Theme BT2: Decarbonising businesses and supply chains

Anaerobic Co-Digestion of Red Meat Industry Wastes

Final Report

Final report

RACE for Business

Anaerobic Co-Digestion of Red Meat Industry Wastes

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Acknowledgement of Country

The authors of this report would like to respectfully acknowledge the Traditional Owners of the ancestral lands throughout Australia and their connection to land, sea and community. We recognise their continuing connection to the land, waters, and culture and pay our respects to them, their cultures and to their Elders past, present, and emerging.

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Executive Summary

The project entitled "*Anaerobic Co-Digestion of Red Meat Industry Wastes*" was undertaken under RACE for 2030's Theme "*T2 – Decarbonising Businesses and Supply Chains*" to evaluate the potential of anaerobic co-digestion (ACoD) as a decarbonisation and bioenergy production pathway for Australia's red meat sector. The study combined experimental research, techno-economic modelling, and impact assessments to optimise and assess the commercial and environmental benefits of ACoD compared to mono-digestion of red meat by-products.

Project Overview

The red meat industry generates a significant amount of high-strength organic by-products, including offal, manure, paunch, fats, and blood. While the red meat industry has identified ways to utilise the majority of the by-products produced, the industry is searching for methods to decarbonise and utilise residual organic by-products. Anaerobic digestion (AD) is a well-established organic treatment technology; however, its performance with red meat by-products can be constrained due to high protein and lipid contents, resulting in ammonia and long-chain fatty acid (LCFA) inhibition. ACoD, which blends two unique feedstocks, offers a practical solution to improve process stability and increase methane yields through dilution of inhibitory compounds and supplementation of limiting nutrients.

Experimental Approach

Eleven red meat processors across Australia participated in this study. Laboratory-scale biochemical methane potential (BMP) studies were conducted to quantify methane yields from proportional mixtures of site-specific by-products and agricultural co-substrates. Batch studies were conducted in three phases, which assessed the baseline methane potential of proportional mixtures, the impact of co-digestion with agricultural residues, and macronutrient optimisation. Key results of these phases include:

- Phase 1 – Mono-digestion: BMPs of red meat proportional mixtures ranged between 175-559 $NL_{CH_4} \cdot kg^{-1}{}_{\text{VS added}}$, varying by site and independent of livestock type.
- Phase 2 – Co-digestion: Agricultural residues, such as grain, brewery waste, and bagasse, were trialled with optimal mixtures yielding improvements of 30-37% in methane productivity.
- Phase 3 – Macronutrient optimisation: macronutrient balances identified an optimal lipid: protein: carbohydrate ratio of 60:20:20, which increased methane yields by 51-75% increase compared to mono-digestion.

Continuous digestion trials validated the findings of the batch experiments under semi-continuous conditions, confirming that feedstock control and co-digestion strategies enhanced methane productivities and process stability, enabling operation at elevated organic loading rates.

Technoeconomic and Impact Assessment

Detailed technoeconomic evaluations were conducted for two processors (NSW4 and WA4) to evaluate the financial performance across three scenarios: mono-digestion, co-digestion, and optimised ACoD. Key findings include:

- Mono-digestion scenarios resulted in negative net present values (NPVs) and poor benefit-cost ratios (BCRs; 0.30 – 0.42) due to the low methane yields and diversion of valuable by-products from market to AD.
- Co-digestion scenarios improved economic performance substantially, supporting NPVs exceeding $221 million for both sites with BCR >1.4, and payback periods of 4 years.
- The optimised ACoD scenario, based on a commercially operating plant in Europe, displayed the potential of red meat ACoD with NPVs 10.3 and 12.3-fold higher than those from co-digestion.

The impact analysis confirmed ACoD delivered significant greenhouse gas reductions, offsetting grid electricity consumption while assisting in the displacement of synthetic fertilisers. The optimised ACoD scenario achieved further greenhouse gas reductions, offsetting all grid consumption and standing out as a significant emissions sink.

Key Project Outcomes

- ACoD increased methane yields by 51-75%.
- ACoD improved process stability and supported operation at elevated organic loading rates in continuous studies.
- Economic returns were strengthened by ACoD strategies, enabling positive returns and strong economic performance.
- Greenhouse gas emission returns were strengthened by implementing ACoD, with facilities significantly reducing processor carbon emissions.

Conclusions

The project demonstrated that controlled co-digestion of red meat by-products with agricultural residues can transform organic products into valuable renewable energy and co-products. ACoD offers a practical, scalable pathway for Australia’s red meat industry to reduce emissions and support the circular economy. The results of this study provide the technical and economic foundation for future demonstration-scale deployment and commercial adoption of the ACoD technology.

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1. List of Abbreviations

ACoD	Anaerobic Co-digestion
AD	Anaerobic Digestion
AMPC	Australian Meat Processor Corporation
BCR	Benefit Cost Ratio
BMP	Biochemical Methane Potential
BRRC	Bioresource Recovery Centre
CAPEX	Capital Expenditure
CH4	Methane
CHP	Combined Heat and Power
CO2	Carbon Dioxide
EOI	Expression of Interest
FOGO	Food and Garden Organics
HRT	Hydraulic Retention Time
HSCW	Hot Standard Carcass Weight
IRG	Industry Reference Group
LCFA	Long Chain Fatty Acid
MLA	Meat and Livestock Australia
OLR	Organic Loading Rate
OPEX	Operational Expenditure
PBP	Payback Period
ROI	Return on Investment
TEA	Technoeconomic Assessment
TS	Total Solids
VFA	Volatile Fatty Acid
VS	Volatile Solids

2. Introduction

2.1 Project Background and Context

The red meat processing sector is one of Australia's largest food processing sectors. In 2023 - 24, the industry generated $17.7 billion in export sales and more than $29 billion in value-added outputs across the sector, equivalent to 1.21 % of Australia's GDP (AMPC, 2024, AMPC, 2025b). This strong economic performance is paired with associated energy and emissions footprints. Estimates in 2024 outlined energy and greenhouse gas emissions from the sector equated to 2,897 MJ and 330 kgCO_2-eq per tonne of hot standard carcass weight (tHSCW), respectively (AMPC, 2025a), equating to 0.24% of national greenhouse emissions (AMPC, 2025a, DCCEEW, 2025).

Over the last decade, major progress has been made within the sector, with processors seeing major reductions in emissions, water consumption, and energy demands (AMPC, 2025a). Moreover, through extensive innovation, the industry has developed novel ways of utilising up to 98% of the carcass to produce value-added products, underscoring the red meat industry as a sustainability-driven sector. Despite this, red meat processors are seeking additional ways to further decarbonise and reduce their environmental impacts. With the red meat industry spanning across Australia, employing more than 39,000 employees and indirectly supporting nearly 150,000 jobs across supporting industries (AMPC, 2025b), the sector represents a valuable opportunity for further sustainable development.

Red meat processor operations produce a variety of by-products, including blood, paunch, manure, and fats, which vary depending on the animals processed and the process plant configuration (Harris and McCabe, 2020). Over recent years, Meat and Livestock Australia (MLA) and the Australian Meat Processor Corporation (AMPC) have commissioned numerous studies to investigate by-product management strategies and renewable energy solutions for the sector (Butler, 2018, Jensen, 2015, AMPC, 2022, AMPC, 2023, Jensen and Tait, 2018, O'Hara, 2022). Anaerobic digestion (AD) has been highlighted as a promising technology to exploit underutilised by-products, generating renewable biogas energy and biofertiliser while reducing carbon emissions, and grid and/or gas demands.

The composition of wastewater generated from the red meat industry is typically rich in fat and protein (Harris and McCabe, 2020, Pagés-Díaz et al., 2014), making it well-suited to AD treatment. However, mono-digestion of protein or lipid-rich substrates can lead to process inhibition or failure due to the accumulation of ammonia (Bayr et al., 2014, Alvarez and Lidén, 2008, Zhang and Banks, 2012) and/or long-chain fatty acids (LCFAs) (Hamawand et al., 2017, Tian et al., 2018). To reduce inhibition or failure risk, co-digestion strategies, which aim to combine red meat by-products with other complementary substrates, are increasingly being explored and implemented to improve process resilience and stability.

Anaerobic co-digestion (ACoD) commonly displays numerous benefits, including higher buffering capacity, increased biogas production, improved nutrient balance, and dilution of inhibitory compounds, often leading to an increased capacity for higher loading rates (Borowski et al., 2018). Operationally, ACoD reduces the risk of digester upsets and may allow for smaller, intensified reactors. However, designing an effective ACoD system remains a technically challenging task as substrate compositions and availability of local co-substrates can vary substantially between sites. As a result, feasibility should be evaluated on a case-by-case basis, considering site-specific factors, including by-product and waste profiles, site location, and surrounding co-feedstock availability.

Compositional analysis has shown the carbon-to-nitrogen (C:N) ratio for meat mixtures generally lies below the optimal range of 20 – 30 (Nazifa et al., 2021), suggesting co-digestion with carbon-rich substrates, such as agricultural residues (Wang et al., 2023, Nazifa et al., 2021), can improve digestion performance. In the context of the red meat industry, carbon-rich feedstocks from agricultural industries, which are currently underutilised, represent a valuable opportunity for the red meat industry. Here, ACoD of agricultural residues with red meat by-products could optimise the carbon-to-nitrogen ratio while addressing ammonia and LCFA inhibition, which can improve process stability and increase gas production.

Therefore, this project aimed to assess the feasibility of AD and ACoD for eleven different red meat processors. By-products from the eleven different sites were assessed for their Biochemical Methane Potential (BMP). Agricultural residues, which were sourced from locally accessible sites close to participating red meat processors, were then mixed with the by-product mixtures at predetermined ratios to assess co-digestion performance and optimise the feedstock macronutrient profile. Selected batch BMP tests were then followed by continuous digestion experiments to validate the performance of the bench-scale tests and assess the risk of inhibition. The findings from this project provide practical insights to industry and contribute to a broader understanding of how ACoD can support the decarbonisation efforts of Australia’s Red meat industry.

2.2 Project Objectives

Red meat industry by-products are rich in proteins, lipids, and nutrients, making them a valuable substrate for bioenergy and biofertiliser production. However, mono-digestion of these materials can result in digester upsets related to ammonia and/or LCFA accumulation. Therefore, processor by-products require co-digestion with carbon-rich substrates to improve nutrient balances and mitigate inhibition risk. Despite the known need for co-digestion, there is significant uncertainty around co-substrate selection and the quantity of co-substrate required to benefit Red Meat by-product digestion.

Therefore, this project aimed to systematically address these uncertainties through assessing the methane potential of different red meat processor by-product mixtures and the impact of co-digestion with different carbon-rich agricultural wastes through batch and semi-continuous experiments. This project also strategically contributed to RACE for 2030’s theme *B5: On-site anaerobic digestion for power generation and natural gas/diesel displacement*.

The objectives of this project were as follows:

1. Conducting a thorough literature review on anaerobic digestion and the benefits of co-digestion.
2. Characterisation of red meat industry by-products and agricultural residues.
3. Benchmarking of red meat by-product biochemical methane potential during mono- and co-digestion studies.
4. Assessment of the risk of process toxicity from ammonia and LCFAs through the operation of semi-continuous digesters during mono- and co-digestion at different operational conditions.
5. Conducting a detailed technoeconomic evaluation on the feasibility of ACoD within the red meat industry, assessing the economic and environmental benefits of mono- and co-digestion strategies.
6. Complete a detailed impact assessment to assess the carbon impacts of commercialising an ACoD facility within the red meat industry.

3. Methodology

3.1 Industry Reference Group Meetings

An Industry Reference Group (IRG) was established shortly after the commencement of the project. The group consisted of key industries, including meat processors, equipment suppliers, and industry representatives (AMPC and MLA). Here, the IRG formed a valuable feedback body, providing critical industry insights and feedback into the project planning, results, and direction, elevating the value of project findings and outcomes for the industry.

3.2 Literature Review

An extensive review of existing literature and previous work was conducted by Tessele Consultants and Griffith University. The literature review focused on AD and ACoD strategies for primary feedstocks rich in nitrogen. This included a review of AD operational parameters and key nutrients required for efficient digestion and common inhibitors encountered, and management strategies to mitigate inhibition. The review concluded by highlighting key economic and environmental considerations for ACoD processes and outlined future research needs to advance ACoD within the red meat industry.

3.3 Batch Biochemical Methane Potential Studies

3.3.1 EOI and Survey

An expression of interest (EOI) and survey pack were prepared for submission to red meat industries across Australia and surrounding agricultural industries. EOI packs included key questions focused on meat processors and the local agricultural industry, with enquiries related to their operations and feedstocks that could be available for AD. A copy of the survey pack is attached in Appendix A.

3.3.2 Inoculum and substrates

A mesophilic anaerobic inoculum, which was obtained from a full-scale digester treating sewage sludge (Queensland Urban Utilities, Luggage Point, Brisbane), was used in all batch experiments in this study. The inoculum was stored at 4 °C until use, before which it was first degassed for 7 days at 37 °C.

Red meat industry substrates were collected from 11 different meat processors across Australia. Upon receipt, samples were immediately processed, using a benchtop kitchen mincer, to produce homogenous proportional mixtures (Figure 1). Proportional mixtures were calculated based on the annual by-product production quantities outlined by each red meat processor in the survey. Agricultural substrates for each proportional mixture were selected based on the survey results (Section 4.3.1) and relative proximity to the participating red meat industries. All substrates were stored at 4 °C until use.

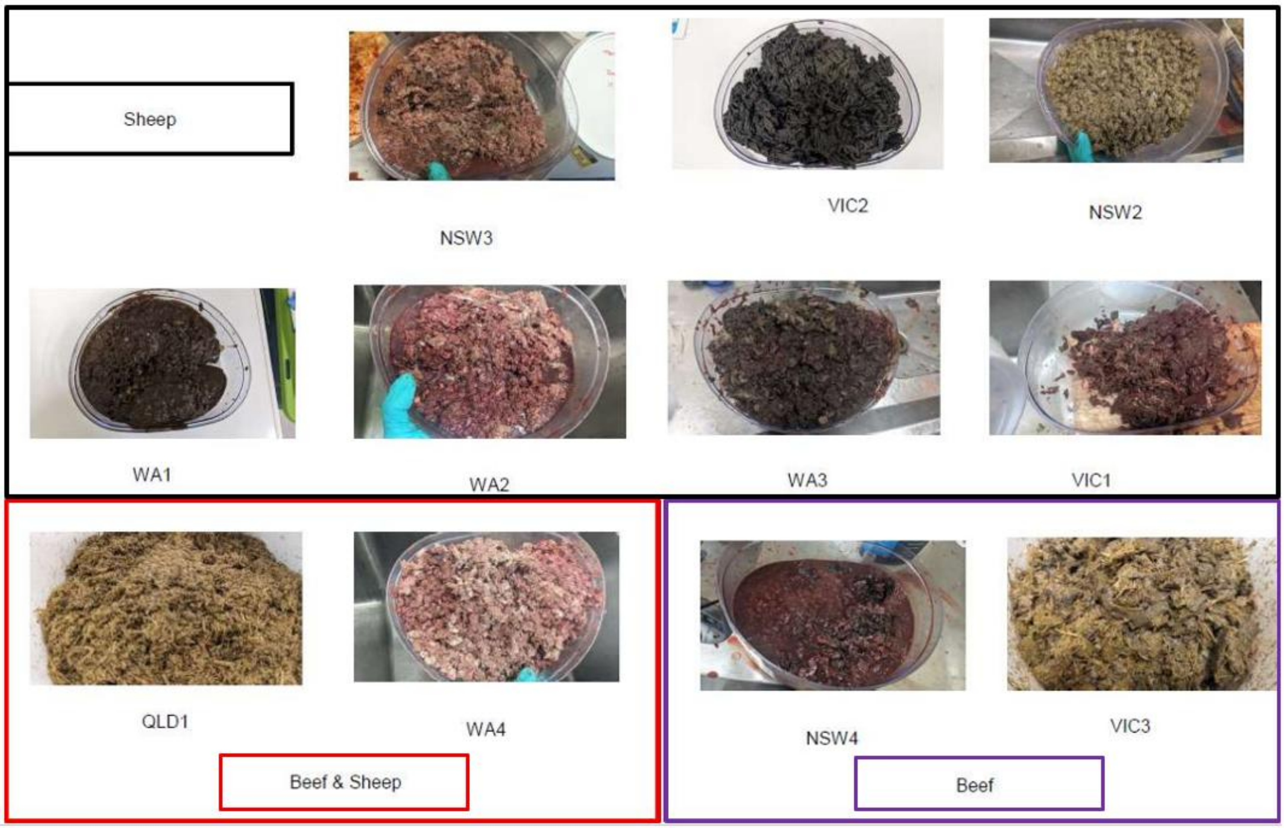


Figure 1: Images of the proportional mixtures produced following processing and mixing of the individual substrates.

3.3.3 Biochemical Methane Potential Tests

Biochemical Methane Potential (BMP) assays were performed using 1000 ml stirred batch reactors with working volumes of 600 ml. Test mixtures comprised of inoculum (450 ml) and a predetermined quantity of the target substrate to achieve an inoculum-to-substrate ratio of 2 (on a volatile solid (VS) basis). Distilled water was added to the inoculum/substrate mixture to ensure a working volume of 600 ml. The digestion vessels were then promptly sealed, purged with nitrogen, and incubated at 37 °C for a minimum of 30 days. A blank triplicate containing just inoculum was run in parallel to determine the inoculum background methane production. The volume of methane produced from the blank was then subtracted from that produced from each of the treatments. The resulting background-corrected methane production was then normalised with respect to the quantity of substrate added (as VS).

3.3.4 Kinetic Modelling

Methane production curves were fitted with a first-order kinetic model (Eq. 1) to estimate he specific methane potential of the substrate.

$$B(t) = B_0 \cdot \left(1 - e^{-k \cdot t}\right) \qquad \text{(Eq. 1)}$$

Where *B(t)* is the blank corrected cumulative methane produced ($NL_{CH4} \cdot kg^{-1}_{VSadded}$) at time *t* (days), B_0 is the specific methane potential ($NL_{CH4} \cdot kg^{-1}_{VSadded}$), and *k* is the first-order rate constant (day^{-1}).

To explore the relationship between the microbial specific growth rate, microbial population density, and methane yield, the modified Gompertz model was fitted to the cumulative methane data.

$$B(t) = B_0 \cdot e^{-e^{\frac{R_{max} \cdot e}{B_0} \cdot (\lambda - t) + 1}} \quad \text{(Eq. 2)}$$

Where $B(t)$ is the blank corrected cumulative methane produced ($NL_{CH4} \cdot kg^{-1}_{VSadded}$) at time t (day), λ is the lag phase (day), R_{max} is the maximum methane production rate ($NL_{CH4} \cdot kg^{-1}_{VSadded} \cdot day^{-1}$).

3.3.5 Analytical Methods

Inoculum and reactor pH were measured using a pre-calibrated pH probe and meter (TPS, Australia). Total solids (TS) and VS were measured according to standard methods (APHA, 1998). Phosphate (PO_4-P) and ammonium nitrogen (NH_4-N) were measured using a Lachat Instruments USA, Quick Chem 8000 Flow Injection Analyser (FIA) as described elsewhere (Kruk et al., 2014). Total and soluble metals, total Kjeldahl phosphorus (TKP), and total Kjeldahl nitrogen (TKN) were measured using an inductively coupled plasma-optima emission spectroscopy (ICP-OES) equipped with WinLab32 for ICP software (Perkin Elmer, USA Optima 7300 DV) as described elsewhere (Bressy et al., 2013). Total carbon and nitrogen in solid samples were measured via combustion as described by Benson et al. (2009).

Daily biogas production was determined by measuring the headspace pressure using a gas manometer (Paulose and Kaparaju, 2021). Biogas composition (CH_4 and CO_2) was measured using a gas chromatograph equipped with a thermal conductivity detector (Shimadzu, 2014). Methods for the measurement procedure are described elsewhere (Paulose and Kaparaju, 2021). The dry biogas and methane volume was normalised to standard temperature and pressure recorded at the time of measuring the biogas volume.

3.4 Continuous Digester Studies

The two selected red meat processors shortlisted during the BMP testing were used for the continuous pilot-reactor studies. Two semi-continuous reactors were employed to assess the performance and stability of biogas production from mono- and co-digestion feedstocks. Here, testing explored digestion performance while varying operational variables, such as ratios of co-substrate digestion, hydraulic retention time (HRT), organic loading rate (OLR), feedstock macro-nutrient composition, and the influence of additives, such as activated carbon and biochar.

3.4.1 Inoculum and substrates

A mesophilic anaerobic inoculum was obtained from a full-scale digester treating sewage sludge (Queensland Urban Utilities, Luggage Point, Brisbane). The inoculum was stored at 4 °C until use. Red meat industry substrates were collected from WA4 and NSW4 every 6 months. Samples were immediately processed upon receipt using a benchtop kitchen mincer to produce homogenous mixtures based on the results of the batch BMP tests. Homogenised feedstocks were frozen for long-term storage and thawed prior to use. Agricultural substrates were collected from the selected agricultural industries and prepared on receipt. Prepared substrates were frozen for long-term storage and thawed prior to use.

3.4.2 Continuous Digestion Experiments

Semicontinuous digestion experiments were conducted in 12 L continuously stirred tank reactors, each with a working volume of 10 L. Each reactor was equipped with a feed port and stopper, effluent valve, heating jacket, gas flow meter, and overhead stirrer. Reactors were manually fed daily on weekdays, and the equivalent amount of digestate was discharged by overflow of the digestate following feed addition. The overflow line was sealed via a water lock to prevent biogas loss through the digestate outlet.

Prior to startup, the inoculum was degassed at 37 °C for 7 days, following which the reactors were filled with 10 L of inoculum and the headspace was purged with nitrogen to ensure anaerobic conditions. During the initial startup phase, the digesters were fed with proportional mixtures from NSW4 (Reactor 1) and WA4 (Reactor 2) at an organic loading rate (OLR) of 0.2 $g_{VS}\cdot L^{-1}\cdot day^{-1}$ and a hydraulic retention time (HRT) of 60 days, following which the OLR was stepwise increased to 2.0 $g_{VS}\cdot L^{-1}\cdot day^{-1}$ (Table 1). Due to the high solids content of the proportional mixtures, the HRT in both reactors was reduced from 60 days to 35 days to accommodate the OLR increase from 1.0 to 2.0 $g_{VS}\cdot L^{-1}\cdot day^{-1}$. Following mono-digestion at an OLR of 2.0 $g_{VS}\cdot L^{-1}\cdot day^{-1}$, agricultural materials (grain for WA4 and bagasse for NSW4) were added to the substrates at predetermined ratios on day 125. Co-digestion continued for 49 days, after which the feedstock was swapped to a macronutrient optimised feedstock determined from the batch BMP tests (Section 3.3).

Table 1: Continuous digestion experiment operation parameters

ID	Exp. Phase	Days	OLR	HRT
NSW4	Mono-digestion	Startup 0-30 days	0.2	60
			0.5	60
		30-73	1.0	60
		73-125	2.0	35
	Co-digestion	125-174	2.0	35
	Co-digestion (macro optimised)	174-265	2.0	35
		265-290	2.5	35
		290-350	2.25	35
WA4	Mono-digestion	Startup 0-37 days	0.2	60
			0.5	60
		37-73	1.0	60
		73-125	2.0	35
	Co-digestion	125-190	2.0	35
	Co-digestion (macro optimised)	190-290	2.5	35
		290-350	2.25	35

3.4.3 Analytical Methods

Analytical methods used were the same as those used for the batch experiments (Section 3.3.5). Daily biogas production was measured using a gas meter (Ritter, MilliGas counter MGC-10). The produced biogas was corrected to dry biogas volume and expressed as the volume at standard temperature and pressure.

3.5 Techno-Economic Assessment

The anaerobic digestion techno-economic assessment (TEA) for NSW4 and WA4 considered 330 days of continuous operation per year. Capital costs (CAPEX) included engineering, procurement, and construction of various components and equipment, including those for the AD equipment, combined heat and power engines, flares, CO_2 recovery units, and biofertiliser plant. Specific CAPEX values for each scenario were determined using the power law (Eq. 2), a standard method for estimating costs for similar projects.

$$C_2 = C_1 * \left(\frac{V_2}{V_1}\right)^n \qquad \text{(Eq. 2)}$$

Where C_1 is the initial cost of the equipment, V_1 is the initial size of the equipment, V_2 is the new equipment size, n is the scaling factor (0.6), and C_2 is the new equipment cost.

Annual operational costs (OPEX) for all scenarios were assumed to be 6% of total scenario CAPEX, with an increase to 12% every 5 years to account for major preventative maintenance. Revenue/benefits included the offset of grid power and natural gas consumption, export of excess power to the grid, CO2 sales, biofertiliser sales, sale of ACCUs, and sale of large-scale generation certificates (LGCs). ACCUs are calculated by determining the total tonnes of CO_2eq avoided through the implementation of the AD, biofertiliser production, and CO_2 recovery. The value of ACCUs was taken as 37.35 AUD·tonne^{-1} (www.cer.gov.au). LGCs were calculated using Eq. 3 (www.cer.gov.au):

$$LGC_P = TP - [(F + A) + D * (1 - M)] \qquad \text{(Eq. 3)}$$

where; LGC_p is eligible renewable electricity generated (MWh), TP is total electricity generated (MWh), F is power generated by ineligible sources (=0 in this case; MWh), A is parasitic load (MWh), D is power distributed by the power station (MWh), M is a marginal distribution loss factor (=1; as power is supplied to local distribution network). LGC sale price was assumed to be 21.25 AUD·MWh^{-1}, based on the 2025 Q2 price (www.cer.gov.au). As LGCs are scheduled to end after 2030, revenue generated from LGCs was included for the first 6 years of the project. Installation and commissioning were assumed to occur over 1 year, during which all revenue was assumed to be zero. Taxation and decommissioning costs were excluded. The diversion of value-added by-products from the market to the AD plant was included as a cost to the project, due to the loss in revenue to the red meat processor resulting from reduced by-product sales.

Scenario profitability was quantified using; 1) net present value (NPV) for a nominal 30-year project life, using a 5% discount rate and 6% escalation rate on future cashflows, 2) return on investment (ROI), 3) payback period, which was taken as the time to recoup the initial capital investment cost using adjusted annual project cashflows, and 4) the benefit cost ratio (BCR). NPV was calculated using Eq. 4:

$$NPV[AUD] = \sum_{n-1}^{T} \frac{C_n}{(1+d)^n} - C_0 \qquad \text{(Eq. 4)}$$

where; C_n is the net cash flow during the time period n, d is the discount rate, and C_0 is the initial capital investment (including fixed and working capital). Return on Investment (ROI) was calculated using Eq. 5:

$$ROI[\%] = \frac{Total\ Project\ Profit}{C_0} \qquad \text{(Eq. 5)}$$

The BCR was calculated using Eq.6:

$$BCR = \frac{Present\ Value\ of\ all\ Benifits}{Present\ Value\ of\ all\ Costs} \qquad \text{(Eq. 6)}$$

All monetary values were quantified in AUD.

A sensitivity analysis was used to determine the effect of ±50% variation in electricity price, natural gas price, CO_2 price, biofertiliser price, ACCU price, CAPEX, OPEX, BMP, plant capacity, discount rate, and escalation rate on the calculated NPV.

3.6 Impact Analysis

The impact of commercialising ACoD at the red meat processor sites was assessed in terms of total carbon offsets for each scenario evaluated in the TEA. Emission factors for natural gas were assumed to be 51.53 kg CO_2eq·GJ^{-1}, while scope 2 and 3 emissions factors for grid electricity were taken as 0.63 and 0.07 kg CO_2eq·kWh^{-1}, respectively (www.dcceew.gov.au). Emissions from the consumption of biogas within a CHP were taken as 6.43 kg CO_2eq·GJ^{-1} (www.dcceew.gov.au), while emissions savings from the displacement of synthetic fertilisers were assumed to be 0.95 kg CO_2eq·$tonne^{-1}$. Scope 3 emissions from the transport of by-products for disposal were assumed to be 17.3 kg CO_2eq·GJ^{-1}, based on the combustion of diesel in a 25-tonne capacity truck (www.dcceew.gov.au). Total round-trip distance was assumed to be 400 km. The overall net greenhouse gas impact of each scenario was determined as the sum of all emission sources and offsets.

3.7 Knowledge Sharing

Shortly after the commencement of the project, a comprehensive knowledge-sharing plan was developed to ensure effective and timely knowledge dissemination across project partners, industry, and the wider research community. The plan included an outline of key knowledge-sharing activities that were to be conducted during the project, including the preparation of regular project update reports and the development and publication of scientific journal articles based on the project results and findings. Additional activities included online and in-person workshops, which extended beyond project partners and invited the wider industry and research community to participate in project discussions and presentations of the project findings.

4. Results and Discussion

4.1 Research activity 1: Establishment of IRG and meetings

An Industry Reference Group (IRG) was established shortly after the commencement of the project and formed a valuable feedback body to the project team. A total of 17 IRG meetings were conducted over the course of this project, providing key industry insights into the project deliverables, findings, and plans. A summary of discussions held at each IRG is provided in Appendix B.

4.2 Research activity 2: Literature review on ACoD and feedstock determination

An in-depth literature review on red meat by-product AD and ACoD, exploring factors including operational considerations, toxicity, inhibitor management, and possible co-digestion substrates. The review highlighted the benefits of co-digestion observed from previous works, emphasising those related to nutrient balancing, improved process efficiency, enhanced process stability, and increased methane yields compared to mono-digestion. Agricultural residues were identified as promising co-substrates for co-digestion with red meat industry by-products, particularly due to their high carbon content and ability to assist in pH stabilisation. The review concluded that, while significant progress has been made, a knowledge gap related to optimal co-digestion ratios still exists, underscoring this as a key focus area for research efforts. A copy of the literature review is available in Appendix C.

4.3 Research activity 3: Biomethane potential tests

The batch BMP methodology was employed to assess the methane potential of the different proportional mixtures. BMP experiments were conducted in three distinct phases, following completion of an EOI survey by Red Meat Processors across Australia. Each experimental phase built on the findings of the previous phase, with the common goal to maximise biogas production.

In Phase 1, individual by-products (blood, hair, offal, etc.) produced from 11 different red meat processors were mixed at predetermined ratios to produce proportional mixtures that simulated realistic scenarios at the different processor sites. These mixtures were subject to BMP testing over >30 days to assess methane yields, nutrient profiles, physicochemical properties, and to establish baseline methane production profiles for each processor.

For Phase 2, fresh proportional mixtures were produced from fresh by-products collected from each processor, along with local agricultural residues, including brewery, grain, and potato wastes. These residues were selected based on reported BMP values, proximity to processing sites, large-scale availability, and year-round supply. The agricultural residues and fresh proportional mixtures were characterised and then co-digested with selected agricultural residues at predetermined ratios, which prioritised red meat by-products as the primary feedstock.

From the 11 red meat processors from Phase 1 and Phase 2, two were shortlisted for Phase 3 testing. Selection was based on a rigorous selection criterion, with processors scored on the following:

- History of collaboration
- Feasibility of scale-up

- Feedstock characteristics
- Economic factors
- Location
- Environmental
- Innovation
- Commitment to the project
- Logistics
- Potential for co-benefits
- Technical expertise
- Preliminary BMP results

Following shortlisting, fresh by-products from the selected red meat processors and agricultural industries were collected and combined at predetermined ratios to target selected lipid, protein, and carbohydrate ratios.

4.3.1 Expression of Interest Survey

A total of 19 Red Meat Processors and 12 Agricultural Industries participated in the survey, providing key information related to their operations and feedstocks available for AD. Participating processors were strategically reduced from 19 to 11 using a thorough weighted selection criterion based on survey responses provided. Table 2 summarises key information obtained from the shortlisted participants.

Table 2: Key information from the shortlisted Red Meat Processor participants from the EOI survey.

Site ID	Location	Animal	By-Product (tonne/year)	Top four by-products
NSW4	New South Wales	Beef	32,700	Skins and Hides (44.25%), Blood (25.81%), Rendering material (14.75%), and Paunch (7.37%)
VIC3	Victoria	Beef	15,000	Paunch (53.33%), Screened solids (26.67%), DAF sludge (13.33%), and Manure (6.67%)
NSW2	New South Wales	Sheep	6,450	Paunch (38.76%), Contrashear content (23.26%), DAF sludge (21.71%), and Manure (7.75%)
WA2	Western Australia	Sheep	10,265	Paunch (25.33%), Inedible Offal (19.48%), Red Contrashear (19.48%), and Skins and Hides (17.05%)
WA1	Western Australia	Sheep	33,311	DAF sludge (64.65%), Skins and Hides (14.59%), Paunch (9.12%), and Manure (7.41%)
VIC1	Victoria	Sheep	3,100	Blood (25.51%), Skins and Hides (25.51%), Inedible Offal (23.59%), and Screened solids (15.95%)
WA3	Western Australia	Sheep	1,420	Blood (32.39%), Inedible Offal (30.99%), Tripe (14.08%), and Skins and Hides (11.62%)
VIC2	Victoria	Sheep	2,236	Primary press sludge (37.14%), Secondary press sludge (31.43%), Contrascreen material (14.29%), and Manure (8.57%)
NSW1	New South Wales	Sheep	9,886	Blood (30.35%), Green Contrashear (27.35%), Inedible Offal (16.12%), and Red Contrashear (10.52%)
WA4	Western Australia	Sheep & Beef	32,564	Blood (36.74%), Skins and Hides (24.25%), Paunch (20.21%), and Rendering material (7.28%)
QLD1	Queensland	Sheep & Beef	11,063	Paunch (86.42%), Tricanter bincontent (10.8%), Contrashear content (2.78%)

Results from the red meat processor survey showed common major by-products produced included paunch, skins and hides, blood, and contrashear screenings (Figure 2). However, the quantity of each by-product produced at each site was dependent on the facility size and its operations.

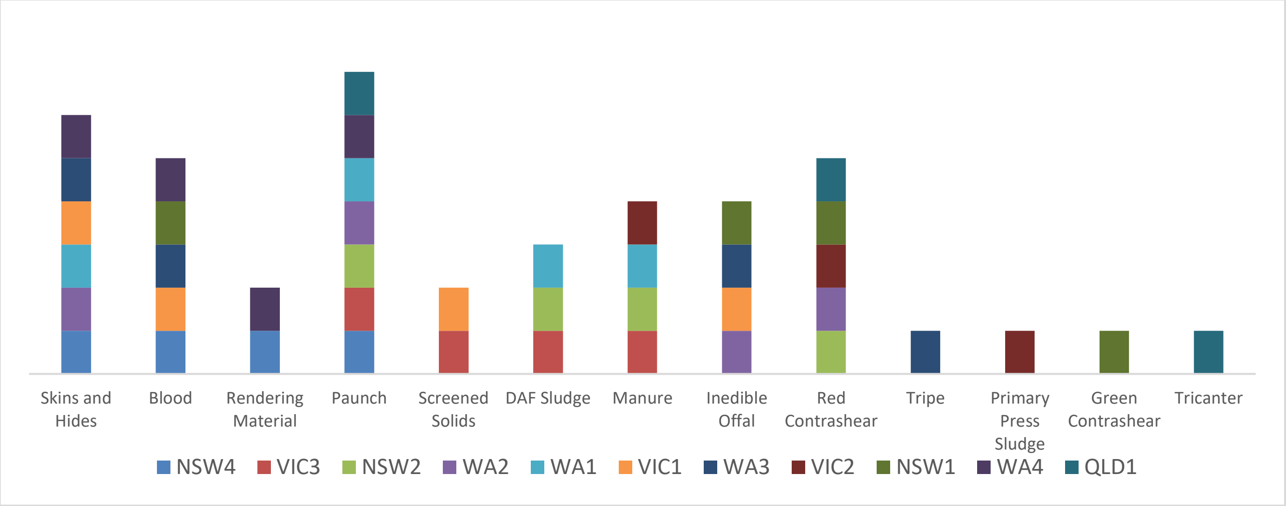


Figure 2: Common major by-products produced from participating red meat industries.

Survey results from agro-industries highlighted food and garden organics (FOGO), bedding, hay, by-products, potato skins, reject potatoes, grains, and mushroom substrate were available to participating red meat industries to support full-scale ACoD operations. Similar to the Red meat industry, by-product type and quantity available for AD were dependent on the agricultural facility size and operations. Importantly, the agro-industries and products available for ACoD were dependent on the relative location to participating Red Meat Industries. This was to ensure a practical approach to co-substrate selection, ensuring that tested substrates were practically available to the Red meat industry.

4.3.2 Phase 1: Proportional Mixture Mono-digestion

By-products from the shortlisted participants (Table 2) were then sampled and combined to produce 11 proportional mixtures based on the annual output of each facility (Figure 3). Each proportional mixture presented its own unique characteristics, such as pH, moisture content, nitrogen content, and fatty acid profile.

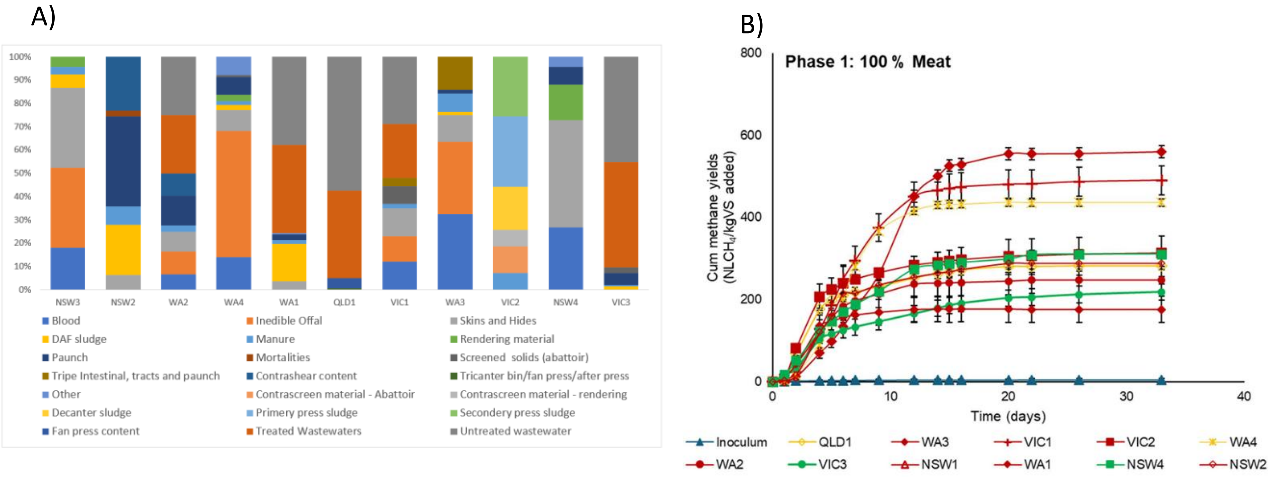


Figure 3: Figure detailing the A) proportional mixture composition from each of the participating red meat processors, and B) BMP curves produced following digestion of each of the proportional mixtures. The line colours refer to the different animals processed at each facility, with Red) Sheep-only, Green) Beef only, and Yellow) Beef and Sheep.

BMP testing of the proportional mixtures (Figure 3 and Table 3) showed the methane potential varied between 175 and 559 $NL_{CH4}·kg^{-1}_{VSadded}$, which was dependent on the type and composition of the substrates. Notably, measured proportional mixture BMPs from sites processing the same livestock varied substantially. For example, BMPs for sites processing sheep ranged from 175 to 559 $NL_{CH4}·kg^{-1}_{VSadded}$. Similarly, beef processor BMPs ranged from 218 $NL_{CH4}·kg^{-1}_{VSadded}$ to 310 $NL_{CH4}·kg^{-1}_{VSadded}$ (Table 3). These findings highlight the importance of dedicated BMP tests to outline the methane potential of unique substrates.

In terms of energy yields, similar to the BMPs, yields varied between sites, with the lowest and highest theoretical yields of 3,534 and 206,068 GJ per year, respectively. Variations in theoretical energy yields were primarily driven by annual by-product production rates and, to a smaller extent, the by-product BMP.

Table 3: BMP test results and estimated energy yield per participant for Phase 1 of the BMP testing.

