However, meeting newness and additionality rules is becoming increasingly difficult because regulators now require covered ponds as a best-practice (and minimum standard) for conventional piggeries – at least from an odour perspective. This tension underscores the need for policy refinement to support adoption of transformational emission reduction technologies, while maintaining integrity in the ACCU Scheme. The extension to the ACCU crediting period to 15 years for flaring and electricity generation projects under the *Carbon Credits (Carbon Farming Initiative – Animal Effluent Management) Methodology Determination Variation* (2025a) represents a significant improvement in policy and will help support the business-case for further adoption of CAPs. The next area that warrants review/investigation is how biogas projects (included in planning applications for new piggeries or a condition of licence agreements) can be eligible under the ACCU Project Scheme.

6.2 Other Opportunities to Reduce Emissions from Uncovered Ponds

6.2.1 Short Hydraulic Retention Time

Methodological Gaps: Short HRT (sHRT) systems are designed to store piggery effluent for less than 30 days, thereby minimising the opportunity for anaerobic conditions and methane generation. The NIR (2025c) assigns a 3% methane conversion factor (MCF) for sHRT systems, after the IPCC (2006). The 2019 refinement to the IPCC, however, includes values for 1, 3-, 4-, 6-, and 12-month storage as well as a variety of climatic zones (IPCC, 2019). The MCFs in the 2019 refinement are considerably higher than what is currently used in the NIR but the <1 month storage time for 'warm temperature moist' and 'warm temperate dry' climates are not inconsistent with the upper band of measured MCFs in Australia. The only published Australian field study (McGahan et al., 2016) found that sHRT systems can achieve methane emission reductions of up to 79% compared to conventional long HRT ponds, with measured MCFs as low as 0.1% in winter and 18% in summer. These findings are consistent with the international literature on sHRT systems in piggeries (Møller et al., 2004).

Further research is needed to measure GHG emissions from sHRT systems, however, this is difficult at present given their limited application.

Practical Challenges: sHRT systems offer a lower CAPEX and OPEX alternative to covered anaerobic ponds (CAPs) or digesters, potentially making them more attractive (and viable) for small to medium-sized piggeries or larger sites where energy recovery is not viable (McGahan, 2024a). Estimated capital costs are typically 20–40% of a CAP system, depending on infrastructure choices (e.g., tanks, pumps, agitators, irrigation equipment) (McGahan, 2024b) whilst benefit-cost analysis show payback periods as short as 3 years when ACCU revenue is included (Wiedemann et al., 2016). A key challenge, however, is that sHRT systems retain much higher concentrations of nitrogen and phosphorus than conventional pond effluent, requiring significantly larger irrigation areas—often 5–10 times greater—to sustainably apply nutrients (McGahan, 2024b). There are, however, mechanisms available to moderate this (see Effluent Treatment Train (complimentary technologies)).

Regulatory and Policy Barriers: As already described, sHRT systems in Australia are rare, therefore regulatory and policy challenges are discussed at a high-level here. One challenge prospective operators may encounter is a requirement to demonstrate sustainable nutrient management in irrigation areas. Use of a solids separator in conjunction with the sHRT system would be an effective mechanism to reduce nutrient loading on irrigation areas where irrigable land is limited (McGahan, 2024a). The ACCU Scheme does not currently have a method which recognises sHRT as an activity that avoids or reduces GHG emissions (and hence, allows the operator to claim ACCU credits). Inclusion of sHRT in the existing Animal Effluent method as a methane avoidance technology (and the potential to generate a return) would likely increase the attractiveness of this technology at farm-level. Further description of a process to include sHRT as an eligible activity under the ACCU Scheme has been provided by McGahan (2024a) and is not repeated here.

Operational & Knowledge Barriers: Although common in European and North American piggery and dairy production, sHRT systems are rare in the Australian pig industry (McGahan, 2024a). As a result, there are limited resources available on how to operate sHRT systems. To build knowledge, a "how-to" guide and webinar for producers has been developed describing the operation of sHRT systems in various pig production regions, their advantages and disadvantages over traditional uncovered and covered ponds, and likely GHG abatement potential. A demonstration site (and detailed case-study and cost-benefit) would also help demonstrate the viability of sHRT in certain systems in Australia.

