Final report

Feasibility of feedlot manure and effluent value adding technologies and strategies

Project code: B.FLT.5018

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Date published: 19 November 2024

PUBLISHED BY
Meat & Livestock Australia Limited
PO Box 1961
NORTH SYDNEY NSW 2059

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

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Abstract

Feedlot waste is a rich source of nutrients and carbon. There is a growing demand for these materials from the cropping sector to improve nutrient use efficiency, sequester carbon in soil and improve soil health. Given the rise in the price of fossil fuel, conventional fertiliser products and finite global phosphorus and potassium resources, it is timely to increase research investment in nutrient capture from feedlot wastes to meet the ever-increasing fertiliser demand in crop industry for ensuring future food security. However, to bolster and protect this market, consistent and effective effluent- and manure- derived circular nutrient products are required. This is a desktop study to determine current volume and management of feedlot manure, feedlot and transport effluent. The project was also aimed to review and assess competing or complementary technology options available globally to value add and reduce greenhouse gas (GHG) emission from feedlot manure and effluents. A life cycle assessment and benefit cost analysis were conducted to evaluate the environmental and economic implications of adopting the shortlisted technologies. The results of both indicate that, unless there are increased returns for processed products, regulatory or social licence reasons for doing so, business-as-usual operations (e.g., stockpiling manure) represent the lowest cost for feedlot manure. The study provides a quantitative and qualitative justification for focusing on marketing and value-adding efforts for feedlot manure, recognising that feedlot effluent represents only a small proportion of industry by-products and macronutrients, and that truck effluent requires cross-industry and cross-sectoral solutions to address spillage.

Executive summary

Background

As the nutrient composition of feedlot manure is a key component of its selling price, opportunities to improve this value or the nutrient availability to increase demand for and the selling price of the product are of key interest. Research-proven strategies and technologies to value-add by-products, however, can be challenging to adopt and may produce negative environmental outcomes and/or result in higher costs of production and increased management complexities with little to no financial return. This study aimed to provide clarity on which strategies and technologies may be viable for the Australian feedlot industry at this time, considering current by-product volumes and handling, the potential for emission reduction, and ultimate impact of lot feeders cashflow.

Objectives

The objectives of the project were to:

1. Perform a survey of the Australian lot feeding industry, and manure and effluent end-users to determine current volumes, handling, revenues, and barriers to further adoption.
2. Perform a global technology scan and undertake a desk-top based feasibility assessment for technologies and strategies suitable for value adding feedlot manure and effluent in Australia.
3. For a shortlist of technologies/strategies for solid manures, liquid effluent and truck effluent, conduct an ex-ante cost-benefit analysis and life cycle assessment, extrapolating the results to whole-of-industry level.

Methodology

An industry survey was conducted to quantify baseline volumes and revenue generated from feedlot manure, effluent, and truck effluent, and also identified barriers to further adoption of the products by end-users. A desktop feasibility was conducted to identify strategies to value-add the manure and effluent streams. Based on a shortlist of value-adding technologies, a life cycle assessment (LCA) and cost-benefit analysis (CBA) was conducted to determine the financial and environmental (GHG emissions) implication of adoption.

Results/key findings

We surveyed over 615,000 head of feedlot capacity and livestock transport companies across Australia to determine the volume and value of manure, effluent and truck effluent to the feedlot industry. For the 2023 Financial Year, annual manure generation was calculated to be 1.8 t/SCU resulting in the generation of more than 2.1 million tonnes of manure across the feedlot industry. Additionally, 4,000 ML of effluent was generated and 107 ML of truck effluent, however, after George et al. (2022), only 36% of this (38 ML) was assumed to be captured. The volume of captured truck effluent represents <1% of total effluent of feedlot industry. Despite the large volumes of this valuable resource, the challenges faced by feedlots in processing and marketing manure products result in a loss of $0.57 for every tonne of manure sold. The sale of stockpiled manure products accounted for roughly 70% of all manure sold with raw and composted manure making up 15% of the market each. Around 35% of manures are used on feedlot owned land. Representatives of and end users (with interests in broadacre cropping, pasture/fodder production, and viticulture/horticulture) were surveyed to determine use cases and barriers to further adoption. The key barriers to further adoption of manures were found to be driven by cost and the consistency of the product, particularly high moisture content.

The high concentration of solids and soluble salts in feedlot effluent and insufficient access to clean irrigation water for shandying was the key barrier to further adoption of effluent irrigation on farm. Findings of the survey suggested that end users value manure and effluent products based on their macronutrient value compared to synthetic fertiliser, with decision making highly weighted toward nitrogen (N) and phosphorus (P) content of the products. Considering the total costs of manure products and the equivalent macronutrient value of N, P, potassium (K) and sulphur (S) (as spread) based on the equivalent costs of synthetic fertiliser suggested that there is unrealised value for raw and stockpiled manure products based on nutrient availability. Composted feedlot manure, however, appeared to be valued about right based on the availability of the nutrients.

A global technology search was also conducted to assess the manure and effluent valorisation technologies. The assessment of the technologies showed that co-composting, composting and pelletising of the manure to formulate organo-mineral fertiliser is the most promising technology in terms of physical stability, nutrient value and performance in the soil. Technologies like filtration (as wastewater filtration) and anaerobic digestion are the suitable options for feedlot and transport effluent. Both nitrogen and phosphorus can be almost completely recovered from separated liquids using chemical and biochemical processes, but the complexity and cost of implementation is very high. The issue with the transport effluent is its small volume. Having transport effluent collection facility available, this type of effluent can undergo anaerobic digestion or can be treated in existing wastewater treatment plant in abattoir.

Current volumes of manure and effluent produced by industry were quantified, revealing that the N, P and K in manure represent over 94% of the total value of the major macronutrients produced by the industry. Raw and stockpiled manure products were found to be undervalued (based on their nutrient content) relative to current selling prices. The LCA and CBA of value-adding technologies confirmed that the bulk of the industry (by stockpiling manure) is already operating lowest cost, and lowest input management. The reason the conventional LCA cannot detect any GHG emission benefit of value-adding technologies is the use of fixed emission factors in emission accounting that developed for standard manure management practices. The results of the special case study on one of value-adding technologies showed financial viability of partially replacing conventional fertilisers with organo-mineral fertiliser. However, there are research and development opportunities to measure value-addition technology specific emission factors and develop manure-based superior organo-mineral fertilisers.

Benefits to industry

This research set out to examine benefits from treating feedlot manure and effluent to deliver better environmental or economic outcomes. These outcomes were difficult to demonstrate from the technical perspective, but other learnings were established including that manure products continue to be undervalued and perhaps the greatest emerging opportunity that can arise from a renewed focus on the value of manure could be stimulated by focusing on building soil carbon. Potential new opportunities for industry were identified, including strategies to engage with local grain producers to supply manure products in exchange for discounted grain.

Future research and recommendations

Based on the findings of this study, there are several recommendations to industry, including in relation to future research. Recommendations for industry include identifying opportunities to engage with end-users on a targeted basis, including to promote circular economy principles, soil health benefit of organo-mineral fertiliser and to alternatively market manure products as a soil carbon

amendment for highly degraded cropland and for resilient soil profile. Recommendations for future research include the development of best practice pen cleaning and maintenance guidance to reduce contamination of feedlot manure to improve the consistency and value of final products. In addition, further research is needed to map nutrient demand (from broadacre cropping, horticulture, etc) against organic nutrient availability (reflecting volumes produced from feedlots, piggeries, and the poultry industry) to understand the potential market at a local level. This may strengthen opportunities for lot feeders to market manure products to particular industries or locations, maximising the value of the manure, and keeping transport costs to a minimum. Recommendations for value-addition of manure include shortening of stockpiling/composting time and transforming composted manure (pelletised and un-pelletised) into superior or high-efficiency hybrid or organo-mineral fertiliser for use in broadacre and horticultural cropping systems, which requires further research investment. This recommendation has a concurrent focus on decreasing processing costs and greenhouse gas emissions relative to conventional composting and pelletising by adjusting current feedlot manure management practices.

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1. Background

In Australia, accredited feedlots are designed, constructed and operated to ensure economic viability and optimal health, performance and welfare of animals, all whilst minimising impact on the environment and community amenity. All liquid and solid effluent from lot feeding of cattle is captured within controlled drainage areas and managed appropriately according to licensing and regulatory conditions.

The majority of feedlot manure is currently stockpiled before sale, however, some feedlots compost manure or sell it raw (unprocessed). The manure products are typically sold directly to agricultural producers and applied to crop, pasture, or horticultural land. As the nutrient composition of feedlot manure is a key component of its selling price, opportunities to improve this value or the nutrient availability to increase demand for and the selling price of the product are of key interest. Similarly, opportunities to turn feedlot effluent (or its nutrients) into a revenue stream are fundamental to the industry marketing the nutrients for circular economy principles. Feedlot manure and effluent is a rich source of nutrients and carbon. The innovative management of the feedlot waste product has potential to recover additional nutrients, reduce GHG emissions and increase its value. The value addition or valorisation of the feedlot waste and its application along with the synthetic fertiliser for crop and pasture production will enhance sustainability of agroecosystem and help the agriculture sector to meet the GHG emission reduction target.