Animal	**Beef**		**Beef and Sheep**		**Goats**	**Sheep**					
ID	NSW4	VIC3	WA4	QLD1	NSW3	WA2	NSW2	VIC1	WA1	VIC2	WA3
Methane yields ($NL_{CH4}·kg^{-1}_{VSadded}$)	310.19 ±15.02	217.89 ±14.93	435.82 ±33.43	281.22 ±11.75	234.28 ±22.03	246.95 ±35.28	288.1 ±40.85	489.96 ±9.53	175.31 ±9.00	313.38 ±32.39	559.23 ±20.46
Methane Content (%)	66.69	54.56	37.46	55.86	60.42	49.99	62.11	49.99	50.77	54.56	49.24
Meat bio-resources ($t·yr^{-1}$)	32,700	15,000	32,564	11,063	9,100	10,265	6,450	3,100	33,311	2,316	1,420
Methane production ($m^3·yr^{-1}$)	2,201,559	480,945	5,254,727	1,046,985	519,135	554,984	462,700	478,043	947,020	90,116	249,221
Organic Matter ($tons·yr^{-1}$)	7,097	2,207	12,057	3,723	2,216	2,247	1,606	976	5,381	288	446
Energy Yield ($GJ·yr^{-1}$)	86,336	18,861	206,068	41,058	20,358	21,764	18,145	18,747	37,138	3,534	9,773

4.3.3 Phase 2: Proportional Mixture Co-digestion

Following the results of Phase 1, sample requests were sent to participating agricultural industries from the survey (Section 4.3.1) with 6 industries supplying co-substrates for BMP testing, which included grain, FOGO, hay, brewery waste, potato waste, and livestock bedding. The received substrates were subject to BMP testing at various co-digestion ratios with the red meat processor proportional mixtures at predetermined ratios (co-substrate loading 0, 5, 25, and 100%). Mono-digestion of the agricultural co-substrates showed grain and potato products had the highest methane potential of the agricultural products assessed (410-418 $NL_{CH4}·kg^{-1}_{VSadded}$), followed by brewery by-products (361 $NL_{CH4}·kg^{-1}_{VSadded}$), hay (311 $NL_{CH4}·kg^{-1}_{VSadded}$), and bedding (241 $NL_{CH4}·kg^{-1}_{VSadded}$). Notably, the NSW4, VIC1, and WA4 agricultural wastes, which are primarily composed of FOGO collected from a nearby farm, produced negligible methane.

Similar to Phase 1, mono-digestion BMPs of proportional mixtures varied across all red meat processors, independent of processor type and livestock processed. Interestingly, implementing co-digestion strategies primarily resulted in a reduction in the BMP compared to proportional mixture mono-digestion, with the exception of NSW4 and NSW2, which experienced a 30-37% increase in BMP when co-digested with their select agricultural substrate at 5% and 25%, respectively (see Appendix D). It was noted that some of the mixtures yielding the highest observed BMPs, namely, NSW4 (609.5 $NL_{CH4}\cdot kg^{-1}_{VSadded}$), NSW1 (433.2 $NL_{CH4}\cdot kg^{-1}_{VSadded}$), and VIC1 (443.7 $NL_{CH4}\cdot kg^{-1}_{VSadded}$), had protein: lipid: carbohydrate ratios of 1:0.9:0.1, 1:0.35:0.05, and 1:0.58:0.03, respectively (Figure 4). Notably, NSW2 co-digested with 25% waste grain, which had a protein: lipid: carbohydrate ratio of 0.81:1.0:0.68, yielded the highest BMP of all mixtures assessed. These variations in the measured BMP suggest the feedstock macronutrient composition could play an important role in the substrate methane yield.

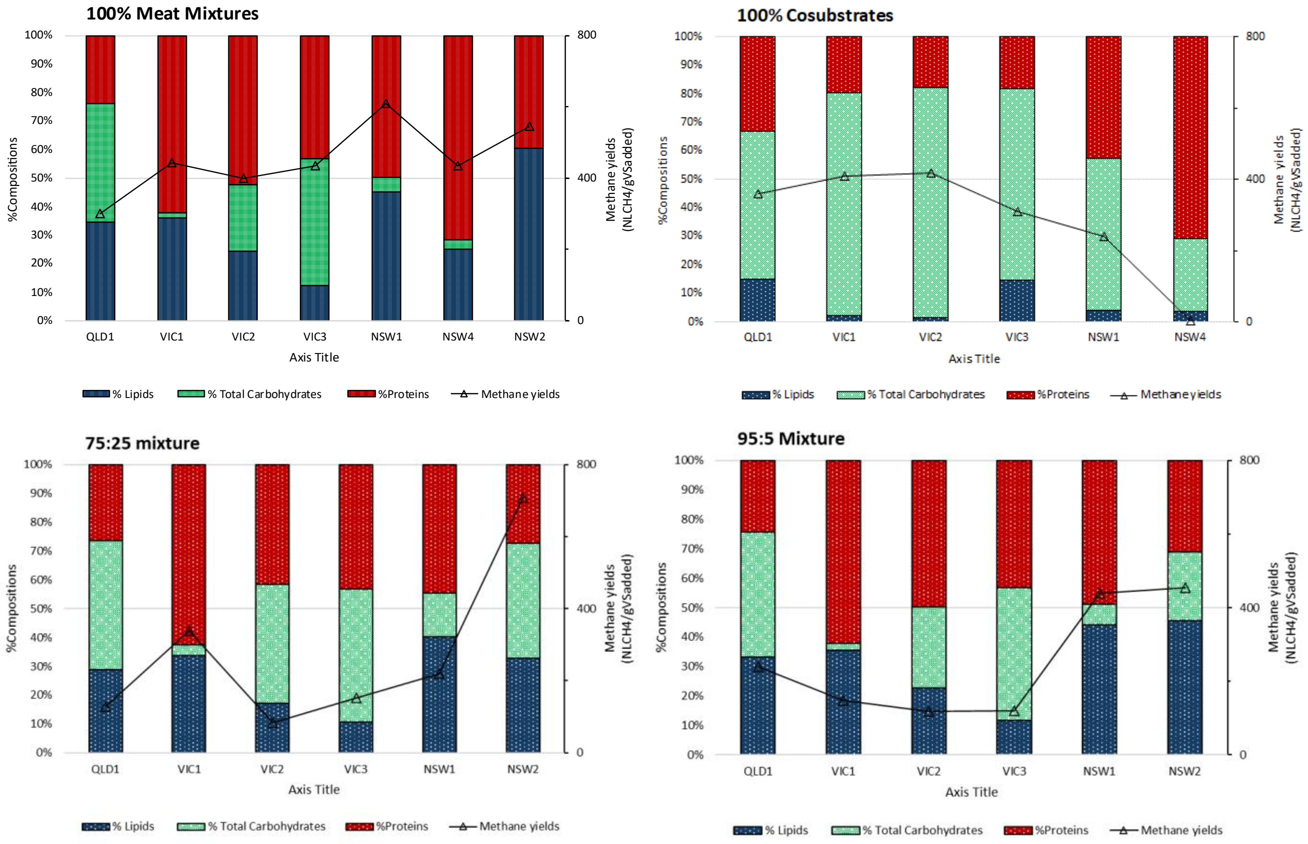


Figure 4: Macronutrient composition and measured BMP of the red meat proportional mixtures at different co-digestion rates.

4.3.4 Phase 3: Macro-nutrient Optimised Co-digestion

Following the findings of Phase 2, Phase 3 testing aimed to optimise the lipid: protein: carbohydrate (LPC) ratio to maximise biogas production. The macronutrient profile of the proportional mixture of sub-feedstocks and co-substrates was analysed to identify major components contributing to the macronutrient ratio observed in Phase 2. Compositional analysis of the different substrates highlighted the dominance of lipids and proteins within the red meat processor by-products, except paunch and manure, which were dominated by carbohydrates (see Appendix D2). Paunch and manure are predominantly composed of lignocellulose (Bai et al., 2023, Liu et al., 2023), a recalcitrant complex molecule composed of cellulose, hemicellulose, and lignin, which resists microbial degradation. All agricultural and food waste co-substrates were dominated by carbohydrates.

BMP testing of co-digestion mixtures at different LPC ratios demonstrated that co-digestion improved methane yields compared to mono-digestion in several cases for both NSW4 and WA4 feedstock mixtures. For WA4, the recorded mono-digestion methane yield was 356.71 $NmL_{CH4}\cdot g^{-1}_{VSadded}$, similar to that achieved in Phase 2 BMP testing. Co-digestion with grain at an LPC ratio of 60:20:20 increased methane yields to 625.27 $NmL_{CH4}\cdot g^{-1}{}_{VSadded}$, representing a 75.28% increase in methane productivity. Co-digestion with corn silage also saw improvements in methane production relative to mono-digestion, with the highest yield of 710.73 $NmL_{CH4}\cdot g^{-1}{}_{VSadded}$ observed at a LPC ratio of 50:21:30.

For NSW4, mono-digestion resulted in a methane yield of 399.38 $NmL_{CH4}\cdot g^{-1}{}_{VSadded}$, while co-digestion with sorghum at a LPC ratio 60:20:20 increased methane yields to 477.74 $NmL_{CH4}\cdot g^{-1}{}_{VSadded}$ (Figure 5B). Co-digestion with bagasse at the same ratio achieved even higher yields, with 602.50 $NmL_{CH4}\cdot g^{-1}{}_{VSadded}$. Improvements in methane production were also observed when NSW4 was co-digested with milk waste, achieving a yield of 458.88 $NmL_{CH4}\cdot g^{-1}{}_{VSadded}$. Overall, the results demonstrate the value of feedstock compositional influences on methane production and the value of feedstock control on maximising methane yields.

Pretreatment of agricultural substrates can improve methane yields by partially hydrolysing the substrate prior to AD. Therefore, an additional test using steam-exploded bagasse was included to assess the impacts of pretreatment on co-digestion. Results showed a reduced yield (310.71 $NmL_{CH4}\cdot g^{-1}{}_{VSadded}$) when NSW4 was co-digested with steam-exploded bagasse, compared to NSW4 mono-digestion. Prolonged storage may have led to the degradation of readily biodegradable compounds or microbial spoilage, negatively affecting its performance as a co-substrate.

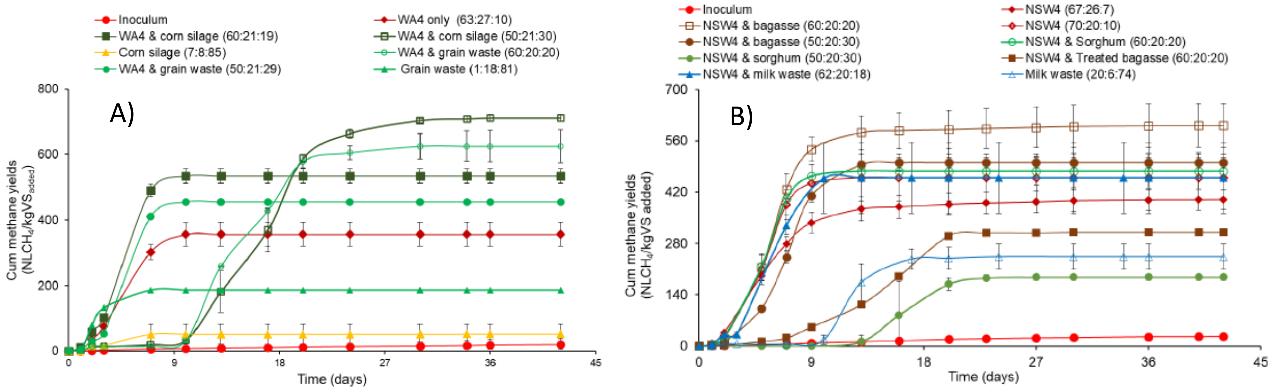


Figure 5: Cumulative methane production for A) WA4 and B) NSW4, at different lipid: protein: carbohydrate co-digestion ratios. Results are presented as the mean of triplicates ± the standard deviation.

4.4 Research activity 4: Continuous ACoD digester experiments

Following phase 3 BMP testing, two pilot digesters were started to assess long-term impacts of mono- and co-digestion on biogas production, methane yields, and process stability. Process performance and methane yields for the semi-continuous digestion experiments are presented in Appendix E. Both digesters were started on proportional mixtures from NSW4 (R1) and WA4 (R2) (mono-digestion phase) at an OLR of 0.2 $g_{VS}\cdot L^{-1}\cdot day^{-1}$. Following startup, the OLR was sequentially increased stepwise to 2.0 $g_{VS}\cdot L^{-1}\cdot day^{-1}$ (Table 4) resulting in a 4.4 and 5.9 fold increase in methane productivity for WA4 and NSW4, respectively (Figure 6). It was noted that continued operation at 2.0 $g_{VS}\cdot L^{-1}\cdot day^{-1}$ resulted in the accumulation of volatile fatty acids (VFAs) and reduced biogas yields (Appendix E) in both digesters, which are characteristic signs of process imbalances and a leading indicator of impending process failure.

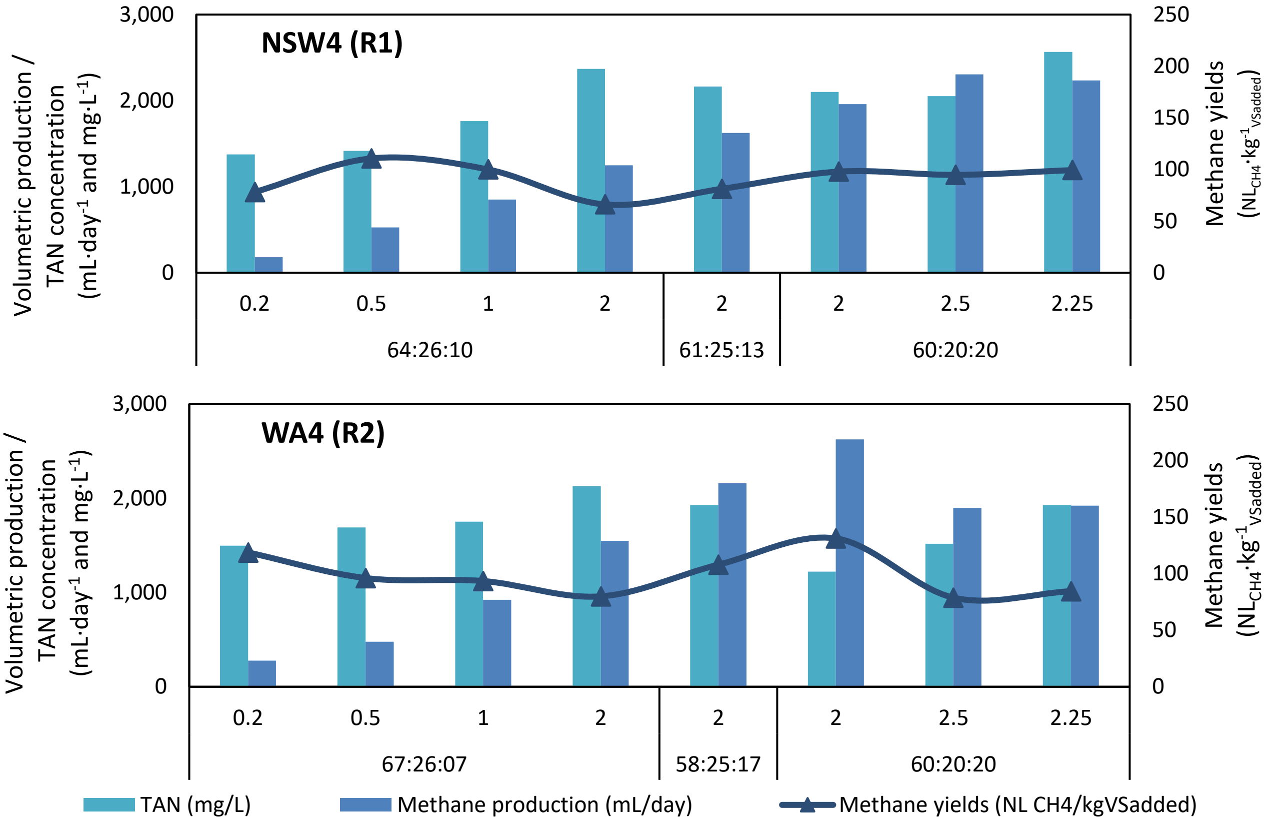


Figure 6: Methane productivity, methane yield, and total ammoniacal nitrogen concentration for the NWS4 and WA4 reactors at each OLR. Ratios displayed under the OLR represent the Lipid: Protein: Carbohydrate ratio.

Introduction of the co-substrate on day 125 (4.2% grain for WA4 and 18.7% bagasse for NSW4) notably recovered both reactors from the trend towards failure by recovering biogas production and reducing the VFA concentration (Appendix E), while also increasing methane productivity by 43% and 32% for WA4 and NSW4, respectively. Notably, the methane yield in both reactors increased following the addition of the co-substrate, with WA4 increasing from 79.9 $\mathrm{Nml_{CH4}\cdot g^{-1}_{VS\ added}}$ to 108.0 $\mathrm{Nml_{CH4}\cdot g^{-1}_{VS\ added}}$, while NSW4 increased from 66.1 $\mathrm{Nml_{CH4}\cdot g^{-1}_{VS\ added}}$ to 81.2 $\mathrm{Nml_{CH4}\cdot g^{-1}_{VS\ added}}$. While methane production in WA4 displayed an oscillatory behaviour, both reactors continuously produced biogas during the co-digestion phase at an OLR of 2.0 $\mathrm{g_{VS}\cdot L^{-1}\cdot day^{-1}}$ without VFA accumulation, pH depression, or significant accumulation of ammonia. Notably, WA4 saw a continual reduction in ammonia nitrogen following the addition of agricultural co-substrates (Appendix E). This underscores the value of ACoD in not only improving methane productivity but also enhancing process stability and diluting inhibitory compounds.

Table 4: Average biogas production rates, methane yields, and biogas methane content over the 297-day continuous digestion experiments for WA4 and NSW4.

			WA4		
	OLR	**Steady state Days**	**Biogas production ($\mathrm{mL\cdot day^{-1}}$)**	**Methane yields ($\mathrm{NL\ CH4\cdot kg^{-1}_{VSadded}}$)**	**Methane concentration (% CH4)**
Mono-digestion	0.2	Startup	499	118.8	56%
	0.5	17-31	780	96.1	61%
	1.0	59-73	1,459	93.5	63%
	2.0	73-104	2,397	79.9	63%
Co-digestion	2.0	170-184	3,325	108.0	65%
	2.0	211-220	4,137	131.2	64%

Co-digestion (60:20:20)	2.5	265-274	3,009	78.8	63%
	2.25	288-294	3,553	96.4	64%
NSW4					
	OLR	**Steady state Days**	**Biogas production (mL·day^{-1})**	**Methane yields (NL CH4·kg$^{-1}_{VSadded}$)**	**Methane concentration (% CH4)**
Mono-digestion	0.2	Startup	337	78.1	53%
	0.5	17-22	908	110.7	58%
	1.0	62-73	1386	99.9	61%
	2.0	73-104	1937	66.1	64%
Co-digestion	2.0	136-153	2444	81.2	67%
Co-digestion (60:20:20)	2.0	225-230	3101	97.9	63%
	2.5	265-275	3575	94.8	65%
	2.25	290-297	3167	89.3	64%

Following the co-digestion phase, feedstock mixtures were exchanged for macro-nutrient optimised mixtures developed in Phase 3 of the BMP testing (lipid: protein: carbohydrate ratio of 60:20:20; Section 4.3.4). Swapping to macro-nutrient optimised feedstocks further enhanced methane production by 23% and 19% for WA4 and NSW4, respectively. On day 220, biochar and activated carbon were added to NSW4 and WA4, respectively, to reduce inhibitor concentrations, following which the NSW4 reactor saw an increase in methane production shortly after the addition of biochar. This increase in methane production coincided with a reduction in TAN and VFA concentration and an increase in methane production (Appendix E).

On approximately day 250, a blockage in the outlet gas line for NSW4 was observed, resulting in a reduction in recorded biogas production. The reactor was opened to clear the blockage, which was caused due to a crust and foam layer that had filled the reactor headspace. Following clearance of the blockage, methane production quickly resumed. While the findings of the continuous digestion experiments highlight the value of the lipids in improving biogas production, they also exhibit the potential operational challenges experienced with a high lipid load feedstock. These findings provide valuable operational insights that should be carefully considered in the design and management of full-scale anaerobic digestion systems, particularly those treating lipid-rich feedstocks.

On day 265, the OLR was increased from 2.0 to 2.5 g_{VS}·L^{-1}·day^{-1}, which saw an increase in TAN and a sharp increase in VFA concentrations (Appendix E) as well as a reduction in methane productivity and yield, indicating the OLR exceeded the maximum achievable value for the process. The OLR was then subsequently reduced to 2.25 g_{VS}·L^{-1}·day$^{-1,}$ following which methane productivity increased and the VFA concentration in both reactors reduced; however, methane yields remained below that achieved at an OLR of 2.0 g_{VS}·L^{-1}·day^{-1}. In practice, facilities would assess the benefits of increased methane yields against the increased plant capacity or reduced plant size (i.e., reduced capital cost), from operation at an elevated OLR. Such considerations should include site-specific factors such as those related to energy costs and demands, by-product and waste profiles, site location, and surrounding co-feedstock availability.

Overall, the continuous experiments highlighted the value of ACoD in improving biogas production, methane yields, and reducing the concentration of inhibitory compounds, thereby enabling operation at elevated OLRs compared to mono-digestion of red meat processor by-products. Methane productivity increased by 43% and 23% when transitioning to co-digestion and macro-nutrient optimised feedstocks, respectively, for WA4, while for NSW4, the transitions yielded a 32% and 19% increase in co-digestion and macro-nutrient optimised feedstocks, respectively.

4.5 Research activity 5: Techno-economic analysis

The techno-economic analysis (TEA) conducted assessed the impact of mono- and co-digestion scenarios for NSW4 and WA4 utilising results from the targeted optimisation experiments conducted as part of this study. A list of site-specific plant and economic assumptions for both NSW4 and WA4 pertaining to the different digestion scenarios are listed in Table 5, while general assumptions utilised across all digestion scenarios are listed in Table 6.

Table 5: List of site-specific assumptions and data used during the TEA modelling for all scenarios

NSW4 - Beef			
Assumption List	**Mono-digestion**	**Co-digestion**	**Optimised Scenario**
Annual Feedstock ($t\cdot year^{-1}$)	22,311	31,815	95,875
Co-feedstock ($t\cdot year^{-1}$)	0	5,940	70,000
Feedstock VS% / TS%	41% / 43%	49% /54%	49% /54%
Methane Yield ($Nml_{CH4}\cdot g^{-1}{}_{VS}$)	100	380	650
VS% Destruction	80%	89%	89%
HRT (Days)	60	35	45
Biogas Methane (%)	63%	65%	58%
WA4 – Sheep and Cattle			
Assumption List	**Mono-digestion**	**Co-digestion**	**Optimised Scenario**
Annual Feedstock ($t\cdot year^{-1}$)	32,468	33,787	102,351
Co-feedstock ($t\cdot year^{-1}$)	-	1,436	70,000
Feedstock VS% / TS%	39% / 42%	48% / 53%	48% / 53%
Methane Yield ($Nml_{CH4}\cdot g^{-1}{}_{VS}$)	94	350	650
VS% Destruction	76%	83%	83%
HRT (Days)	60	35	45
Biogas Methane (%)	63%	65%	58%

Table 6: List of general assumptions utilised in every scenario assessed for the TEA.

Assumption	**WA4**
Boiler Efficiency	90%
CHP Electrical Efficiency	42.5%
CHP Thermal Efficiency	40.6%
Methane Energy	35.8
Electricity Price ($AUD\cdot kWh^{-1}$)	0.38
Gas Price ($AUD\cdot kWh^{-1}$)	0.05
ACCU Value ($AUD\cdot Tonne\ CO_2e^{-1}$)	37.35
Biofertiliser cost ($AUD\cdot Tonne^{-1}$)	600
CO2 Cost ($AUD\cdot Tonne^{-1}$)	1120
Biogas FIT ($AUD\cdot kWh^{-1}$)	0.05
Electrical FIT ($AUD\cdot kWh^{-1}$)	0.048
Co-substrate cost ($AUD\cdot Tonne^{-1}$)	20
LGC value ($AUD\cdot MW^{-1}$)	40

Proportional Mixture Value (AUD·Tonne^{-1}) *	WA4: 351; NSW4: 557

* Represents the averaged value based on individual value and disposal costs for individual feedstocks, normalised to percent contribution within the mixed feedstock.

4.5.1 Mono-digestion Scenario

Experimental results from mono-digestion experiments for NWS4 and WA4 were utilised within a detailed techno-economic evaluation to assess economic viability and value for the red meat industry to implement the AD technology. The assessment considered biogas production from proportional feedstock mixtures, which were subsequently utilised within boilers or combined Heat and Power (CHP) engines for energy generation. The evaluation also considered the integration of carbon dioxide (CO_2) recovery and biofertiliser production as additional revenue streams, which were accompanied by associated capital and operational costs. Facilities, which included anaerobic digestion, biofertiliser production, and CO_2 recovery, were termed a Bioresource Recovery Centre (BRRC).

Figure 8 and Figure 9, and Table 7 present the mass and energy balance for the mono-digestion scenarios, while Table 7 also provides an outline of major equipment sizing for NSW4 and WA4. Overall, as WA4 had 46% more available feedstock compared to NSW4, WA4's BRRC required an additional digester, larger blending and digestate storage tanks, and an expanded biofertiliser plant. Consequently, the capital costs (CAPEX) for the WA4 biogas facility increased to accommodate the larger quantity of feedstock (Table 8). Notably, while the greater feedstock availability resulted in increased biogas production for WA4, the larger methane yield and VS concentration from the NSW4 feedstock meant that WA4's total biogas output was only 16% greater, highlighting the importance of optimisation strategies to increase biogas output to maximise biogas facility capital utilisation. Moreover, while the digestion process generated heat for on-site use, the thermal energy produced from the CHP engines was insufficient to meet the biofertiliser plant's total heat demand. Additional heat was therefore required for drying the dewatered digestate solids, resulting in a total cost estimated between \$212,317 - \$312,125 for the two facilities.

Table 7: Mass and energy balance, and equipment size for the mono-digestion Scenarios

	NSW4	**WA4**
	Mass Balance	
Feed (tonne/day)	61.1	89.0
Feed VS (%)	41%	35%
Feed TS (%)	43%	36%
Dilution water (tonne/day)	134.5	195.7
Biogas (Nm3/day)	3,975.3	4,621.1
Methane (Nm3/day)	2,504.4	2,911.3
Methane Energy (GJ/day)	89.7	104.2
Digestate (tonne/day)	175.55	260.99
Digestate TS(%)	3.6%	3.2%
CO2 Production (Tonne/day)	4.8	5.6
	Energy Balance	
Electricity Production (kWh/day)	10,593	12,314
Heat Production (kWh/day)	10,120	11,764
Digester Power (kWh/day)	1,059	1,231
Digester Heat (kWh/day)	1,012	1,176

Biofertiliser Plant Heat Demand (kWh/day)	9,108	9,411
CO2 Plant Energy (kWh/day)	2,055	2,389
	Equipment Sizing	
Blending Tank Working Volume (m3)	214	311
Digesters Working Volume (m3)	4,292	4,164
Numb. Digesters	2	2
Digestate Holding Tank (m3)	214	311
Engine	Avus 500 plus	Avus 500 plus
Numb. Engines	2	2
Digestate Dewatering (tonne/day)	175.55	260.99
Digestate Drier (tonne Cake/day)	28.3	38.0
Pelletiser (tonne Biofertiliser/day)	7.34	9.84
CO2 Recovery (kg inlet CO2/day)	7,801	9,069

The economic analysis estimated total capital investment (CAPEX) for NSW4 and WA4 at $14,177,172 and $21,740,183, respectively (Table 8). Differences in CAPEX were primarily driven by differences in total feedstock quantities to be processed, raw feedstock solids concentration, and methane yield (Table 5). The capital cost breakdown was similar for both facilities (Figure 7), with minor differences in capital contributions from the biogas plant and the CO_2 recovery plant, which were primarily determined by biogas production rates, biogas methane concentrations, plant capacity, and volatile solid reduction.

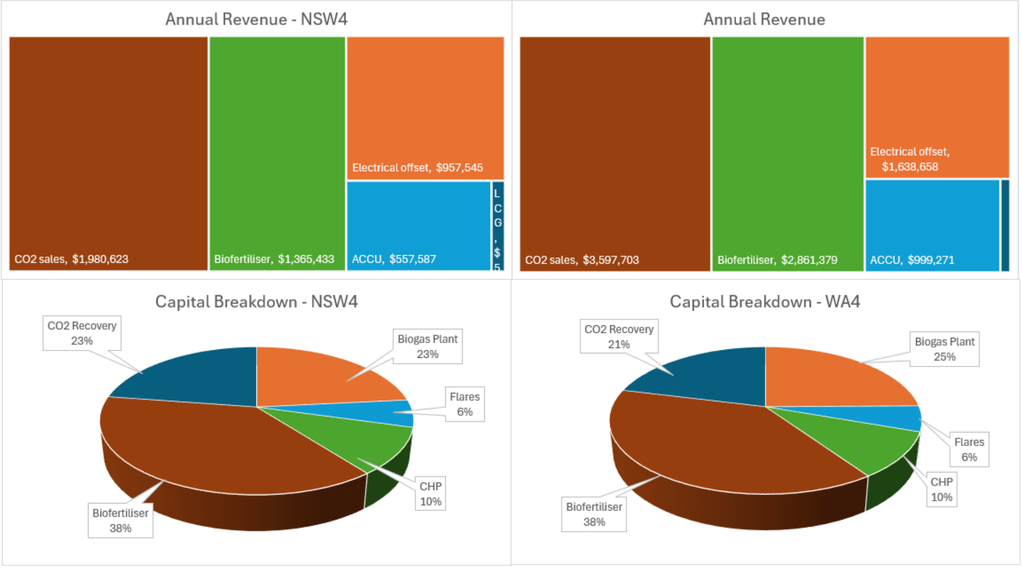
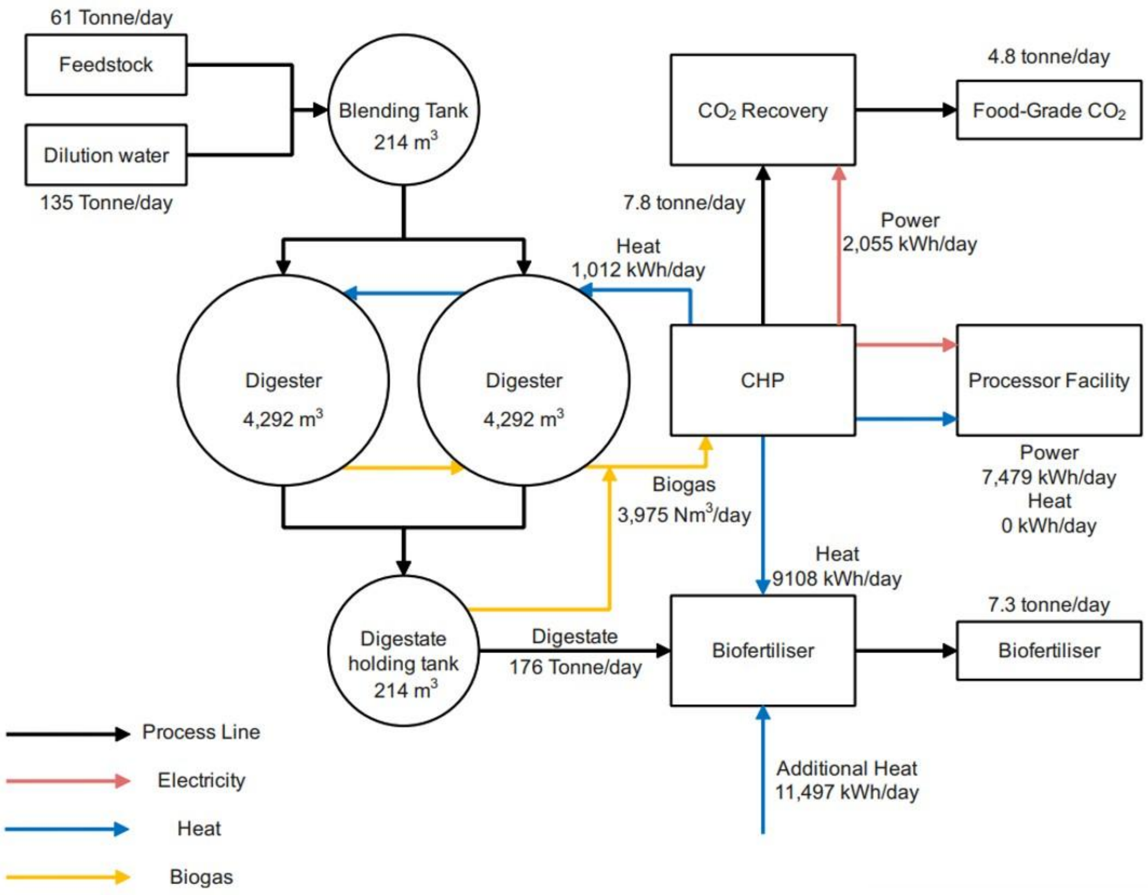


Figure 7: Annual revenue and capital expenditure breakdown for NSW4 and WA4 for the mono-digestion scenario.

In terms of revenue, value generated through the sale of CO_2 was the single largest revenue stream for both WA4 and NSW4. Additional revenue was generated through biofertiliser sales, ACCU's, and LGCs, which, when combined with the CO_2 sales, totalled $4.7 million and $8.9 million annually for NSW4 and WA4, respectively. Despite these positive revenue streams, the overall financial performance of the mono-digestion BRRC remained negative (Table 8). The diversion of high-value by-products, such as offal and rendering material, from existing markets to AD reduced the net economic return, outweighing the benefits from the BRRC. Consequently, mono-digestion scenarios generate net present values (NPVs) < 0 and benefit-cost ratios (BCR) of 0.30 and 0.42 for NSW4 and WA4, respectively (Table 8). These findings highlight that mono-digestion of red meat industry by-products alone is economically challenging and requires process improvements or co-digestion strategies to achieve financial viability.



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Project Name: RACE 2030 Anaerobic Co-digestion

Project Code: 1076

Drawing Description: NSW4: Mono-digestion Block Flow Diagram

Drawing Number: TC-2025-1076-001

Revision: V-01

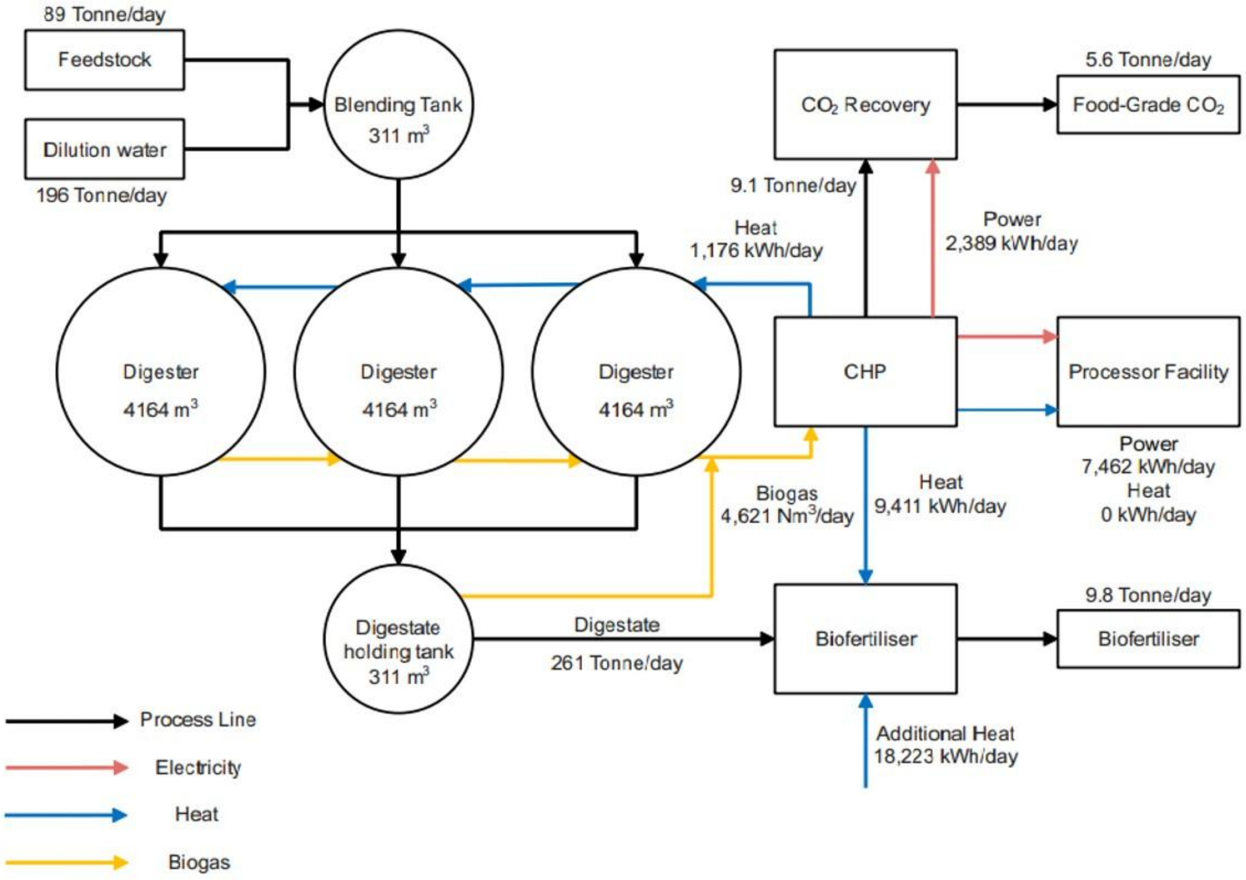
Drawn: CBÜHLMANN

Checked: CBÜHLMANN

Approved: N/A

Date: 07.11.2025

Figure 8: Block flow diagram detailing the mono-digestion mass and energy balance for NSW4



TESSELE

Project Name: RACE 2030 Anaerobic Co-digestion

Project Code: 1076

Drawing Description: WA4: Mono-digestion Block Flow Diagram

Drawing Number: TC-2025-1076-004

Revision: V-01

Drawn: CBÜHLMANN

Checked: CBÜHLMANN

Approved: N/A

Date: 07.11.2025

Figure 9: Block flow diagram detailing the mono-digestion mass and energy balance for WA4

A sensitivity analysis on key project variables is shown in Figure 10. Results showed the project was most sensitive to the by-product price, and the discount and escalation rate, indicating project revenue is dependent on future cash flows and on the price growth of the different revenue streams. Plant capacity and methane yield were the next most significant variables impacting profitability, emphasising the critical role of improved biogas production in process economics. Overall, the analysis underscored that the poor economic performance of mono-digestion was primarily linked to low methane yields, which can be addressed through ACoD and targeted process optimisation (Section 4.5.2).

Figure 10: Mono-digestion sensitivity analysis on project NPV with selected parameters. Each parameter was varied by ±50% and the resulting deviation in the project NPV was recorded.