6.2.2 Solids Separation

Solids separation (to remove VS, N, and other matter) from piggery effluent streams has been extensively reviewed (Watts, Tucker, Pittaway, & McGahan, 2001; Watts, Tucker, Pittaway, McGahan, et al., 2001). The emission reduction potential is established with solids separation being an eligible activity under the Animal Effluent method. In 2022, approximately 10% of manure produced in Australian piggeries was treated with some form of solids separation (Copley et al., 2024). Despite this, there are no known registered ACCU projects involving solids separation at piggeries. Further investigation is needed to understand the underlying reasons. Specifically, it should be assessed whether producers are unaware that they can register a project and generate ACCUs. Another possibility is that the ACCU potential (and financial return) is too low compared to biogas projects to offset project registration and auditing costs. Producers with registered biogas projects have cited compliance with audit processes as a significant challenge, both in terms of costs and time.

Alternatively, there may be other aspects associated with registering a project that add cost and complexity, such as the need for a weighbridge.

6.2.3 Pond Additives

In New Zealand, treating effluent with additives such as polyferric sulphate is now a recommended emission reduction process in dairy systems (McGahan, 2024a). Australian research to assess the methane abatement potential in piggery effluent is ongoing (George et al., 2025a). Recent lab trials by George et al. (2025a) resulted in a 52.9% reduction in methane yield for ferric sulphate. Acidification of piggery effluent has previously been found to reduce methane emissions by 95-99% (Ambrose et al., 2023) whilst calcium-cyanamide was found to reduce GHG emissions from piggery effluent by 99% at certain dosages (Holtkamp et al., 2023). Ongoing research is needed in this area, including to assess the cost-effectiveness and any adverse effects (e.g., odour, disposal challenges for effluent). There may also be potential to register a method under the ACCU Scheme, focusing on prevention/inhibition (rather than avoidance or destruction). If additives prove to be expensive (or required at high rates, driving up costs), ACCU potential may make the technology financially viable/attractive to producers.

6.2.4 Effluent Treatment Train (complimentary technologies)

The three technologies described previously (sHRT, solids separation, pond additives) have high stacking potential, i.e., the potential to be used consecutively in an effluent treatment train to yield improved outcomes. Solids separation prior to sHRT storage, for example, can reduce the required land area by 30–40% by removing significant amounts of nutrients and improve irrigation logistics (McGahan, 2024b). In addition, it could also remove coarse materials that cause clogging/are difficult to irrigate, reduce settled solids in the tank to allow easier total removal, and convert a proportion of the liquid waste stream to a solids fertiliser/soil amendment that can readily be removed/sold off-farm (McGahan, 2024a). Integration of solids separation prior to a pond with additives to reduce methane emissions may significantly reduce the amount (and cost) of additive required to achieve a given GHG emission reduction. Similarly, it may be possible to integrate additives into a sHRT or solids separation and sHRT effluent treatment process. Calcium cyanamide, for example, has nitrification inhibiting characteristics which may reduce emissions from effluent irrigation.

6.3 Energy

APL has numerous producer-facing resources available in relation to on-farm energy use, including renewable energy, biogas, self-assessments, benchmarking, factsheets and guidance around reducing costs that are of relevance to GHG emission reduction (e.g., All Energy Pty Ltd, 2022; APL, 2015, 2018, 2022a, 2022b; Tucker & McGahan, 2015). This is in addition to a myriad of other research projects that have investigated alternative energy sources for piggeries and/or assessed differences between production systems and farms (e.g., Copley et al., 2024; McGahan et al., 2013; Skerman et al., 2015; Skerman & Collman, 2012; Tait & McCabe, 2020a; Wiedemann et al., 2017).