Valorisation of feedlot manure and effluent includes management techniques that facilitate retaining or increasing nutrient and energy values of the waste. There are many valorisation techniques/strategies in practice or under research and development. However, not all of these technologies are effective for nutrient retention and reduction of GHG emissions or economically viable. Research-proven strategies and technologies to manage, process or value-add by-products, however, can be challenging to adopt. Benefits can be associated with trade-offs. In some cases, the strategies can produce negative environmental outcomes (e.g., higher greenhouse gas emissions) and/or result in higher costs of production and increased management complexities with little to no financial return. This study aimed to provide clarity on which strategies and technologies may be viable for the Australian feedlot industry at this time, considering current by-product volumes and handling, the potential for emission reduction, and ultimate impact of lot feeders cashflow.

Our approach was to conduct a survey by including large to small lot feeders to capture the volume of manures and effluents produced in the Australia feedlot and current management practices. For this project the valorisation technologies were shortlisted, and cost-benefit and life cycle analyses were performed of the top listed technologies to assess their feasibility in Australian beef feedlots.

The principal target audience of the study is the Australian feedlot industry; however, several findings are of relevance to the end-users of feedlot industry by-products and to broader groups where there are perceived issues in relation to certain by-products (e.g., truck effluent).

This research is a key reference and justification for the prioritisation of future R&D projects relating to feedlot manure and effluent, and best practice management for lot feeders, supporting the findings of previous related studies (see McGahan et al. 2010). The findings of the feedlot-level life cycle assessment and cost-benefit analysis offers lot feeders precompetitive information to judge whether a certain proposed technology or strategy is feasible or worthwhile at this time.

The project is unique because the outcome of the project not only provides estimates of volume of manure and effluent but also a cost-effective alternative management strategy for reducing nutrient loss and greenhouse gas emission.

2. objectives

The objective of the project was to determine the feasibility of feedlot manure and effluent value adding technologies and strategies in the Australian lot feeding industry. To meet this objective the project was divided into two phases of work.

The objective of Phase 1 of the project was to survey the Australian lot feeding industry to determine:

a) Feedlot industry manure and effluent (including truck effluent) management practices.
b) Baseline volume and revenue generation of current manure and effluent management practices (including transport effluent).
c) Current value that end users assign to manure and effluent products and determine the mechanisms for this as well as barriers to adoption by grain growers and the horticultural industry.

Phase 2 of the project aimed to identify technologies and strategies suitable for value adding feedlot manure and effluent and determine their feasibility in the Australian context. The specific objectives were to:

a) Perform a global technology scan and undertake a desk-top based feasibility assessment for technologies and strategies suitable for value adding feedlot manure and effluent in Australia. A total of 30 technologies or strategies, 10 each for solid manures, liquid effluent and truck effluent to be reviewed and reported.

b) For the top 3 shortlisted technologies/strategies in each category (solid manures, liquid effluent, and truck effluent - total = 9): a. Conduct an ex-ante cost benefit and sensitivity analysis that considers capital and operational costs (including R&M and pen cleaning costs), along with potential revenue benefits over market benchmarks identified in Phase 1. Extrapolate the results of the cost benefit analysis to the industry survey results from Phase 1 and compare to industry business as usual. b. Assessment of the emissions profile (by way of life cycle analysis) of the proposed solution(s) or technology(s) compared to business as usual, extrapolated to the whole industry using results from the survey in Phase 1.

3. Methodology

3.1 Phase 1

3.1.1 Survey design and preparation

A survey program was conducted to collect information from feedlots and manure product end users to determine baseline volumes and the revenue generated from manure and effluent management. Feedlot operators and end-users were also asked what they believe are the barriers to adoption of feedlot manure and effluent products. Cattle transport companies were also surveyed to determine effluent disposal practices. The following tasks were undertaken as a part of the survey program:

- Survey design and preparation.
- Survey distribution.
- Analysis.

Separate surveys were developed for feedlot operators, manure product end users and cattle transport operators. Participants were prompted to provide information relating to either the 2023 calendar year or 2023 financial year. The survey questionnaire templates used are provided in the Appendix**.**

The survey was designed to meet the following project objectives and answer a range of questions, including:

- Survey at least 15 lot feeder businesses to capture 50% of Australian feedlot cattle capacity (over 600,000 head).
- For solid manures:
    - Application of raw manure to feedlot owned land (amount and $/t value)
    - Application of screened and stockpiled manure to feedlot owned land (amount and $/t value)
    - Sale of raw manure to third party(s) for land application (amount and $/t value)
    - Sale of raw manure to third party(s) for further processing on site or off site (amount and $/t value)
    - Sale of screened and stockpiled manure to third party(s) for land application (amount and $/t value)
    - Sale of screened and stockpiled manure to third party(s) for further processing on site or off site (amount and $/t value)
    - Sale of compost to third party(s) for land application (amount and $/t value)
    - Sale of compost to third party(s) for further processing on site or off site (amount and $/t value)
    - Manure valuation strategy (e.g. nutrient pricing, or simple supply/demand)
    - Pen cleaning frequency and cost ($/tonne) of extracting manure from pens
    - End user question – how they value manure and effluent products?
- For liquid effluent:
    - Prevalence and amount of liquid effluent used for irrigation on feedlots
    - Cost of using liquid effluent for irrigation
    - End user question – how they value manure and effluent products?

    - For truck effluent
    - Amount of truck effluent from incoming feeder cattle
    - Current strategies to handle truck effluent or truck washing effluent by industry
    - End user question – how they value manure and effluent products?
- From the results of the survey determine the current volume and value of manure and effluent to the Australian lot feeding Industry.
- From the results of the survey determine how end users value manure and effluent products. Report this in the results and determine barriers to more widespread adoption by end users.
- Collate and analyse the results of the survey by different geographical regions.

3.1.2 Survey distribution

A national list of feedlots for inclusion in the survey was developed by Integrity Ag in collaboration with MLA from industry knowledge and experience. Feedlots were grouped by capacity (<10,000 head and >10,000 head) and geographical region (as per Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) regions) and distributed to participants to ensure representative coverage of these groups. Feedlot surveys were conducted either as interviews (online meetings and face-to-face) or through participants filling out an online digital survey. The list of feedlots for inclusion in the survey grew as information was gathered through survey responses.

End user and cattle transport contacts for inclusion in the end user and cattle transport surveys were gathered from responses to the feedlot survey and from industry contacts. Once identified, surveys were conducted by participants filling out an online digital survey or by phone call.

All surveys were conducted from 12 April 2024 to 31 May 2024.

3.1.3 Data analysis

The survey responses were grouped by ABARES region and the relative percentage contribution to industry capacity/turnover of each ABARES region (and State) was calculated. These values were then used as a representative sample of the entire feedlot industry for extrapolation against industry capacity data.

Baseline capacity and turnover data for FY23 for New South Wales, Victoria, Queensland, South Australia, and Western Australia was sourced from the MLA Q4 2023 Lot Feeding Brief (MLA, 2024). Additional capacity and turnover data were added to the MLA baseline data from the Tasmanian survey results. From the baseline data, estimated head on feed and turnover was calculated for each ABARES region for feedlots >10,000 head and <10,000 head.

Survey results were exported to Microsoft Excel® and basic statistics (counts and averages weighted by turnover) were calculated for key survey questions by category (size and ABARES region). Where available, results were compared to the literature to determine validity.

This process was repeated for end user and transport company surveys.

3.2 Phase 2

3.2.1 Global technology search

The global technology search was performed in Scopus and Web of Science databases and relevant professional Australian and International websites using an appropriate combination of key words and limit the search for last 24 years (2000 – 2024) to capture recent research and development. A list of search keys can be found in Table 1.

Table 1. **A list of Scopus database search keys**

Scopus Search keys
Manure OR Feedlot AND value-add AND nutrient
Effluent AND Feedlot AND Cattle AND Nutrient
Solid liquid separation AND Manure AND Feedlot OR Dairy OR Cattle
Manure AND Feedlot AND Cattle AND Management
Effluent AND Feedlot AND Cattle AND Management
Manure AND Feedlot OR Dairy OR Cattle AND Valorisation
Manure AND Feedlot AND Cattle AND Management AND Techn*
Effluent AND Feedlot AND Cattle AND Management AND Techn*
Manure AND feedlot AND cattle AND management AND emission AND Techn*
Manure AND feedlot AND Cattle AND Anaerobic digestion
Vermicompost AND Emission AND Manure
Manure AND feedlot OR dairy AND compost*
Manure AND Feedlot OR Dairy OR Cattle AND Organo-mineral Fertil*
Manure AND Feedlot OR Dairy OR Cattle AND Biomass conversion

The output of the search was further refined by omitting the articles not closely relevant to the current study. A list of keys used to refine the search results are given in Table 2. Any entries in the search appeared without author name, publication name or date has also been removed. The peer reviewed articles and book chapters were retained in the refined search database.

Table 2. Keys used to refine the initial Scopus search results

Antibiotics	Drug
Hormones	Mortality
Pathogen	Heavy & trace metals
Biodegradation & Antibiotics	Hygiene
Pesticides	Toxicology
Parasite	Diatom
E. coli	Egg & Shell
Amoxicillin	Salinity
Antimicrobial	Aquifers
Pharmaceutical	Social
Tetracycline	Weed seeds
Gene	Ecological
Human health & Safety	Distillers

In addition to the peer reviewed publications, we also used various reports published by various government, non-government agencies and research organisations. A list of grey literature used is given in Table 3.