Table 8: Summary of TEA findings

	NSW4 – Beef			**WA4 – Sheep and Cattle**		
	Mono-Digestion	**Co-Digestion**	**Optimised Scenario**	**Mono-Digestion**	**Co-Digestion**	**Optimised Scenario**
Capital Costs						
Digestion Facility	$3,315,455	$4,087,529	$8,216,599	$5,391,295	$5,455,620	$9,341,381
Boiler	-	-	-	-	-	-
CHP	$2,291,756	$6,785,797	$17,749,412	$3,401,311	$7,425,954	$17,297,898
Biofertiliser plant	$5,361,673	$6,707,757	$13,002,347	$8,357,633	$7,946,665	$13,039,429
CO2 recovery	$3,208,288	$9,667,097	$27,676,478	$4,589,944	$10,538,204	$26,852,680
Total	$14,177,172	$27,248,181	$65,151,193	$21,740,183	$31,366,444	$66,531,388
Operational Costs						
Digestion Facility	$198,927	$245,252	$492,996	$323,478	$327,337	$560,483
Boiler	-	-	-	-	-	-
CHP	$137,505	$407,148	$1,064,965	$204,079	$445,557	$1,037,874
Biofertiliser plant	$321,700	$402,465	$780,141	$501,458	$476,800	$782,366
CO2 recovery	$192,497	$580,026	$1,660,589	$275,397	$632,292	$1,611,161
Total	$850,630	$1,634,891	$3,909,072	$1,304,411	$1,881,987	$3,991,883
Annual Revenue						
Heat Offset+ Grid	-$212,317	$463,289	$3,544,591	-$312,125	$484,468	$3,182,349
Power Offset + Grid	$957,545	$6,210,170	$13,368,976	$1,638,658	$9,764,032	$12,512,274
ACCU	$557,587	$3,860,332	$20,034,264	$999,271	$4,445,150	$19,038,687
LGC	$50,118	$325,040	$1,674,206	$72,582	$299,226	$1,456,366
Biofertiliser	$1,365,433	$1,983,347	$5,976,856	$2,861,379	$2,630,741	$6,005,292
CO2 Sales	$1,980,623	$12,450,108	$71,867,249	$3,597,703	$14,375,535	$68,337,491
Total	$4,698,989	$25,292,286	$112,499,406	$8,857,467	$31,999,151	$110,532,459
Profitability						
NPV (AUD)	-$344,896,551	$221,317,213	$2,729,076,228	-$365,702,980	$239,416,755	$2,466,626,495
ROI (%)	-2332%	913%	4196%	-1581%	864%	3808%
Annualised ROI (%)	-	8%	13%	-	8%	13%
BCR	0.30	1.49	5.33	0.42	1.44	4.87
Payback Period (years)	0.00	4.00	2.00	0.00	4.00	2.00

4.5.2 Co-digestion Scenarios

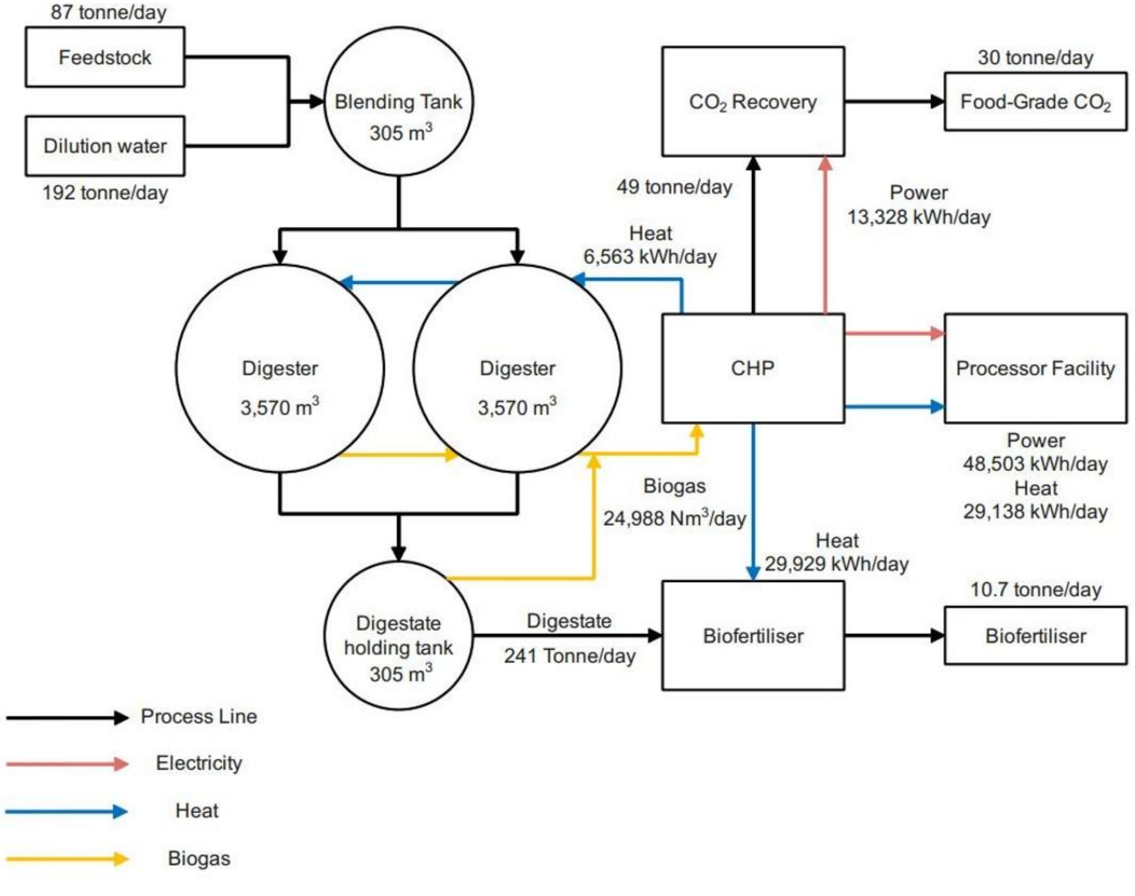
Experimental results from co-digestion optimisation studies for NSW4 and WA4 were incorporated within the detailed technoeconomic evaluation to assess the benefits of advanced ACoD strategies on the BRRC economic performance. The reduced HRT and the addition of agricultural residues resulted in both NSW4 and WA4 plants being similar in overall biogas plant size, each requiring two digesters, and comparably sized blending and digestate storage tanks (Table 9).

Despite their similar scale, biogas production differed markedly between the two scenarios (Table 9, Figure 11, and Figure 12). NSW4 produced 36% more biogas than WA4, despite the difference between their comparable feedstocks being only 8.7%. This higher biogas output increased the NSW4 BRRC capacity requirements for downstream CHP and CO_2 recovery systems (Table 8). The primary driving factor for this variation was the higher VS concentration in the NSW4 feedstock (49%) compared to WA4 (37%), resulting in greater organic loading to the NSW4 digesters.

Notably, while the mono-digestion scenarios required supplementary heat to meet the biofertiliser plant's thermal demands, the additional biogas generated under ACoD configurations provided thermal energy that exceeded the requirements for the biofertiliser plant. This eliminated the need for an external heat supply, fully offsetting the biofertiliser plant's energy demands and providing surplus heat capable of covering approximately 10-20% of the overall thermal requirements of the NSW4 and WA4 red meat processing plants.

Table 9: Mass and energy balance, and equipment size for the Co-digestion Scenarios

	NSW4	**WA4**
	Mass Balance	
Feed (tonne/day)	87.2	92.6
Feed VS (%)	49%	37%
Feed TS (%)	54%	39%
Dilution water (tonne/day)	191.8	203.6
Biogas (Nm3/day)	24,988.3	18,431.7
Methane (Nm3/day)	16,242.4	11,980.6
Methane Energy (GJ/day)	581.5	428.9
Digestate (tonne/day)	240.91	267.79
Digestate TS(%)	3.8%	2.9%
CO2 Production (Tonne/day)	30.5	22.5
	Energy Balance	
Electricity Production (kWh/day)	68,702	50,675
Heat Production (kWh/day)	65,630	48,410
Digester Power (kWh/day)	6,870	5,068
Digester Heat (kWh/day)	6,563	4,841
Biofertiliser Plant Heat Demand (kWh/day)	29,929	25,360
CO2 Plant Energy (kWh/day)	13,328	9,831
	Equipment Sizing	
Blending Tank Working Volume (m3)	305	324
Digesters Working Volume (m3)	3,570	3,791
Numb. Digesters	2	2
Digestate Holding Tank (m3)	305	324
Engine	Avus 500 plus	Avus 500 plus
Numb. Engines	4	4
Digestate Dewatering (tonne/day)	240.91	267.79
Digestate Drier (tonne Cake/day)	41.2	34.9
Pelletiser (tonne Biofertiliser/day)	10.65	9.03
CO2 Recovery (kg inlet CO2/day)	49,038	36,171



TESSELE

Project Name: RACE 2030 Anaerobic Co-digestion

Project Code: 1076

Drawing Description: NSW4: Co-digestion Block Flow Diagram

Drawing Number: TC-2025-1076-002

Revision: V-01

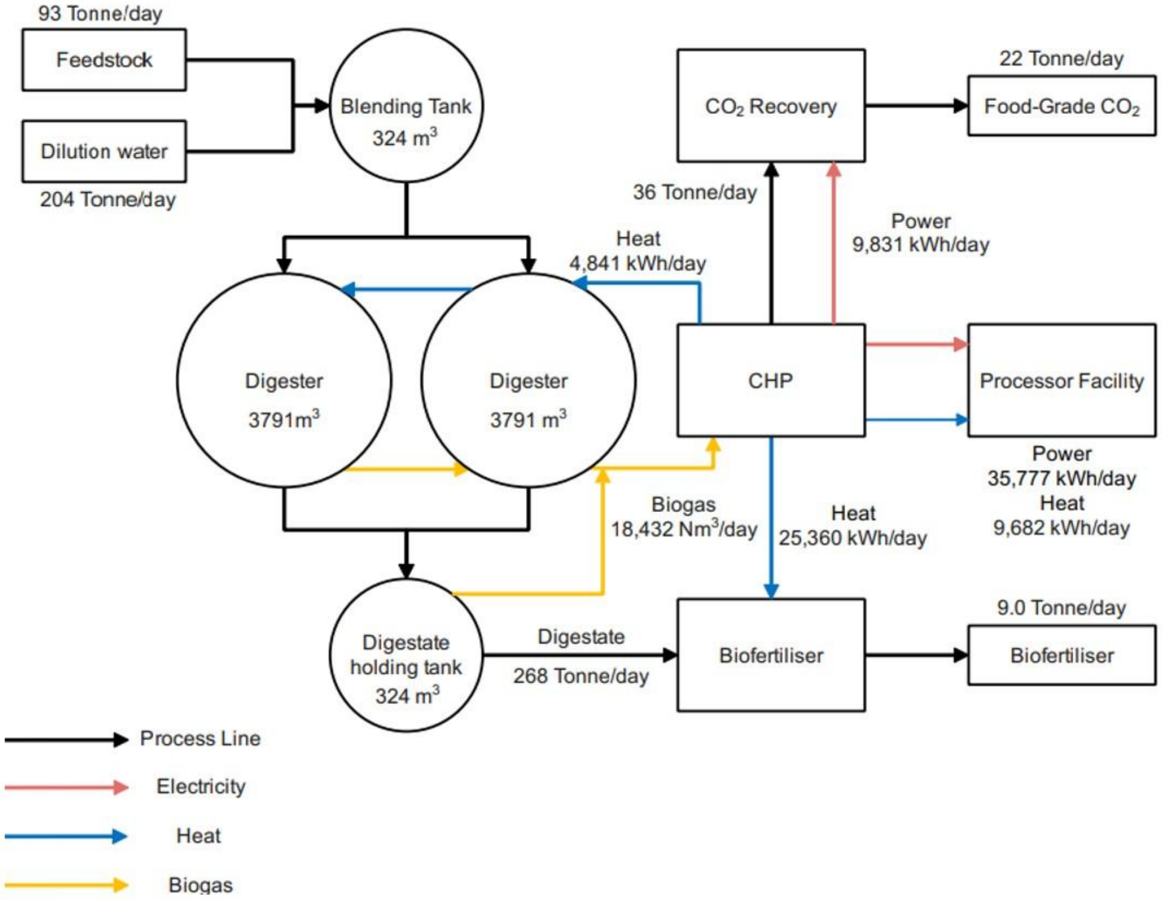
Drawn: CBÜHLMANN

Checked: CBÜHLMANN

Approved: N/A

Date: 07.11.2025

Figure 11: Block flow diagram detailing co-digestion mass and energy balance for NSW4



TESSELE

Project Name: RACE 2030 Anaerobic Co-digestion

Project Code: 1076

Drawing Description: WA4: Co-digestion Block Flow Diagram

Drawing Number:
TC-2025-1076-005

Revision: V-01

Drawn: CBÜHLMANN

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Date: 07.11.2025

Figure 12: Block flow diagram detailing co-digestion mass and energy balance for WA4

Overall, ACoD resulted in a significant increase in the economic performance for both NSW4 and WA4, with NPVs of $221 and $239 million for NSW4 and WA4, respectively. Additional economic indicators supported the observed performance improvement with a return on investment (ROI), payback period, and BCR of 913%, 4 years, and 1.49, respectively, for NSW4. Similarly, WA4 also displayed an improved economic position with an ROI, PBP, and BCR of 864%, 4 years, and 1.44, respectively.

In terms of investment, required CAPEX increased for co-digestion scenarios compared to mono-digestion due to the increased quantity of feedstock processed, and a significant increase in biogas production following optimisation of ACoD. Investment in CO2 recovery technologies was the largest contributor to CAPEX (Figure 13), overtaking the biofertiliser for mono-digestion (Figure 7), due to the increased production of biogas (i.e., higher CO_2 production).

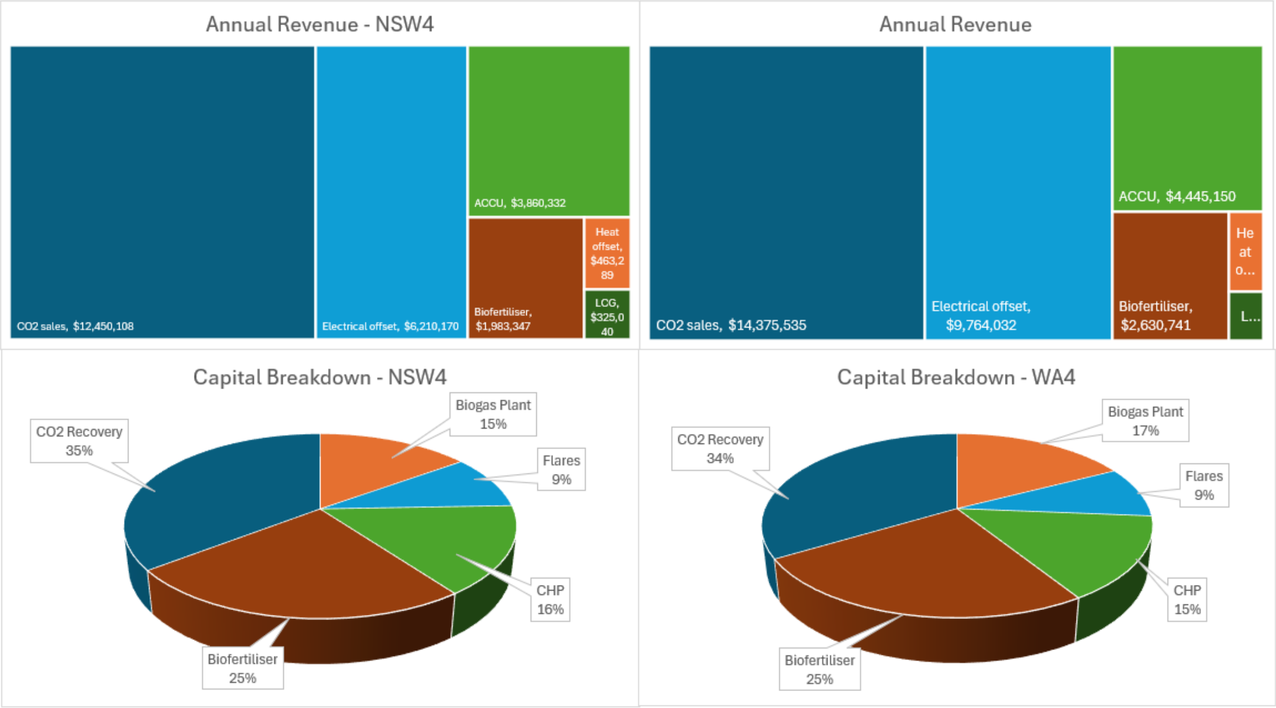


Figure 13: Annual revenue and capital expenditure breakdown for NSW4 and WA4 for the co-digestion scenario.

Improvements in economic performance were largely driven by improvements in the methane yield and larger annual feedstock processed, due to the inclusion of agricultural feedstocks. CO_2 sales were the single largest revenue source for both sites, followed by electrical offsets and ACCUs. The primary drivers for the improved economic performance of ACoD over mono-digestion were related to the increased quantity of feedstock processed from the addition of agricultural co-substrate, and improved methane yields following implementation of optimised ACoD strategies. Notably, both NSW4 and WA4 required the integration of power generation and CO_2 recovery for profitability (biofertiliser production not required). While the results from this study significantly improved the methane yield, economic indicators outlined that the implementation of additional BRRC processes were required for profitability.

A sensitivity analysis on key project variables is shown in Figure 14. WA4 was more sensitive to changes in the selected parameters than NSW4, likely due to the NPV, total value of by-products, and biogas production rate being larger than NSW4 (Table 8). In contrast to the mono-digestion scenario, the methane yield, electricity price, CO_2 price were highlighted as major drivers of project profitability, while the influence of financial parameters, such as the discount and escalation rate, was significantly reduced, reflecting the high biogas production rate and proportional rise in energy output. The price of the by-products remained a strong influencer of project profitability; however, its impact has been reduced and is in line with other major variables (i.e., methane yield, electricity price, etc.). Interestingly, plant capacity had a marginal impact on profitability for WA4 when it was increased. Changes in the NPV with capacity were driven by the market value of the by-products, which was assumed to be $351 per tonne for WA4, and the larger proportion of valuable red meat by-products included within the AD feedstock (i.e., larger quantity of annual feedstock), resulting in a higher total value of feedstock utilised within the BRRC. Overall, the sensitivity analysis highlighted the importance of ACoD in improving economic performance and project resilience under varying market and financial conditions.

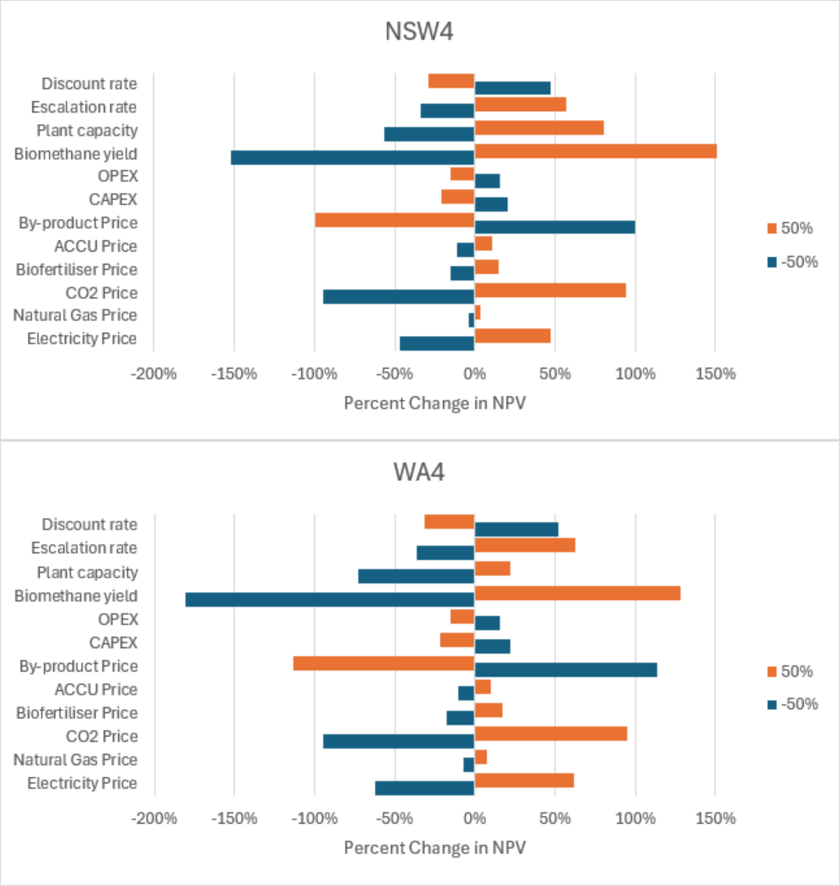


Figure 14: Co-digestion sensitivity analysis on project NPV with selected parameters. Each parameter was varied by ±50%.

4.5.3 Optimised Scenario

Implementation of ACoD strategies significantly enhanced the performance of red meat by-product AD through targeted optimisation of feedstock composition, resulting in improved biogas production for both processors assessed. Despite these gains, substantial potential still remains to further enhance biogas from red meat by-products. To illustrate this potential, an additional ACoD scenario was evaluated using production and operational data from a state-of-the-art commercial facility in Linköping, Sweden. This commercial biogas facility operates with a mixed feedstock composed of red meat by-products, agricultural residues, and food waste from the surrounding region. Based on available data and operational performance, a methane yield of approximately 650 $\mathrm{Nml_{CH_4}\cdot g_{VS}^{-1}}$ was used to represent typical full-scale performance.

Implementation of optimised feedstock recipes, operational strategies, and biogas production rates significantly expanded both NSW4 and WA4 facilities to account for larger by-product throughput and co-digestion ratios. The optimised ACoD facilities were designed with six digesters, larger blending and digestate storage tanks, higher capacity engines, expanded CO2 recovery systems, and larger capacity biofertiliser plants (Figure 16 and Figure 17)

Similar to the co-digestion scenario, the overall plant size for NSW4 and WA4 remained comparable, although WA4 had a slightly larger digester capacity. An elevated biogas production rate was again observed for NSW4 relative to WA4, consistent with the previous scenarios, primarily attributed to the greater feedstock VS concentration.

As in the co-digestion scenario, the thermal energy generated exceeded the demands of the biofertiliser plant (Table 10). However, under the optimised configuration, the total thermal output was sufficient to meet nearly all of NSW4's site-wide thermal demands and would fully exceed those for WA4. Furthermore, power generation for both facilities exceeded more than double on-site demands, creating opportunities for expanded grid exports or establishing power supply agreements with nearby businesses, further enhancing project revenue from energy generation.

Table 10: Mass and energy balance, and equipment size for the Optimised Scenarios

	NSW4	**WA4**
	Mass Balance	
Feed (tonne/day)	262.7	280.7
Feed VS (%)	49%	37%
Feed TS (%)	54%	39%
Dilution water (tonne/day)	577.9	617.6
Biogas (Nm3/day)	144,242.9	116,407.9
Methane (Nm3/day)	83,660.9	67,516.6
Methane Energy (GJ/day)	2,995.1	2,417.1
Digestate (tonne/day)	726.00	812.14
Digestate TS(%)	3.8%	2.9%
CO2 Production (Tonne/day)	175.8	141.9
	Energy Balance	
Electricity Production (kWh/day)	353,866	285,580
Heat Production (kWh/day)	338,046	272,813
Digester Power (kWh/day)	35,387	28,558
Digester Heat (kWh/day)	33,805	27,281
Biofertiliser Plant Heat Demand (kWh/day)	90,191	76,911
CO2 Plant Energy (kWh/day)	68,650	55,402
	Equipment Sizing	
Blending Tank Working Volume (m3)	919	983
Digesters Working Volume (m3)	4,611	4,928
Numb. Digesters	6	6
Digestate Holding Tank (m3)	919	983
Engine	Avus 1000b	Avus 1000b
Numb. Engines	4	4
Digestate Dewatering (tonne/day)	726.00	812.14
Digestate Drier (tonne Cake/day)	124.1	105.8

Pelletiser (tonne Biofertiliser/day)	32.11	27.38
CO2 Recovery (kg inlet CO2/day)	283,069	228,444

Economic modelling of the optimised scenario for NSW4 and WA4 underscored the financial benefits of process optimisation with a 10.3 and 12.3-fold increase in NPV compared to co-digestion scenarios (Table 8). In revenue distribution terms, the optimised scenario performed similarly to the co-digestion scenario, with the CO_2 sales remaining the primary revenue source; however, ACCUs overtook electrical offsets. Overall, all revenue streams observed a marked increase compared to co-digestion scenarios.

The increased methane productivity also led to a proportional rise in the CAPEX allocated to power generation and CO2 recovery infrastructure (Table 8 and Figure 15). Importantly, both NSW4 and WA4 were profitable under the optimised ACoD scenario with CHP configuration, achieving NPVs of $184 million and $119 million, respectively. These results highlight the significant economic value of optimising ACoD processes and underscore the broader potential of red meat digestion as a viable and scalable bioenergy pathway.

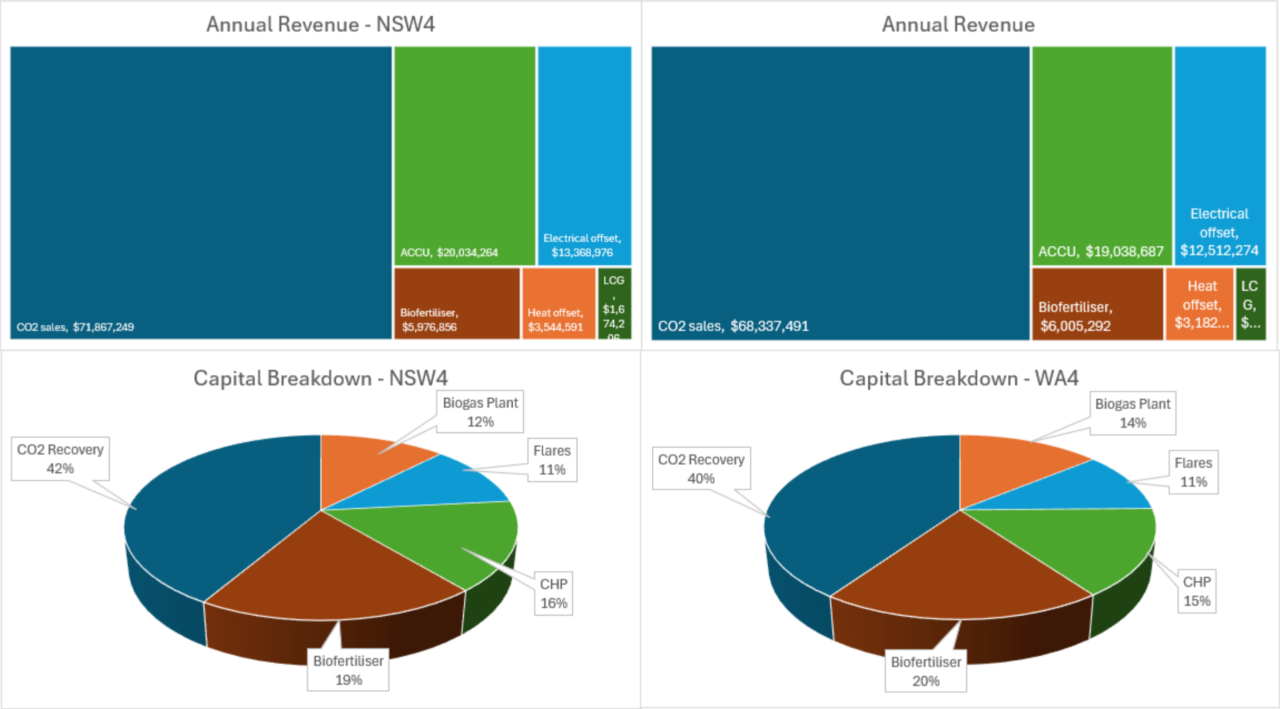
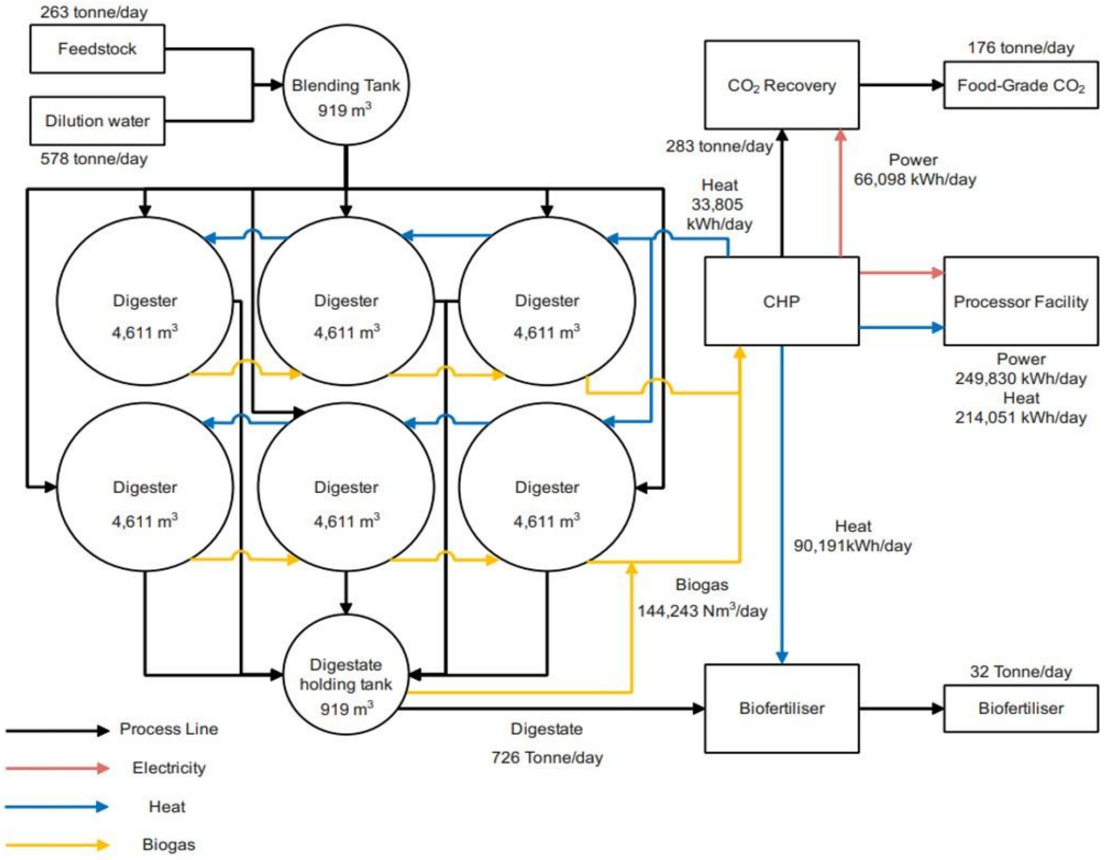


Figure 15: Annual revenue and capital expenditure breakdown for NSW4 and WA4 for the optimised scenario.



TESSELE

Project Name: RACE 2030 Anaerobic Co-digestion

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Drawing Description: NSW4: Optimised Scenario Block Flow Diagram

Drawing Number: TC-2025-1076-003

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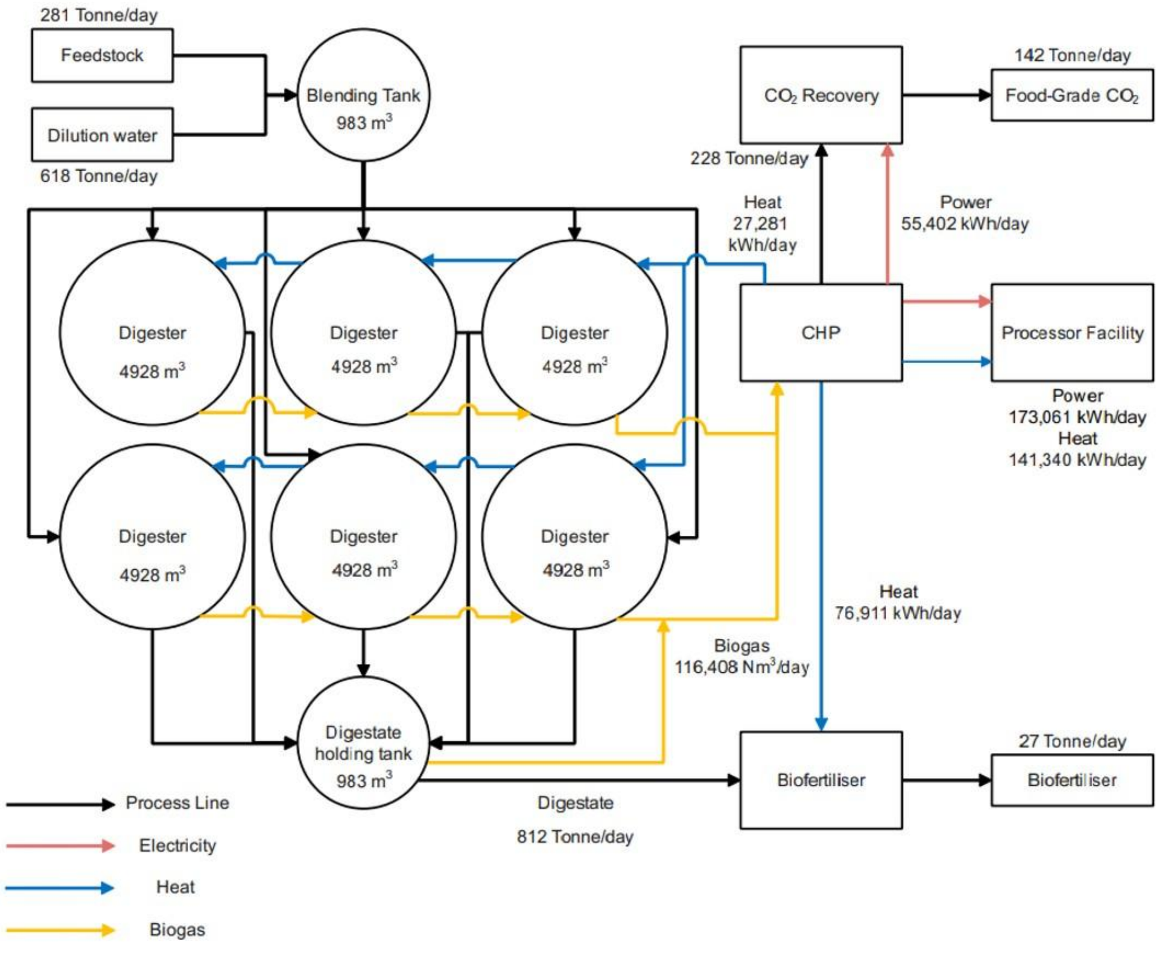
Figure 16: Block flow diagram detailing optimised scenario mass and energy balance for NSW4



TESSELE

Project Name: RACE 2030 Anaerobic Co-digestion

Project Code: 1076

Drawing Description: WA4: Optimised Scenario Block Flow Diagram

Drawing Number: TC-2025-1076-006

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Figure 17: Block flow diagram detailing optimised scenario mass and energy balance for WA4

A sensitivity analysis on key variables is shown in Figure 18. The methane yield and CO_2 price remained major drivers of project profitability, consistent with the co-digestion scenario. Notably, the influence of the by-product price has decreased significantly compared to mono- and co-digestion cases, demonstrating the benefits of process optimisation and enhanced methane yields in improving economic stability. Furthermore, the higher methane yield eliminated the minor observed increase in profitability with plant capacity observed in the WA4 co-digestion scenario, resulting in a significant increase in projected NPV with greater capacities (Figure 18). Overall, the analysis underscores the value of process optimisation in enhancing both the economic performance and resilience of the project.

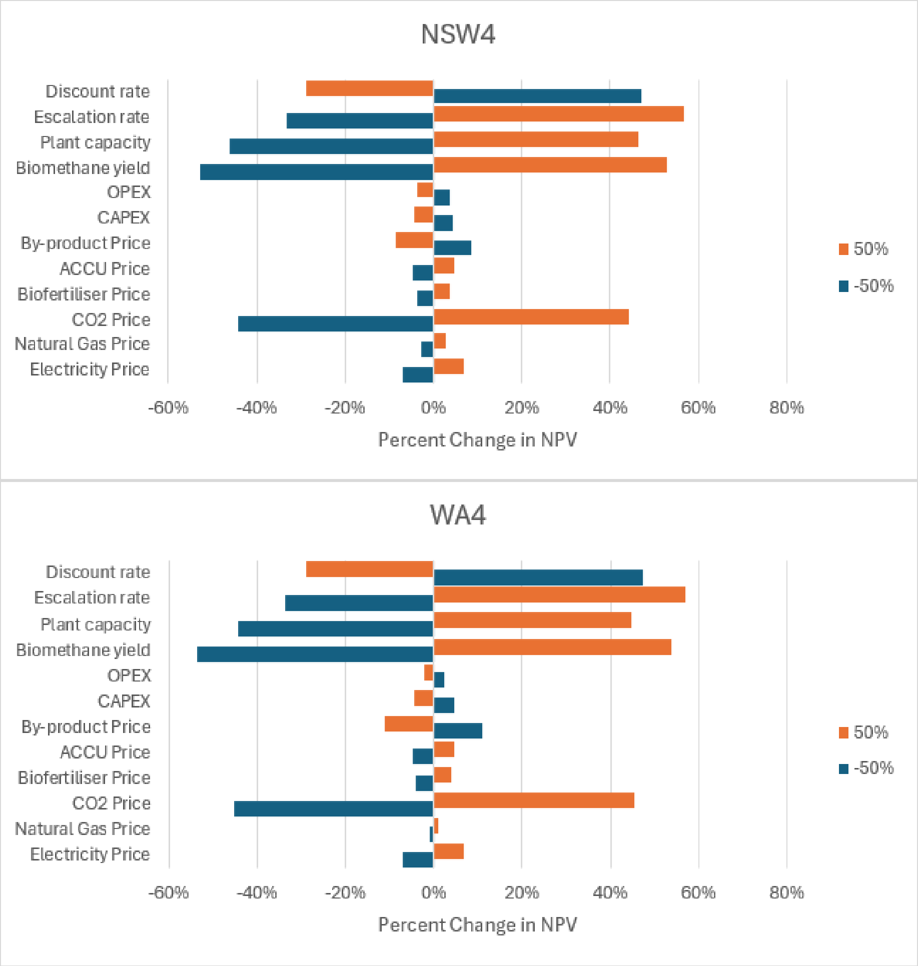


Figure 18: Optimised sensitivity analysis on project NPV with selected parameters. Each parameter was varied by ±50%.

4.6 Research activity 6: Impact analysis

The impact analysis evaluated the environmental implications of commercialising the ACoD process within the Australian red meat industry. Carbon balance modelling, encompassing Scope 1, 2, and 3 emissions, demonstrated a net reduction in greenhouse gas emissions across all assessed scenarios. Under the mono-digestion scenario, reductions in grid energy imports contributed to lower emissions; however, the facility remained a net CO_2 emitter due to residual electricity demand. Additional emission savings were achieved through the sale of recovered CO_2 and the displacement of synthetic fertilisers, further contributing to overall carbon reduction.

In the co-digestion scenario, the substantial increase in biogas productivity led to a marked decrease in grid electricity imports (Figure 19) and facilitated CO_2 sales that generated significant Scope 1 and 2 emission offsets, equating to 39,707 kg CO_2 eq.·year^{-1} for NSW4, and up to 36,643 kg CO_2 eq.·year^{-1} for WA4 (Table 11). For vertically integrated processors incorporating direct on-farm fertiliser utilisation, the increased processing of diverse feedstocks also enhanced Scope 3 emissions reductions through increased biofertiliser production and CO_2 mitigation through nutrient recycling and displacement of conventional fertilisers, equating to 3,140 kg CO_2 eq.·year^{-1} and 4,165 kg CO_2 eq.·year^{-1} for NSW4 and WA4, respectively. These findings illustrate the clear environmental advantages of ACoD in enhancing CO_2 offset potential.

Table 11: Emissions balance values for all scenarios assessed

	NSW4 – Beef			**WA4 – Sheep and Cattle**		
	Mono-Digestion	**Co-Digestion**	**Optimised Scenario**	**Co-Digestion**	**Mono-Digestion**	**Optimised Scenario**
			Production (tonne/year)			
By-product disposal	0	0	0	0	0	0
Co-substrate transport	0	21	253	0	5	253
Total Base Electrical demands	18,746	18,746	18,746	18,659	18,659	18,659
Total Base Gas demands	14,428	14,428	14,428	4,957	4,957	4,957
Biogas Combustion	210	1,365	6,768	382	1,576	6,684
Electrical Energy Imports *	16,042	1,207	0	13,747	0	0
Natural Gas Imports *	12,742	3,492	0	1,894	0	0
Total Emissions	33,385	34,561	40,195	23,998	25,197	30,553
Total Remaining Emissions Post Energy Offset	28,994	6,085	7,021	16,023	1,581	6,937
			Savings (tonne/year)			
By-product disposal	81	115	333	183	191	436
Electrical Offsets	2,704	17,539	18,746	4,912	18,659	18,659
Natural Gas offsets	1,686	10,937	54,238	3,063	4,957	4,957
Food-grade CO2 production	1,768	11,116	61,782	3,212	12,835	61,016
Bio-fertiliser production	2,162	3,140	9,112	4,531	4,165	9,508
Total Savings	8,402	42,847	144,211	15,901	40,808	94,576
Total Carbon Impact	24,983	-8,287	-104,016	8,097	-15,611	-64,023

* Represents total remaining energy imports, inclusive of energy produced

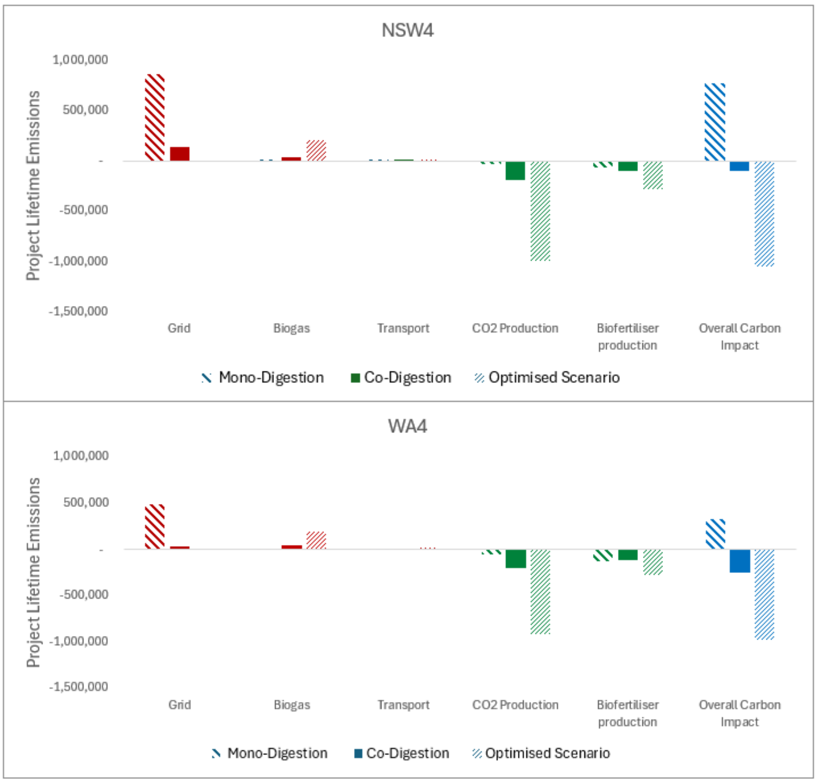


Figure 19: Carbon balance for each scenario assessed. Bars coloured in red represent a net production of CO_2, bars in green represent a CO_2 reduction, and bars in blue represent the summation of all emissions for each scenario.