There are a number of emerging/more novel technologies that warrant development of further resources to either demonstrate or investigate their practical and financial viability for Australian piggeries. At least one pig producer is operating a ground-source heat pump, a technology which has been successfully applied in the meat chicken industry (Donovan, 2023) with support from the Australian Renewable Energy Agency (ARENA). Trigeneration has been investigated at desktop level (e.g., Skerman et al., 2015; Tait & McCabe, 2020a) but no published studies are available of its application at farm-level in Australian piggeries. Additional research may be needed first to retrofit absorption chillers that run on natural gas (and evaluate the associated cost) before proceeding to an on-site trial. Theoretically, methane captured in CAPs/digesters could be compressed and used in vehicles (with retrofitted fuel systems) as an alternative transport fuel. This would likely work best where the piggery generates excess biogas and where there is a fixed transport route run regularly (e.g., farm to abattoir) as the engine could then be sized according to fuel required to travel this distance and the return journey. If the technology is viable, it may be possible to apply this (with slight variations) in other industries – e.g., dairy farms with CAPs/digesters and compressed methane could fuel milk trucks (though trucks typically collect from multiple farms). An alternative explored at desktop level by Tait & McCabe (2020a), may be to sell piggery biogas to commercial gas manufacturer-suppliers. Options to better utilise (and financially capitalise on) excess biogas warrant further investigation and are a good opportunity for cross-collaborative research with other agri-food sectors (dairy, abattoir) as well as the transport and energy sectors. Trial sites may have high co-funding potential through ARENA and other supply chain partnerships.

6.4 Collaboration Potential

There is significant collaboration potential across the RDCs for projects relevant to the Australian pork industry. The major collaborating industries include: poultry (meat chicken and egg), dairy, feedlot, meat processing, and grains. In short, the general areas for collaboration are:

- Effluent management and use – dairy, meat processing, feedlot.
- By-product management (stocking, composting, land application) – poultry, feedlot, dairy.
- Feed (formulation and procurement) – poultry, feedlot, dairy.
- Energy (incl. on-farm generation) – dairy, poultry, feedlot.
- Removals – all land-based agricultural industries.

Consideration may need to be given to the length of funding cycles for RDC projects (particularly major research). Where the required projects are multi-year (+3 years), for example, it can be difficult to scope these within the existing open call timeframes as there is limited opportunity (within the parameters) to demonstrate the benefit and engage with potential collaborators (and resolve administrative and cost-sharing or in-kind agreements). An alternative process for major collaborative R&D opportunities may be needed.

Another need (but also potential opportunity) is to better engage with supply chain partners (meat processors/wholesalers, manufacturers, retailers, and lenders). Ultimately, part of this process would be to ensure that the pork industry is working towards a coherent and agreed plan to avoid conflicting messaging or expectations. At a minimum, this process should be to ensure that target-setting organisations/stakeholders clearly outline the mechanisms available for financial and non-financial assistance to facilitate adoption of emission reduction initiatives at farm-level.

6.5 General Needs for Emission Reduction Resources

Discussions with the pork industry and other stakeholders on supporting on-farm adoption of emission reduction strategies consistently highlighted one key theme. That theme being that the greatest traction and interest will be achieved when the message is focussed on enhancing productivity, and reducing cost-of-production, rather than positioning emissions reduction as the primary benefit. Additionally, engagement is highest when resources are directly relevant/applicable to the individual farm – such as representative, real-world case-studies and benefit-cost analyses.

Examples and case studies demonstrating real-world implementation of profitable on-farm emission reduction is essential. Several stakeholders indicated that producers prefer one-on-one (or near one-on-one) advice and support for implementing farm-level emission reduction. This would be challenging to provide (and especially at a high standard) for service providers lacking deep understanding and experience with the farming system in question i.e., generalist, broad-level advice or strategies are insufficient.

Messaging or framing of emission reduction initiatives or resources may also need to be reconsidered to avoid producer fatigue or attrition. There may be opportunities to engage with less traditional external collaborators in key areas. Dairy Australia, for example, indicated that it has been/is working with behavioural science experts to enhance producer interest and engagement, and that this process has yielded an increase in the number of farmers attending workshops over the past 12 to 18 months.

6.6 Improving Data Capture

6.6.1 Producers

Monitoring inputs and outputs in pig production systems is fundamental to tracking business costs and pig productivity, underpinning management decisions and highlighting areas of success and areas for improvement to producers. Producers may also be required to capture and report data for regulatory reasons, such as for ACCU Scheme projects, carbon neutral certifications, and planning applications (expansion). Representative and accurate data capture is fundamental to achieving this but so too are resources that reduce costs to the producer (e.g., consultant's fees), provide accurate, enterprise-specific results, and contribute to building capacity and knowledge of the user.