Table 3. List of grey literature used in the current report

Name of the report	Publisher
The benefits of using compost for mitigating climate change report	Department of Environment, Climate Change and Water NSW, Sydney.
Energy from feedlot wastes: Feasibility study options	Meat & Livestock Australia, Sydney
Biogas Opportunities for Australia	Australian Renewable Energy Agency (ARENA)
Australia's bioenergy roadmap	Australian Renewable Energy Agency (ARENA)
Outlook for biogas and biomethane: Prospects for organic growth	International Energy Agency, France (IEA), Paris
Increasing the Value of Animal Manure for Farmers	U.S. Department of Agriculture (USDA), USA.
On-Farm composting handbook	Northeast Regional Agricultural Engineering Service, Ithaca, N.Y.
Reference manual for the establishment and operation of beef cattle feedlots in Queensland	Department of Primary Industries and Fisheries, Queensland Brisbane
Identifying impacts from food and farm digestates: Final Report	The Waste and Resources Action Programme (WRAP), Oxon, UK & Aqua Enviro Ltd., West Yorkshire, UK.
Market analysis of opportunities in Australia for anaerobic digestion deployment	ReNu Energy Limited
Beef cattle feedlots: Waste management and utilisation	Meat & Livestock Australia, North Sydney, NSW
Thermal Energy Recovery from Feedlot Manure – Pilot Trials	Meat & Livestock Australia, North Sydney, NSW
Feedlot Mass Balance and Greenhouse Gas Emissions – A Literature Review	Meat & Livestock Australia, North Sydney, NSW
Wastes to profits	Meat & Livestock Australia, North Sydney, NSW
Feasibility of using feedlot manure for biogas production	Meat & Livestock Australia, North Sydney, NSW
Energy from feedlot wastes: Feasibility study options	Meat & Livestock Australia, North Sydney, NSW
Pilot testing pyrolysis systems and reviews of solid waste use on boilers	Meat & Livestock Australia, North Sydney, NSW
Quantification of Feedlot Manure Output for Beef-Bal Model Upgrade	Meat & Livestock Australia, North Sydney, NSW
Effect of feed withdrawal on truck effluent, animal welfare, carcase characteristics and microbiological contamination of feedlot cattle	Meat & Livestock Australia, North Sydney, NSW
Review of effluent spillage and animal welfare during livestock transport: A discussion paper	Meat & Livestock Australia, North Sydney, NSW

The technologies will be assessed depending on the Technology Readiness Level using an assessment framework proposed by United Nations Environmental program (UNEP, 2012). Based on the assessment top 10 technologies of manure and effluent management will be selected. The technology assessment criteria and evaluation matrix are given in Tables 4 and 5.

Table 4. Technology assessment criteria, weight and scoring range

Criteria	Weight	Scoring range	
		Technology 1	Technology…
Benefits	10	1–10	1–10
Drawbacks	10	1–10	1–10
Biomass volume reduction	10	1–10	1–10
Nutrient loss/recovery	10	1–10	1–10
Ammonia & GHG emission	10	1–10	1–10
Capital and operation cost	10	1–10	1–10
Operational volume	10	1–10	1–10
Operation for manure per 10000 head feedlot	10	1–10	1–10
Science based innovation potential for feedlots	10	1–10	1–10
Technology readiness level for feedlots	10	1–10	1–10

Table 5: **Technology evaluation matrix**

Criteria*	Weight	Technology 1		Technology…	
		Assigned score	Weight x Assigned score	Assigned score	Weight x Assigned score
Total weighted score					

** Criteria, weights and scoring are shown in Table 4*

3.2.2 Lifecycle assessment of technologies

The life cycle assessment (LCA) was conducted in two stages. First, a representative 10,000 SCU feedlot was developed using the *Feedlot Carbon Footprint Calculator v12.1* (Wiedemann & Longworth, 2024) Agricultural emissions were determined using methods not inconsistent with the National Greenhouse Gas Inventory – NGGI (Department of Industry Science and Resources, 2022) except where specified, and energy-related emissions were determined using methods from the National Greenhouse Accounts Factors (Commonwealth of Australia, 2023). Fifth Assessment Report (AR5) global warming potentials over a 100-year time horizon (GWP_{100}) of 28 for methane and 265 for nitrous oxide (Commonwealth of Australia, 2023) were used. Methane density was assumed to be 0.6784 kg / m3.

The 10,000 SCU feedlot with a mix of short-, mid-, and long-fed cattle, corresponding to a weighted average of 144 days of feed (which aligns with the industry average of 140 days determined by the industry survey in Phase 1) and was assumed to be located in Queensland and to stockpile manure (as

this was the most common strategy reported in the industry survey). Truck effluent was assumed to be treated offsite and were outside the emission boundary.

The emission boundary of the LCA was cradle-to-feedlot gate, with results reported in tonnes of carbon dioxide equivalent (t CO_2-e), disaggregated into Scope 1, 2 and 3 greenhouse gas emissions. Emissions associated with land application of manure products were also assessed to draw a true comparison between the greenhouse gas emissions arising from different manure processing methods.

The emission boundary of the LCA was cradle-to-feedlot gate, with results reported in tonnes of carbon dioxide equivalent (t CO_2-e), disaggregated into Scope 1, 2 and 3 greenhouse gas emissions. The Greenhouse Gas (GHG) Protocol (2014) defines these as:

- Scope 1: direct GHG emissions that occur from sources that are owned or controlled by the business.
- Scope 2: GHG emission from the generation of purchased electricity consumed by the business.
- Scope 3: GHG emissions that are a consequence of the activities of the company but occur from sources not owned or controlled by the company.

An additional theoretical scenario (the uptake of a covered anaerobic digester and using biogas as an onsite energy source to replace LPG/natural gas), where manure was captured in a similar fashion to what is done within some dairy free stall barns, using either slats or flushed lanes. This was explored using a 10,000 SCU feedlot, to demonstrate the difference between the potential energy generation, costs and benefits, and greenhouse gas emissions for a strongly contrasting and novel approach to manure management. As there are no Australian-specific emission factors for feedlot manure treated in a covered anaerobic digester/covered pond, factors for pigs were used (Commonwealth of Australia, 2024).

Following the completion of the first stage of the LCA, the results were extrapolated to industry level based on a total capacity in 2023 of 1.2 million SCU. Queensland-specific methane conversion factors (MCFs) and grid electricity emission factors were used in this analysis. As more than half of the industry is located in Queensland and there is no material difference between MCFs, this did not result in a material error. Industry-wide results were reported separately to the 10,000 SCU analysis.

3.2.3 Cost-benefit analysis

An ex-ante private cost-benefit analysis (CBA) was completed. The CBA covered the shortlisted nine technologies/strategies – three technologies/strategies for each product category (manure, feedlot effluent and transport effluent) against a business-as-usual (BAU) scenario. The BAU scenario was for the 10,000 SCU feedlot that stockpiled manure.

The CBA for the technologies was completed using data collected from the survey (e.g., pen cleaning and processing costs, selling prices), the literature, and supplemented where needed with cost estimates collected from key stakeholders, including industry and service providers. Costs associated with capital, operating, and inputs were all accounted for in the analysis. The lifespan of each technology was assumed to be ten years. A discount rate of 4% was used to determine the present value of costs and benefits associated with each technology/strategy.

3.2.4 Adoption rates

Realistic adoption rates for each technology (see section 4.2.6) were determined using the CSIRO's Adoption and Diffusion Outcome Prediction Tool – ADOPT. A detailed description of the development and underlying method of ADOPT has been published in the peer-reviewed literature (Kuehne et al., 2017) and is not repeated in detail here. Briefly, the tool predicts peak adoption level and time to near peak adoption based on four aspects of adoption (See How ADOPT Works).

- Characteristics of the innovation
- Characteristics of the population
- Actual advantage of using the innovation
- Learning of the actual advantage of the innovation

The underlying data entered into ADOPT are reported in the Appendix.

3.2.5 Case study analysis of pelletised organo-mineral fertiliser

For one strategy to value-add manure (into pelletised organo-mineral fertiliser), case study analysis was conducted to evaluate whether the product was a financially viable replacement for synthetic fertilisers (urea, DAP, MOP etc) and whether there was any environmental benefit (from a product carbon footprint perspective) of doing so.

Gross margins reported by NSW DPI (NSW DPI, 2012) for maize silage and wheat (no till) were updated using 2023 prices and new synthetic fertiliser application rates calculated. The product carbon footprints of the maize silage and wheat were determined using a modified version of the Grains Greenhouse Accounting Tool (G-Gaf) (Eckard & Armstrong, 2016) , which included field emissions associated with application of pelletised feedlot manure and the embodied emissions of the pellets. For both crop types, business-as-usual (BAU) production (synthetic fertilisers) was compared with an alternative scenario where the system used pelletised organo-mineral fertilisers in place of synthetic. Key assumptions and results for the case studies are reported in the Appendix, including a sensitivity analysis of assumptions regarding the nitrogen use efficiency (NUE) of the organo-mineral fertiliser, and a sensitivity analysis of assumptions regarding the emission boundary of the product carbon footprint of the organo-mineral fertiliser.

4. Results

4.1 Phase 1

The Australian feedlot industry is spread across 16 ABARES regions with Queensland and New South Wales making up 86% of industry turnover

Table 6). Average head on feed numbers for 2023 were estimated to be 1,244,712 head with a turnover of 3,270,010 head (MLA & Lukey, 2024).