The optimised scenario further amplified these benefits, achieving zero grid electricity imports and maximising CO_2 offsets. Although higher biogas utilisation for power generation resulted in greater direct CO_2 production, the combined effects of elevated methane productivity, CO_2 recovery, and expanded biofertiliser output yielded overall emission reductions exceeding those of the co-digestion scenario. Notably, the optimised scenarios raise emissions reduction (Scope 1 and 2) figures to 85,068 - 135,099 kg CO_2 eq.$\cdot$year^{-1}, with Scope 3 values achieving an additional 9,112 - 9,508 kg CO_2 eq.$\cdot$year^{-1} with direct on-farm fertiliser use (Table 11).

For the industry, these findings demonstrate that optimised ACoD can deliver tangible decarbonisation outcomes and energy self-sufficiency. Although the scale of the optimised scenario may exceed the capacity of individual processors, the results highlight the potential of joint-venture biogas hubs that share infrastructure, feedstocks, and benefits (incl. reduced energy costs, ACCU generation, and fertiliser production). Collectively, the carbon balance analysis underscores the substantial emissions reduction potential of ACoD and highlights the importance of continued process optimisation for achieving net-zero outcomes in the red meat industry.

5. Knowledge Sharing and IP

5.1 Summary of Knowledge Sharing Activities

The project team undertook a range of knowledge-sharing activities throughout the project to ensure effective dissemination of findings to the public, academia, and industry stakeholders. The following section summarises the key activities completed over the course of the project.

Project reports

The project team prepared and delivered four progress reports, each summarising key findings and updates approximately every four months. In addition, an annual report (December 2024) captured the main achievements and outcomes from the first project year. This final report consolidates the results, insights, and overall outcomes from the entire project duration.

IRG Meetings

Regular IRG meetings were arranged to discuss project findings, progress, and future project plans and direction. The IRG comprised representatives from key sectors, including meat processors, equipment suppliers, and industry organisations, facilitating the effective exchange of knowledge and ensuring project outcomes were aligned with industry needs.

Workshops and Online Webinar

Over the course of the project, the team hosted two in-person workshops (26 March 2025 and 22 October 2025) at Griffith University and one online webinar hosted by RACE on 13 August 2024.

The webinar provided an overview of the project's early findings and fostered open discussions on biomethane production potential, co-digestion strategies, and opportunities for improving biogas yields. More than 30 participants attended and actively contributed through Q&A sessions, offering valuable insights from diverse industry perspectives.

The workshops served as key forums for sharing results, exploring industry applications, and facilitating direct dialogue between researchers and stakeholders. A video summarising highlights from the 26 March 2025 workshop is available here:

https://www.youtube.com/watch?v=hYtu-b9fJ3M

Publications:

Four publications have been prepared as part of this project, with the goal of being submitted shortly after project closure. The publications will be key to disseminating knowledge to the wider academic and industry community. The titles of each piece of work are as follows:

- Anaerobic digestion of solid wastes from Australian red meat processing industries: effect of chemical composition of meat wastes on biochemical methane potential'
- Anaerobic digestion of solid wastes from Australian red meat processing industries: effect of codigestion and chemical composition of meat wastes on biochemical methane potential
- Anaerobic codigestion of solid organic wastes from beef processing industry: influence of lipids, proteins and carbohydrate ratios on biochemical methane potential

- Anaerobic co-digestion of red meat processing wastes using a continuous stirred tank reactor: Effect of lipids, proteins and carbohydrate ratio on biomethane yields and digestate characteristics

5.2 Summary of IP management

There was no IP generation from this feasibility project. All contact information and communications were treated in confidence. The design conditions for the BMP tests and pilot-scale operation of the continuous studies remain Griffith IP. IRG members provided their recommendations and guidance to assist in the research activities; however, they cannot use the design calculations and process conditions for their commercial use.

6. Conclusions and Recommendations

This study aimed to optimise biogas production from red meat by-products through ACoD with agricultural residues. Overall, the results demonstrated that ACoD significantly enhanced methane yields, process stability, and overall system performance compared to mono-digestion.

Feedstock variability was identified as a major determinant of performance, with biochemical methane potentials (BMPs) ranging from 175-559 $NL_{CH_4}\cdot kg^{-1}{}_{VS}$ added across processors in Phase 1, even within the same livestock category. This variability was also evident during Phase 2, underscoring the importance of site-specific feedstock characterisation. Phase 3 established an optimal LPC ratio of 60:20:20, which further improved methane yields beyond earlier co-digestion trials.

Continuous digestion experiments validated the laboratory findings, confirming the benefits of feedstock control under semi-continuous conditions. Implementation of the optimal LPC ratio increased methane productivity by 57-69% compared to mono-digestion, and 21–22% compared to co-digestion, while also enabling stable operation at elevated OLRs. The addition of biochar and activated carbon effectively mitigated ammonia and LCFA inhibition, supporting continued reactor stability under intensified loading.

Techno-economic modelling translated these performance gains into strong financial outcomes. ACoD scenarios delivered positive NPVs exceeding $221 million and payback periods of approximately four years for both NSW4 and WA4. The optimised ACoD scenario demonstrated even greater potential, with projected annual revenues of $112 million (NSW4) and $111 million (WA4), highlighting the long-term commercial viability of co-digestion for the red meat industry (Figure 20).

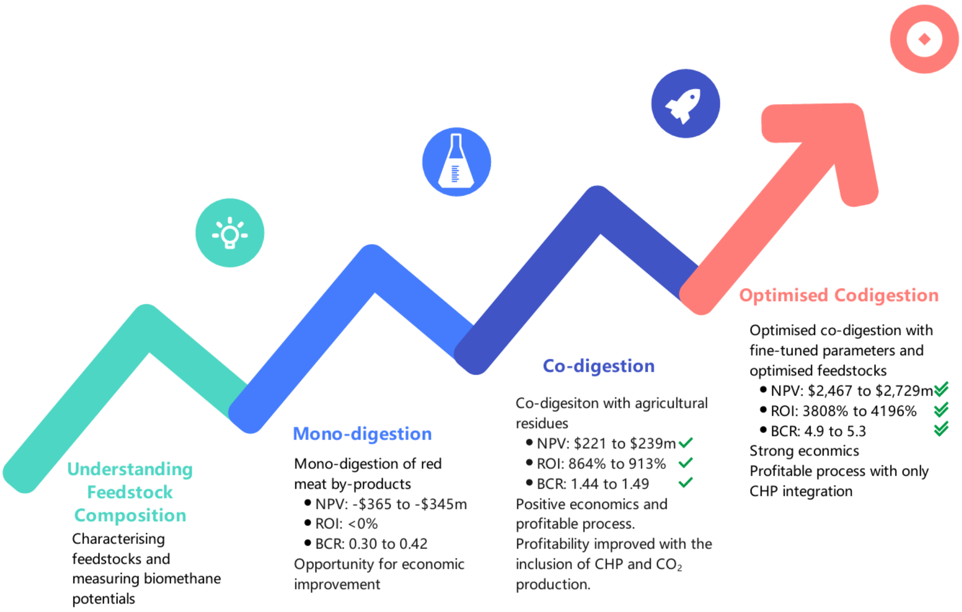


Figure 20: Graphical summary of the TEA findings

Environmental impact analysis further reinforced these benefits. Both co-digestion and optimised scenarios achieved substantial greenhouse gas reductions, offsetting grid electricity use and displacing synthetic fertilisers. While mono-digestion reduced emissions relative to baseline operations, it remained a net emitter due to continued reliance on grid electricity imports. In contrast, ACoD and optimised configurations achieved significant carbon reductions for processors across both sites.

In summary, this project demonstrated that targeted feedstock optimisation and ACoD integration can transform red meat processing by-products into valuable bioresources, enabling major gains in energy productivity, emissions reduction, and economic return (Figure 21). These outcomes provide a strong foundation for the red meat industry to adopt ACoD as a key pathway toward decarbonisation and circular bioresource utilisation.

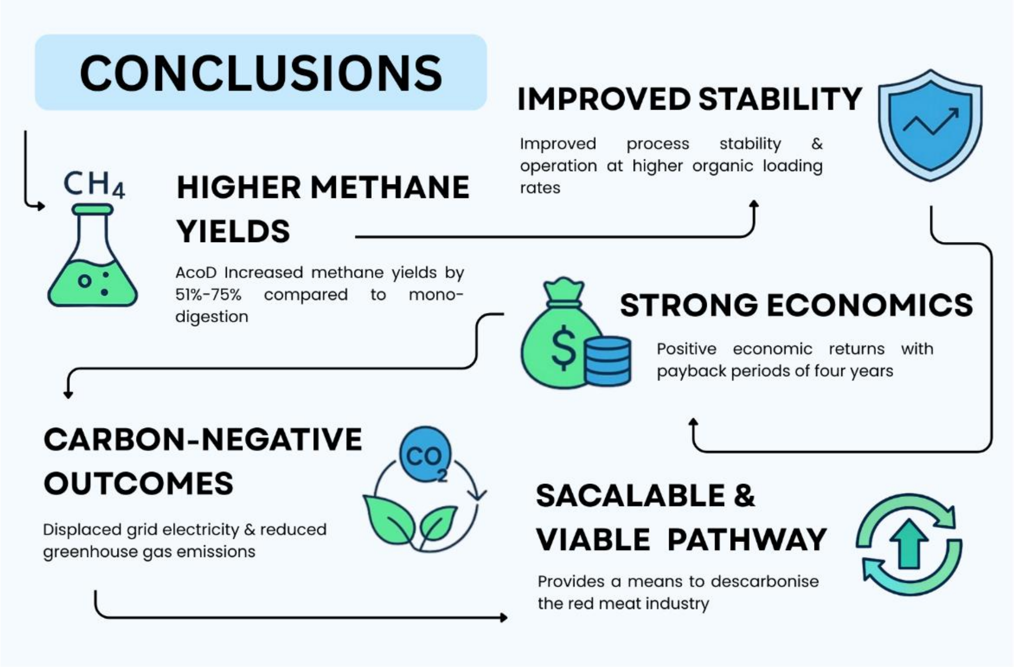


Figure 21: Summary of key project conclusions

6.1 Recommendations

Optimised feedstock ratios

This study identified a LPC ratio of 60:20:20 as optimal for enhancing methane production in red meat industry co-digestion systems. However, continuous digestion studies indicated that elevated organic loading rates can still result in ammonia and long-chain fatty acid (LCFA) inhibition. Future research should further refine feedstock optimisation strategies to maintain or improve methane yields while mitigating inhibition risks, including adaptive feeding regimes, implementation of two-staged digestion, and co-substrate blending strategies (Figure 22).

Advance Digestate Valorisation and Regulatory Engagement

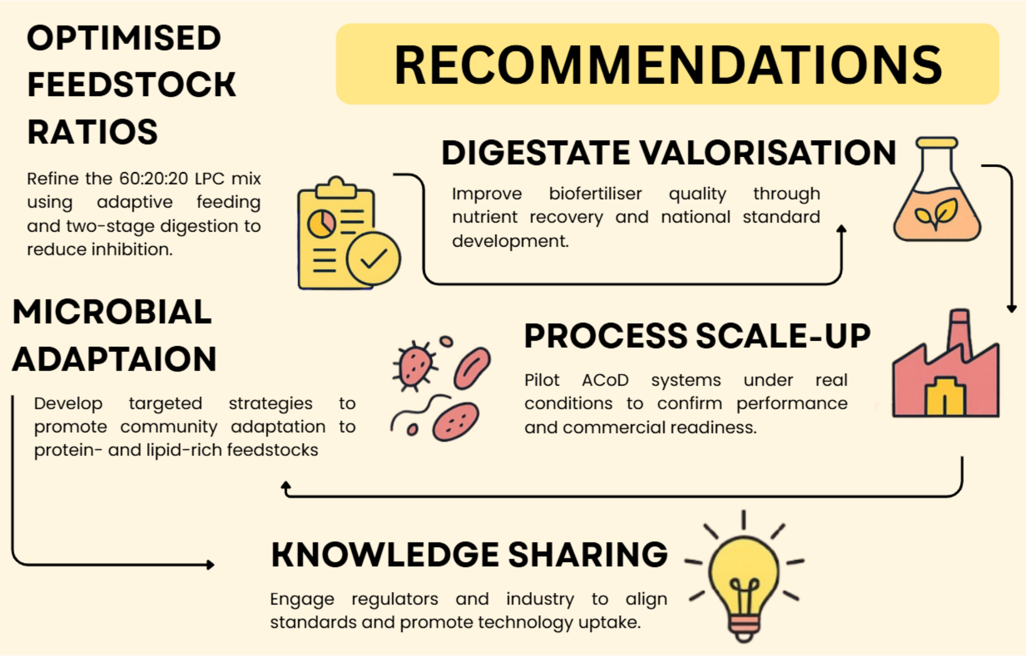
While this study focused primarily on ACoD optimisation for biogas production, biofertiliser development remains a key challenge due to the lack of consistent standards and regulatory pathways in Australia. Future work should investigate digestate treatment and nutrient recovery methods, such as ammonia stripping, phosphorus recovery, and solid-liquid separation, to enhance product quality. In parallel, the development of recommendations for updated national standards and guidelines for digestate-derived biofertilisers is needed to support safe use, improve regulatory clarity, and enable market uptake across Australian jurisdictions. A RACE for 2030 project (24.BT2.R.0792) co-funded by AMPC, focused on this recommendation, is currently underway at the time of this report.

Process Scale-Up

Further studies should advance the ACoD process to pilot-scale demonstration to validate laboratory findings under realistic operational conditions. Pilot trials should include continuous monitoring of biogas production, methane concentration, and digestate quality to evaluate long-term process stability and scalability. Successful demonstration at pilot scale will be essential for de-risking the technology for the Australian context, informing full-scale design, and supporting commercial adoption by red meat processors.

Microbial Community Adaptation

Future research should focus on understanding and managing microbial community dynamics in ACoD systems. Targeted studies should aim to identify microbial populations responsible for the degradation of complex red meat substrates and determine how operating conditions influence their activity. Strategies to promote the growth of beneficial microbial consortia, particularly those tolerant to high protein and lipid concentrations, will be critical to enhancing methane yields and process robustness under challenging feedstock compositions.



RECOMMENDATIONS

OPTIMISED FEEDSTOCK RATIOS

Refine the 60:20:20 LPC mix using adaptive feeding and two-stage digestion to reduce inhibition.

DIGESTATE VALORISATION

Improve biofertiliser quality through nutrient recovery and national standard development.

MICROBIAL ADAPTAION

Develop targeted strategies to promote community adaptation to protein- and lipid-rich feedstocks

PROCESS SCALE-UP

Pilot ACoD systems under real conditions to confirm performance and commercial readiness.

KNOWLEDGE SHARING

Engage regulators and industry to align standards and promote technology uptake.

Figure 22: Summary of key project recommendations

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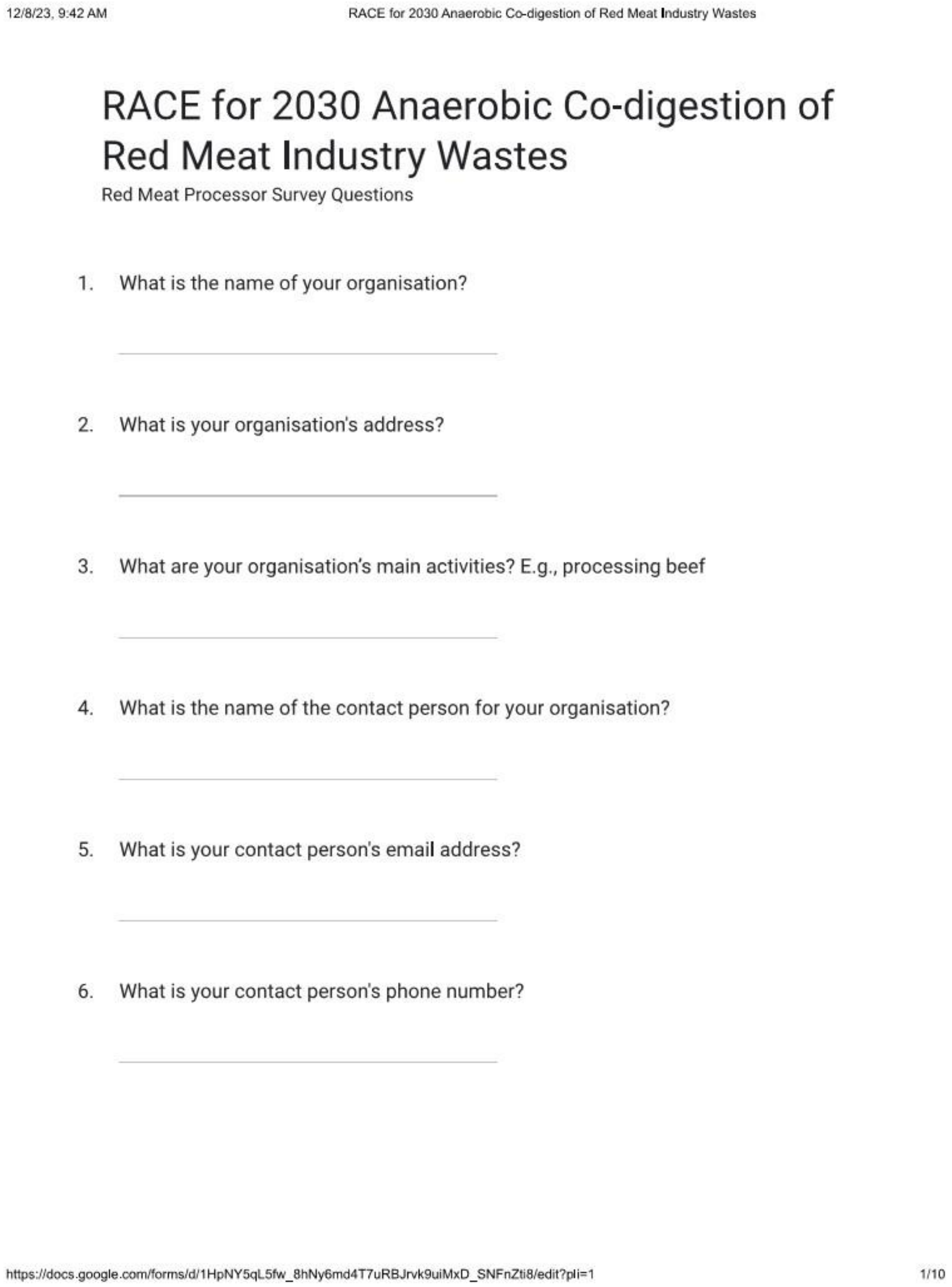
8. Appendices

8.1 Appendix A: Survey Package

Red Meat Processor Survey Questions



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RACE for 2030 Anaerobic Co-digestion of Red Meat Industry Wastes

Red Meat Processor Survey Questions

1. What is the name of your organisation?

2. What is your organisation's address?

3. What are your organisation's main activities? E.g., processing beef

4. What is the name of the contact person for your organisation?

5. What is your contact person's email address?

6. What is your contact person's phone number?

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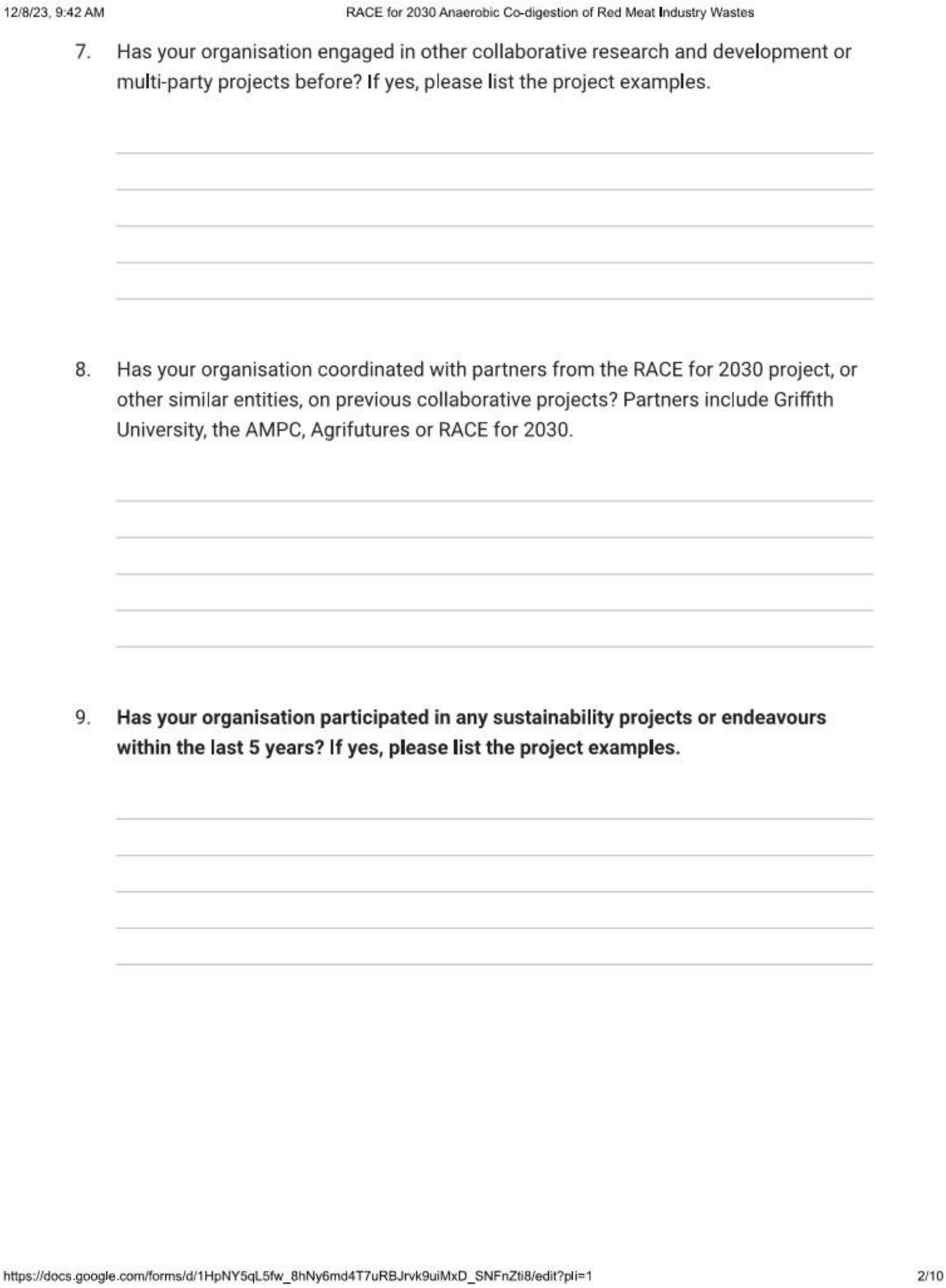
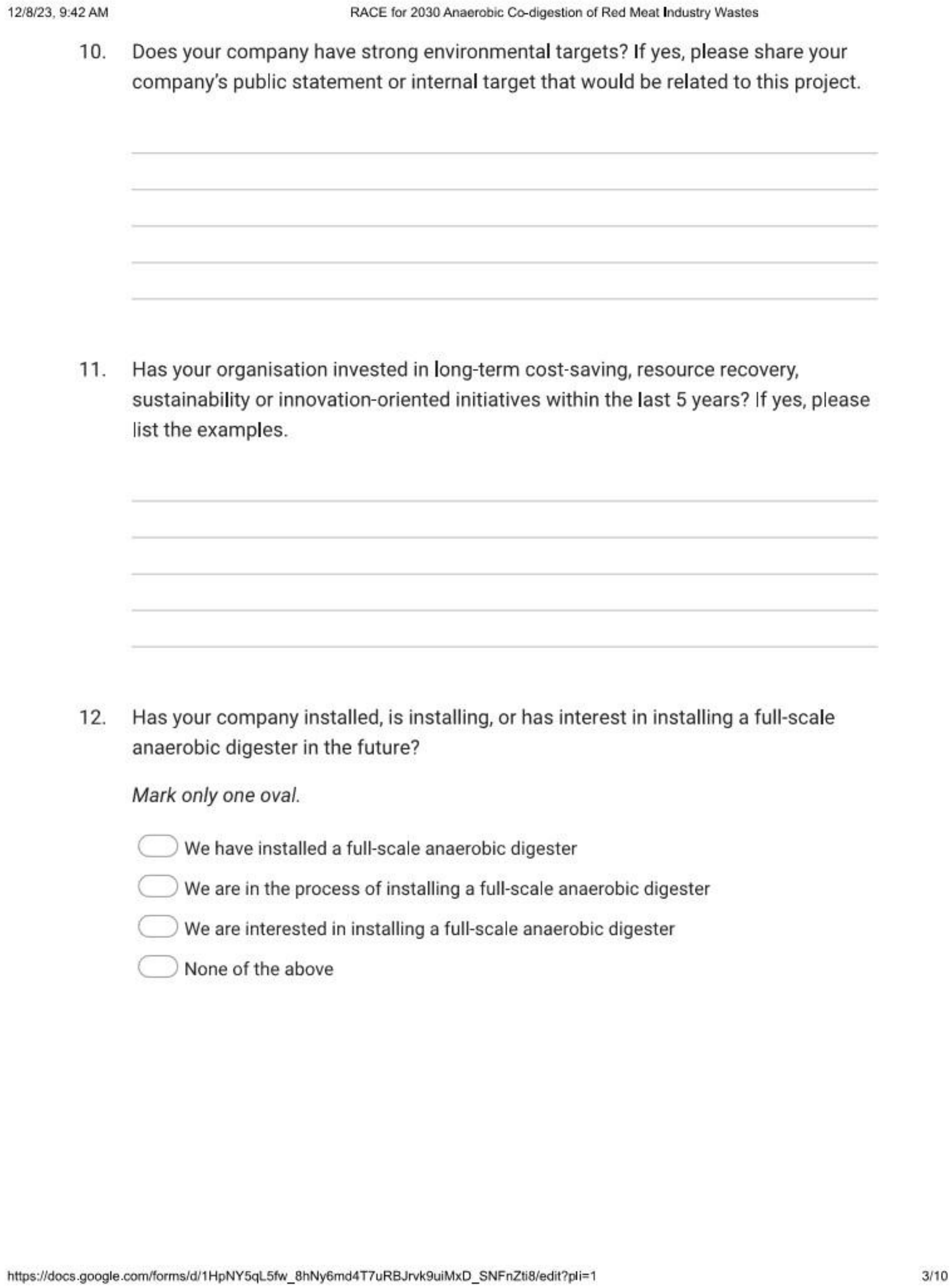


7. Has your organisation engaged in other collaborative research and development or multi-party projects before? If yes, please list the project examples.

8. Has your organisation coordinated with partners from the RACE for 2030 project, or other similar entities, on previous collaborative projects? Partners include Griffith University, the AMPC, Agrifutures or RACE for 2030.

9. **Has your organisation participated in any sustainability projects or endeavours within the last 5 years? If yes, please list the project examples.**



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10. Does your company have strong environmental targets? If yes, please share your company's public statement or internal target that would be related to this project.

11. Has your organisation invested in long-term cost-saving, resource recovery, sustainability or innovation-oriented initiatives within the last 5 years? If yes, please list the examples.

12. Has your company installed, is installing, or has interest in installing a full-scale anaerobic digester in the future?

Mark only one oval.

○ We have installed a full-scale anaerobic digester
○ We are in the process of installing a full-scale anaerobic digester
○ We are interested in installing a full-scale anaerobic digester
○ None of the above

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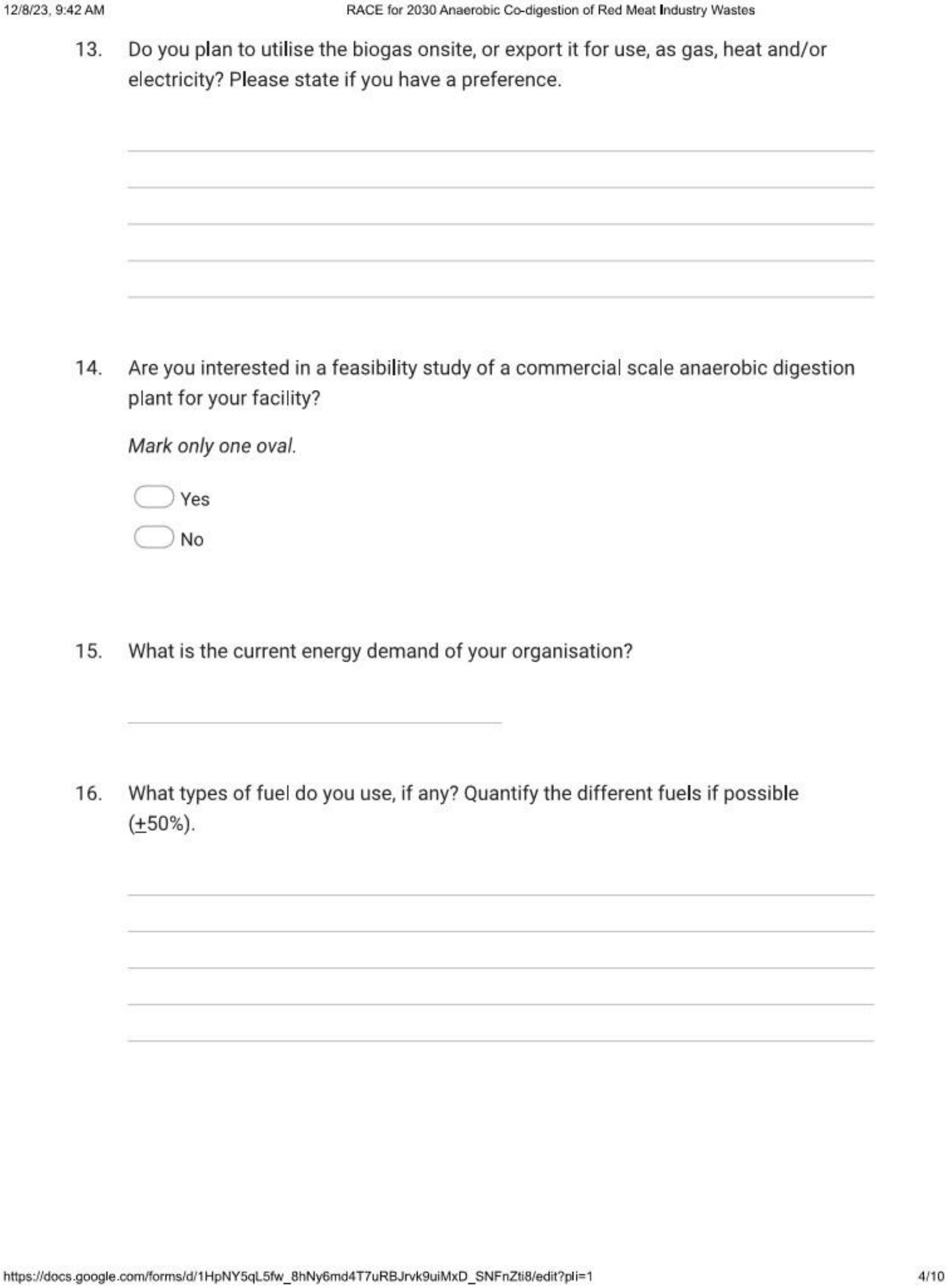

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13. Do you plan to utilise the biogas onsite, or export it for use, as gas, heat and/or electricity? Please state if you have a preference.

14. Are you interested in a feasibility study of a commercial scale anaerobic digestion plant for your facility?

Mark only one oval.

○ Yes

○ No

15. What is the current energy demand of your organisation?

16. What types of fuel do you use, if any? Quantify the different fuels if possible (±50%).

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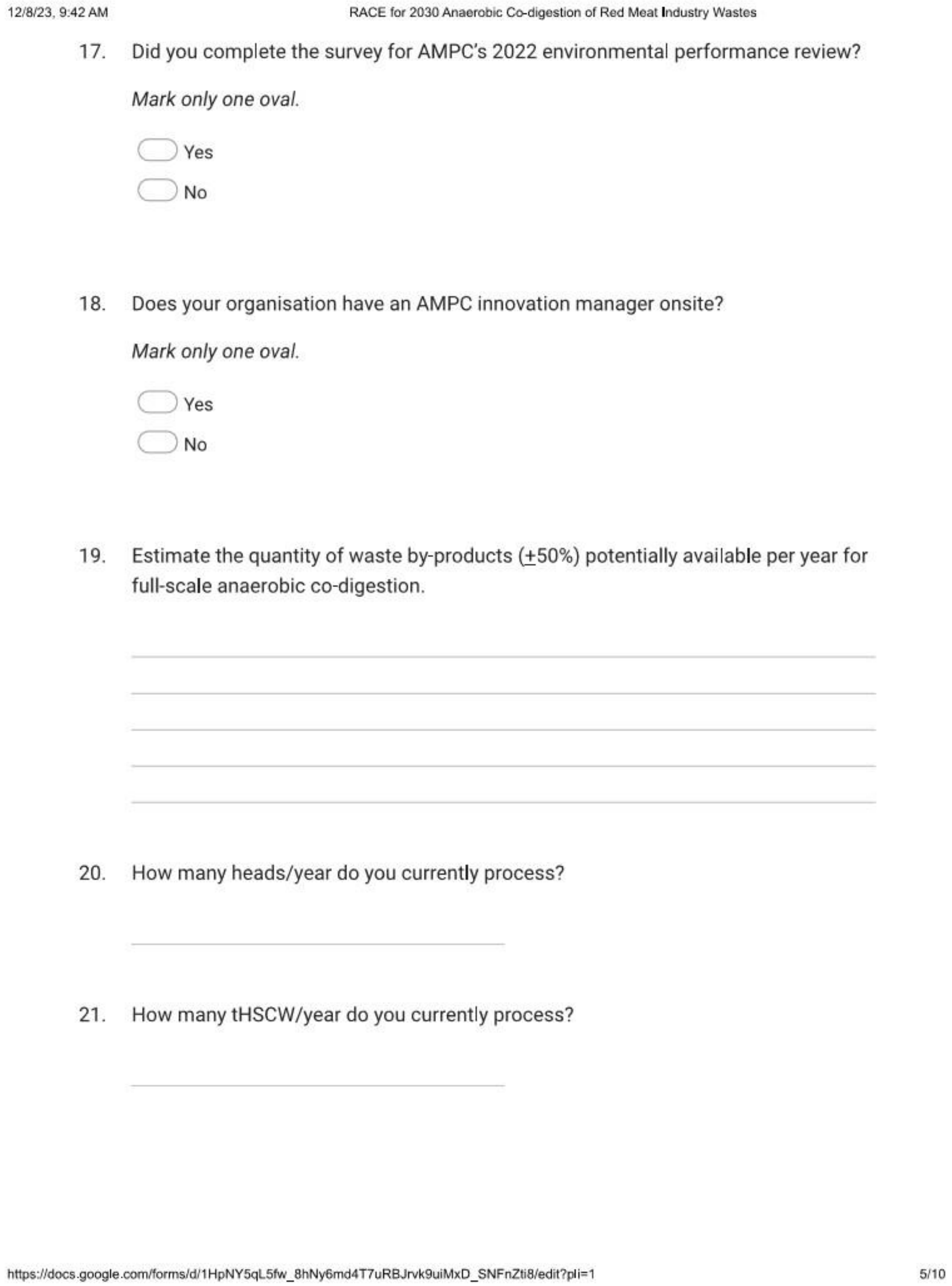


17. Did you complete the survey for AMPC's 2022 environmental performance review?

Mark only one oval.

○ Yes

○ No

18. Does your organisation have an AMPC innovation manager onsite?

Mark only one oval.

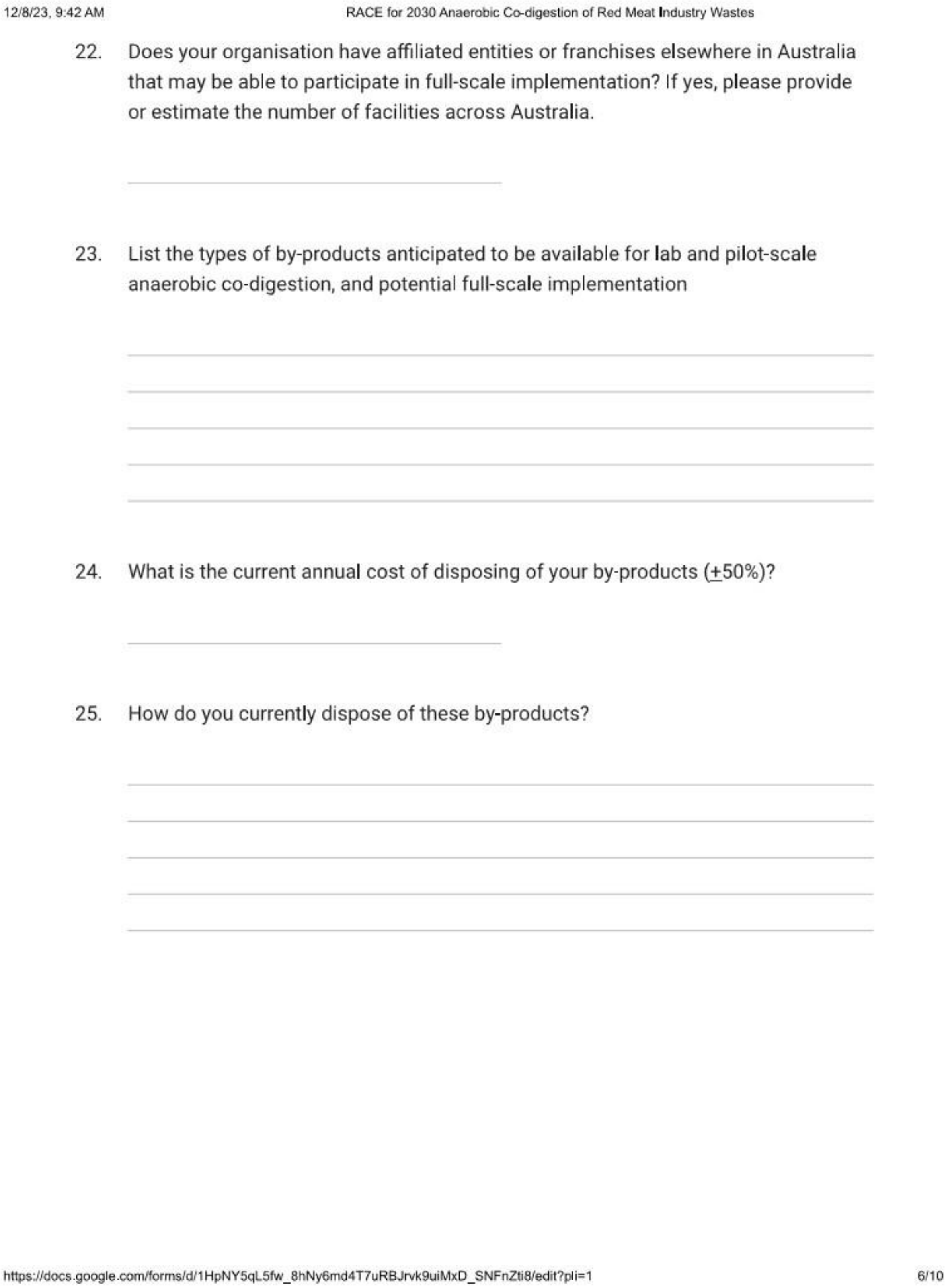
○ Yes

○ No

19. Estimate the quantity of waste by-products (±50%) potentially available per year for full-scale anaerobic co-digestion.

20. How many heads/year do you currently process?

21. How many tHSCW/year do you currently process?



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22. Does your organisation have affiliated entities or franchises elsewhere in Australia that may be able to participate in full-scale implementation? If yes, please provide or estimate the number of facilities across Australia.