There are currently two main publicly available piggery GHG assessment tools available in Australia. The first, PigBal, (McGahan et al., 2025), is primarily a nutrient and mass balance model which was recently updated to include Scope 1 and 2 GHG emission calculations. The GHG methods used in the National Inventory Report (Commonwealth of Australia, 2025b) are derived from previous versions of PigBal. The recent update was independently validated to ensure that it remains consistent with the NIR and best practice. The second tool, the Agricultural Innovation Australia (AIA) Environmental Accounting Platform (EAP) (AIA, 2025) is based on the Pork Greenhouse Account Framework P-GAF) (PICCC, 2025), administered by the University of Melbourne, and is a derivative of the MLA Sheep & Beef (SB)-GAF. There are relative strengths and limitations of both tools. The authors of this report have previously provided technical advisory to APL regarding minimum viable updates to the pork-GAF/EAP in order to improve the level of accuracy (which has been implemented). In addition, through that process and the recent independent validation of PigBal, further discussion of limitations and potential updates to the tools was provided. This has not been repeated here.

More generally, however, a current gap in both tools is that neither incorporates a scenario analysis component for users to easily evaluate how certain strategies or technologies might reduce their on-farm (or product-based) GHG emissions. Attempting to calculate this separately may be time consuming and increase the margin of error for producers. Pork industry and other industry stakeholder consultation indicates that the ability to easily (and at low to no cost) estimate emission reduction potential would be of value to producers.

6.6.2 Industry

Fundamental to monitoring industry progress against goals set in the APL Sustainability Framework 2021-2030, changes over time, and contributions to Australia's national emission reduction targets, is a mechanism for industry to collect and aggregate data from a large number of piggeries. As a portion of industry shifts to determining their emissions for public reporting, as well as meeting evolving customer expectations, there is a need for a system by which to do so without requiring producers to provide data multiple times via different platforms which may use conflicting methods and / or generate results with varying levels of accuracy.

7. Recommendations

This gap analysis demonstrates the need for a clear pathway for research and extension to drive the next phase of emission reduction in the pork industry. Whilst there are numerous opportunities for collaborative research, extension development, and producer engagement to drive on-farm emission reduction, the following have been identified as first-order priorities for the Australian pork industry. Note that these are not listed in any particular order of priority.

Research Priorities

1. **Measure GHG emissions from covered anaerobic ponds (including secondary ponds) and range areas (ideally, include composting).** There is a high degree of uncertainty as to whether the current factors are representative of Australian conditions, meaning that sectoral (and farm-level) emissions may be higher or lower than currently estimated. This information gap creates the risk of misdirecting investment towards over-estimated sources or away from under-estimated sources. A first order priority is to verify that current emission factors are accurate and then prioritise investment accordingly. There is collaborative opportunity here with dairy and meat processing (anaerobic ponds) and poultry production (free range areas).
2. **Conduct a benchmarking study of existing CAPs/digesters.** This project would assess performance (methane production) and describe factors contributing to low and high performance where observed. It would also quantify up-to-date costs (CAPEX, operating, maintenance, third-party management/expertise), and engage with producers to review challenges and learnings from the pre-feasibility, design, construction, and operating phases. The findings would be detailed in a producer-facing guide covering key aspects of CAP/digester system design, operation and biogas yield including expected ranges in performance and factors leading to fluctuations and variation. This would directly address concerns (a gap) raised by producers. A logical extension to the project (once all benchmarking data is compiled) is to develop a standardised design manual for CAPs/digesters.
3. **Conduct a feasibility study on centralised food waste processing facility.** This would identify the most prospective locations for the facility (proximity to food waste sources, end-users) and how to mitigate or avoid potential issues (e.g., ensuring restricted animal material will not be found in processed material fed to ruminants). There is significant collaborative potential for this study with other industry and supply chain partners (e.g., major food retailers, food service, food processors). Facilities of this nature would also support the Federal Government's commitment to halve food waste by 2030 (Commonwealth of Australia, 2017).
4. **Update PigBal to include GHG emissions for outdoor production and Scope 3 estimates.** An update to the model (mass and nutrient flows, and underlying pig production components) is needed to ensure that PigBal can function meaningfully for outdoor production. This would also be of benefit for producers where nutrient levels in range areas are under increasing focus from regulators. Inclusion of Scope 3 emission factors for major sources (feed, energy, purchased inputs) would ensure that producers (particularly small to medium-sized farms not captured by mandatory climate-related financial disclosures obligations) have an endorsed tool that provides them with insights for multiple purposes (nutrient management, GHG emission measurement, and tracking).