Of the 3,270,010 head turnover, 68% were from feedlots of >10,000 head in capacity and the remaining 32% were from feedlots with a capacity <10,000 head (MLA & Lukey, 2024).

Table 6. Estimated Australian feedlot industry statistics by ABARES region for 2023

ABARES Region	Cattle on feed (head)	Turnover (head)	Regional contribution to industry turnover (%)
Queensland	**742,237**	**1,958,091**	**59.9%**
Northern Coastal - Mackay to Cairns	8,081	21,317	0.7%
QLD Central North	10,085	26,606	0.8%
Western Downs and Central Highlands	238,481	629,136	19.2%
Eastern Darling Downs	385,321	1,016,513	31.1%
Southern Coastal - Curtis to Moreton	100,269	264,519	8.1%
New South Wales	**320,317**	**845,027**	**25.8%**
North West Slopes and Plains	105,505	278,333	8.5%
Tablelands (Northern Central and Southern)	35,900	94,708	2.9%
Central West	36,099	95,233	2.9%
Riverina	142,813	376,754	11.5%
Victoria/Tasmania	**76,748**	**188,811**	**5.8%**
Wimmera	19,232	46,028	1.4%
VIC Central North	17,309	41,425	1.3%
Southern and Eastern Victoria & Tasmania	40,206	101,358	3.1%
Western Australia	**56,956**	**150,254**	**4.6%**
Central and Southern Wheat Belt	50,037	132,002	4.0%
South West Coastal	6,919	18,252	0.6%
South Australia	**48,454**	**127,827**	**3.9%**
Murray Lands and Yorke Peninsula	18,855	49,742	1.5%
South East	29,599	78,085	2.4%
Total	**1,244,712**	**3,270,010**	**100%**

The survey collected data on the breakdown of cattle in three classes: domestic (<100 days on feed [DOF]), short-fed export (100 – 200 DOF) and long-fed export (>200 DOF). Average values of 86, 118 and 250 were adopted to represent the DOF of domestic, short-fed and long-fed cattle. Based on this, an average DOF of 140 was calculated from the survey data.

From DOF, a weighted average number of cattle on feed was generated for each feedlot from the survey data, resulting in an average of 18,783 head.

Entry and exit weights were assigned to each cattle class based on industry knowledge. Average entry and exit weights of 415 kg and 632 kg respectively were calculated from this for the surveyed operations. This equated to an industry average daily gain (ADG) of 1.6 kg LW/day. Based on the

calculated average entry and exit weights for each feedlot, the industry average liveweight for cattle on feed was calculated to be 523 kg or 0.95 Standard Cattle Units (SCU).

4.1.1 Feedlot manure

Manure is harvested from the surface of feedlot pens by feedlot staff or contractors before direct land application or stockpiling in a designated area. In some operations (especially in summer-dominant rainfall areas), manure is stockpiled (i.e., manure cleaned from most of the pen area and then stored) within the pen for an extended period prior to removal.

The national average pen cleaning interval was found to be 72 days (n = 25) at a cost of $9.86/t (n = 8) to the feedlot (**Table** 7). There was no correlation observed between pen cleaning frequency and manure harvesting cost per tonne. No relationship (P = 0.44) was identified between pen cleaning interval and general weather pattern (summer vs winter dominant) though the small dataset was acknowledged.

Table 7. Average pen cleaning interval and cost (weighted by mass of harvested manure)

State	Pen cleaning interval (days)	Manure harvesting cost ($/t)	Annual manure yield (t / head / year)
NSW	83	10.21	2.2
QLD	68	9.25	1.6
SA	65	10.67	1.2
VIC/TAS	62	11.43	2.0
WA	117	ND	0.7
National	**72**	**9.86**	**1.7**

ND: No data.

Only two of the respondents used large volumes of bedding in general feedlot pens with most operators utilising bedding in quarantine or hospital pens. Pen bedding was used by 36% of survey respondents, with wood chip being the most popular bedding material. Cereal straw was used in the feedlots surveyed in Victoria and South Australia.

Annual harvested manure yield (wet mass, n = 24) was 1.7 t/head (1.8 t/SCU) with a range of 0.7 to 3.7 t/head (see **Figure *1***). One other feedlot reported manure harvest rates that equated to a yield of 6.8 t/SCU.

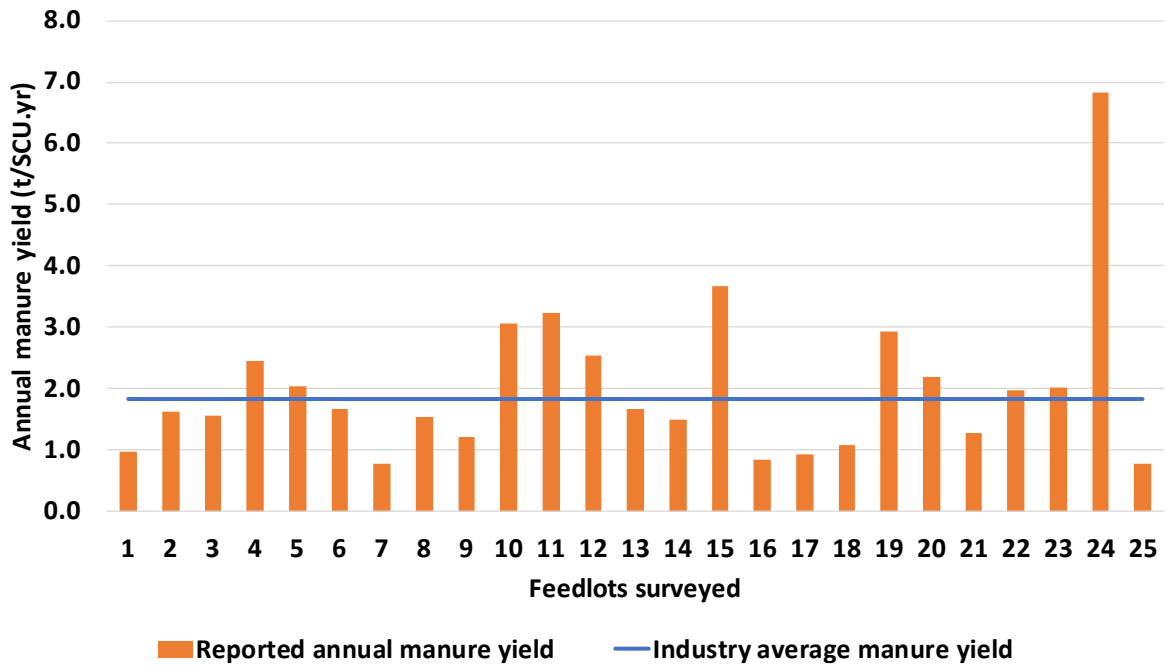

Figure 1. Reported annual harvested manure yields from surveyed feedlots (n = 25) and industry average harvested manure yield

This is within the ranges stated in the literature (R. J. Davis et al., 2010; Tucker et al., 2015) of 0.4 to 5.6 t TS/SCU. The average of close to 2 t was slightly high based on biological production rates. From industry average harvested manure yield and the national estimate for head on feed, total manure generation for the feedlot industry was estimated to be 2.15 million tonnes in 2023.

Excretion rates may vary in cattle based on intake and digestibility, but this will result in a reasonably narrow range, potentially from 0.5 t to 1.2 t on a dry basis, assuming 80% digestibility, at point of excretion. Assuming industry average moisture levels of 35%, this may result in 0.8 to 1.8 t (wet basis) per SCU. However, manure will degrade on the feed pad, resulting in lower mass at harvesting than at excretion.

The wide range in manure harvest rates is influenced by a number of variables beyond biological factors. Harvesting may not cover a full year resulting in lower apparent yields or may cover more than a full year increasing apparent yield. Many feedlots added woodchip or other bedding, which will contribute some mass. The volume of bedding used is typically limited by the cost and will not add several tonnes to the harvested manure levels without being prohibitively expensive.

With these variables noted, the dominant variable influencing high reported manure removals is soil contamination. Davis et al, (2010) found this could be ¾ of the material removed from the pen and in some cases even more. Considering this, soil contamination is likely for the higher harvested rates reported from feedlots.

Once stockpiled, manure is aged on an ad-hoc basis before being applied to land on or offsite, composted, or sold to third parties for further processing into specialised products, such as specially marketed compost or granules. Manure composted by the feedlot may also occasionally be sold for further processing into specialised products.

Manure product flows are summarised by region and end use in **Table** 8 (by %) and by end use in **Table 9** (by mass). Stockpiled manure accounted for around 70% of feedlot industry manure product sold by mass. Raw and composted products accounted for 15% each.

Table 8. Manure product flows (by %) summarised by end-use and State

Region	Raw			Stockpiled			Composted		
	Applied on-site	Applied off-site	FP*	Applied On-site	Applied off-site	FP*	Applied On-site	Applied off-site	FP*
NSW	3%	0%	ND	9%	1%	11%	ND	ND	ND
QLD	8%	ND	ND	4%	19%	13%	ND	9%	ND
SA	ND	ND	ND	3%	ND	ND	1%	1%	ND
VIC/TAS/WA	4%	0%	0%	3%	2%	6%	1%	3%	1%
Total	**15%**	**0%**	**ND**	**19%**	**21%**	**30%**	**2%**	**12%**	**1%**

**FP: Further processing.*

ND: No data.