23. List the types of by-products anticipated to be available for lab and pilot-scale anaerobic co-digestion, and potential full-scale implementation

24. What is the current annual cost of disposing of your by-products (±50%)?

25. How do you currently dispose of these by-products?

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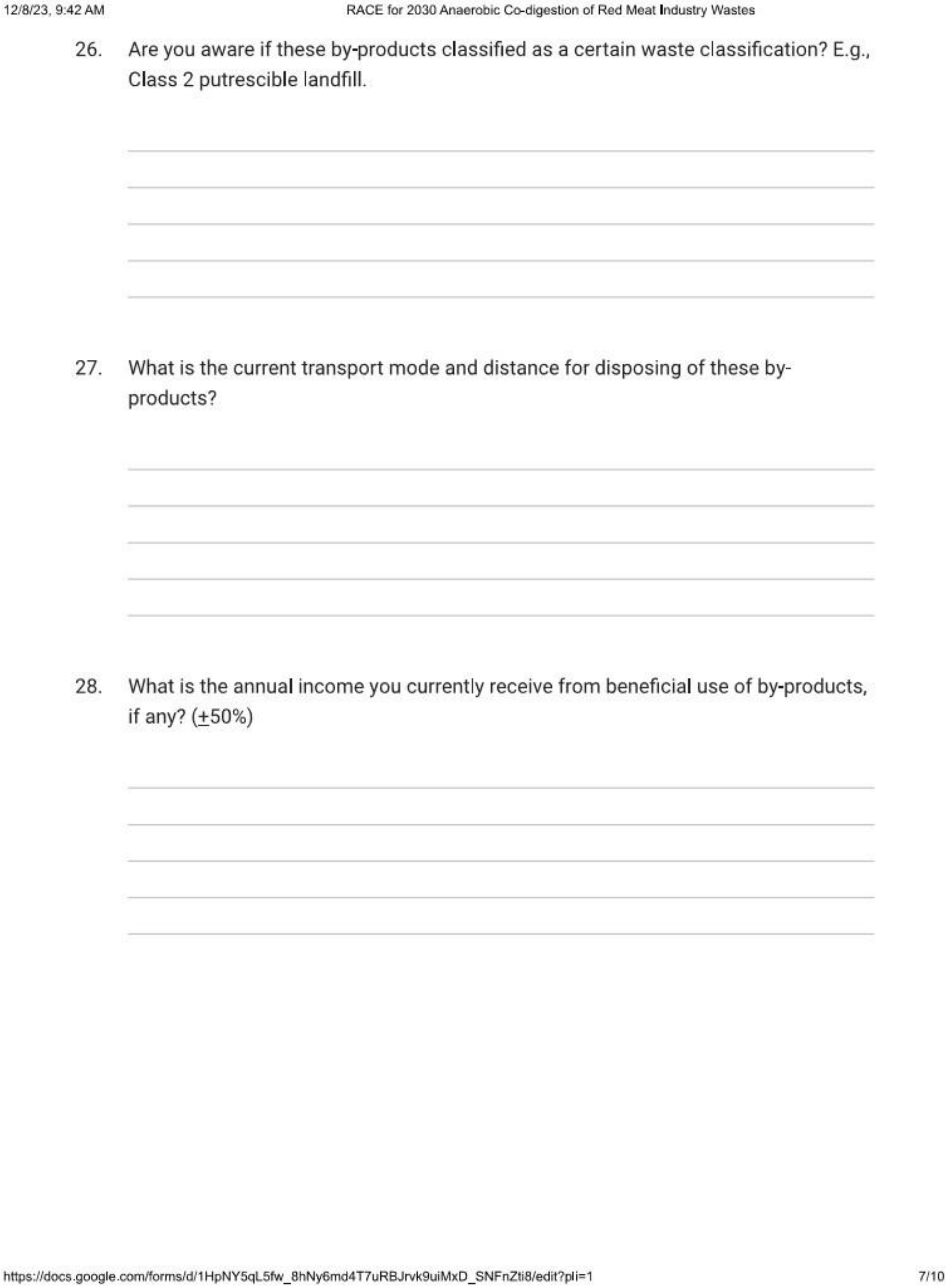

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26. Are you aware if these by-products classified as a certain waste classification? E.g., Class 2 putrescible landfill.

27. What is the current transport mode and distance for disposing of these by-products?

28. What is the annual income you currently receive from beneficial use of by-products, if any? (±50%)

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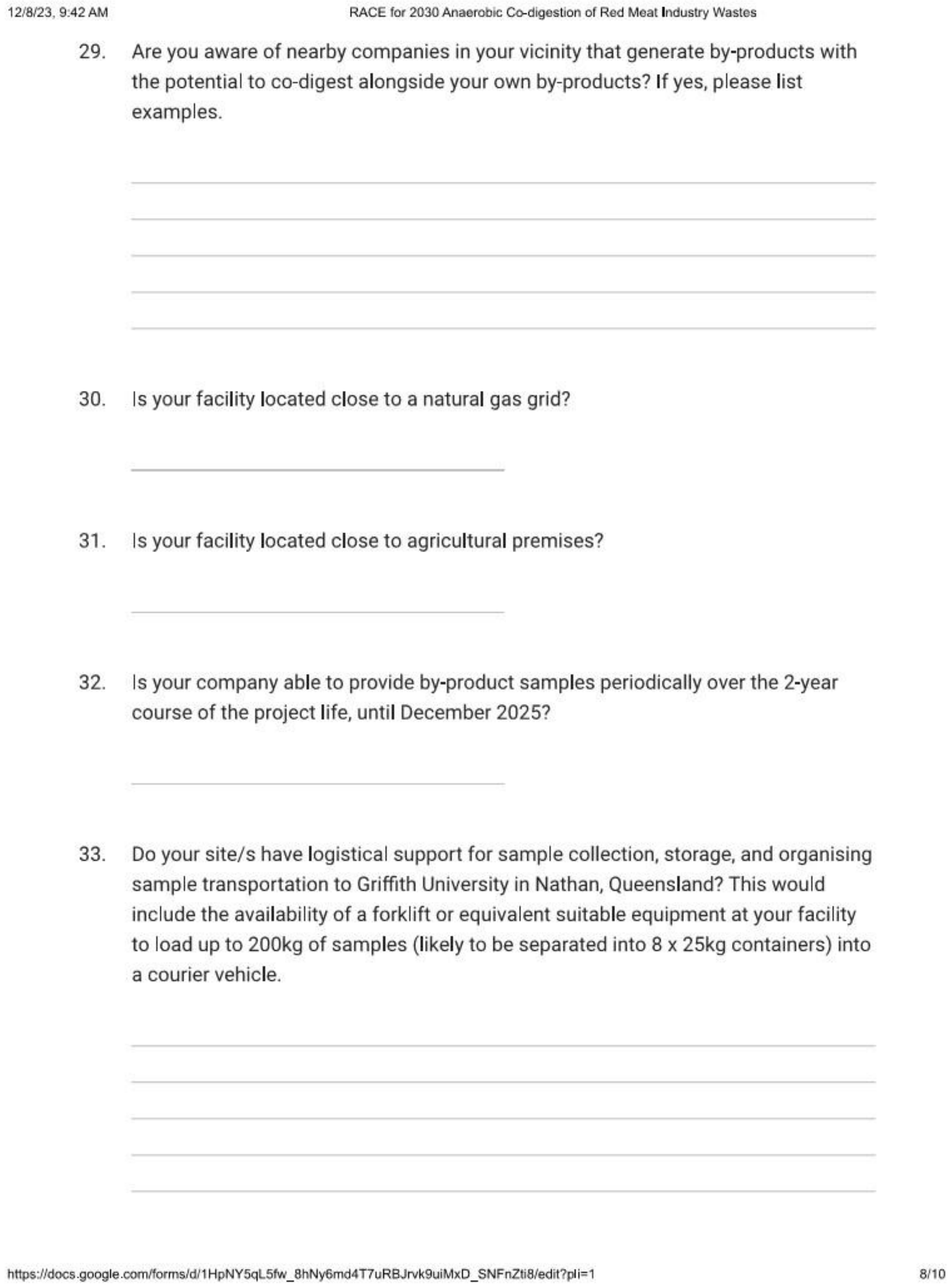


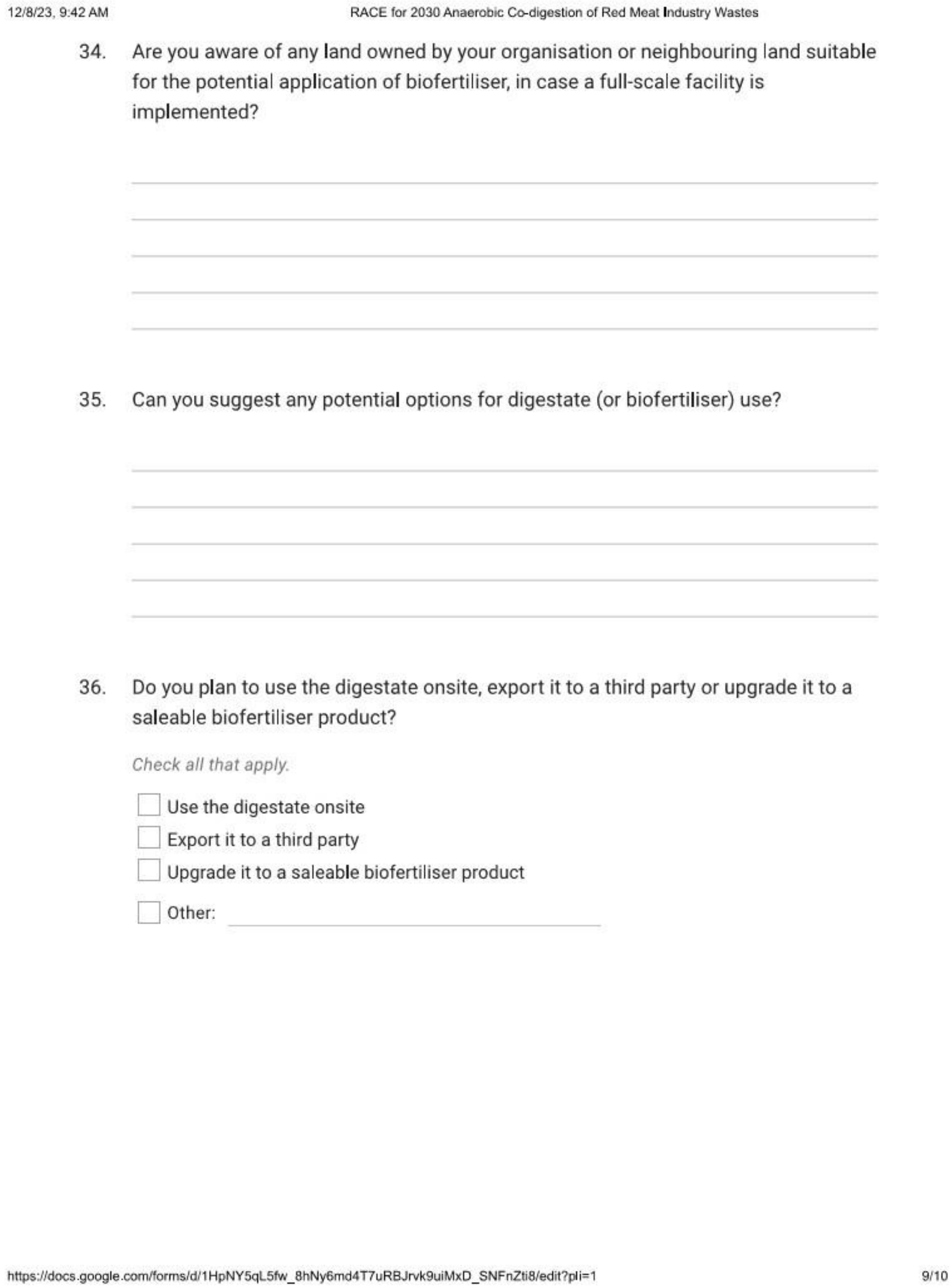
29. Are you aware of nearby companies in your vicinity that generate by-products with the potential to co-digest alongside your own by-products? If yes, please list examples.

30. Is your facility located close to a natural gas grid?

31. Is your facility located close to agricultural premises?

32. Is your company able to provide by-product samples periodically over the 2-year course of the project life, until December 2025?

33. Do your site/s have logistical support for sample collection, storage, and organising sample transportation to Griffith University in Nathan, Queensland? This would include the availability of a forklift or equivalent suitable equipment at your facility to load up to 200kg of samples (likely to be separated into 8 x 25kg containers) into a courier vehicle.



34. Are you aware of any land owned by your organisation or neighbouring land suitable for the potential application of biofertiliser, in case a full-scale facility is implemented?

35. Can you suggest any potential options for digestate (or biofertiliser) use?

36. Do you plan to use the digestate onsite, export it to a third party or upgrade it to a saleable biofertiliser product?

Check all that apply.

☐ Use the digestate onsite
☐ Export it to a third party
☐ Upgrade it to a saleable biofertiliser product
☐ Other:

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37. List your sites practical experience in waste management, renewable energy or sustainability processes?

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8.1.1 Agricultural Industry EOI

RACE for 2030 BUSINESS

RACE for 2030 Fast Track Project
Theme **B5**: Anaerobic digestion for electricity, transport and gas

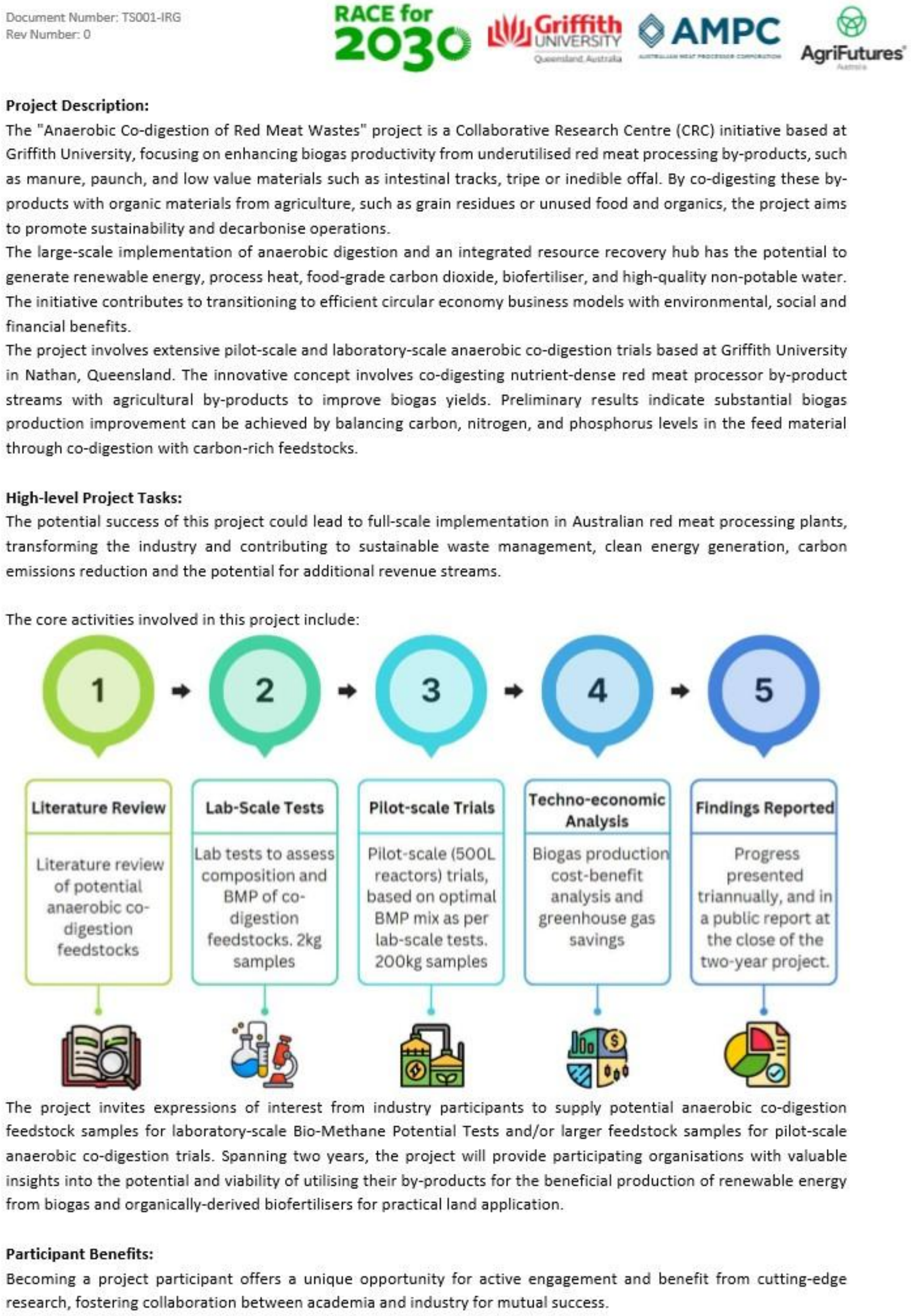
RACE FOR 2030 – ANAEROBIC CO-DIGESTION OF RED MEAT INDUSTRY WASTES

Expression of Interest for Co-Digestion Feedstock Suppliers

Abstract

The Anaerobic Co-digestion of Red Meat Industry Wastes project for Race for 2030 is a collaborative Cooperative Research Centre (CRC) between AMPC, Griffith University and AgriFutures Australia. It involves pilot-scale and laboratory-scale anaerobic co-digestion studies at Griffith University in Brisbane, Queensland. The core objective of improving biogas productivity from underutilised red meat processing by-products will enhance sustainability and decarbonise operations. By-products such as manure, paunch, and low-value materials such as intestinal tracks, tripe, and inedible offal, will be co-digested with organic agricultural industry by-products, producing biomethane for renewable energy generation. The project is seeking expressions of interest from industry participants to provide co-digestion feedstock for the laboratory-scale tests and/or for the pilot-scale trials. Materials such as grain residues, Food and Garden Organics (FOGO), dairy by-products, and other food production and agro-industry by-products will be tested as co-digestion feedstock with red meat processing industry by-products. Participants will receive information on the Bio-Methane Potential of their by-products. This work aims to identify and verify the optimal combinations of feedstock to maximise renewable energy production while concurrently producing biofertiliser.

AMPC, Griffith University, AgriFutures
kendall.ferraro@tessele.com



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Rev Number: 0

Project Description:

The "Anaerobic Co-digestion of Red Meat Wastes" project is a Collaborative Research Centre (CRC) initiative based at Griffith University, focusing on enhancing biogas productivity from underutilised red meat processing by-products, such as manure, paunch, and low value materials such as intestinal tracks, tripe or inedible offal. By co-digesting these by-products with organic materials from agriculture, such as grain residues or unused food and organics, the project aims to promote sustainability and decarbonise operations.

The large-scale implementation of anaerobic digestion and an integrated resource recovery hub has the potential to generate renewable energy, process heat, food-grade carbon dioxide, biofertiliser, and high-quality non-potable water. The initiative contributes to transitioning to efficient circular economy business models with environmental, social and financial benefits.

The project involves extensive pilot-scale and laboratory-scale anaerobic co-digestion trials based at Griffith University in Nathan, Queensland. The innovative concept involves co-digesting nutrient-dense red meat processor by-product streams with agricultural by-products to improve biogas yields. Preliminary results indicate substantial biogas production improvement can be achieved by balancing carbon, nitrogen, and phosphorus levels in the feed material through co-digestion with carbon-rich feedstocks.

High-level Project Tasks:

The potential success of this project could lead to full-scale implementation in Australian red meat processing plants, transforming the industry and contributing to sustainable waste management, clean energy generation, carbon emissions reduction and the potential for additional revenue streams.

The core activities involved in this project include:

1 → 2 → 3 → 4 → 5

Literature Review	Lab-Scale Tests	Pilot-scale Trials	Techno-economic Analysis	Findings Reported
Literature review of potential anaerobic co-digestion feedstocks	Lab tests to assess composition and BMP of co-digestion feedstocks. 2kg samples	Pilot-scale (500L reactors) trials, based on optimal BMP mix as per lab-scale tests. 200kg samples	Biogas production cost-benefit analysis and greenhouse gas savings	Progress presented triannually, and in a public report at the close of the two-year project.

The project invites expressions of interest from industry participants to supply potential anaerobic co-digestion feedstock samples for laboratory-scale Bio-Methane Potential Tests and/or larger feedstock samples for pilot-scale anaerobic co-digestion trials. Spanning two years, the project will provide participating organisations with valuable insights into the potential and viability of utilising their by-products for the beneficial production of renewable energy from biogas and organically-derived biofertilisers for practical land application.

Participant Benefits:

Becoming a project participant offers a unique opportunity for active engagement and benefit from cutting-edge research, fostering collaboration between academia and industry for mutual success.

The benefits of participating in the project by providing feedstock for testing include:

BIOFERTILISER PRODUCTION
Potential for ' by-products to be transformed into valuable biofertilisers .

RENEWABLE ENERGY POTENTIAL
Production of renewable energy from biogas aligns with sustainability practices

BIO-METHANE POTENTIAL & TAILORED ANALYSIS
Comprehensive BMP test results and detailed analysis of participants' feedstock

OPTIMISATION ADVICE
Receive recommendations based on lab tests for optimising co-digestion

TECHNO-ECONOMIC INSIGHTS
Cost-benefit assessments and GHG savings, aiding business decisions

PILOT-SCALE TRIALS
Pilot-scale co-digestion trials, assess the likely performance of co-digesting feedstock on a larger scale.

CONTRIBUTE TO INDUSTRY GROWTH
Project contribution enables the advancement of participants' industrial sector.

EARLY ACCESS TO RESULTS
Receive early access of results before official publications for early implementation

TWO-YEAR COLLABORATION
Stay informed throughout the two-year project duration, receiving regular result updates

VISIBILITY & RECOGNITION
Enhance professional reputation in renewable energy and research communities

By participating in this innovative initiative, participants not only contribute to the advancement of knowledge but also gain practical, applicable insights that can positively impact their organisation's sustainability and resource utilisation practices.

Participants' Commitment:

The commitment required from the selected participants involves:

1	SMALL BY-PRODUCT SAMPLES	Supply small feedstock samples (2kg samples) and arrange for transport to Griffith University, QLD for BMP and characteristic analysis from Jan 2024 to potentially Dec 2025.
2	LARGE BY-PRODUCT SAMPLES	Send 200kg feedstock samples for pilot-scale anaerobic digestion at Griffith University, QLD, from May 2024 to Oct 2025. Frequency and number of samples TBD, approx. every 2-3 months.
3	BY-PRODUCT DATA FOR TECHNO-ECONOMIC ASSESSMENT	Provide feedstock data for techno-economic analysis, including quantities of co-digestion feedstock available at the participant organisation, and the current cost of disposal or income received from its current uses.
4	LOCAL CO-DIGESTION SUBSTRATE	If participants have local co-digestion substrates for testing, inform the project team in the EOI response. Options include grain residues, FOGO, dairy by-products, fruit and vegetable production by-products, food processing residues, and other agro-industrial 'wastes' from the vicinity.

About the Participants:

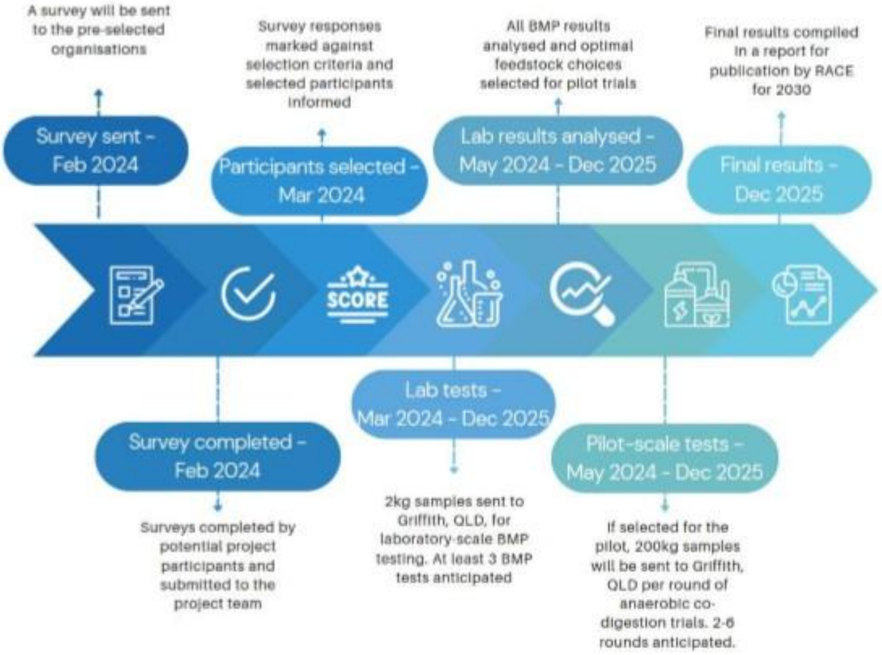
Sought participants are organisations capable of providing by-product samples that could potentially become anaerobic co-digestion feedstock. The samples will undergo laboratory-scale testing for Bio-Methane Potential. If identified as a viable feedstock with significant energy production potential, the sample will be selected for further evaluation. The shortlisted by-products will lead to a larger sample undergoing anaerobic co-digestion with by-products from the red meat processing industry. The project's target participants are those from other agro-industries, such as grain processors, FOGO collectors, councils, dairies, fruit and vegetable producers, food processors, and other related industries. Participants will be able to provide the collective with underutilised by-products, particularly those with high carbon content, that could be utilised as anaerobic co-digestion feedstock.

Expressing Interest:

If you are interested in being considered for as a project participant, please respond to this Expression of Interest with a brief statement expressing your interest in participating, and what by-products you are expecting to provide.

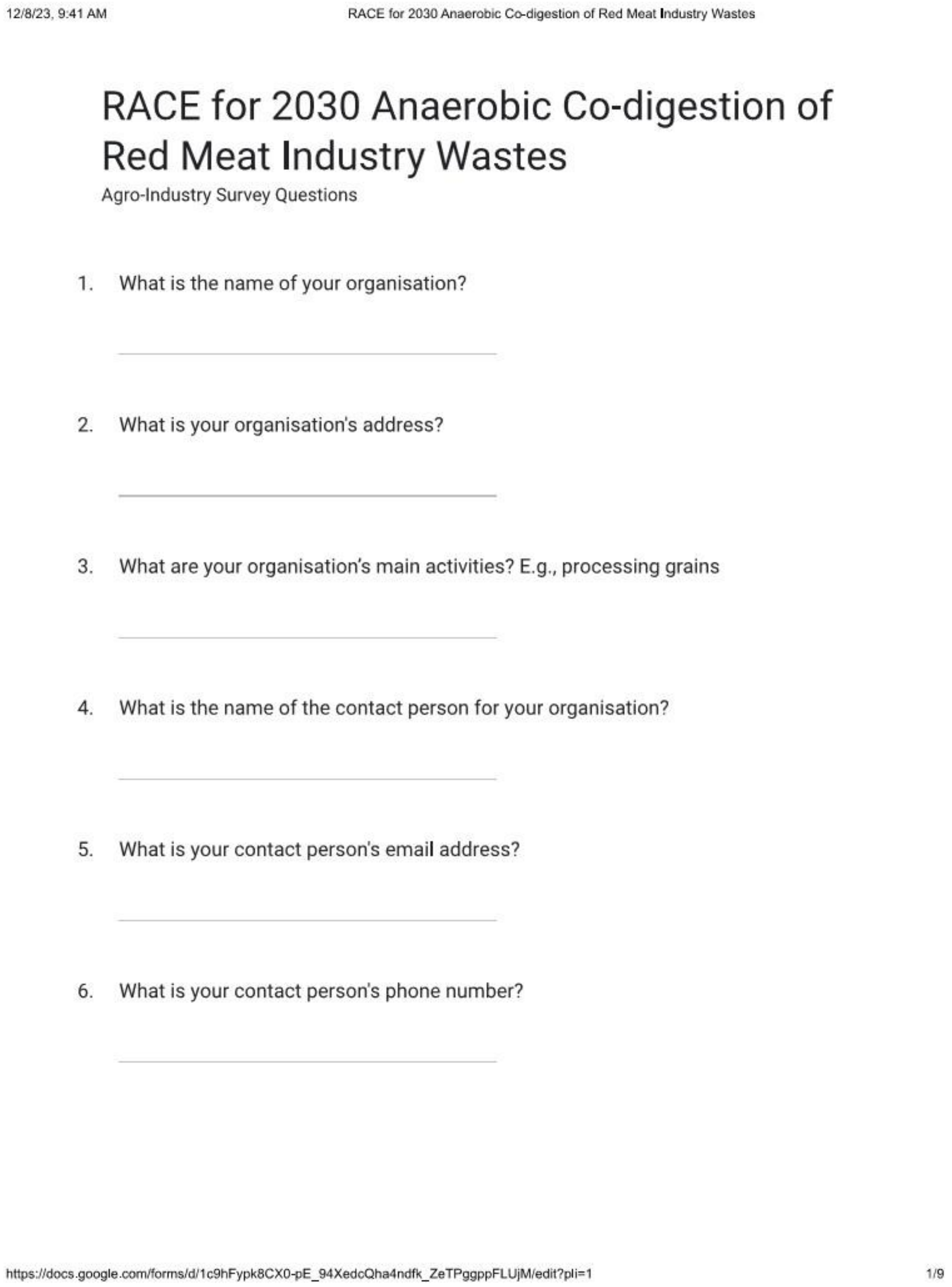
Selection Process:

The project team are selecting participants based on a selection criterion determined for the success of the project. Refer to the below for the selection process and next steps.



We look forward to collaborating with you on this exciting and innovative project that connects the red meat processing sector and agricultural industry. Together, we aim to make a meaningful contribution to national renewable energy and sustainability efforts.

8.1.2 Agricultural Industry Survey Questions



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RACE for 2030 Anaerobic Co-digestion of Red Meat Industry Wastes

Agro-Industry Survey Questions

1. What is the name of your organisation?

2. What is your organisation's address?

3. What are your organisation's main activities? E.g., processing grains

4. What is the name of the contact person for your organisation?

5. What is your contact person's email address?

6. What is your contact person's phone number?

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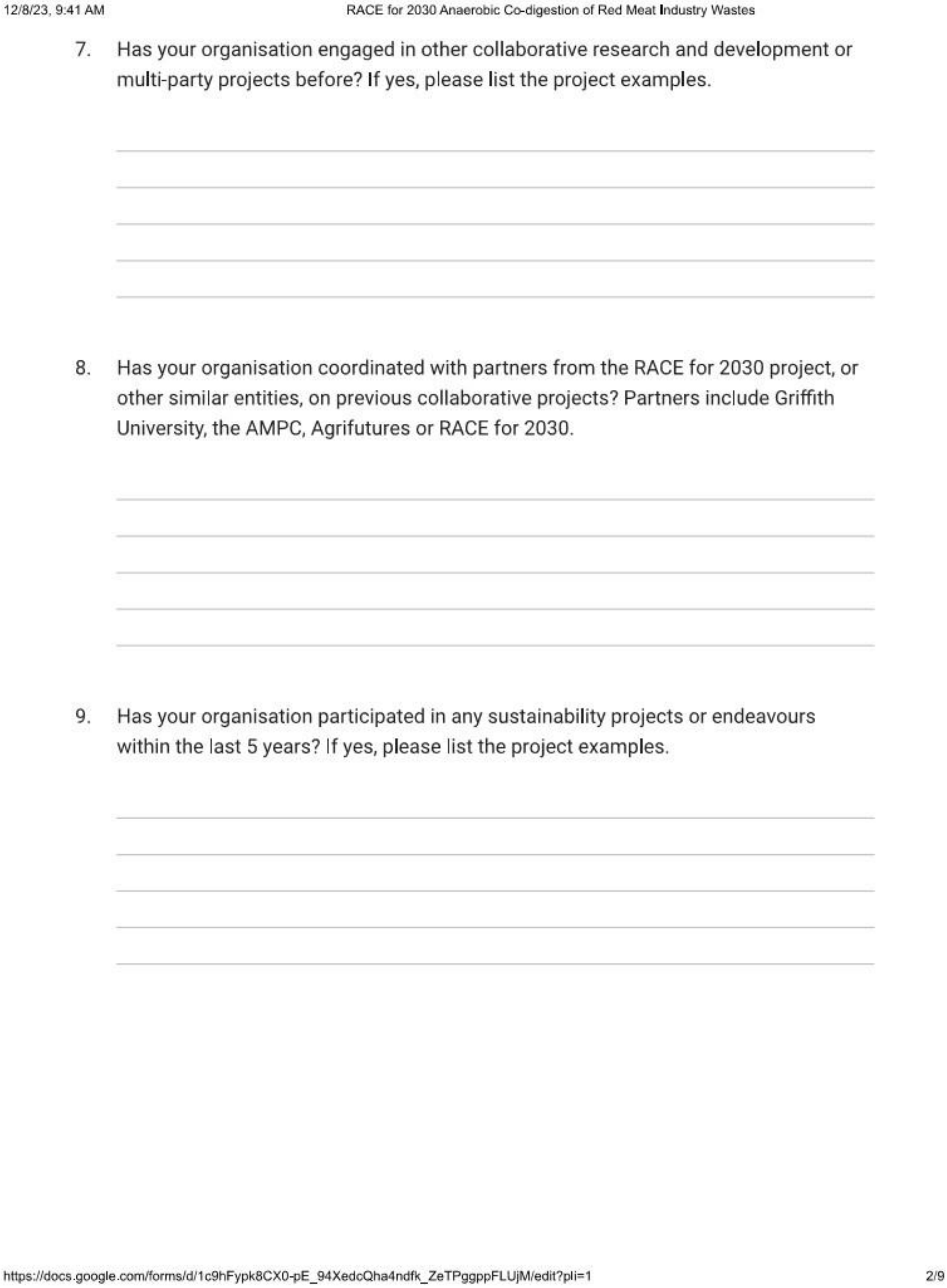
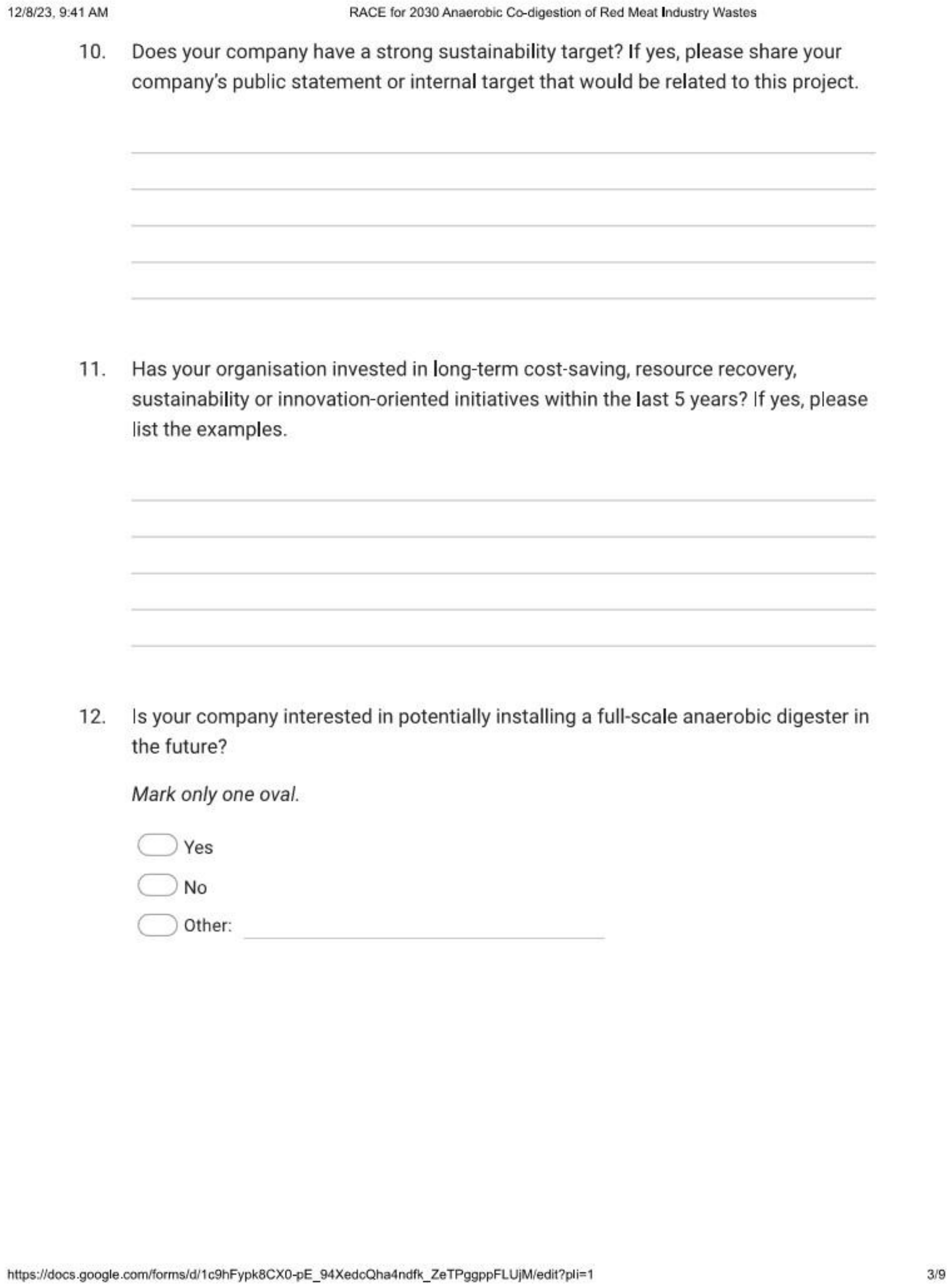


7. Has your organisation engaged in other collaborative research and development or multi-party projects before? If yes, please list the project examples.

8. Has your organisation coordinated with partners from the RACE for 2030 project, or other similar entities, on previous collaborative projects? Partners include Griffith University, the AMPC, Agrifutures or RACE for 2030.

9. Has your organisation participated in any sustainability projects or endeavours within the last 5 years? If yes, please list the project examples.



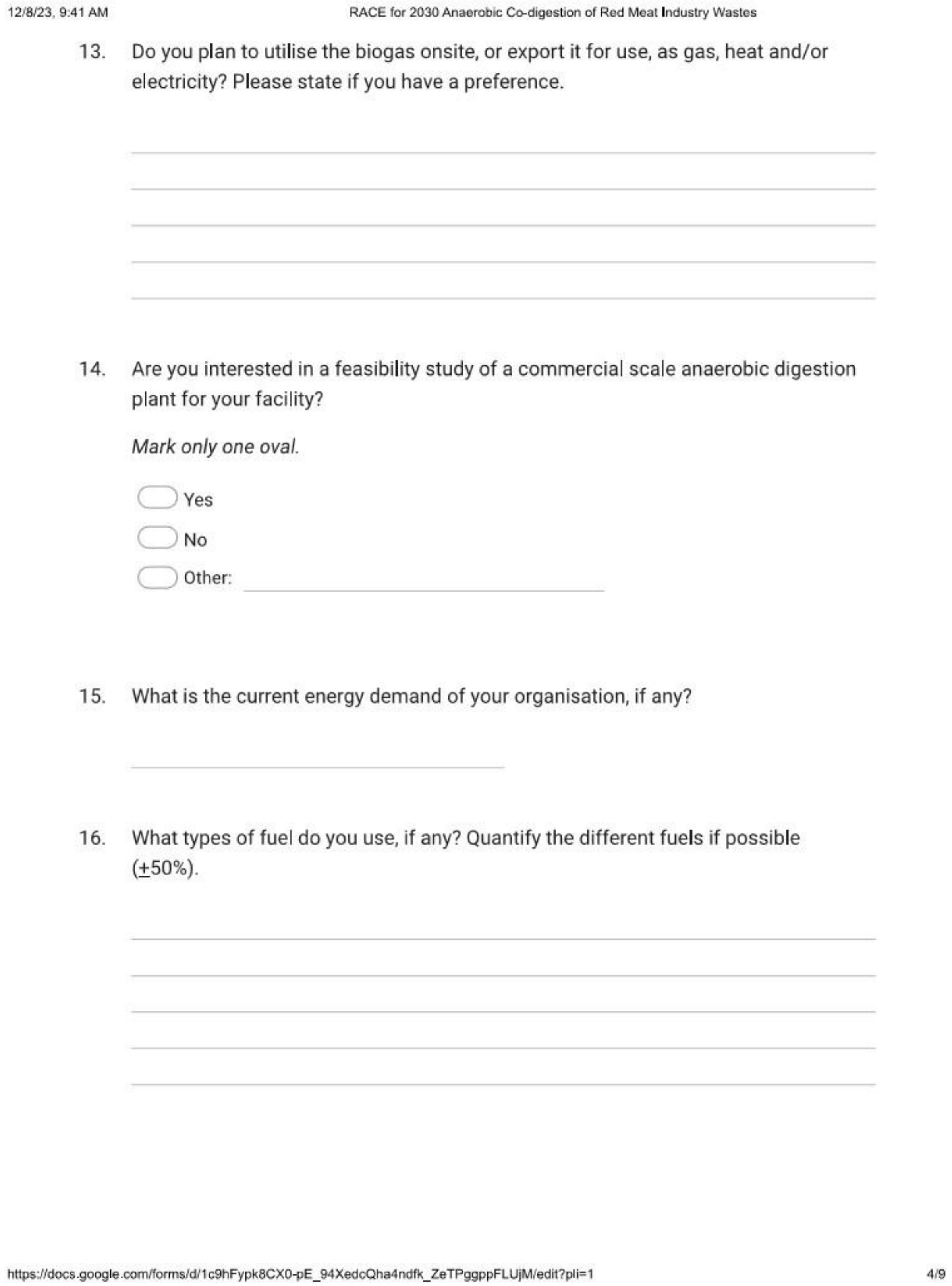
10. Does your company have a strong sustainability target? If yes, please share your company's public statement or internal target that would be related to this project.