5. **Foster development of low emission grain supply chains.** This is a major collaborative opportunity for several industries, including the grains, poultry, feedlot, and dairy industries. There are programs of work underway that could be extended to support this, e.g., the Low Emissions Intensity Farming Systems (LEIFS) program (PIRSA, 2025).
6. **Quantify GHG emissions from use of piggery manure (deep litter) to offset inorganic fertiliser use and build soil carbon.** Field-level assessments should be conducted (for multiple soil types/regions) to assess the soil carbon benefit from repeated application of piggery spent litter. An LCA of the grain (as compared with baseline production with only inorganic fertiliser) should be conducted to assess the product carbon footprint where inorganic fertiliser is displaced. It would also be beneficial to assess the gross margin for the crop. This is a collaborative opportunity with the grains sector.
7. **Establish a demonstration site with an integrated treatment train involving solids separation, sHRT, chemical dosing, and soil injection.** This will act as on-ground evidence of the viability (technical, financial, practical) of sHRT in the Australian pig industry and demonstrate how, in conjunction with other strategies, traditional management challenges can be mitigated. The authors are aware of an Australian pork producer currently operating a sHRT system with soil injection. This would be the ideal demonstration site – a solids separator could be relatively easily integrated into the system. Pending the outcomes of current research into pond additives, dosing could also be integrated in future.

Across these (and other research opportunities), APL should continue to work with other RDCs on mutual solutions. Where collaborative opportunities are identified, but project governance/administration presents a challenge to administer across multiple RDCs, it should be considered whether there is a role for the Federal Government in acting as a central administrator for these projects.

Extension and Adoption Recommendations

1. **Develop an online database and decision support tool for piggery GHG emission reduction opportunities.** This would take the information contained in the matrix and put it in an easy-to-navigate, online format that allows users to screen emission reduction strategies for relevance to their farm, evaluate trade-offs, and identify producer-facing resources to assist in decision-making and on-ground implementation. As described elsewhere in this report, resources which also outline the financial implications of strategies and technologies typically receive more interest from producers. Where possible, the tool should include this information.
2. **Develop a series of up-to-date case studies and benefit-cost analyses of emerging and novel strategies and technologies.** Ideally, these would be based on real-world application to ensure that producers engage positively with the resources (i.e., reduce uncertainty). Priority topics may include sHRT, ground source heat pumps, electrification, reduced stocking rate/increased rotation in outdoor. The benefit-cost analysis results could then be integrated into the decision support tool. The need for this updated and expanded case-studies and benefit-cost analysis was raised by industry stakeholders over the course of this project, particularly where a technology is technically feasible but has very low adoption.
3. **Develop producer-facing resources that outline the financial benefit (and emission reduction potential) of productivity improvements.** Though similar to the point raised above, this process would be worth conducting separately (and for a greater number of

housing and production systems). The need for this first-principles type of resource was raised by industry stakeholders over the course of this project.

4. **Update and relaunch of PigGas or similar**. The PigGas Calculator was a valuable tool which pork producers could use to conduct a high-level estimate of their farm emissions and also run 'what if' scenario analysis to assess the emission reduction potential of various strategies (Kruger et al., 2013). As the AIA EAP is a more recent high-level calculator (than PigGas), it may be the best means of relaunching a 'what if' scenario analysis tool for industry.
5. **Develop case study examples of very low emission piggeries, particularly from a consequential life cycle assessment (cLCA) perspective.** Note that this would also require a research project to undertake the cLCA. Certain production systems (100% of manure treated in covered ponds, energy generation from biogas, high volumes of diverted food waste, by-products and residuals in feed) generate very low emission pork.

Data Capture Recommendations

A core need is the development of a data capture system that allows APL to cost-effectively and efficiently collect data from producers to track performance over time. In the longer-term, this would also likely reduce the burden on industry as the number of reporting obligations grows (to industry, customers, and regulators where relevant). The upfront investment cost to design such a platform may be relatively high but would avoid long-term costs in the future. The platform could also be designed for purposes that go beyond GHG assessment, e.g., to collect and store APL producer survey data.

8. Intellectual Property

There is no intellectual property arising from this project.

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10. Publications Arising

None at this time.