Table 9. Manure product flows (in wet tonnes) summarised by end-use

End use	Raw	Stockpiled	Composted	Total
Applied - onsite	323,007	415,324	24,133	**762,463**
Applied - offsite	354	454,697	266,665	**721,716**
Further processing	ND	650,380	16,625	**667,004**
Total	**323,360**	**1,520,401**	**307,422**	**2,151,184**

ND: No data.

4.1.1.1 Manure composition

Feedlot manure is a nutrient rich soil amendment with high organic matter; however, final product composition depends on any processing steps undertaken. Typical composition of raw, stockpiled, and composted manures determined previously by Tucker et al. (2015) are presented in Table 10 as 2015 values.

Survey respondents were asked to provide up to date laboratory analyses for manure products, however, limited responses (n = 6) were received, and stockpiled manure was the only product covered. A publicly available analysis was found for one composted product and included in the data. These values are also reported in **Table 10** as 2023 values.

Table 10. Typical macronutrient composition of manure products from Tucker et al. (2015) compared with 2023 survey results

		Product		
		Raw	**Stockpiled**	**Composted**
Moisture %	**2015**	34	36.8	26
	2023	ND	27.4	25
N %	**2015**	2.5	2.18	2.11
	2023	ND	2.05	2.1
P %	**2015**	0.96	0.8	1.31
	2023	ND	1.54	0.9
K %	**2015**	1.86	1.86	2.49
	2023	ND	1.28	2
S %	**2015**	0.44	0.45	0.42
	2023	ND	0.46	0.6
TOC %	**2015**	ND	ND	ND
	2023	ND	21.9	28

Compared with the literature values from Tucker et al. (2015) for stockpiled manure, reported N was similar (2.05% vs 2.18%), P was considerably higher (1.54% vs 0.80%), K was lower (1.28% vs 1.86%), S was similar (0.46% vs 0.45%), and moisture was lower (27.4% vs 36.8%). TOC was not previously reported.

The total nutrient volumes produced in feedlot manure products were determined (see **Table** 11) using the volumes reported in **Table 9** and the typical macronutrient compositions from the industry survey reported in 10 (except for raw manure which used the Tucker et al. (2015) values from 10.

Table 11. Total volume and key macronutrients produced in feedlot manure products in 2023

	Mass produced – wet basis (t/yr)	**Mass produced – dry basis (t/yr)**	**N (t/yr)**	**P (t/yr)**	**K (t/yr)**
Raw manure	323,360	210,184	5,255	2,018	3,909
Stockpiled manure	1,520,401	1,109,893	22,753	17,092	14,207
Composted manure	307,422	230,567	4,842	2,075	4,611
Total	**2,151,184**	**1,550,644**	**32,849**	**21,185**	**22,727**

4.1.1.2 Manure marketing and end-use

The main markets for manure products were determined from end user responses (n = 7) to survey questions on how the products were utilised. Several respondents indicated that manure products were used in more than one application, e.g., broadacre cropping and pasture/fodder production, hence the percentages do not sum to 100%. Over two-thirds of respondents (n=7) used manure products in broadacre cropping, and over half used manure products in pasture or fodder production and in horticulture (products for human consumption) and vegetable production (**Figure *2***). Two of the end-users surveyed were feedlot managers; both reported that feedlot manure products were used in broadacre cropping, and one reported that the products were also used in pasture or fodder

production. One respondent reported manure products being used in every end-market listed in **Figure *2***.

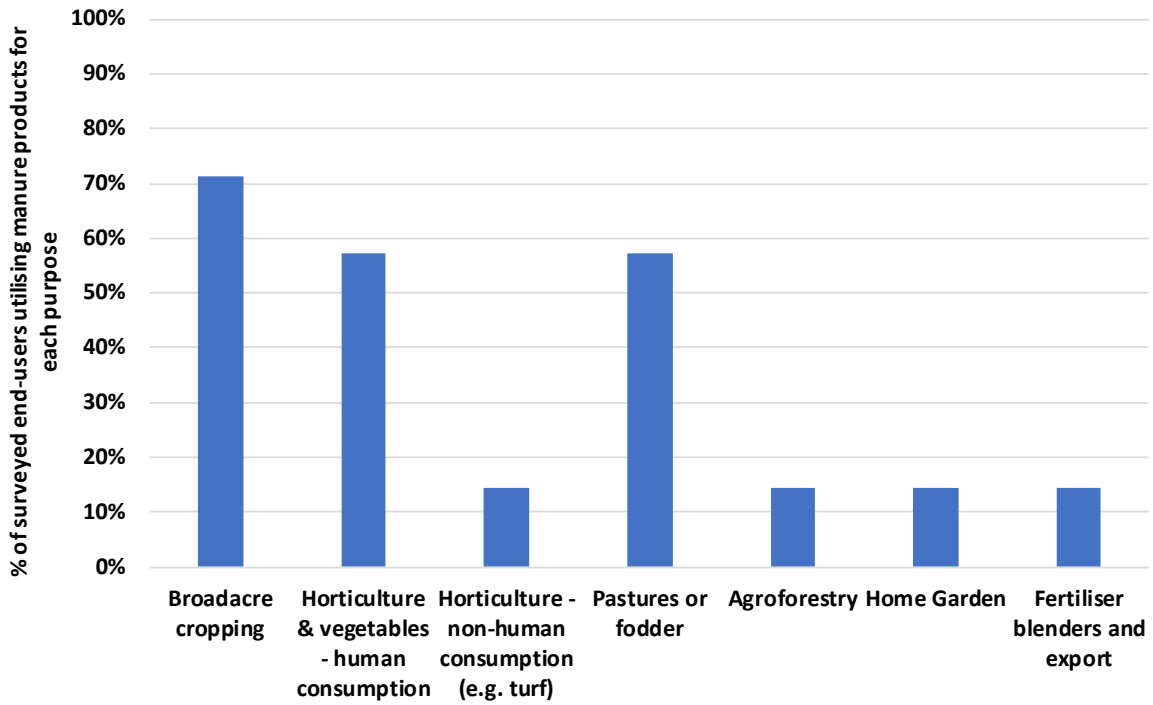

Figure 2. End-uses for manure products (n = 7)

Based on information from interviews with end-users, higher value manure products (e.g., composted manure) were more commonly used in horticulture and irrigated cropping whereas lower value products (e.g. raw and stockpiled manure) were more commonly used in dryland cropping and grazing scenarios due to the lower relative gross margins per hectare of the land used.

Reported application rates for manure products used in broadacre cropping and grazing scenarios ranged from 5 to 60 t/ha, however, frequency of application ranged from annual to every three to four years. In horticultural or similar (e.g., tree crops, viticulture) applications, products were reported as being used for mulch or (in pellet form) applied down tubes/tree guards at an equivalent rate of 0.1t/ha.

End users reported that they calculated application rates based on soil analyses and crop removal rates. One agronomist interview suggested best practice in cropping scenarios was calculation of application rates based on P requirements with supplementary N sources (typically as urea) to meet crop requirements.

A common use case for manure products was the amelioration of degraded land via large upfront application rates. One lot feeder operating an integrated feedlot, grain and grazing business shared their experience of purchasing heavily degraded neighbouring land and improving soil fertility with manures to drastically improve carrying capacity and expand their backgrounding enterprise. In another interview, one agronomist, who advises on the use of manures in grazing systems, reported

a $28/head improvement in animal performance from restoring soil biology through manure application.

Separate to the interviews conducted as part of this project, a Central Queensland agronomist used application rates of 20 t/ha in year 1 and 40 t/ha in year 2 of a crop research program and then "mined" the nutrients for the next 8 years – "No nitrogen was applied to that system after 2016 [through to 2024] and its performance was (and still is) stellar"(Aisthorpe, 2024, GRDC Groundcover Issue 169) – however application costs were very high. Considering this was in a public trial, some concerns arise from seeing this approach taken and communicated considering it is not best practice from an environmental perspective to use such very high application rates.

4.1.1.3 Manure value

Gross margins were calculated for each manure product by subtracting sale price from the sum of manure harvesting cost and any additional processing cost (Table 12). Composted manure sold to further processing resulted in the highest calculated gross margin, however, this was based on a very limited dataset. Stockpiled manure sold to further processing had the worst calculated gross margin. All stockpiled manure products resulted in negative calculated gross margins on average (i.e. manure management was a net cost to the business). Note that this may not be the case on an individual feedlot basis (e.g., if there are lower than average pen cleaning or processing costs and/or a higher selling price for stockpiled manure).

Table 12. Calculated gross margins for feedlot manure products, where all values are reported in $/t.

		End use		
		Applied on-site	**Applied off-site**	**Further processing**
Manure harvesting cost		**9.86**		
Raw	**Processing cost**	0	N/D	N/D
	Sale price	10.39	N/D	N/D
	Gross margin	**0.53**	**N/D**	**N/D**
Stockpiled	**Processing cost**	3.76		
	Sale price	13.21	12.71	10.92
	Gross margin	**-0.41**	**-0.91**	**-2.7**
Composted	**Processing cost**	12.51		12.52
	Sale price	24.67	25.26	30
	Gross margin	**2.3**	**2.89**	**7.62**

ND: No data.