11. Has your organisation invested in long-term cost-saving, resource recovery, sustainability or innovation-oriented initiatives within the last 5 years? If yes, please list the examples.

12. Is your company interested in potentially installing a full-scale anaerobic digester in the future?

Mark only one oval.

○ Yes
○ No
○ Other:



13. Do you plan to utilise the biogas onsite, or export it for use, as gas, heat and/or electricity? Please state if you have a preference.

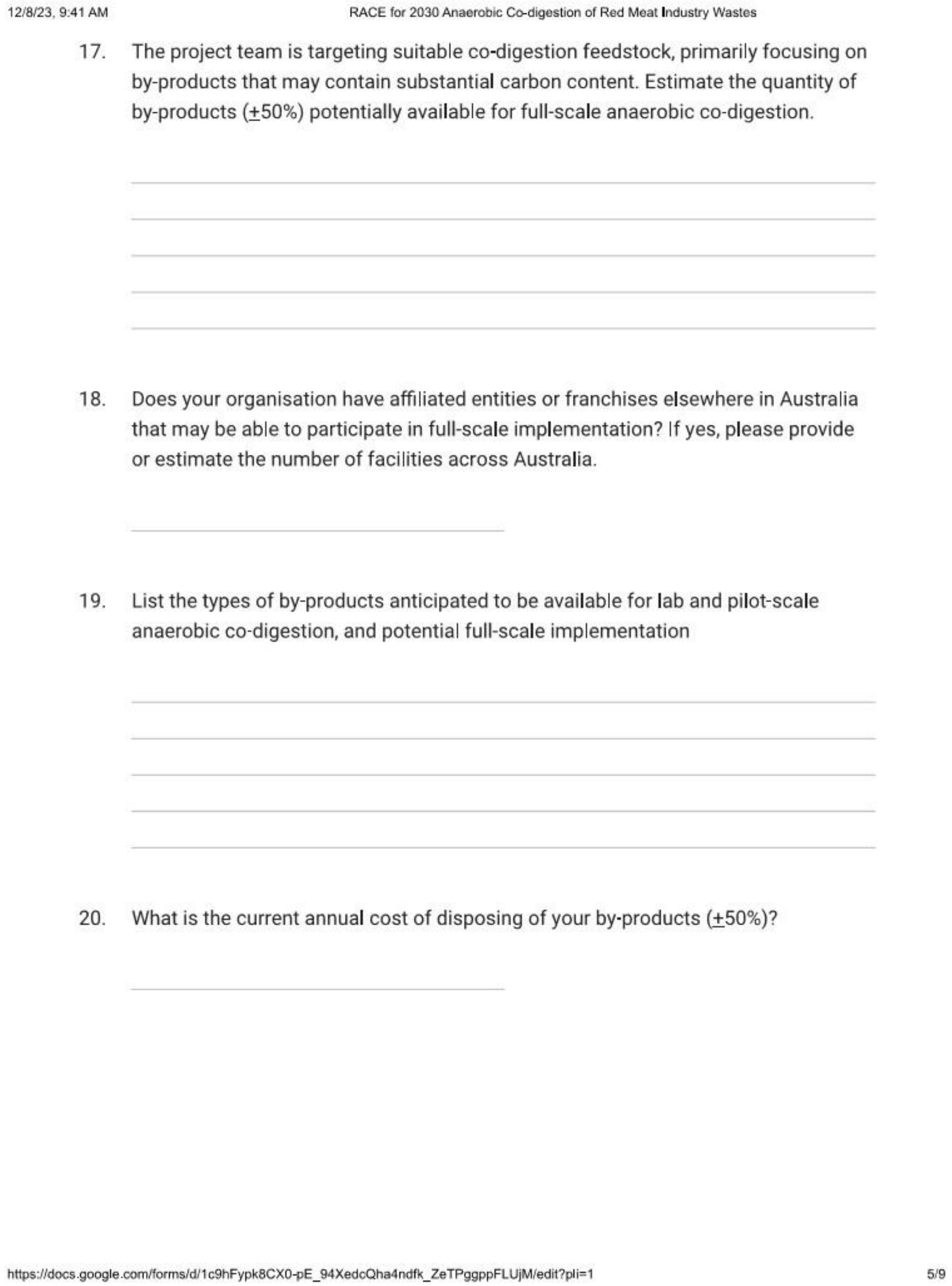
14. Are you interested in a feasibility study of a commercial scale anaerobic digestion plant for your facility?

Mark only one oval.

○ Yes
○ No
○ Other: ____________

15. What is the current energy demand of your organisation, if any?

16. What types of fuel do you use, if any? Quantify the different fuels if possible (±50%).

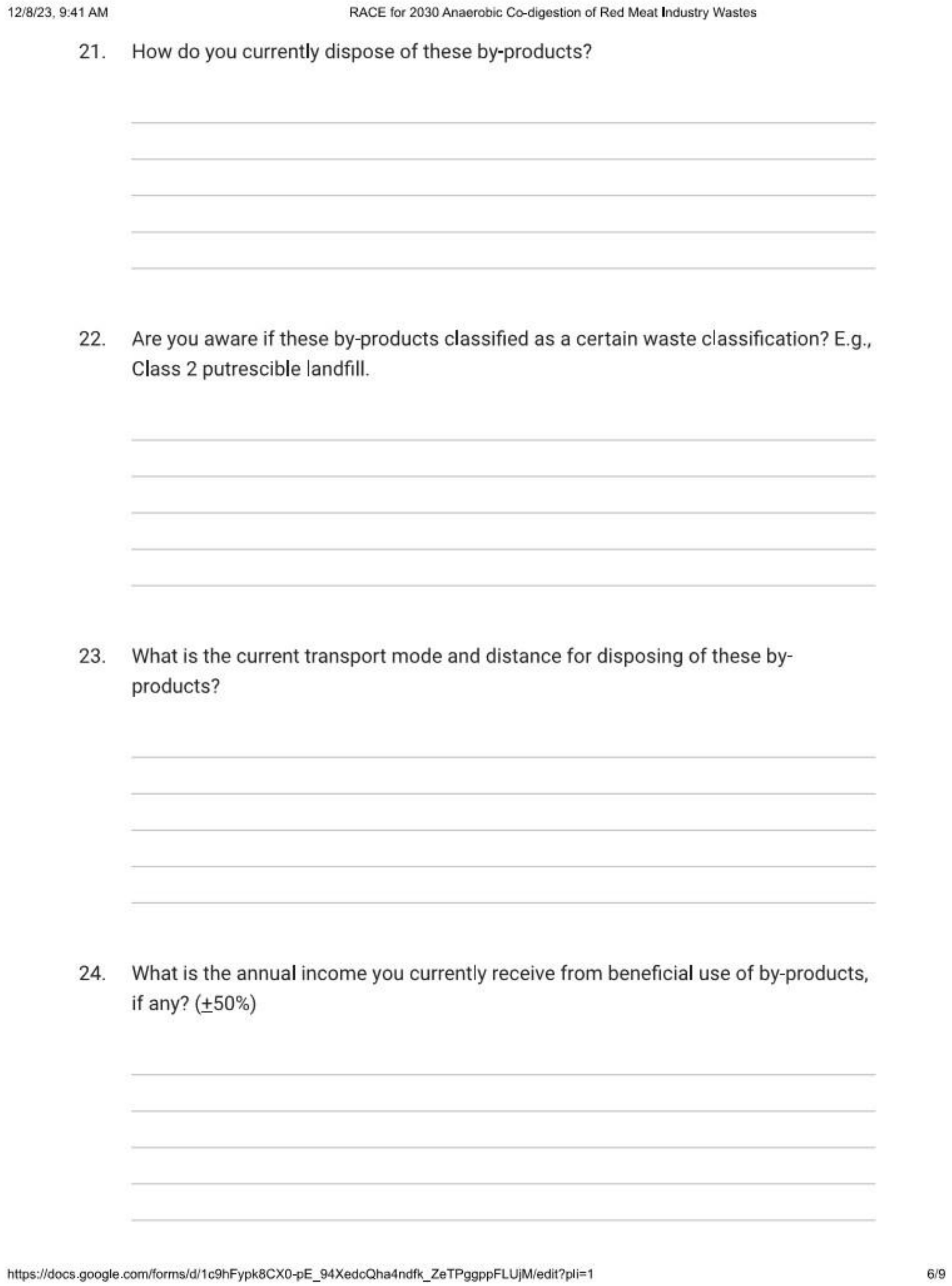


17. The project team is targeting suitable co-digestion feedstock, primarily focusing on by-products that may contain substantial carbon content. Estimate the quantity of by-products (±50%) potentially available for full-scale anaerobic co-digestion.

18. Does your organisation have affiliated entities or franchises elsewhere in Australia that may be able to participate in full-scale implementation? If yes, please provide or estimate the number of facilities across Australia.

19. List the types of by-products anticipated to be available for lab and pilot-scale anaerobic co-digestion, and potential full-scale implementation

20. What is the current annual cost of disposing of your by-products (±50%)?



12/8/23, 9:41 AM RACE for 2030 Anaerobic Co-digestion of Red Meat Industry Wastes

21. How do you currently dispose of these by-products?

22. Are you aware if these by-products classified as a certain waste classification? E.g., Class 2 putrescible landfill.

23. What is the current transport mode and distance for disposing of these by-products?

24. What is the annual income you currently receive from beneficial use of by-products, if any? (±50%)

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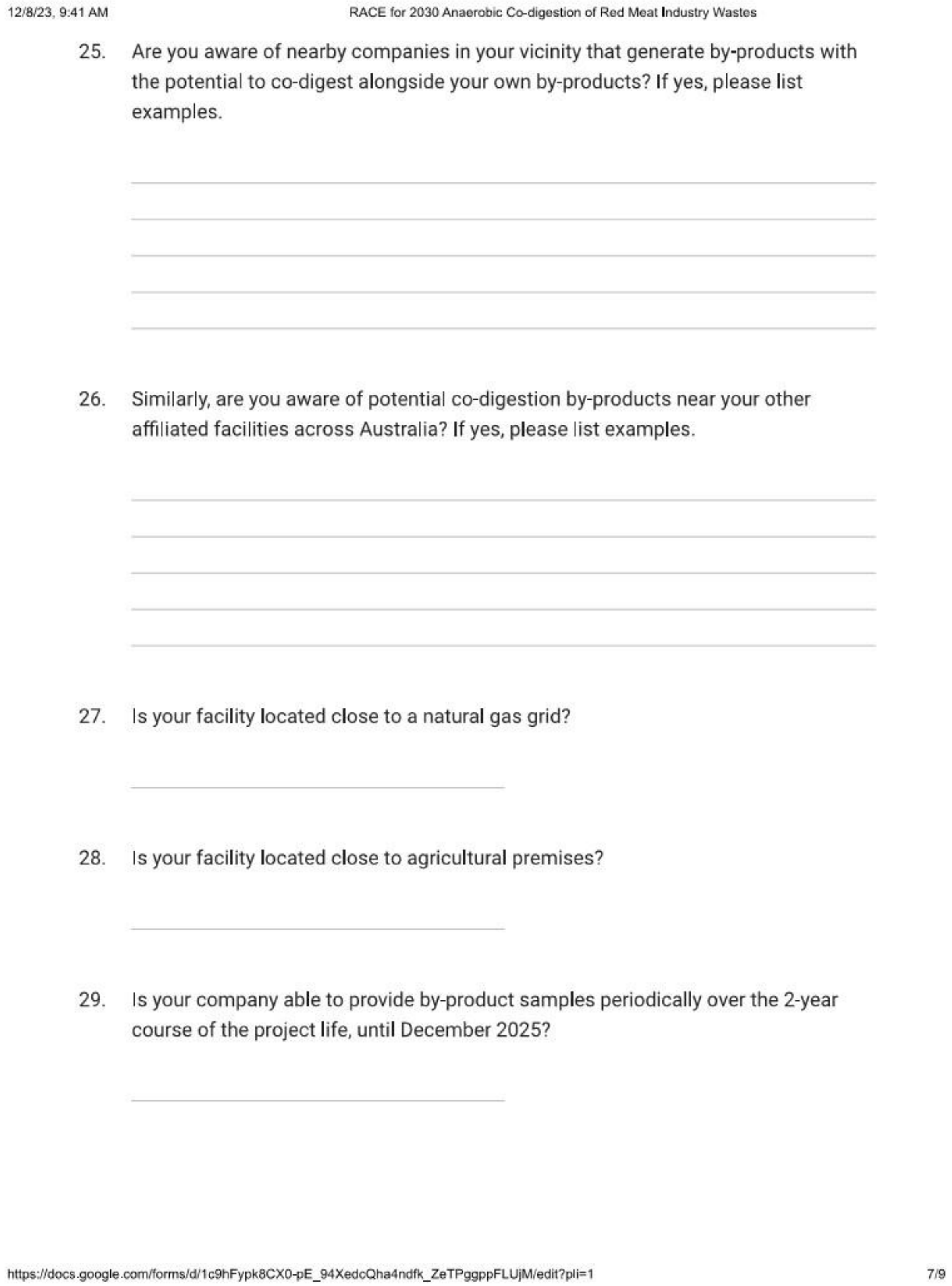

12/8/23, 9:41 AM RACE for 2030 Anaerobic Co-digestion of Red Meat Industry Wastes

25. Are you aware of nearby companies in your vicinity that generate by-products with the potential to co-digest alongside your own by-products? If yes, please list examples.

26. Similarly, are you aware of potential co-digestion by-products near your other affiliated facilities across Australia? If yes, please list examples.

27. Is your facility located close to a natural gas grid?

28. Is your facility located close to agricultural premises?

29. Is your company able to provide by-product samples periodically over the 2-year course of the project life, until December 2025?

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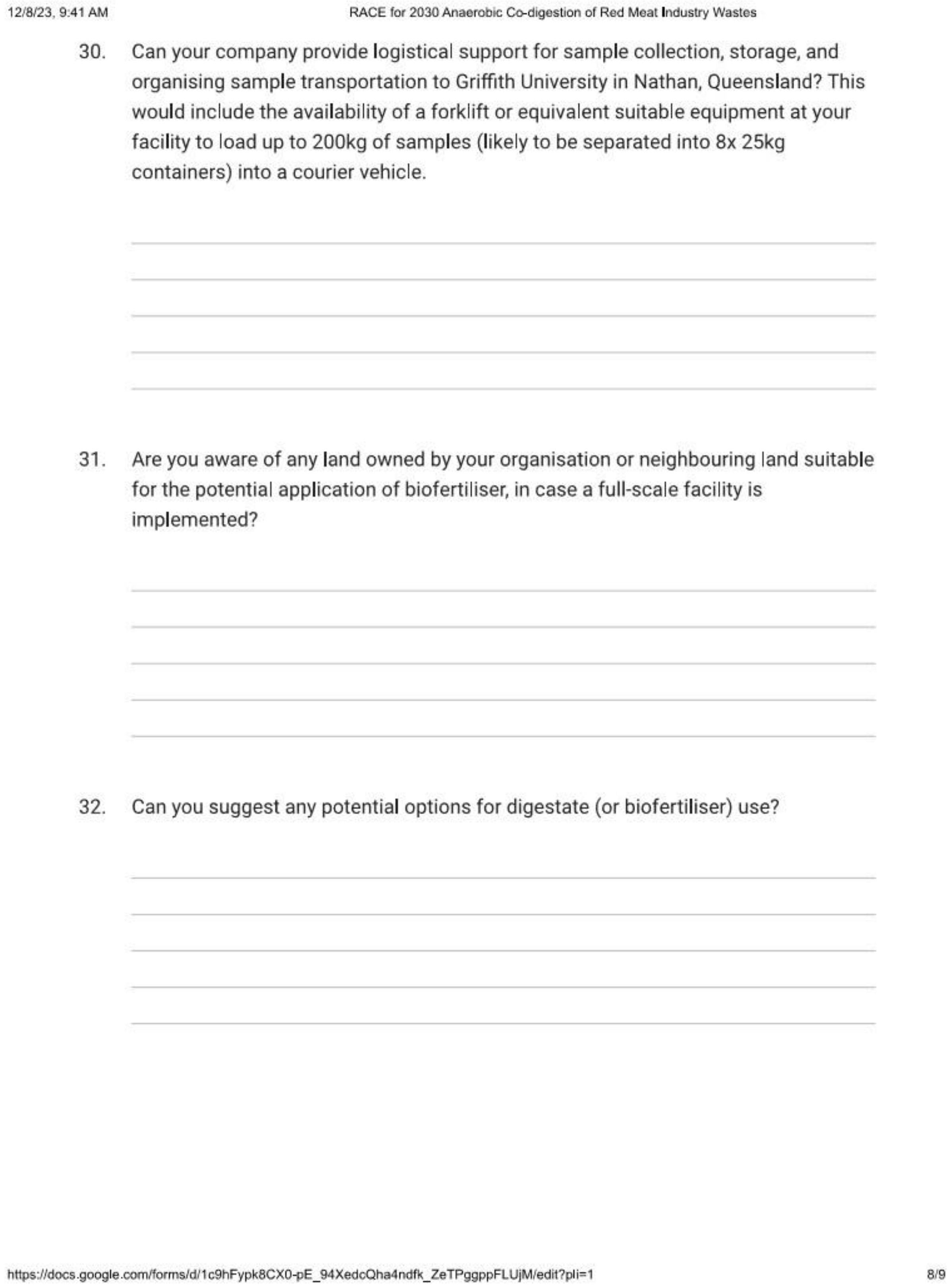

12/8/23, 9:41 AM RACE for 2030 Anaerobic Co-digestion of Red Meat Industry Wastes

30. Can your company provide logistical support for sample collection, storage, and organising sample transportation to Griffith University in Nathan, Queensland? This would include the availability of a forklift or equivalent suitable equipment at your facility to load up to 200kg of samples (likely to be separated into 8x 25kg containers) into a courier vehicle.

31. Are you aware of any land owned by your organisation or neighbouring land suitable for the potential application of biofertiliser, in case a full-scale facility is implemented?

32. Can you suggest any potential options for digestate (or biofertiliser) use?

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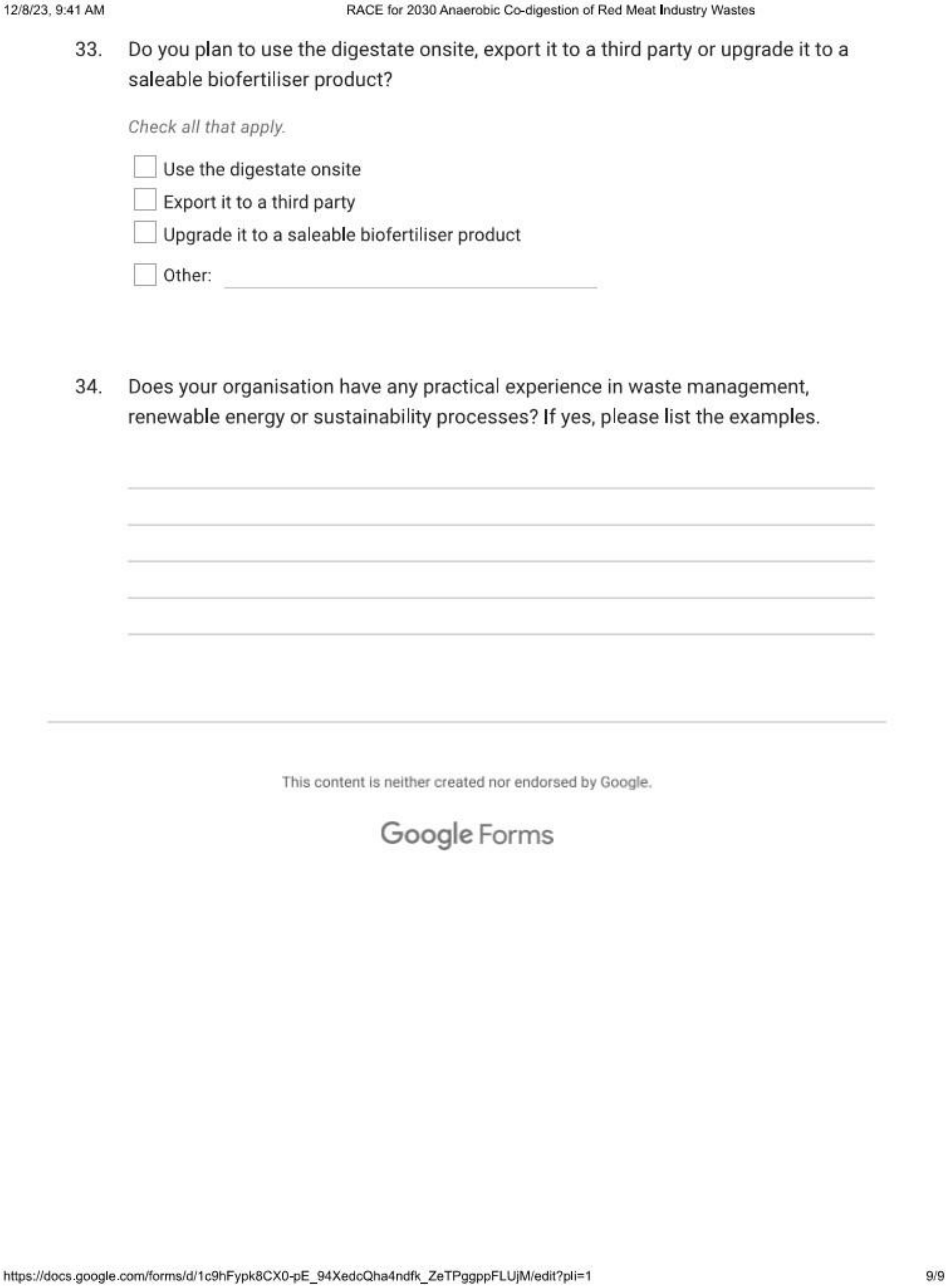

12/8/23, 9:41 AM RACE for 2030 Anaerobic Co-digestion of Red Meat Industry Wastes

33. Do you plan to use the digestate onsite, export it to a third party or upgrade it to a saleable biofertiliser product?

Check all that apply.

- ☐ Use the digestate onsite
- ☐ Export it to a third party
- ☐ Upgrade it to a saleable biofertiliser product
- ☐ Other: ____________________

34. Does your organisation have any practical experience in waste management, renewable energy or sustainability processes? If yes, please list the examples.

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Google Forms

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8.2 Appendix B: IRG Meeting Summaries

IRG meeting – 15th December 2023

The initial meeting of the Industry Reference Group (IRG) on 15th December 2023 set forth the project's objectives, methodology, and expected outcomes, emphasising key activities such as conducting lab-scale and pilot-scale anaerobic co-digestion studies to optimise biomethane production. For further details, please refer to the appended meeting minutes and presentation slides.

Initial enquiries from stakeholders centred on distinguishing this project from the Wastes for Profits initiative to prevent overlap. The unique benefits of IRG membership, the expected level of commitment, and the specialised expertise contributed by each member were clearly delineated.

IRG meetings – 8 February and 14 March 2024

Meetings on 8 February and 14th March 2024 concentrated on organising the operational setup at the Griffith Laboratory, coordinating sample collection from red meat processor survey participants, and advancing research on co-digestion feedstock for the literature review. Measures were intensified to streamline the coordination of sample collection and analysis, and efforts to secure participation from red meat processors and co-digestion feedstock sources were ongoing. Discussions on how to enhance engagement for future meetings were also highlighted, with suggestions including setting fixed meeting dates and improving presentation methods.

IRG meeting – 23rd April 2024

The IRG meeting held on 23rd April 2024 (IRG Meeting 4), the IRG focused on understanding variations in bio-resource availability and the importance of site-specific processes, which influence methane yields. The baseline BMP tests for red meat processors began in April and were completed in June 2024 (Phase 1 BMP testing). Discussions highlighted the differing methane yields from beef and sheep sites due to variations in the type and chemical composition of bio-resources and their proportions used, emphasising the need for continuous monitoring and testing to optimise biogas production.

IRG meeting – 23rd May 2024

In the subsequent meeting on 23rd May 2024 (IRG Meeting 5), significant progress was reported in mono-digestion BMP tests, with a comparison of methane yields from 11 sites. The team discussed the importance of information sharing among project participants, planning a webinar for August to disseminate BMP test results. Additionally, the meeting underscored the importance of investigating factors affecting BMP, with plans to conduct individual BMP tests for validation.

IRG meeting – 19th June 2024

The meeting on 19th June 2024 (IRG Meeting 6) reviewed project progress, including the BMP CoD strategy and pilot-scale inspections. A key discussion point was the technologies for biomethane and biogas, with an emphasis on understanding why the red meat processing industry has fewer ACCUs projects compared to piggeries. The meeting also noted the importance of updating the AD advisory tool database and exploring collaborative opportunities with Dairy Australia to leverage dairy co-substrates for co-digestion.

IRG meeting – 10th July 2024

On 10th July 2024 (IRG Meeting 7), the IRG reviewed detailed analyses of Phase 1 mono-digestion of RMP solid bio-resource mix BMP results, highlighting that free ammonia is a major inhibitor in biogas production, with volatile fatty acids (VFAs) and microbial adaptation playing crucial roles. The discussion identified blood, offal, skin, and hides as high-potential substrates for methane yields, while also noting the challenges posed by substrates like DAF sludge and manure. The meeting emphasised the need for optimal C/N ratios and practical assessment of agricultural co-substrates to enhance methane production.

IRG Meeting – 1st August 2024

The IRG Meeting 8 (1st Aug 2024) discussed progress on the BMP tests and plans for a public webinar leading into 500 L pilot-scale trials. The group explored glycerins potential to boost methane yields, ranking co-digestion substrates by biogas uplift, and assessing the cost-benefit of diverting valuable feedstocks to anaerobic digestion. They emphasised including techno-economic analysis of feedstocks and paunch pre-treatments, engaging with EPA and regulators on waste classification, and involving grant agencies in future webinars to support scaling. Recording of the workshop was also proposed to improve project accessibility.

IRG Meeting – 5th September 2024

The IRG Meeting 9 (5th Sept 2024) focused on HAZOP safety studies, methane yield variations between digestion phases, and the performance of CoD mixtures. The team discussed promising substrates such as grain and brewery waste, with some results showing higher methane yields from agro-substrates and optimal lipid-to-protein ratios. Potential use of glycerol as a methane booster and various pre-treatments, including hydrothermal, nitric acid, and nitrous acid, were also considered for inclusion in the techno-economic assessment

IRG Meeting – 3rd October 2024

The IRG Meeting 10 (3rd Oct 2024) covered substrate pre-treatment requirements, particularly for paunch material, and strategies to mitigate ammonia inhibition in red meat waste digestion. The group reviewed optimal co-substrate ratios based on carbohydrates, proteins, and lipids, and progress on 10L reactor commissioning to establish continuous operation baselines. Health and safety were emphasised following a reactor incident elsewhere, highlighting safe loading protocols. Discussions also included pre-treatment temperature ranges (around 70 °C) using waste heat, DAF sludge coagulant impacts, and techno-economic considerations for scaling up.

IRG Meeting – 7th November 2024

The IRG Meeting 11 (7th Nov 2024) discussed ongoing 10L mono-digestion and upcoming co-digestion tests, with substrate selection due mid-November. Preparations for pilot-scale commissioning were advanced, including HAZOP safety approvals and meat mincer installation. The group reviewed pre-treatment options, including pasteurisation, sterilisation, hydrothermal, and alkaline treatments, balancing performance gains with budget constraints. Updates included new research partnerships (QUT, CSIRO) for the Digestate Management Project and exploring brewery and sugarcane wastes for Casino. Discussions also addressed avoiding FOGO due to contamination, identifying potential fertiliser trial partners, and scheduling the final 2024 meeting and future session frequency

IRG Meeting – 5 December 2024

The IRG Meeting 12 (5th December), which was the final IRG meeting of 2024, and the first IRG meeting of this Progress Report 3 reporting period. Discussions included the need to appoint a new hazardous classification consultant and plans for scheduling the next IRG in early 2025. Co-substrate selections were refined, with corn silage and grain for WA, and dairy by-products, sugarcane bagasse, mill mud, and sorghum for NSW. Analysis of proportional mixtures focusing on protein, lipid, and carbohydrate ratios continued. Economic assessments of pre-treatment strategies were underway, with input from IRG members being sought. The Year 1 annual report was submitted to the RACE portal.

IRG Meeting – 6 February 2025

The IRG Meeting 13 (6th February) discussed key topics including the effects of lipid, protein, and carbohydrate ratios on biogas production, with 60:20:20 identified as the optimal ratio for NSW and WA substrates. The IRG members were informed that to progress the project, pilot-scale tests at Griffith University would utilise existing commissioned 10 L reactors, and the 500 L reactors would be reassigned to a new digestate valorisation project. Pre-treatments like steam explosion and hydrothermal methods showed limited benefits, potentially due to the impact of the age of the pre-treated substrates available. Plans for a project workshop on 26 March were discussed, including recording options. Future project phases were outlined, with a focus on biosolids management.

IRG Meeting – 6 March 2025

During IRG Meeting 14 (6th March), the team recapped findings on substrate ratios, reaffirming the 60:20:20 Lipid:Protein:Carbohydrate balance as optimal. The 10 L CSTR reactors are performing well at 2 g VS/L·d OLR, with plans to gradually increase loading until reactor stress is observed. NSW4 and WA4 substrates are under continuous assessment, with WA4 yielding more consistent biogas. Preparations for the biogas workshop on 26 March were finalised, including a video recording and stakeholder interviews. Feedback suggested tailoring the workshop content to industry stakeholders.

Stakeholder Workshop – 26th March 2025

The in-person stakeholder workshop, which was held at Griffith University’s Nathan Campus, QLD, on 26 March 2025, had strong attendance from project collaborators and industry stakeholders. The workshop delivered a comprehensive update on the RACE for 2030 Anaerobic Co-Digestion project, outlining its overarching objectives, current progress, and the next stages of development. The presentation included a detailed review of experimental findings from both batch BMP tests and semi-continuous pilot-scale digestion trials. The presentation outlined the benefits provided from co-digestion with improvements in methane yield and energy recovery highlighted.

The Bioresource Recovery Centre concept was also presented, detailing the integration of wastewater treatment, anaerobic digestion with CO_2 recovery, digestate processing, and water reuse. The presentation highlighted how anaerobic co-digestion forms part of a holistic approach for industry application. The techno-economic assessment showcased the feasibility of such an integrated facility, with co-digestion shown to significantly improve financial viability and environmental outcomes.

Attendees were also given a guided tour of the laboratory facilities and shown the two 400 L pilot-scale anaerobic digesters. The event concluded with a Q&A session and networking lunch, fostering valuable industry discussions.

A video highlighting the project was created from this workshop and can be found here:

https://www.youtube.com/watch?v=hYtu-b9fJ3M

IRG Meeting – 1st May 2025

During IRG Meeting 15 (1st May), the team recapped the findings of the continuous 10 L reactors, highlighting the benefits of co-digestion, having seen improved methane yields and reactor stability. The 10 L reactors were shown to perform well at an organic loading rate of 2.0 gvs·L·-1day-1 with plans to slightly modify the operational parameters to improve process stability. The economic assessment targets and timeline were outlined with plans to present the concept design in July and the draft assessment to be presented in September, prior to finalisation for the final report. Key questions, which aimed to confirm site-specific information, including annual co-product production and site energy consumption, were presented to participating Red Meat Processors. The workshop at Griffith was highlighted and the IRG members were reminded to provide feedback in the produced footage prior to the closure date (2/05/2025).

IRG Meeting – 3rd July 2025

For IRG Meeting 16 (3rd July), the team recapped the current progress and performance of the 10 L reactors, highlighting the benefits seen after the addition of biochar and activated carbon. The reactors were operating at an organic loading rate of 2.0 gvs·L·-1day-1 which was increased to 2.5 gvs·L·-1day-1 on the 30th of June. The economic assessment targets were reviewed and expanded to include an assessment of the macronutrient optimised scenario. The assessment timeline was also reviewed, and the equipment selection and sizing were provided to IRG members for their feedback. Key biogas plant operational parameters and process conditions were also provided along with engineered digestion pathways utilising operational conditions often seen in industry.

IRG Meeting – 18th September 2025

The IRG Meeting 17 (18th Sept 2025) focused on updates from the 10 L reactors, where operations were briefly halted for an asbestos inspection, later cleared. Results showed stable performance with biochar and activated carbon improving methane production by reducing ammonia stress. Differences in substrate performance between sites were linked to feedstock variability and livestock type. The group reviewed post-digestion BMP results, TEA assumptions, and scenario analyses, discussing energy use, gas pricing, ACCU eligibility, and feedstock cost sensitivities. Actions were assigned to refine TEA parameters, update diagrams, and clarify model assumptions. Updates also covered RACE Stage 2 progress and internal changes, noting Tracey Colley's resignation and upcoming workshops

8.3 Appendix C: Literature Review

Literature Review: Anaerobic co-digestion of red meat industry by-products with food organics or agricultural by-products

Prepared by Tessele Consultants for RACE for 2030

Abstract

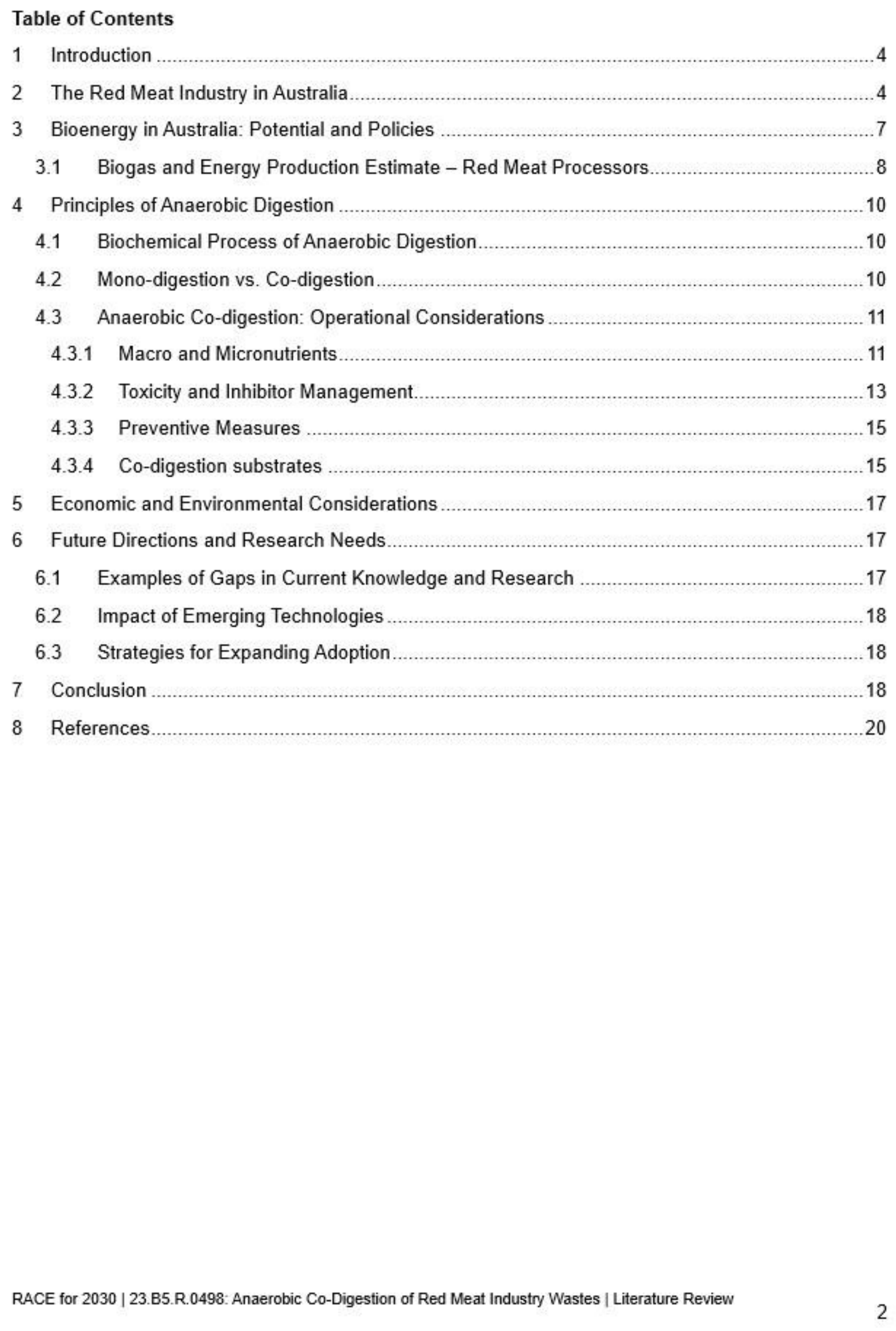
The urgency to combat climate change and reduce greenhouse gas emissions has propelled the search for sustainable and renewable energy sources. Among various strategies, anaerobic co-digestion, particularly involving red meat industry by-products along with agricultural and food organics, emerges as a promising solution. This literature review explores the advancements, potential, and challenges associated with anaerobic co-digestion in Australia, highlighting its significance in the bioenergy sector and its contribution to environmental sustainability.

Australia's position as a global leader in the red meat industry, generating substantial organic by-products, sets a robust foundation for bioenergy production. Anaerobic digestion, a process of converting organic matter into biogas without oxygen, plays a pivotal role in this context. The review delves into the biochemical process of anaerobic digestion, comprising hydrolysis, acidogenesis, acetogenesis, and methanogenesis. It underscores the enhanced efficiency and stability offered by co-digestion over mono-digestion, attributing these to improved nutrient balance and microbial health.

Despite the clear advantages, several research gaps are identified, necessitating further investigation into feedstock mixture optimisation, advanced pre-treatment technologies, and microbial community dynamics. Addressing these gaps could significantly enhance biogas yields and process efficiency. Moreover, emerging technologies such as automation, real-time monitoring, genetic engineering, and integration with other renewable energies present promising avenues to revolutionise anaerobic co-digestion processes.

The review also acknowledges the logistical, economic, and environmental considerations critical to the sustainability of co-digestion projects. It emphasises the importance of local feedstock sourcing, economic benefits from waste management and energy production, and the environmental impact of reducing landfill waste. Strategic measures, including regulatory support, market development for digestate, and technological knowledge transfer, are highlighted as essential for expanding the adoption of co-digestion facilities in Australia.

Anaerobic co-digestion represents a win-win scenario for Australia, offering a viable path towards achieving its renewable energy and environmental sustainability goals. However, realising its full potential requires a concerted effort in research, policy support, and industry innovation. This literature review establishes a comprehensive foundation for future studies and initiatives aimed at optimising and promoting anaerobic co-digestion as a cornerstone of Australia's renewable energy portfolio.



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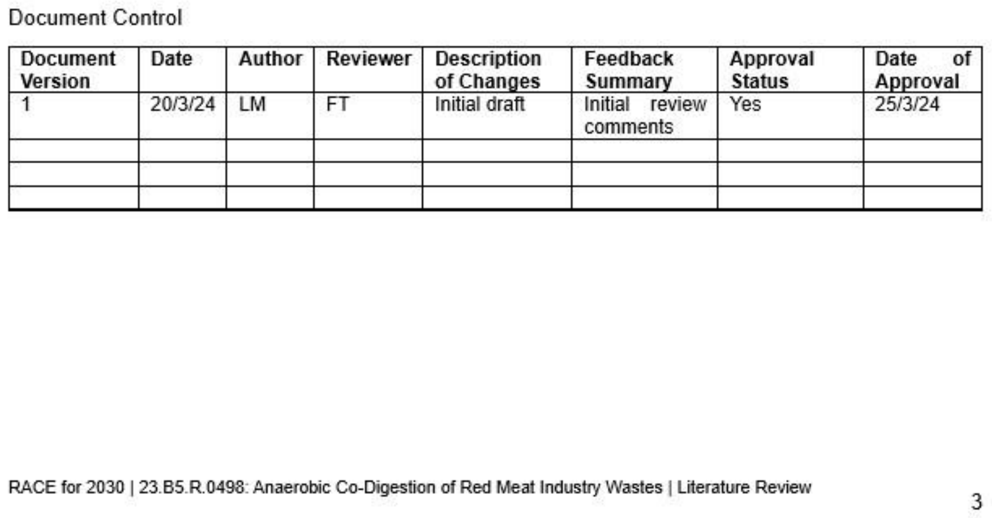


Document Control

Document Version	Date	Author	Reviewer	Description of Changes	Feedback Summary	Approval Status	Date of Approval
1	20/3/24	LM	FT	Initial draft	Initial review comments	Yes	25/3/24

1 Introduction

The urgency to mitigate climate change and reduce greenhouse gas emissions has led to a significant shift towards renewable energy sources, incorporating both traditional methods like solar, wind, and hydroelectric power and innovative approaches that leverage biological processes to convert organic waste into energy (Dennett, 2023). Bioenergy, with a focus on biogas production through anaerobic digestion, stands out as a critical renewable energy source. This method not only addresses waste disposal challenges but also contributes to the renewable energy matrix, offering a sustainable solution to environmental concerns (Alvarez & Liden, 2008; Hejnfelt & Angelidaki, 2009). Australia is at the vanguard of the bioenergy revolution, thanks to its vast biomass resources derived from extensive agricultural activities. The red meat industry, in particular, plays a crucial role in this sector, producing a significant volume of organic by-products that, while traditionally viewed as waste, represent a valuable resource for bioenergy production (Australian Bureau of Statistics, 2020). This underscores the country's potential to enhance its renewable energy portfolio and achieve environmental sustainability goals. Anaerobic digestion, the process through which microorganisms break down organic matter in the absence of oxygen to produce biogas—a mixture of methane and carbon dioxide—serves not only as an effective waste management strategy but also as a source of renewable energy. The methane generated during this process is a potent fuel for heating, electricity generation, and vehicle fuel, highlighting the multifaceted benefits of this technology (Bayr et al., 2012). However, the process of co-digestion, which involves combining various types of organic waste materials for simultaneous digestion, remains an underexplored avenue with the potential to significantly enhance biogas yield and operational efficiency. Co-digestion facilitates the balancing of nutrient profiles in the digester, optimises the microbial environment, and can mitigate issues related to the toxicity of certain feedstocks, presenting an opportunity to optimise biogas production further (Cuetos et al., 2008; Palatsi et al., 2011). This review explores the potential of anaerobic co-digestion in Australia, focusing particularly on the by-products of the red meat industry. By exploring how these by-products, in conjunction with other organic wastes such as agricultural residues and food organics, can be utilised to maximise biogas production, this paper aims to shed light on the scientific, technological, and policy landscapes that surround co-digestion. It seeks to underscore the significant role that anaerobic digestion can play in advancing Australia's renewable energy goals and fostering a more sustainable future, highlighting the critical need for continued research and development in this area (Dennett, 2023; Martin-Gonzalez et al., 2010).

2 The Red Meat Industry in Australia

Australia is a global powerhouse in the red meat industry, consistently ranking as one of the world's top beef exporters. With the sector contributing significantly to the national economy, Australia prides itself on a sophisticated, sustainable, and highly efficient red meat production and processing industry. In 2023, Australia produced approximately 2.1 million tons of beef and veal, accounting for about 4% of global production. Despite its relatively small population, Australia exports around 70% of its red meat production, underlining its vital role in the international meat trade. The nation's red meat industry benefits from extensive grazing lands, advanced breeding techniques, and strict quality control measures, positioning it favourably in the global market.

The processing of red meat generates a wide array of by-products, often categorised into edible and non-edible types. Edible by-products include organs and other parts not typically sold as mainstream cuts but are valuable in other markets. Non-edible by-products comprise bones, blood, trimmings, and fat, which traditionally have found uses in rendering, fertiliser production, and animal feed. The industry also produces a significant volume of wastewater and solid waste, presenting both challenges and opportunities for sustainable management. Annually, the sector is estimated to generate thousands of tons of solid waste and millions of litres of wastewater, emphasising the need for effective waste management strategies.

Australian Meat Processor Corporation (AMPC) is the specialist R&D provider for Australian meat processors – wherever they are, whatever their markets, no matter their size. There are over 127 Red Meat Processing Facilities (RMPF) registered in AMPC's database, ranging from small to large facilities across Australia (as shown in Figure 1).

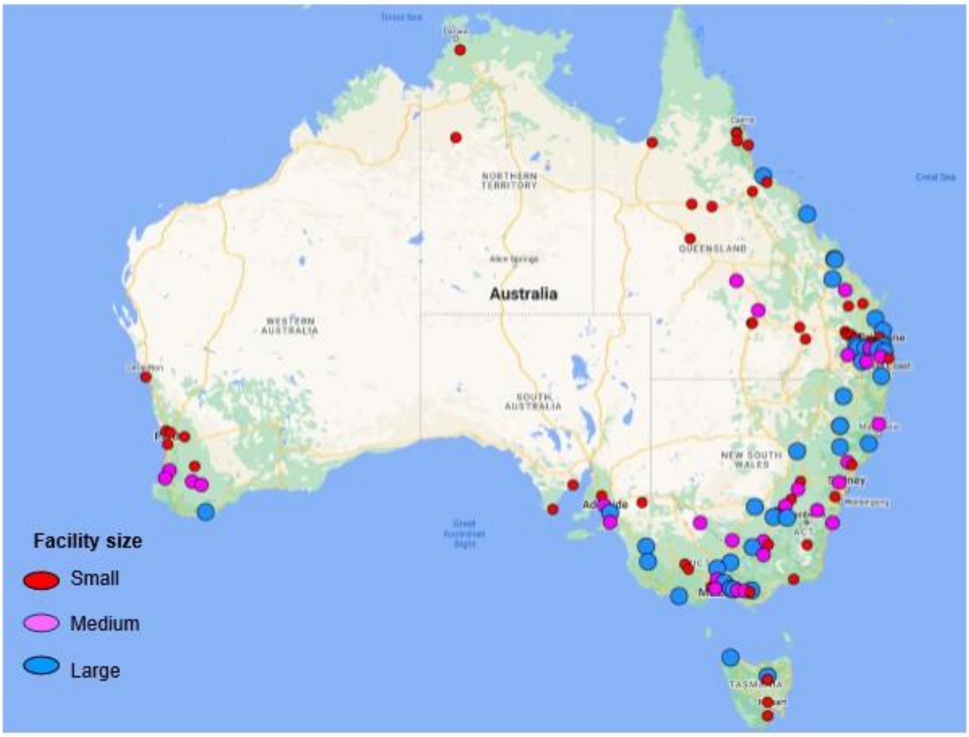


Figure 1 AMPC member facilities map prepared by Tessele Consultants for AMPC.

Historically, the management of red meat by-products in Australia focused on disposal and rendering, with limited attention to environmental impacts or resource recovery. Solid wastes were often sent to landfills, while wastewater was treated and discharged with minimal energy recovery. However, the growing awareness of environmental sustainability and the potential for resource recovery has spurred a paradigm shift in how these by-products are managed.

Recent years have witnessed a significant move towards sustainability and the exploration of waste-to-energy initiatives within the industry. Biogas production through anaerobic digestion of organic by-products has emerged as a promising avenue, offering dual benefits: reducing waste and generating renewable energy. Modern rendering plants have also become more efficient, capturing more value from by-products through the production of tallow, meat and bone meal, and other commodities. Additionally, there is an increasing interest in finding innovative uses for by-products, including in pharmaceuticals, nutraceuticals, and the development of biomaterials.

The shift towards sustainable by-product management is supported by advancements in technology, policy incentives, and a growing recognition of the economic value inherent in these materials. Waste-to-energy projects, in particular, are gaining traction, supported by both government and industry initiatives aimed at reducing emissions and contributing to Australia's renewable energy targets. This transition not only addresses environmental concerns but also enhances the economic resilience of the red meat sector by diversifying income streams and reducing waste disposal costs.

Although the country produces a remarkable quantity of red meat annually, the by-products generated in the process significantly outnumber the primary products. Specifically, for every ton of processed hot standard carcass weight (tHSCW)—a metric that quantifies the weight of an animal carcass post-slaughter—approximately 6.5 kilolitres of water and 2.4 gigajoules of energy are expended (Tessele, 2023). Historically, the wastewater produced in meat processing has been channelled directly into the facility's wastewater system for treatment system, while the solid waste is segregated and transported to landfills, leading to disposal costs without yielding any revenue. In terms of energy, the consumption required to process one ton of tHSCW can sustain a three-person household for about 35 days, assuming a daily average energy usage of 18.71 kWh nationwide. Notably, a significant portion of this energy is sourced from the grid, which, in Australia, predominantly relies on coal-fired power plants. Table 1 summarises the amount of wastewater produced and energy consumed.

Table 1 Red meat facilities (AMPC members) production and consumption of wastewater and energy.

State	RMP Facilities	Combined tHSCW/yr	Wastewater production (kL/yr)*	Energy Consumption (TJ)**
NSW	23	1,118,595	7,668,354	2684.63
NT	2	36,485	237,153	87.56
QLD	47	1,843,055	11,979,855	4423.33
SA	11	262,533	1,706,464	630.08
TAS	5	161,772	1,051,519	388.25
VIC	28	992,680	6,452,426	2382.43
WA	12	397,157	2,644,861	953.18
TOTAL	*128*	*4,812,278*	*31,740,633*	*11,549*

* Considering an average 6.5 kL/ tHSCW

** Considering an average of 2.4 GJ/ tHSCW

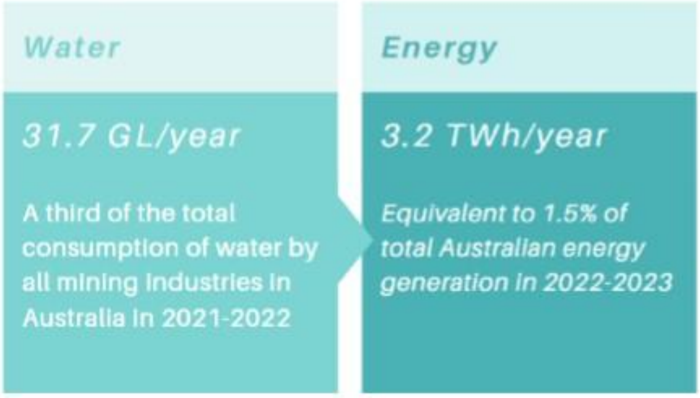


Figure 2 Red Meat Industry annual consumption comparison. (Tessele, 2023)

Amidst the increasing global emphasis on Environmental, Social, and Corporate Governance (ESG)—criteria that outline responsible corporate practices and guide the investment choices of socially conscious investors—companies are transforming their operational strategies. They are striving for more sustainable processes, aiming to minimise their environmental footprint and transform by-products into valuable resources. Additionally, Australia's commitment to the Paris Agreement, which includes a target to reduce greenhouse gas emissions by up to 28% below 2005 levels by 2030, underscores the urgency for industries to adopt cleaner and more efficient processes. This commitment also highlights the need for companies to reduce their reliance on grid power by developing innovative and effective solutions on-site.

3 Bioenergy in Australia: Potential and Policies

Bioenergy plays an integral role in diversifying Australia's energy sources, representing about 5% of the nation's renewable energy output. This reflects a significant portion of Australia's energy composition, drawing from biomass sources like wood, crop residues, and organic waste for electricity and heat. Technological progress, particularly in anaerobic digestion for biogas production, underscores the sector's expansion, offering a renewable alternative by transforming organic refuse into energy (Alvarez & Liden, 2008; Hejnfelt & Angelidaki, 2009).

The trajectory of Australia's bioenergy sector is marked by the commissioning of multiple large-scale plants in recent years, contributing more than 800 megawatts to the grid. These installations largely capitalise on waste from agriculture, municipalities, and forestry, showcasing the widespread adoption of anaerobic digestion technologies to process diverse organic wastes into biogas (Bayr et al., 2012; Bouallagui et al., 2009). Figure 3 shows schematically the biogas value chain.

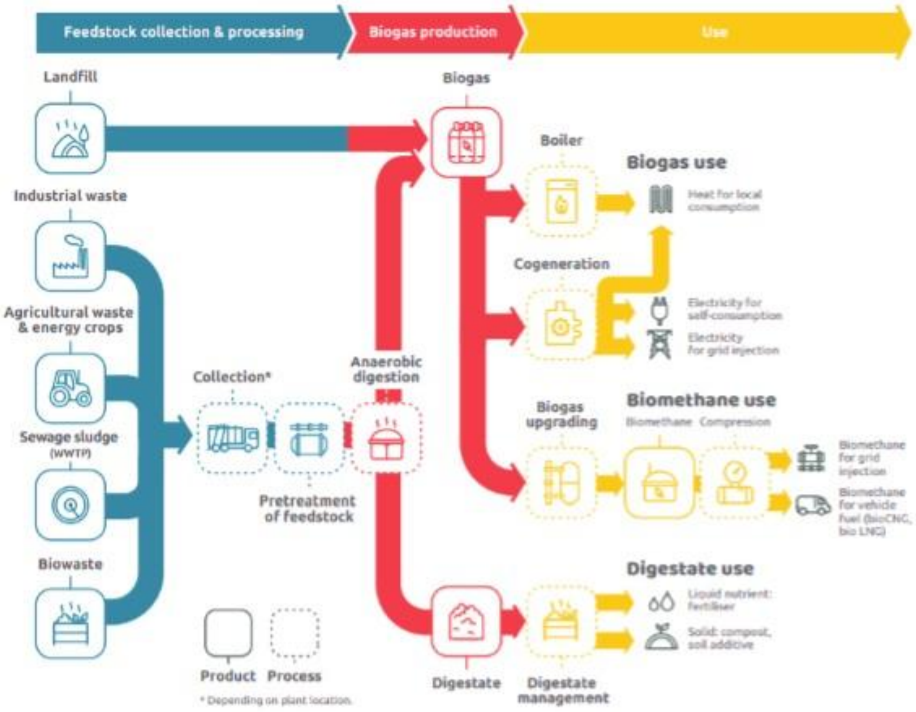
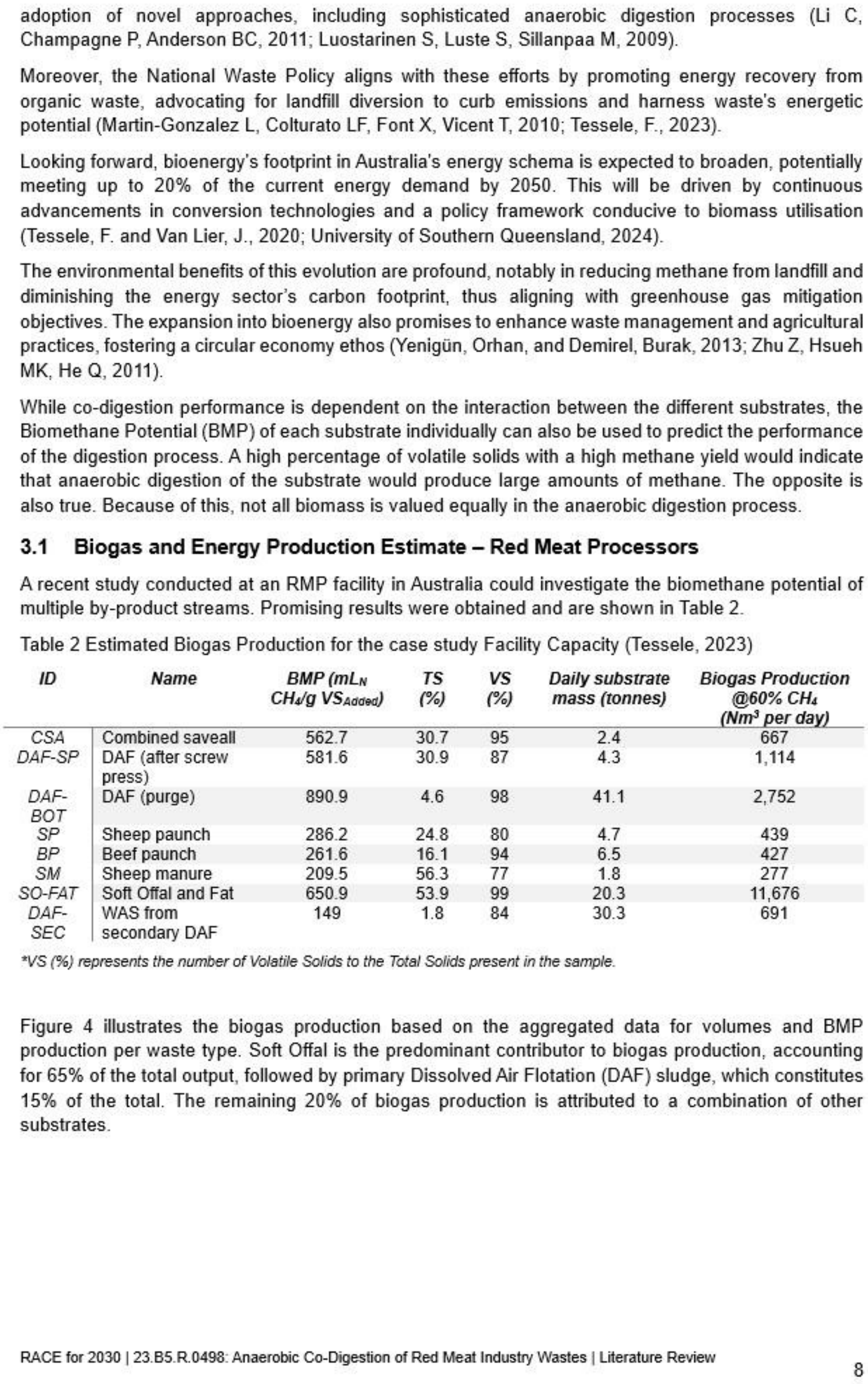


Figure 3 Biogas value chain (Source: ENEA, 2019)

Recognising bioenergy's capacity to bolster energy security, minimise emissions, and promote waste sustainability, the Australian government has launched several initiatives. The Renewable Energy Target (RET) serves as a cornerstone, propelling the country toward sourcing 33,000 gigawatt-hours from renewables by 2020, and catalysing bioenergy investments (Diaz et al., 2011; Ek et al., 2011).

Financial incentives and research funding from entities like the Clean Energy Finance Corporation (CEFC) and the Australian Renewable Energy Agency (ARENA) have also played a pivotal role. Their support aims at enhancing bioenergy technology efficiencies, driving down costs, and encouraging the



adoption of novel approaches, including sophisticated anaerobic digestion processes (Li C, Champagne P, Anderson BC, 2011; Luostarinen S, Luste S, Sillanpaa M, 2009).

Moreover, the National Waste Policy aligns with these efforts by promoting energy recovery from organic waste, advocating for landfill diversion to curb emissions and harness waste's energetic potential (Martin-Gonzalez L, Colturato LF, Font X, Vicent T, 2010; Tessele, F., 2023).

Looking forward, bioenergy's footprint in Australia's energy schema is expected to broaden, potentially meeting up to 20% of the current energy demand by 2050. This will be driven by continuous advancements in conversion technologies and a policy framework conducive to biomass utilisation (Tessele, F. and Van Lier, J., 2020; University of Southern Queensland, 2024).

The environmental benefits of this evolution are profound, notably in reducing methane from landfill and diminishing the energy sector's carbon footprint, thus aligning with greenhouse gas mitigation objectives. The expansion into bioenergy also promises to enhance waste management and agricultural practices, fostering a circular economy ethos (Yenigün, Orhan, and Demirel, Burak, 2013; Zhu Z, Hsueh MK, He Q, 2011).

While co-digestion performance is dependent on the interaction between the different substrates, the Biomethane Potential (BMP) of each substrate individually can also be used to predict the performance of the digestion process. A high percentage of volatile solids with a high methane yield would indicate that anaerobic digestion of the substrate would produce large amounts of methane. The opposite is also true. Because of this, not all biomass is valued equally in the anaerobic digestion process.

3.1 Biogas and Energy Production Estimate – Red Meat Processors

A recent study conducted at an RMP facility in Australia could investigate the biomethane potential of multiple by-product streams. Promising results were obtained and are shown in Table 2.

Table 2 Estimated Biogas Production for the case study Facility Capacity (Tessele, 2023)

ID	*Name*	*BMP (mL$_N$ CH$_4$/g VS$_{Added}$)*	*TS (%)*	*VS (%)*	*Daily substrate mass (tonnes)*	*Biogas Production @60% CH$_4$ (Nm^3 per day)*
CSA	Combined saveall	562.7	30.7	95	2.4	667
DAF-SP	DAF (after screw press)	581.6	30.9	87	4.3	1,114
DAF-BOT	DAF (purge)	890.9	4.6	98	41.1	2,752
SP	Sheep paunch	286.2	24.8	80	4.7	439
BP	Beef paunch	261.6	16.1	94	6.5	427
SM	Sheep manure	209.5	56.3	77	1.8	277
SO-FAT	Soft Offal and Fat	650.9	53.9	99	20.3	11,676
DAF-SEC	WAS from secondary DAF	149	1.8	84	30.3	691

**VS (%) represents the number of Volatile Solids to the Total Solids present in the sample.*

Figure 4 illustrates the biogas production based on the aggregated data for volumes and BMP production per waste type. Soft Offal is the predominant contributor to biogas production, accounting for 65% of the total output, followed by primary Dissolved Air Flotation (DAF) sludge, which constitutes 15% of the total. The remaining 20% of biogas production is attributed to a combination of other substrates.

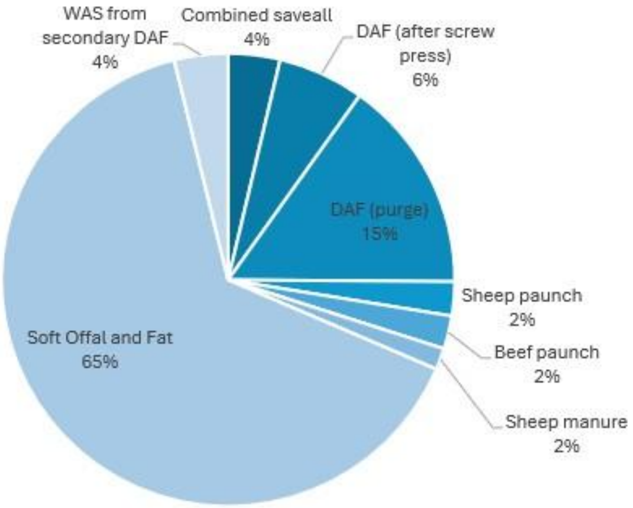


Figure 4 Biogas Production Proportional to the Organic Stream.

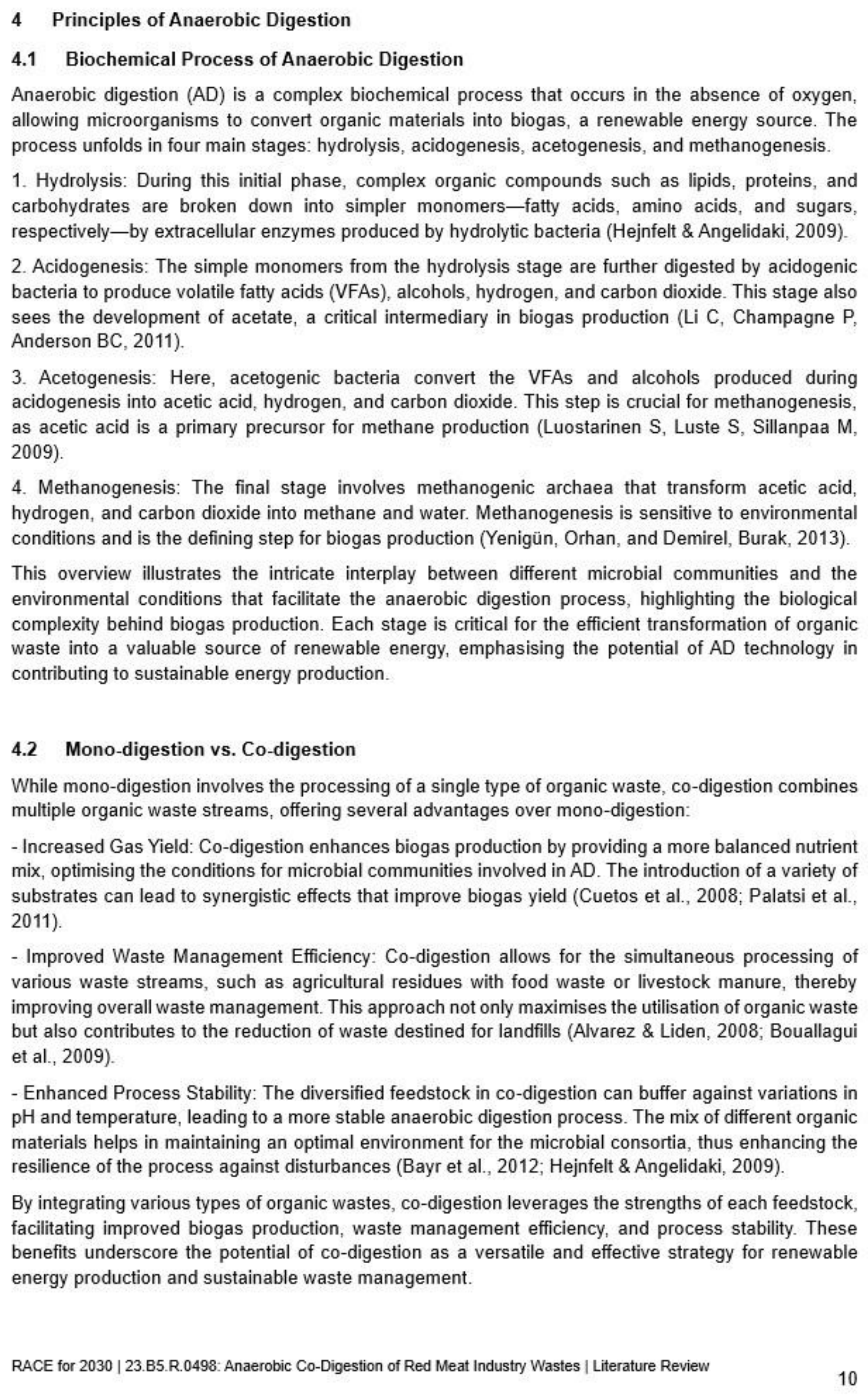
The case study facility, with an annual throughput exceeding 80,000 tHSCW, serves as a significant benchmark for nationwide predictive analysis. This study estimates an energy yield of 1.2 GJ per ton of HSCW, considering biogas production from all waste streams previously outlined in Table 2. Table 3 presents the calculated annual potential energy derived solely from biogas generation, focusing on by-products of the red meat industry.

Table 3 Estimated Potential Energy from all RMP facilities in Australia (Tessele, 2023)

State	*RMP Facilities*	*Combined (tHSCW/yr)*	*Potential Energy (PJ/yr)**
NSW	23	1,118,595	1.34
NT	2	36,485	0.04
QLD	47	1,843,055	2.21
SA	11	262,533	0.32
TAS	5	161,772	0.19
VIC	28	992,680	1.19
WA	12	397,157	0.48
TOTAL	128	4,812,278	5.77

**Considering 1.2 GJ per t.HSCW*

The ascension of bioenergy, with a spotlight on anaerobic digestion, heralds a symbiotic blend of environmental stewardship and economic viability for Australia. Ongoing governmental and industrial support remains crucial for unlocking bioenergy's full potential as a cornerstone of Australia's renewable energy narrative.



4 Principles of Anaerobic Digestion

4.1 Biochemical Process of Anaerobic Digestion

Anaerobic digestion (AD) is a complex biochemical process that occurs in the absence of oxygen, allowing microorganisms to convert organic materials into biogas, a renewable energy source. The process unfolds in four main stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

1. Hydrolysis: During this initial phase, complex organic compounds such as lipids, proteins, and carbohydrates are broken down into simpler monomers—fatty acids, amino acids, and sugars, respectively—by extracellular enzymes produced by hydrolytic bacteria (Hejnfelt & Angelidaki, 2009).

2. Acidogenesis: The simple monomers from the hydrolysis stage are further digested by acidogenic bacteria to produce volatile fatty acids (VFAs), alcohols, hydrogen, and carbon dioxide. This stage also sees the development of acetate, a critical intermediary in biogas production (Li C, Champagne P, Anderson BC, 2011).

3. Acetogenesis: Here, acetogenic bacteria convert the VFAs and alcohols produced during acidogenesis into acetic acid, hydrogen, and carbon dioxide. This step is crucial for methanogenesis, as acetic acid is a primary precursor for methane production (Luostarinen S, Luste S, Sillanpaa M, 2009).

4. Methanogenesis: The final stage involves methanogenic archaea that transform acetic acid, hydrogen, and carbon dioxide into methane and water. Methanogenesis is sensitive to environmental conditions and is the defining step for biogas production (Yenigün, Orhan, and Demirel, Burak, 2013).

This overview illustrates the intricate interplay between different microbial communities and the environmental conditions that facilitate the anaerobic digestion process, highlighting the biological complexity behind biogas production. Each stage is critical for the efficient transformation of organic waste into a valuable source of renewable energy, emphasising the potential of AD technology in contributing to sustainable energy production.

4.2 Mono-digestion vs. Co-digestion

While mono-digestion involves the processing of a single type of organic waste, co-digestion combines multiple organic waste streams, offering several advantages over mono-digestion:

- Increased Gas Yield: Co-digestion enhances biogas production by providing a more balanced nutrient mix, optimising the conditions for microbial communities involved in AD. The introduction of a variety of substrates can lead to synergistic effects that improve biogas yield (Cuetos et al., 2008; Palatsi et al., 2011).

- Improved Waste Management Efficiency: Co-digestion allows for the simultaneous processing of various waste streams, such as agricultural residues with food waste or livestock manure, thereby improving overall waste management. This approach not only maximises the utilisation of organic waste but also contributes to the reduction of waste destined for landfills (Alvarez & Liden, 2008; Bouallagui et al., 2009).

- Enhanced Process Stability: The diversified feedstock in co-digestion can buffer against variations in pH and temperature, leading to a more stable anaerobic digestion process. The mix of different organic materials helps in maintaining an optimal environment for the microbial consortia, thus enhancing the resilience of the process against disturbances (Bayr et al., 2012; Hejnfelt & Angelidaki, 2009).

By integrating various types of organic wastes, co-digestion leverages the strengths of each feedstock, facilitating improved biogas production, waste management efficiency, and process stability. These benefits underscore the potential of co-digestion as a versatile and effective strategy for renewable energy production and sustainable waste management.

4.3 Anaerobic Co-digestion: Operational Considerations

Anaerobic co-digestion capitalises on the simultaneous treatment of diverse organic waste streams, creating synergies particularly beneficial when combining red meat by-products with other forms of organic waste. Such combinations enrich the nutrient mix and bolster microbial activity, essential for optimising biogas yield (Buendia et al., 2009; Shanmugam and Horan, 2009).

Nutrient Balance: Integrating nitrogen-rich red meat by-products with carbon-dense agricultural residues or food waste fine-tunes the carbon-to-nitrogen (C:N) ratio. This careful calibration is crucial for sustaining a healthy microbial ecosystem, averting nitrogen-induced inhibition, and ensuring efficient decomposition (Shanmugam et al., 2009; Siripong and Dulyakasem, 2012).

4.3.1 Macro and Micronutrients

In biological treatment processes, nitrogen and phosphorus are paramount as macronutrients for the growth and sustenance of anaerobic bacteria, crucial for methane production. These bacteria utilise ammoniacal-nitrogen (NH4+ –N) and orthophosphate-phosphorus (HPO4– –P), whose bioavailability significantly depends on their solubility in the digestion environment (Yenigün & Demirel, 2013; Angelidaki et al., 2011).

The demand for nitrogen and phosphorus within the digester correlates with the volume and chemical oxygen demand (COD) of the feed sludge. This necessity varies with the organic loading rates introduced into the system, highlighting the importance of maintaining established COD:N:P ratios. For example, ratios of 1000:7:1 for high-strength wastes and 350:7:1 for lower loadings have been recommended to ensure microbial efficiency and gas output, indicating a minimal carbon-to-nitrogen (C/N) ratio of 25:1. These ratios reflect the empirical composition of bacterial cells, with nitrogen and phosphorus constituting about 12% and 2%, respectively, of their dry weight (Li et al., 2011; Kabouris et al., 2009).

Considering that approximately 10% of the COD fed into the digester is converted into new bacterial biomass, with a growth yield of 0.1 kg volatile suspended solids (VSS) per kg COD removed, one can estimate the specific nutrient requirements for effective digester operation. For instance, for a feed sludge COD of 10,000 mg/L at an 80% degradation rate, the essential amounts for nitrogen and phosphorus would be 96 mg/L and 16 mg/L, respectively. This methodical approach ensures sufficient nutrient provision for maintaining microbial vitality and optimizing biogas production within the anaerobic digester (Bayr et al., 2012; Shanmugam and Horan, 2009).

Methanogens, responsible for methane production, depend on a distinct set of enzyme systems, underlining their unique micronutrient requirements. Elements like cobalt, iron, nickel, and sulphide are vital for their metabolic pathways, playing critical roles in enzymes that convert organic substrates into methane. These micronutrients are essential not just for substrate breakdown but for ensuring the digester's peak performance, especially as they are involved in the direct conversion of acetate into methane (Hejnfelt & Angelidaki, 2009; Palatsi et al., 2011).

Additionally, micronutrients such as molybdenum, tungsten, and selenium, along with others like barium, calcium, magnesium, and sodium, should be considered for their roles in maintaining digester stability and preventing operational issues. The presence of adequate micronutrients is especially crucial in conditions where volatile fatty acids accumulate, as deficiencies can lead to symptoms misidentified as toxicity (Cuetos et al., 2010; Diaz et al., 2011).

Properly addressing both macro- and micronutrient needs in anaerobic digesters is fundamental to preserving stability and avoiding disruptions, underpinning the significance of comprehensive nutrient management for effective biogas production. Table 4 presents the Elementary Composition of Bacterial Cells (Gerardi, 2003).

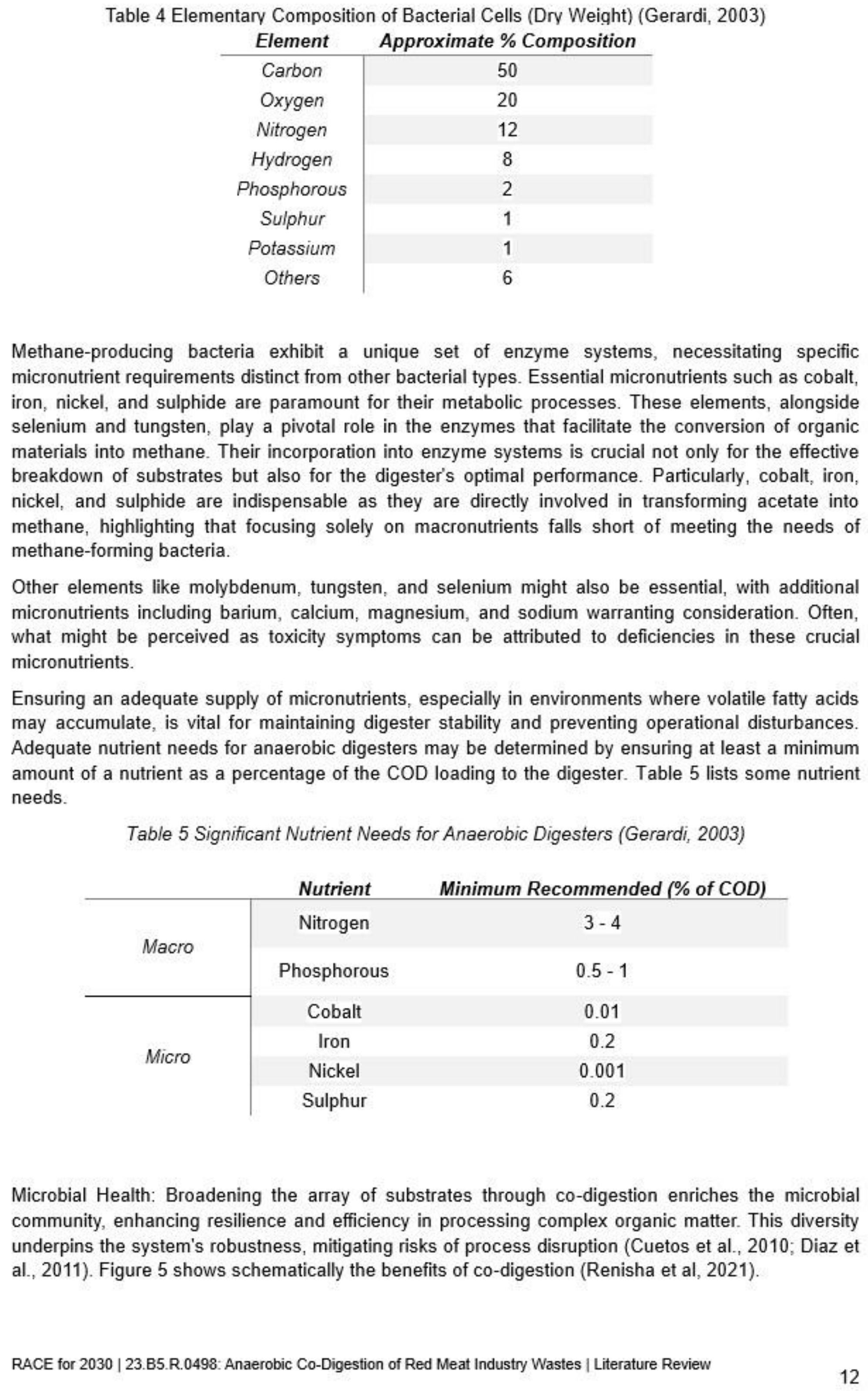


Table 4 Elementary Composition of Bacterial Cells (Dry Weight) (Gerardi, 2003)

Element	*Approximate % Composition*
Carbon	50
Oxygen	20
Nitrogen	12
Hydrogen	8
Phosphorous	2
Sulphur	1
Potassium	1
Others	6

Methane-producing bacteria exhibit a unique set of enzyme systems, necessitating specific micronutrient requirements distinct from other bacterial types. Essential micronutrients such as cobalt, iron, nickel, and sulphide are paramount for their metabolic processes. These elements, alongside selenium and tungsten, play a pivotal role in the enzymes that facilitate the conversion of organic materials into methane. Their incorporation into enzyme systems is crucial not only for the effective breakdown of substrates but also for the digester's optimal performance. Particularly, cobalt, iron, nickel, and sulphide are indispensable as they are directly involved in transforming acetate into methane, highlighting that focusing solely on macronutrients falls short of meeting the needs of methane-forming bacteria.

Other elements like molybdenum, tungsten, and selenium might also be essential, with additional micronutrients including barium, calcium, magnesium, and sodium warranting consideration. Often, what might be perceived as toxicity symptoms can be attributed to deficiencies in these crucial micronutrients.

Ensuring an adequate supply of micronutrients, especially in environments where volatile fatty acids may accumulate, is vital for maintaining digester stability and preventing operational disturbances. Adequate nutrient needs for anaerobic digesters may be determined by ensuring at least a minimum amount of a nutrient as a percentage of the COD loading to the digester. Table 5 lists some nutrient needs.

Table 5 Significant Nutrient Needs for Anaerobic Digesters (Gerardi, 2003)

	Nutrient	*Minimum Recommended (% of COD)*
Macro	Nitrogen	3 - 4
	Phosphorous	0.5 - 1
Micro	Cobalt	0.01
	Iron	0.2
	Nickel	0.001
	Sulphur	0.2

Microbial Health: Broadening the array of substrates through co-digestion enriches the microbial community, enhancing resilience and efficiency in processing complex organic matter. This diversity underpins the system's robustness, mitigating risks of process disruption (Cuetos et al., 2010; Diaz et al., 2011). Figure 5 shows schematically the benefits of co-digestion (Renisha et al, 2021).

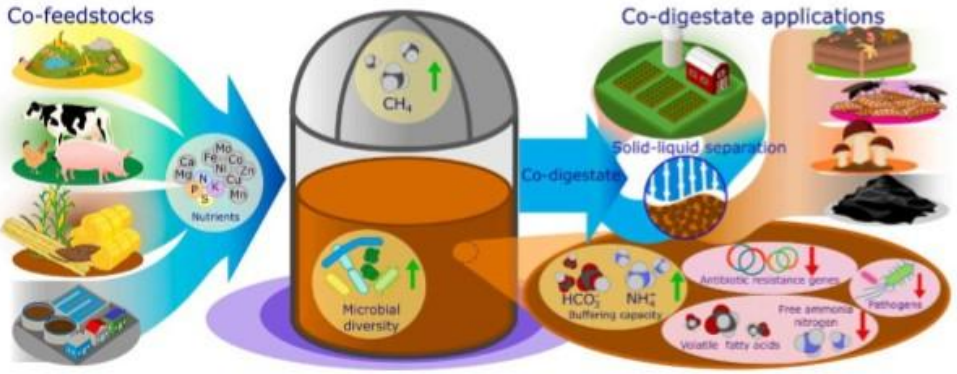


Figure 5 Co-digestion and its benefits (Renisha et al, 2021).