Based on calculated manure product flows (Table 9) and gross margins (Table12), industry revenue was estimated by State (**Table** 13). Based on the available data, manure harvesting and processing was found to be a loss-making exercise for the industry at present.

Table 13. Calculated industry revenues and gross margins for manure processing, reported by State

State	Manure products sold (t)	Revenue ($)	Gross margin ($)	Gross margin ($/t)
NSW	534,676	$6,282,161	-$722,447	-$1.35
QLD	1,125,812	$15,805,645	-$536,451	-$0.48
SA	80,442	$1,347,107	$40,328	$0.50
TAS/VIC/WA	410,254	$6,118,958	-$963	-$0.00
National	**2,151,184**	**$29,553,871**	**-$1,219,532**	**-$0.57**

Respondents were asked to provide insight into how pricing structures were determined for feedlot manure products and these results are reported in Figure 3. As the respondents generally gave more than one reason or basis for pricing structures, the percentages do not sum to 100%. The x axis lists all the stated bases for pricing structures, and the y axis demonstrates the percentage of respondents who indicated that they use each pricing structure.

Twelve respondents provided insight into pricing structures for raw manure, with over 30% of these respondents indicating that cost-recovery was the or one of the key valuation strategies. Twenty respondents provided detail for stockpiled manure with several indicating that multiple strategies are used to determine pricing. 50% of these respondents stated that supply/demand drivers and previous pricing structures were key considerations. Seven respondents answered for compost pricing, with over half citing supply and demand as the major or one of the major considerations. Previous pricing structures were also referenced by more than 40% of compost respondents.

There were two respondents for other manure products (e.g., pellets or granules). One respondent stated that both nutrient pricing for carbon and the general composition were key considerations whilst the other respondent stated that an in-kind arrangement was used to determine the selling price of the manure product.

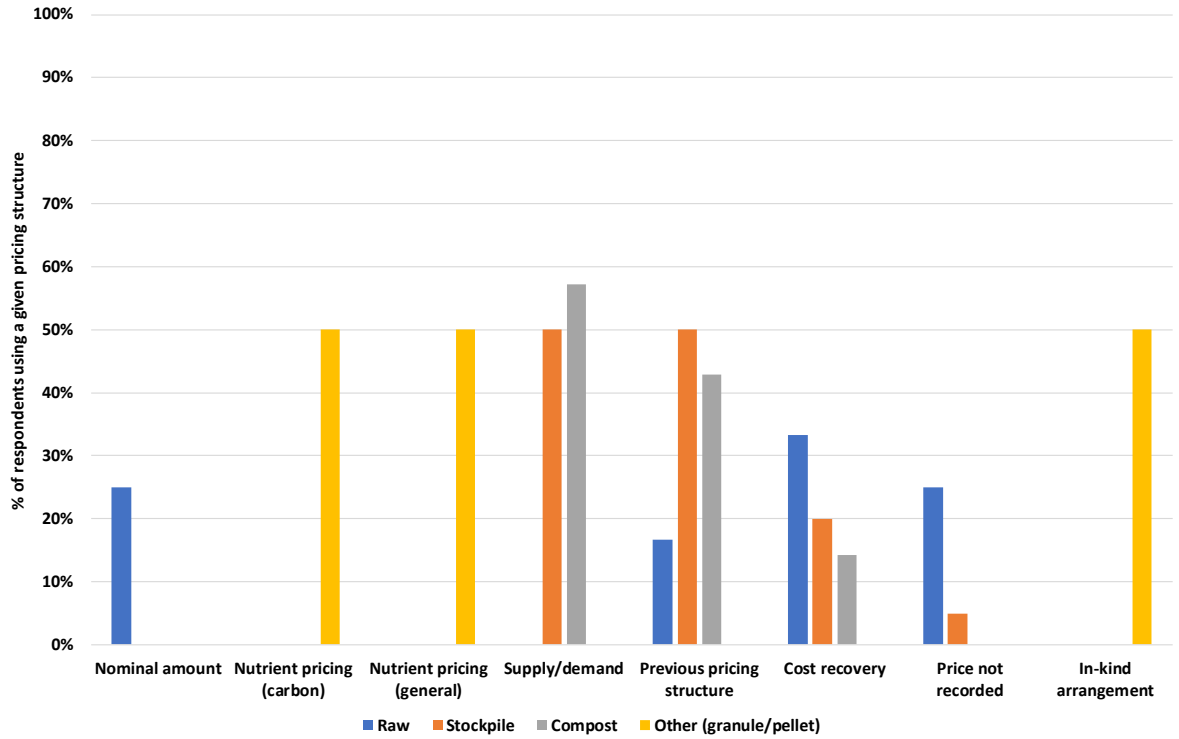

Figure 3. Feedlot manure product pricing structures

Based on the responses in Figure 3, a large number of lot feeders are relying on previous pricing structures to set selling prices for manure products. Reevaluating selling prices in light of nutrient composition and/or investigating whether the broader market price for manure products has changed may be of value to these businesses, e.g., to determine whether there is scope to raise selling prices by marketing the products better, e.g., based on nutrient content.

From the composition of manure products presented in Table 10 and spot prices for corresponding synthetic fertilisers, macronutrient values were calculated for each product (Table 14) equivalent to the value at the point of delivery to the farm/end-user.

The synthetic fertilisers used to represent each macronutrient were urea for N (46% N), triple superphosphate (TSP) for P (46% as P_2O_5 [converted to 20% as P]), MOP for K (50% K), and gypsum for S (19% S).

Total theoretical nutrient values were determined as the sum of the values of all nutrients, however, as these values are highly unlikely to ever be realised, reasonable discounted nutrient values were also determined. The discounted rates valued 50% of the P and K, and 30% of the N available in the raw and stockpiled products and 10% of the N in the compost. This is a reasonable assumption given the challenges associated with handling and applying manure relative to synthetic fertilisers (may require specialised equipment and management). Several nutrients must also be balanced with plant requirements (e.g., a nutrient budget required), and may not be in forms that are readily available to the crop, which may increase the need for sampling of soil and plant tissues to monitor nutrient levels. Further, manure is a diffuse nutrient source compared to fertiliser which can be banded with seed, and as a result needs to be applied at higher rates over several years to ensure sufficient levels for cropping. These factors typically increase the management and handling requirements of manure

relative to conventional fertilisers. Further detail on the challenges associated with using manure products is provided in 4.1.1.4 Barriers to further adoption.

Table 14. Total costs of manure products and the equivalent macronutrient value (as spread), based on equivalent costs of synthetic fertiliser.

Parameter	Raw	Stockpiled	Composted
Industry average selling price ($/t)	$10.39	$12.71	$25.26
Transport and spreading costs ($/t)	$30.00	$30.00	$30.00
Total cost to end user ($/t)	$40.39	$42.71	$55.26
$N/t**	$26.49	$24.34	$25.68
$P/t *	$21.84	$39.19	$23.63
$K/t*	$15.72	$12.12	$19.50
$S/t*	$0.88	$0.73	$0.97
Total theoretical macronutrient value ($/t)	$64.94	$76.37	$69.77
Total discounted macronutrient value ($/t)	**$26.73**	**$32.95**	**$24.13**
Variance – nutrient value	$13.66	$9.76	$31.13
Variance – current selling price	-$16.34	-$20.24	$1.13

*Price and composition of synthetic nutrient equivalents: Triple Superphosphate for P ($700 $/t – 20% P), Muriate of Potash for K ($650/t – 50% K) (Cacula Pistoia, 2023), gypsum for S ($40/t – 18.6% S) **. N based on urea ($750/t – 46% N). N discounted to consider loss rates and nutrient availability. Assumed 30% available from raw and stockpiled, and 10% from composted.

**No data available so value for stockpiled manure used.

Based on Table 14, there is unrealised value for raw and stockpiled feedlot manure products based on the available nutrients. However, Table 14 indicates that composted feedlot manure may be about right based on the availability of the nutrients.

One key variable in this analysis is whether the theoretical relative advantages of compost (more consistent product, potentially easier to store and spread) are known and realised by the end-user. If end-users, for example, view all feedlot manure products as blanketly more challenging to use than synthetic alternatives the discounted rates in Table 14 may be an accurate reflection of the market. However, end users that recognise the relative advantages of compost over stockpiled or raw manure indicate other factors are contributing to the valuation than captured by nutrient value alone. This may include better handling, less bulk, no weed seeds, no odour and low or no pathogen problems which opens up market opportunities for horticultural crops with higher capacity to pay. Interestingly, the selling price of raw manure has increased considerably over the past two-decades whereas the selling price of composted feedlot manure has decreased, i.e., end-users are valuing manure products based on nutrient composition (which is not necessarily better in compost) and are not recognising or valuing other benefits of composted feedlot manure over raw product.

A review of feedlot manure product prices reported in the literature (EA Systems, 2002; Madden, 2011; Tucker et al., 2015; Wylie, 2008) was conducted, and prices adjusted for inflation (to 2023), and then compared with the results of this industry survey (see Table 11). From 2002 to 2023 the average selling price of raw manure increased by 87%, the selling price of stockpiled manure held roughly constant (increased by 7% over 2008 – 2023), whilst the selling price of composted manure was found

to have fallen by 28% between 2002 and 2023. There may have been limited datasets available in the earlier analysis, however, the broad trend that may be interpreted is that end-users are less willing to pay higher prices for a value-added product such as compost when the nutrient composition is similar to that of a cheaper, raw product. Lot feeders wishing to sell composted manure should therefore adopt or focus on strategies that sell to high value markets that value other characteristics such as low odour, pathogens and weed seeds, such as horticulture or even bagged product.

One newer value factor in manure is the carbon value. This was difficult to quantify, as the decomposition rate is uncertain and further research is needed to quantify long-term sequestration potential. That noted, some value is likely from a carbon sequestration perspective, and this is an area warranting further research.

The end-users surveyed and interviewed (n = 8) also reported what for what they principally valued feedlot manure products (see Figure 4). 75% of the surveyed end-users valued manure based on macronutrients (mainly N and P), 12.5% on carbon value ,and 12.5% on application equipment availability (e.g., ease of application) .

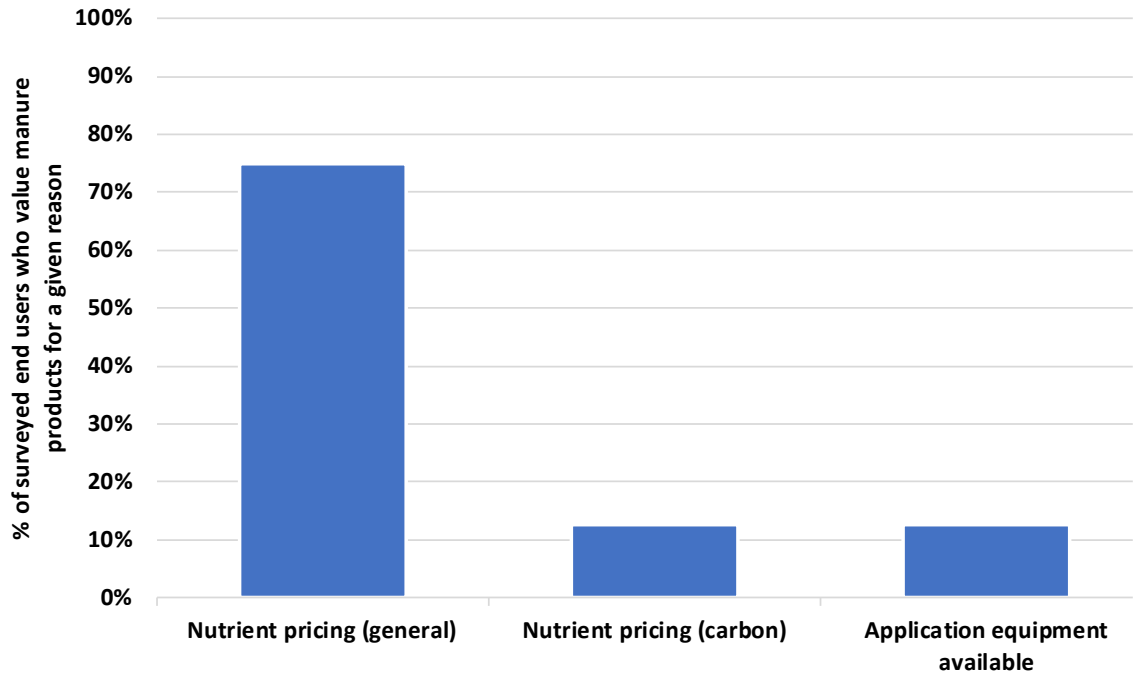

Figure 4. End-user manure product valuation (n = 8)

End users reported that their valuation considers the total cost of the product applied to the paddock (sum of costs for the product, transportation and spreading) against the equivalent cost to use synthetic fertiliser. When choosing synthetics vs manures, end users will generally choose the lowest cost option that meets the nutrient needs of the crop. Based on discussions with some end users, a rule of thumb is that if the total cost of the product applied to the paddock is <$50/t it will generally be more cost effective than using synthetic fertiliser to meet crop requirements. If end users are incorporating the product into the soil through tillage, total costs are higher (due to increased application costs).

In cropping systems where end users are calculating application rates to meet P requirements, additional N inputs may be required, which must be considered when comparing costs and choosing between synthetic fertilisers or manure products. If application rates were calculated to meet N requirements, there would be a risk of P losses to the environment which can lead to poor outcomes for local water quality and aquatic ecosystems. Grazing systems typically rely on N fixation from legumes in the pasture sward to meet N requirements. Therefore, tailoring application rate to meet P requirements is a cost-effective approach in such systems (GRDC, 2013; Lovett & Scott, 1996) , and it is the principal macronutrient on which feedlot manure products should be valued.

4.1.1.4 Barriers to further adoption

Both lot feeders and end users were asked to provide opinions on the challenges associated with marketing manure products to end-users and the barriers to further adoption of manure products by end-users. In Figure 5 and Figure 6, the x axes list all the stated barriers to adoption, and the y axes correspond to the percentage of respondents who cited each barrier to adoption, i.e., as many respondents cited more than one barrier, the percentages do not sum to 100%.

For lot feeders, more than half reported that they had to overcome contamination and moisture issues (see Figure 5), with a small proportion also citing that they had faced regulatory barriers to selling their manure products as an effective fertiliser.

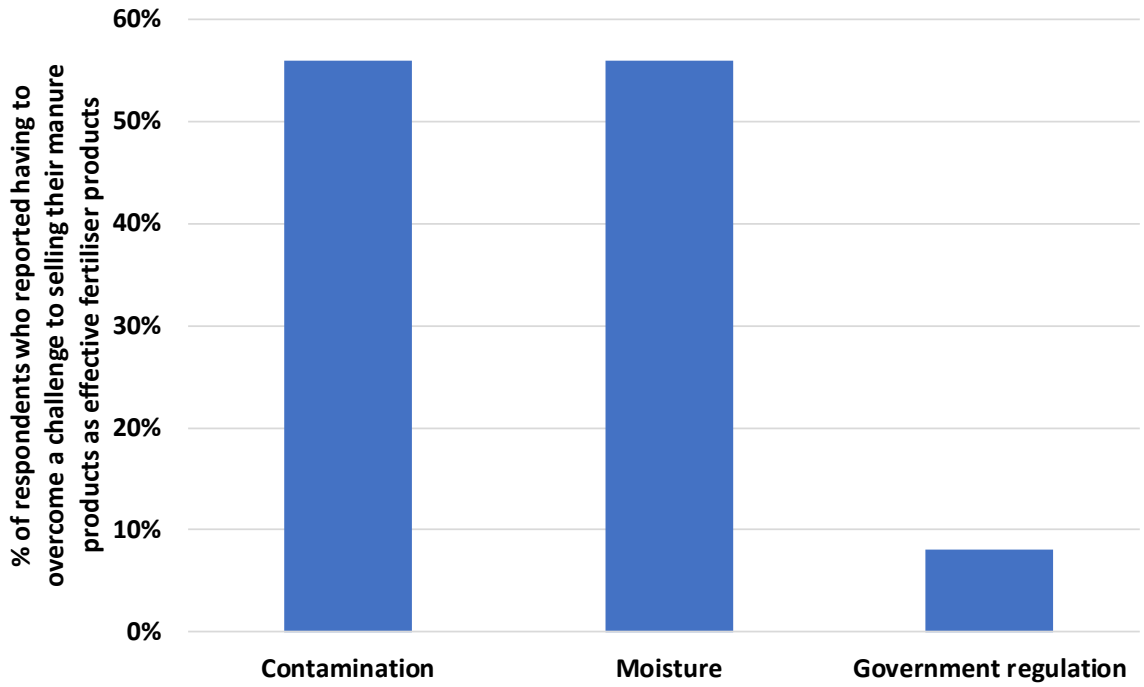

Figure 5. Reported challenges to selling feedlot manure as a fertiliser (n = 25)

Both lot feeders and end-users were surveyed as to what barriers exist to wider uptake of manure products by end-users. Application challenges (including equipment) and the costs associated with transporting and spreading manure products were the most commonly identified barriers (see Figure 6). Almost all end-users (six out of seven) cited transport costs as a barrier to adoption. Approximately a third of those surveyed reported product consistency (or lack of) as a barrier with several also identifying a disconnect between regional supply and demand as a barrier.

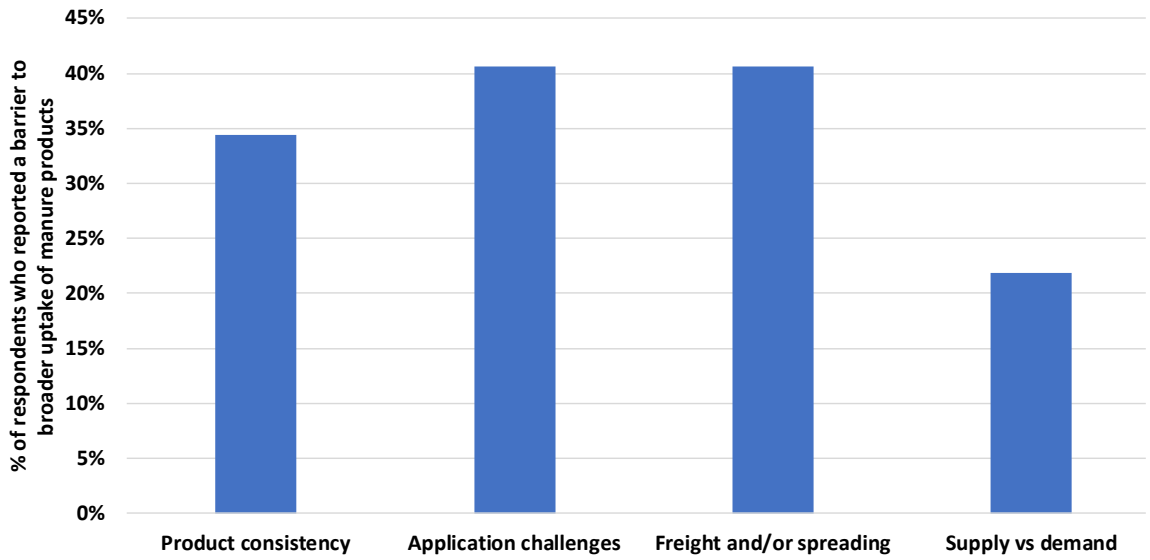

Figure 6. Reported barriers to broader adoption of feedlot manure products by end-users (n = 32)

There are two themes from the survey responses to barriers to adoption: cost and product consistency and practical considerations. Cost incorporates the wide spatial distribution of manure and subsequent transport costs, as well as application challenges/costs. Product consistency and quality includes moisture and gravel contamination.