To fully harness the potential of anaerobic co-digestion, several operational facets must be adeptly managed:

- Optimal Temperature Ranges: The process thrives under both mesophilic (30-40°C) and thermophilic (50-60°C) conditions. Although thermophilic environments can accelerate decomposition and increase biogas output, mesophilic settings are often favoured for their greater stability and reduced energy requirements (Kabouris et al., 2009; Luostarinen and Luste, 2010).

- pH Levels: Maintaining a pH range of 6.8 to 7.2 is pivotal for the vitality of methanogenic bacteria. Co-digestion provides a natural pH buffering capacity, particularly with the inclusion of agricultural wastes that can neutralise pH fluctuations (Nda-Umar and Uzowuru, 2011; Luste and Luostarinen, 2010).

- Retention Times: The selection of hydraulic retention time (HRT) is contingent on the specific characteristics of the feedstock and operational temperature. Longer HRTs may be necessary to fully break down tougher or more fibrous materials, necessitating a judicious approach to prevent system overload and maintain gas production efficiency (Ponsa et al., 2011; Ware and Power, 2016).

Nonetheless, co-digestion processes encounter distinct challenges:

4.3.2 Toxicity and Inhibitor Management

The presence of inhibitors such as ammonia from protein-rich materials or sulphur compounds can impede microbial processes. Strategies for diluting these feedstocks, pre-treatment to reduce inhibitory concentrations, and gradual acclimatisation of the microbial population are key to managing these challenges (Li et al., 2011; Palatsi et al., 2011). Signs of toxicity within an anaerobic digester can emerge swiftly or gradually, contingent on the toxicity form and the toxic waste's level. Such indicators encompass the depletion of hydrogen and methane, declines in alkalinity and pH, and a surge in volatile acid levels. A wide array of substances can induce toxicity in anaerobic digesters, with ammonia, hydrogen sulphide, and heavy metals being the most frequently encountered culprits.

Figure 6 shows the toxicity level for both organic and inorganic compounds.

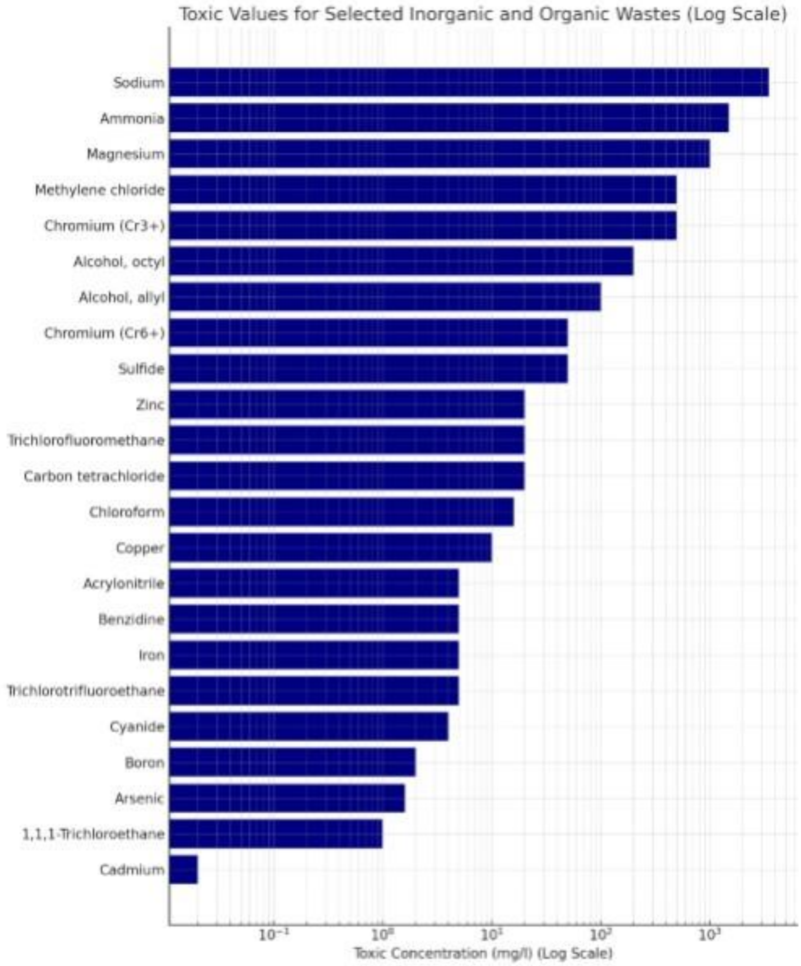


Figure 6 Toxicity levels of Organic and Inorganic compounds (Tessele adapted from Gerardi, 2003)

Inhibition of anaerobic digestion in red meat processing facilities by-products treatment can often be traced back to high ammonia levels, which originate from the breakdown of proteins present in these wastes, as well as from the accumulation of long-chain fatty acids (LCFA) resulting from lipid degradation. Fats, grease, and oils (FOG) are the primary contributors to chemical oxygen demand (COD) in food waste processing, with FOG being notably resistant to biodegradation due to their low bioavailability. Additionally, the by-products of lipid hydrolysis, namely lipids and long-chain fatty acids, are known to hinder methanogenic activity. Furthermore, FOG can lead to operational challenges, such as the formation of floating layers and foam, which can result in stratification and impede the adsorption processes within the biomass. Nonetheless, FOG's high COD content is associated with substantially higher biogas yields compared to other food waste components, making it a valuable addition to enhancing biogas production in anaerobic digestion processes. (Ihsan Hamawand, 2015)

Trace levels of heavy metals like cobalt, molybdenum, and nickel can actually function as beneficial additives, boosting the enzymatic activities of methane-producing bacteria. However, when present in moderate to high concentrations, these same heavy metals can become toxic to the bacteria in anaerobic digesters. Metals such as copper, nickel, and zinc are particularly harmful to methane-producing bacteria, even at relatively low levels, due to their solubility in the anaerobic digestion environment. To mitigate their toxicity, these metal ions can be chemically transformed into less harmful metal sulphides.

4.3.3 Preventive Measures

Diligent monitoring of essential process parameters can forestall and address imbalances. A varied feedstock mix can help dilute potential inhibitors, reducing the risk of toxic shock. Staggered or phased feeding strategies also contribute to effective load management, enhancing overall system equilibrium (Martin-Gonzalez et al., 2010; Tessele et al., 2020).

Embracing these operational strategies and addressing inherent challenges, anaerobic co-digestion stands out as an efficacious approach for both waste management and renewable energy generation. By leveraging the combined strengths of various organic waste streams, this method not only fosters energy sustainability but also supports broader environmental management goals, affirming the critical need for continued exploration and refinement in this domain (Wan et al., 2011; Yenigün and Demirel, 2013).

4.3.4 Co-digestion substrates

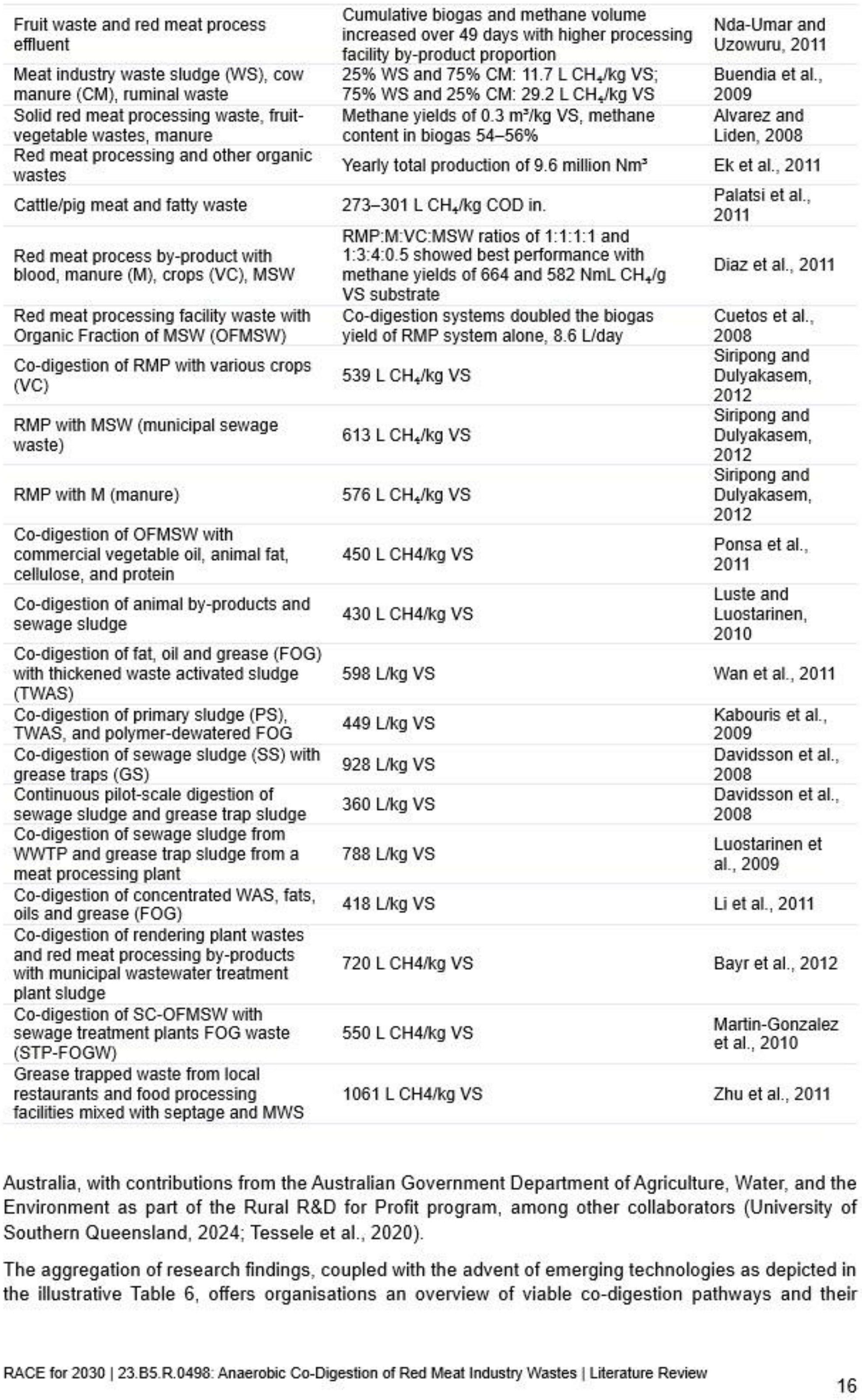
The exploration of feedstock optimisation strategies for enhancing anaerobic digestion through co-digestion is well-established in the scholarly realm. Numerous investigations have been dedicated to delineating the intricate interplay between operational variables and methane production efficiencies. Despite a robust body of literature that delineates critical parameters for co-digestion efficacy, the translation of these findings into practical applications encounters hurdles, particularly in feedstock selection and the application of generalised optimal conditions across varied operational contexts, posing a significant challenge within biochemical engineering disciplines (Hejnfelt & Angelidaki, 2009; Alvarez & Liden, 2008).

While the implementation of mono-digestion processes remains technically viable, it markedly falls short of exploiting the full potential for biomethane generation achievable through co-digestion strategies. This recognition has precipitated a global trend towards the establishment of co-digestion facilities, motivated by the imperative to identify and harness optimal and plentiful feedstock sources. Such initiatives are crucial for organisations aiming to enhance their biogas production capacities or improve the nutrient profiles of produced biofertilisers (Buendia et al., 2009; Shanmugam and Horan, 2009).

Against this backdrop, the collective insights garnered from extensive research have been instrumental in forging innovative analytical tools designed to aid stakeholders in assessing the feasibility of co-digestion ventures. A quintessential example of such innovation is the Anaerobic Digestion Advisor (AD Advisor), developed by the University of Southern Queensland's Centre for Agricultural Engineering. This tool empowers users to perform preliminary economic evaluations of anaerobic digestion projects, specifically those leveraging waste streams from the red meat processing and intensive livestock sectors. The AD Advisor's development was facilitated through the support of Meat and Livestock. Table 6 presents the summary of the findings on co-digestions.

Table 6 Condensed literature review on co-digestion.

Substrate	Biogas Yield and Comments	References
Wastewater from leather industry with municipal solid waste	Biogas maximized from 560 mL (leather waste alone) to 6518 mL with optimum blend	Shanmugam et al., 2009
Fruit and vegetable waste (FVW) with red meat processing wastewater (RMP)	Better biogas yield than separate digestions of RMP and FVW	Bouallagui et al., 2009
Pig processing by-products with pig manure	Biogas production increased from 3.3 dm^3/day to 5.5 dm^3/day, specific yield of 489 dm^3/kg VS	Hejnfelt and Angelidaki, 2009



Fruit waste and red meat process effluent	Cumulative biogas and methane volume increased over 49 days with higher processing facility by-product proportion	Nda-Umar and Uzowuru, 2011
Meat industry waste sludge (WS), cow manure (CM), ruminal waste	25% WS and 75% CM: 11.7 L CH_4/kg VS; 75% WS and 25% CM: 29.2 L CH_4/kg VS	Buendia et al., 2009
Solid red meat processing waste, fruit-vegetable wastes, manure	Methane yields of 0.3 m^3/kg VS, methane content in biogas 54–56%	Alvarez and Liden, 2008
Red meat processing and other organic wastes	Yearly total production of 9.6 million Nm^3	Ek et al., 2011
Cattle/pig meat and fatty waste	273–301 L CH_4/kg COD in.	Palatsi et al., 2011
Red meat process by-product with blood, manure (M), crops (VC), MSW	RMP:M:VC:MSW ratios of 1:1:1:1 and 1:3:4:0.5 showed best performance with methane yields of 664 and 582 NmL CH_4/g VS substrate	Diaz et al., 2011
Red meat processing facility waste with Organic Fraction of MSW (OFMSW)	Co-digestion systems doubled the biogas yield of RMP system alone, 8.6 L/day	Cuetos et al., 2008
Co-digestion of RMP with various crops (VC)	539 L CH_4/kg VS	Siripong and Dulyakasem, 2012
RMP with MSW (municipal sewage waste)	613 L CH_4/kg VS	Siripong and Dulyakasem, 2012
RMP with M (manure)	576 L CH_4/kg VS	Siripong and Dulyakasem, 2012
Co-digestion of OFMSW with commercial vegetable oil, animal fat, cellulose, and protein	450 L CH4/kg VS	Ponsa et al., 2011
Co-digestion of animal by-products and sewage sludge	430 L CH4/kg VS	Luste and Luostarinen, 2010
Co-digestion of fat, oil and grease (FOG) with thickened waste activated sludge (TWAS)	598 L/kg VS	Wan et al., 2011
Co-digestion of primary sludge (PS), TWAS, and polymer-dewatered FOG	449 L/kg VS	Kabouris et al., 2009
Co-digestion of sewage sludge (SS) with grease traps (GS)	928 L/kg VS	Davidsson et al., 2008
Continuous pilot-scale digestion of sewage sludge and grease trap sludge	360 L/kg VS	Davidsson et al., 2008
Co-digestion of sewage sludge from WWTP and grease trap sludge from a meat processing plant	788 L/kg VS	Luostarinen et al., 2009
Co-digestion of concentrated WAS, fats, oils and grease (FOG)	418 L/kg VS	Li et al., 2011
Co-digestion of rendering plant wastes and red meat processing by-products with municipal wastewater treatment plant sludge	720 L CH4/kg VS	Bayr et al., 2012
Co-digestion of SC-OFMSW with sewage treatment plants FOG waste (STP-FOGW)	550 L CH4/kg VS	Martin-Gonzalez et al., 2010
Grease trapped waste from local restaurants and food processing facilities mixed with septage and MWS	1061 L CH4/kg VS	Zhu et al., 2011

Australia, with contributions from the Australian Government Department of Agriculture, Water, and the Environment as part of the Rural R&D for Profit program, among other collaborators (University of Southern Queensland, 2024; Tessele et al., 2020).

The aggregation of research findings, coupled with the advent of emerging technologies as depicted in the illustrative Table 6, offers organisations an overview of viable co-digestion pathways and their attendant advantages. This consolidated knowledge base significantly streamlines the project initiation process, eliminating the need for extensive, resource-intensive research and development phases, thereby contributing to the broader objective of global decarbonisation (Palatsi et al., 2011; Diaz et al., 2011).

5 Economic and Environmental Considerations

The sustainability of anaerobic co-digestion projects is intricately tied to various logistical, economic, and environmental aspects, particularly regarding feedstock sourcing and transportation. These factors play a crucial role in determining the feasibility and overall impact of co-digestion initiatives (Hejnfelt & Angelidaki, 2009).

Logistics and Sourcing: The geographical proximity of feedstock sources to co-digestion facilities significantly influences project viability by affecting transportation costs. Efficient local feedstock supply chains and collaborations with waste producers are essential strategies for reducing these expenses and enhancing project feasibility (Alvarez & Liden, 2008).

Economic Aspects: Although feedstock acquisition costs are paramount, co-digestion projects can yield substantial economic advantages. These include savings from integrated waste management practices, income from renewable energy production, and revenues generated from the utilisation of digestate as a biofertiliser. These economic benefits underscore co-digestion's role in promoting sustainable waste treatment and energy production solutions (Bayr et al., 2012).

Environmental Impact: Beyond its economic advantages, co-digestion contributes significantly to environmental sustainability. By diverting waste from landfills, co-digestion projects can markedly reduce greenhouse gas emissions and mitigate environmental pollution. Nevertheless, it is imperative to conduct thorough environmental assessments to understand the implications of feedstock transportation and processing fully. Such assessments ensure that co-digestion projects align with broader environmental sustainability goals (Martin-Gonzalez et al., 2010; Cuetos et al., 2008).

The effective implementation of co-digestion projects in Australia hinges on a deep understanding of the involved feedstocks, including their characteristics and how they interact within the co-digestion process. Additionally, the success of these projects depends on meticulous planning around logistical, economic, and environmental considerations. Strategic feedstock mixing, aligned with a comprehensive approach to managing these factors, is fundamental to optimising the performance of co-digestion systems and realising their potential benefits. By addressing these considerations, co-digestion can significantly contribute to Australia's renewable energy landscape and its environmental sustainability objectives (Palatsi et al., 2011; Ek et al., 2011).

6 Future Directions and Research Needs

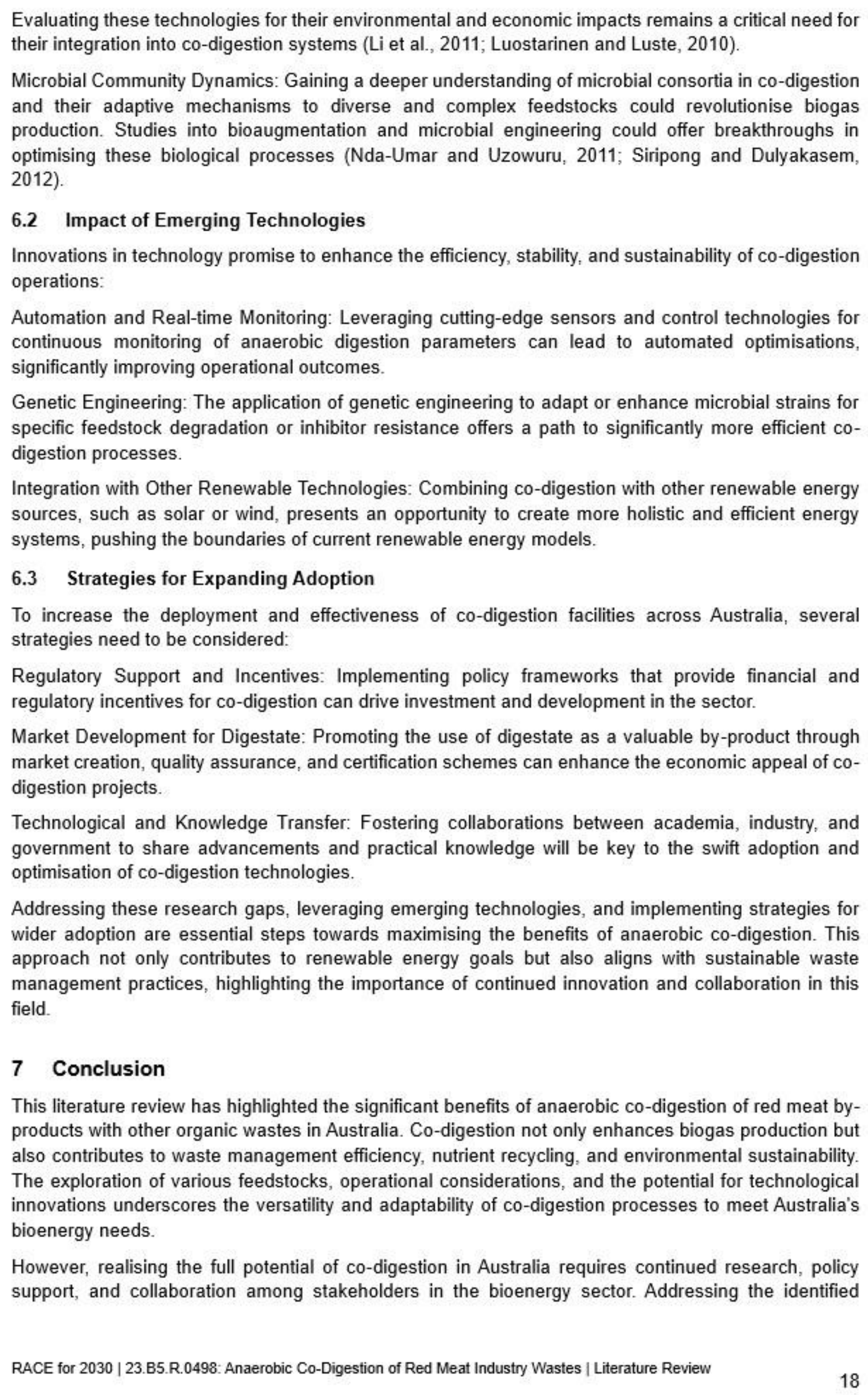
The pursuit of enhancing anaerobic co-digestion technology uncovers several areas necessitating further investigation, despite the significant advancements made thus far:

The advancement of anaerobic co-digestion technology has illuminated several areas requiring further exploration to overcome current limitations and unlock its full potential.

6.1 Examples of Gaps in Current Knowledge and Research

Optimisation of Feedstock Mixtures: While studies like those by Ware and Power (2016) have demonstrated the benefits of specific feedstock combinations in co-digestion, there remains a significant gap in understanding the optimal mixtures. The variability of waste streams and their impact on co-digestion efficacy necessitates detailed research into the effects of different feedstock proportions on system performance and biogas quality over time (Diaz et al., 2011; Shanmugam et al., 2009).

Advanced Pre-treatment Technologies: Exploring new pre-treatment methods to enhance the digestibility of tough feedstocks, such as lignocellulosic materials, is crucial for increasing biogas yields.



Evaluating these technologies for their environmental and economic impacts remains a critical need for their integration into co-digestion systems (Li et al., 2011; Luostarinen and Luste, 2010).

Microbial Community Dynamics: Gaining a deeper understanding of microbial consortia in co-digestion and their adaptive mechanisms to diverse and complex feedstocks could revolutionise biogas production. Studies into bioaugmentation and microbial engineering could offer breakthroughs in optimising these biological processes (Nda-Umar and Uzowuru, 2011; Siripong and Dulyakasem, 2012).

6.2 Impact of Emerging Technologies

Innovations in technology promise to enhance the efficiency, stability, and sustainability of co-digestion operations:

Automation and Real-time Monitoring: Leveraging cutting-edge sensors and control technologies for continuous monitoring of anaerobic digestion parameters can lead to automated optimisations, significantly improving operational outcomes.

Genetic Engineering: The application of genetic engineering to adapt or enhance microbial strains for specific feedstock degradation or inhibitor resistance offers a path to significantly more efficient co-digestion processes.

Integration with Other Renewable Technologies: Combining co-digestion with other renewable energy sources, such as solar or wind, presents an opportunity to create more holistic and efficient energy systems, pushing the boundaries of current renewable energy models.

6.3 Strategies for Expanding Adoption

To increase the deployment and effectiveness of co-digestion facilities across Australia, several strategies need to be considered:

Regulatory Support and Incentives: Implementing policy frameworks that provide financial and regulatory incentives for co-digestion can drive investment and development in the sector.

Market Development for Digestate: Promoting the use of digestate as a valuable by-product through market creation, quality assurance, and certification schemes can enhance the economic appeal of co-digestion projects.

Technological and Knowledge Transfer: Fostering collaborations between academia, industry, and government to share advancements and practical knowledge will be key to the swift adoption and optimisation of co-digestion technologies.

Addressing these research gaps, leveraging emerging technologies, and implementing strategies for wider adoption are essential steps towards maximising the benefits of anaerobic co-digestion. This approach not only contributes to renewable energy goals but also aligns with sustainable waste management practices, highlighting the importance of continued innovation and collaboration in this field.

7 Conclusion

This literature review has highlighted the significant benefits of anaerobic co-digestion of red meat by-products with other organic wastes in Australia. Co-digestion not only enhances biogas production but also contributes to waste management efficiency, nutrient recycling, and environmental sustainability. The exploration of various feedstocks, operational considerations, and the potential for technological innovations underscores the versatility and adaptability of co-digestion processes to meet Australia's bioenergy needs.

However, realising the full potential of co-digestion in Australia requires continued research, policy support, and collaboration among stakeholders in the bioenergy sector. Addressing the identified

research gaps, leveraging emerging technologies, and implementing strategies for wider adoption are essential steps toward integrating co-digestion into Australia's renewable energy portfolio. With concerted efforts, co-digestion can play a pivotal role in advancing Australia's bioenergy sector and contributing to global environmental sustainability goals.

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8.4 Appendix D: Supplementary Batch Experimental Data

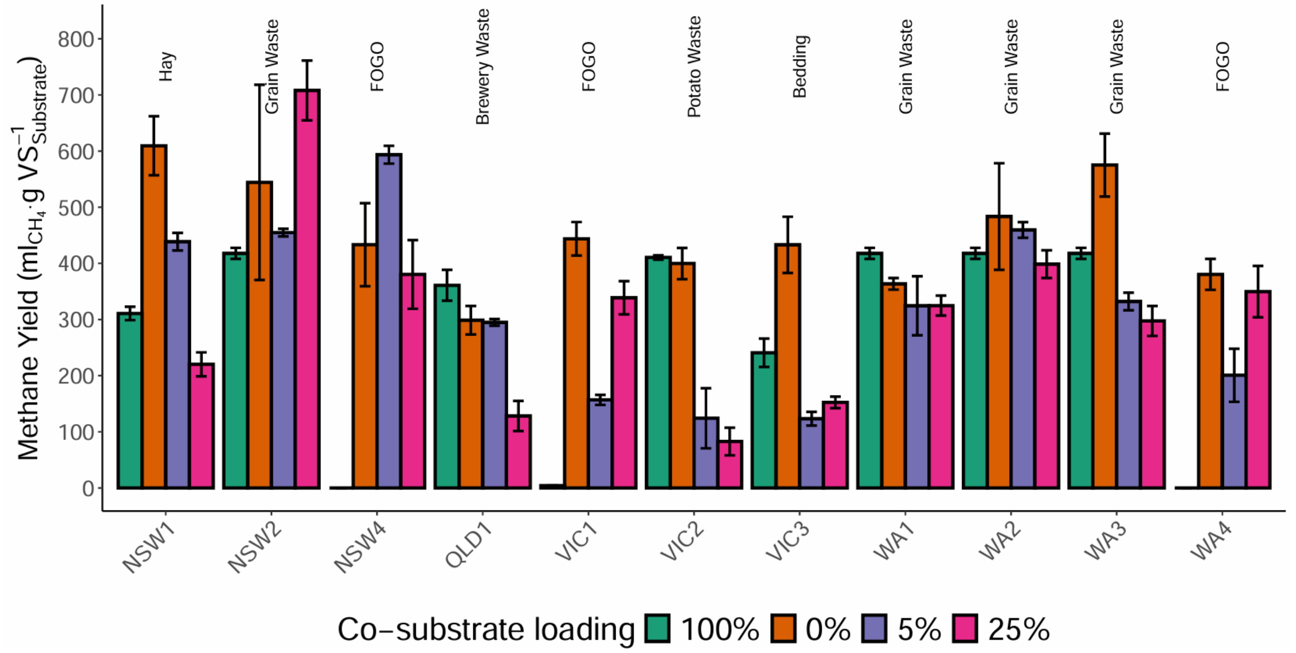

Figure C1: Measured biochemical methane potential from Phase 2 testing. Co-substrates used in each co-digestion study are presented at the top of the chart. Results are presented as the mean of triplicates ± the Standard Deviation.

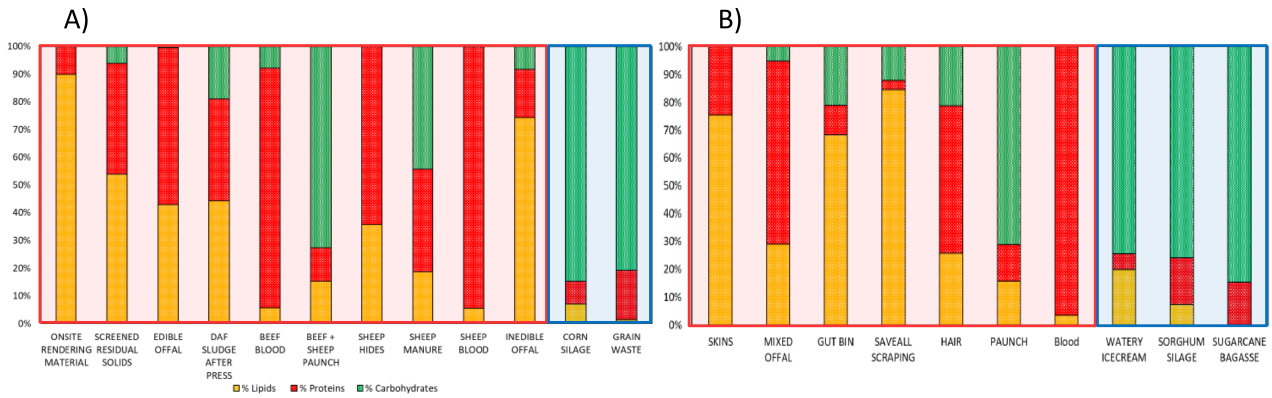

Figure C2: Macronutrient profile of the different sub- and co-feedstocks for A) WA4 and B) NWS4. The red box highlights the Red Meat Processor sub-feedstocks, while the co-substrates are highlighted by the blue box.

8.5 Appendix E: Supplementary Continuous Experimental Data

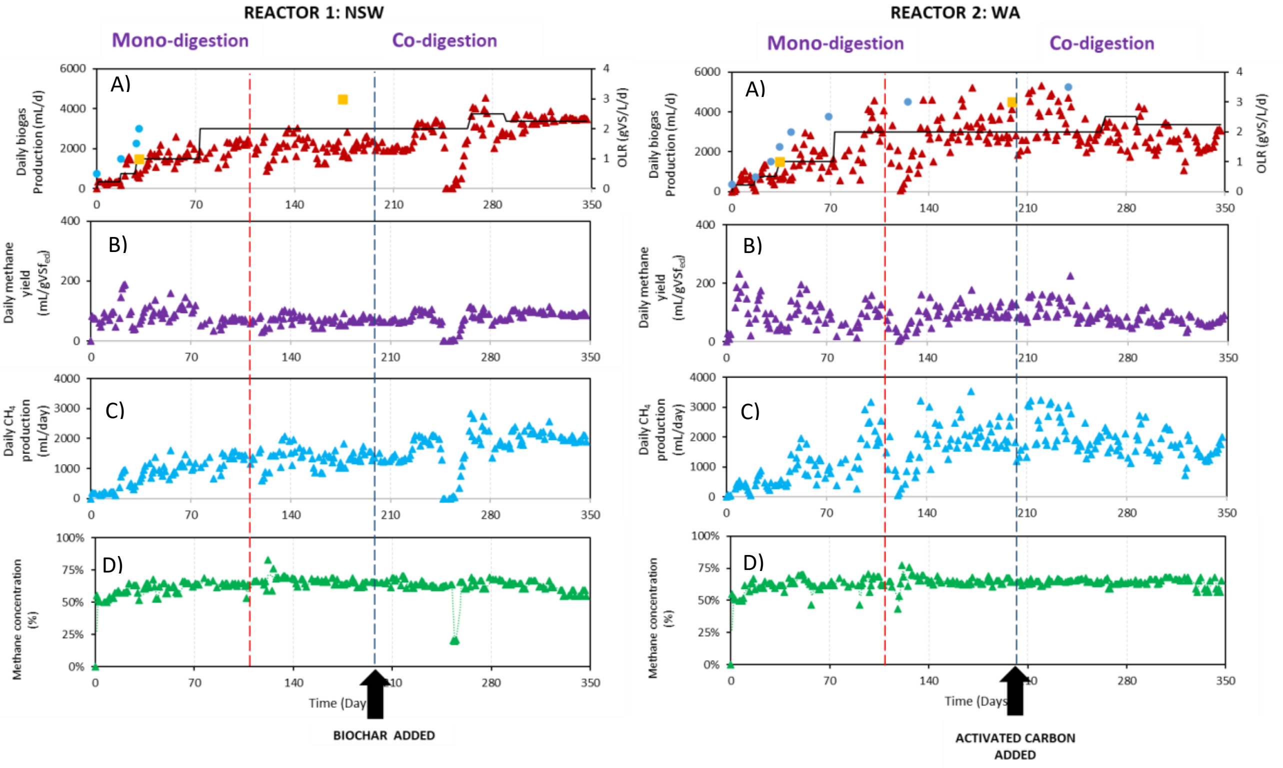

Figure E1: Figure showing the A) Biogas productivity, B) methane yield, C) methane productivity, and D) biogas methane concentration for WA4 and NSW4 over the entire continuous experiment. The red dashed line indicates the start of co-digestion, while the blue line indicates the start of biochar and activated carbon addition.

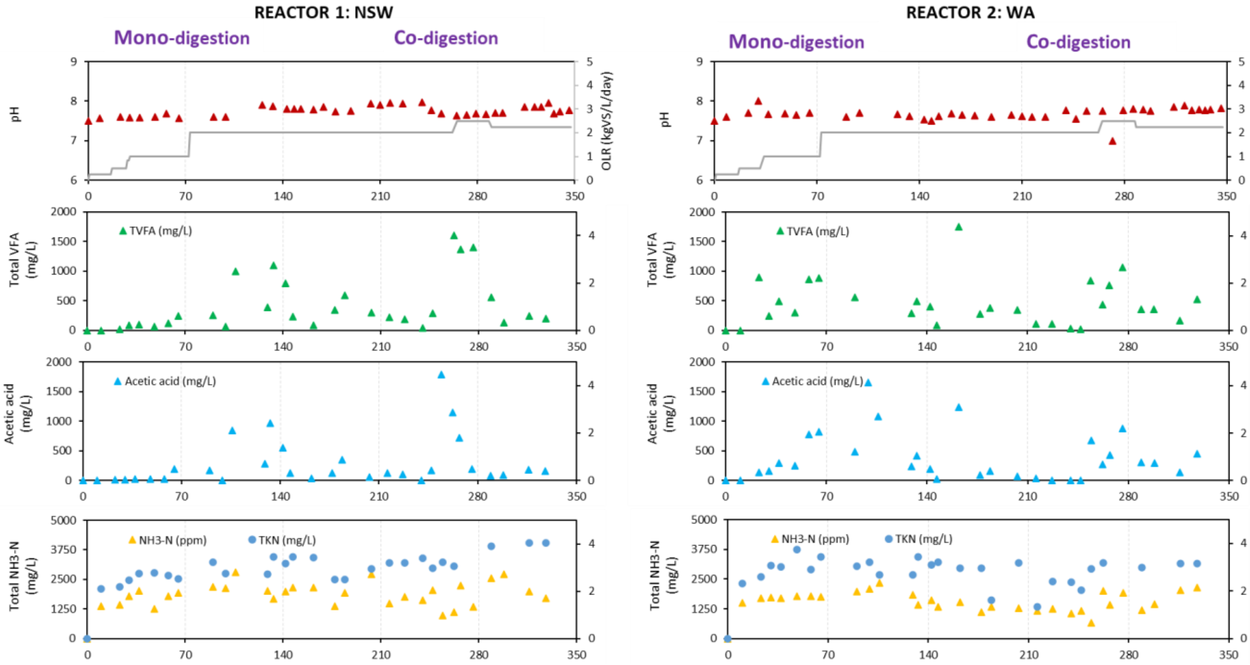

Figure E2: Figure showing A) reactor pH, B) total volatile fatty acid concentration, C) acetic acid concentration, and D) total ammonia nitrogen concentration for WA4 and NSW4 over the entire continuous experiment.

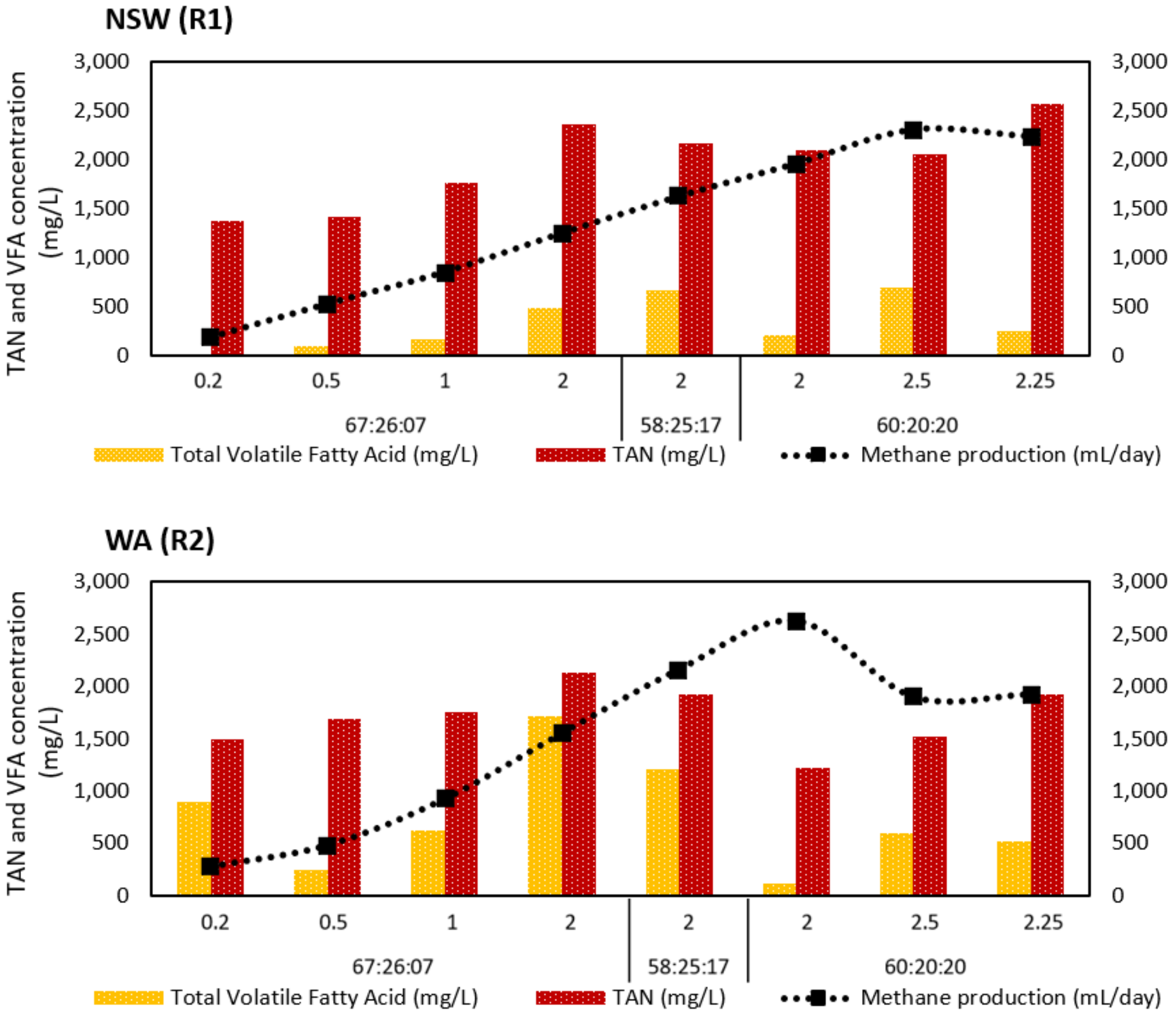

Figure E3: Total VFA and ammoniacal nitrogen concentration, and daily methane production from the WA4 and NSW4 reactors.

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