Where contamination levels are high, it may be necessary to harvest manure from pens more frequently. In some cases, feedlots with a more frequent pen cleaning frequency reported lower quantities of manure harvested per SCU (data not shown) as these lot feeders were harvesting purer manure (i.e., with less dirt and gravel).

As discussed in 4.1.1.3 Manure value, a total cost for manure products applied to the paddock should be <$50/t to be cost effective against synthetic fertilisers (at current prices). The applied cost reflects the cost of the material itself plus freight plus the cost of spreading the material. Feedlots with large on-site or nearby mixed farming (grain and grazing) enterprises have the advantage of heavily reduced transport costs which make manure products more cost competitive when compared with synthetic fertilisers (at current prices). For end-users outside the feedlot industry, however, transport costs can be a major cost barrier to use of feedlot manure products. One agronomist (surveyed as an end-user) stated that he recommends raw feedlot manure to clients if it can be purchased for less than $15/t, and transported for less than $20/t, allowing an additional $16/t for spreading. This maintains the applied cost at less than $50/t and makes the product a viable alternative to synthetic fertilisers.

One lot feeder reported that a factor contributing to the price sensitivity of end users is that, particularly in southern farming or single crop systems, applications of fertilisers occur in between harvests when producers are carrying a large amount of debt without guarantee of a good season ahead. This lot feeder used a novel strategy to reduce risk for the end-user by supplying a low to no interest line of credit to producers supplying grain to the feedlot with the cost of manure coming out of the final bill for the grain. The result was increased demand for feedlot manure products in the local area and a circular economy where nutrients supplied to crops to grow grain to feed cattle were provided by manure from the cattle eating the grain. The same concept could be extended by marketing manure products for use on grazing country backgrounding cattle for feedlots.

The wide geographic distribution of manure across the country and its inherently high transport cost/kg of nutrient are key barriers to the further adoption of manure use. Exacerbating the issue is that there is a geographic disconnect between where manure is generated and where there is the greatest nutrient demand. Approximately 70% of the feedlot industry is located on the QLD Darling Downs or on the NSW Northwest Slopes and Plains, where there is an abundance of highly fertile agricultural land and lower demand for fertiliser at present. Fertiliser spend per hectare is highest in southern Australia, particularly in the Wheatbelt, Riverina, Mallee and Wimmera where farming intensity is higher or soil fertility is generally lower, or a combination of both (ABARES & Read, 2023) (Figure 7).

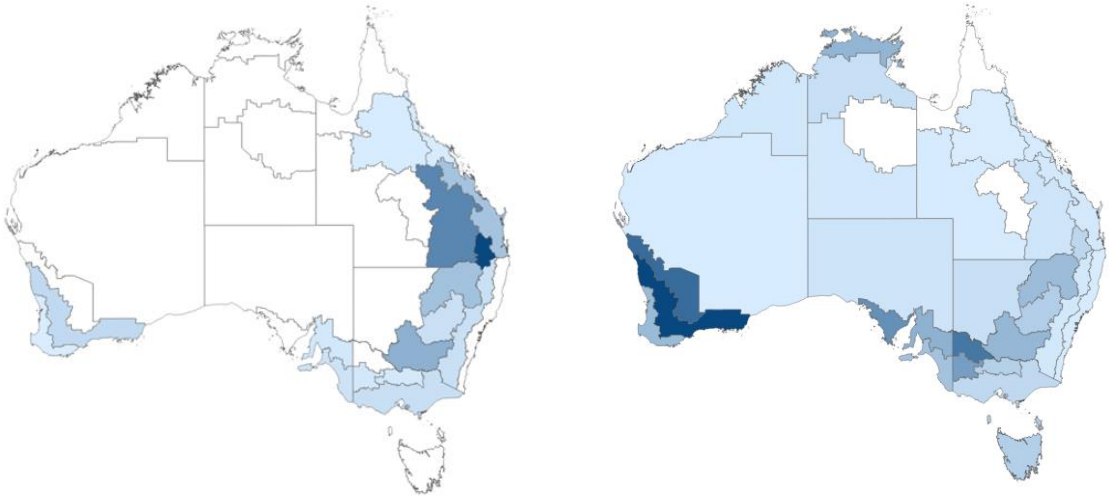

Figure 7. Left: Distribution of feedlot cattle (head of feed). Right: Annual farm fertiliser spend ($/ha).

Note: Cattle data for Tasmania are consolidated into the Southern and Eastern Victoria ABARES region.

Based on these findings, nutrient producers (i.e., feedlots) should target sources of nutrient demand (e.g., farms) with the highest nutrient demand, highest capacity to pay, or alternatively the lowest quality/fertility soil. The greatest chance of identifying a market will be from targeting producers of the highest margin crops with the highest nutrient demand. The best available market will likely need to be identified on a region-by-region basis (i.e., it is not feasible to transport manure from the Darling Downs to the WA Wheatbelt). Depending on location, some feedlots will be better positioned (e.g., have more available markets) than others. Feedlots currently lacking high local demand should work to market manure products to less traditional sources of nutrient demand (e.g., not broadacre cropping or horticulture). For example, it may be possible to market co-composted manure as soil carbon ameliorant (however a long-term benefit from application may be uncertain) or as a general soil improver to degraded land (see example in 4.1.1.3 Manure value).

Research into "manure sheds" (i.e., identifying the lands surrounding concentrated animal operations onto which manure by-products can be applied to meet nutrient demands) has previously been conducted at regional-scale in Australia but is not known to have been conducted at a national-scale in Australia. A recent study in the US (Spiegal et al. 2020), reviewed N and P generation by county

(from beef, dairy, poultry, and pig production) against demand for N and P by country to understand the practical potential for nutrient cycling at a local and national level. This could provide new insight into management at regional scale.

4.1.2 Feedlot effluent

4.1.2.1 Effluent generation

92% of the feedlots surveyed reported that effluent was irrigated to land. The remainder of the respondents used evaporation only effluent systems. Of the 23 respondents irrigating effluent, only a limited number (n = 5) were able to provide sufficient data to determine effluent yield. Average annual yield (weighted by reported capacity) was calculated to be 3.2 ML/1,000 head (3 ML/1,000 SCU/year), with a range of 0.2 to 5.3 ML/1,000 head/year. The reported average yields broadly align with those presented by Tucker et al. (2011) of 2.5 – 5.0 ML/1000 head/year. Based on an FY23 industry average of 1,244,712 cattle on feed (MLA & Lukey, 2024), industry effluent generation was estimated to be 3,990 ML per annum.

4.1.2.2 Effluent composition

Survey respondents were asked to provide effluent (and manure) composition data; however, no effluent data were provided. Typical feedlot effluent pond quality from (Tucker et al., 2015) is presented below (Table 15), alongside the total nutrients produced in feedlot effluent by the industry in 2023, calculated using the stated concentrations and the total effluent volume.

Table 15. Macronutrient concentrations of feedlot effluent ponds (Tucker et al., 2015) and calculated totals produced by the feedlot industry in 2023

Parameter	Concentration (kg/ML)	Total produced in effluent (t/year)
Total Nitrogen (N)	220	878
Total Phosphorous (P)	71	283
Potassium (K)	1092	4,357

Feedlot effluent value (Table 16) was calculated from the typical composition of feedlot effluent (Table 16), and spot prices for corresponding synthetic fertilisers. The synthetic fertilisers used to represent each macronutrient were urea for N (48% N), triple superphosphate (TSP) for P (46% as P_2O_5 [converted to 20% as P]), MOP for K (50% K) and gypsum for S (19% S). Total theoretical nutrient values were determined as the sum of the values of all nutrients, however, as these values are highly unlikely to ever be realised, reasonable discounted nutrient values were also determined. The discounted rates valued the effluent at 50% the value of the N, P and K contained in the product. This is a reasonable assumption given the challenges associated with handling, storing, transporting, and applying feedlot effluent.

Table 16. Macronutrient value of feedlot effluent

	Per megalitre	Industry total
N ($)	$359	$1,431,183
P ($)	$249	$991,506
K ($)	$1,420	$5,664,155
Total theoretical macronutrient value ($)	**$2,027**	**$8,086,844**
Total discounted macronutrient value ($)	**$1,013**	**$4,043,422**

Note: Price and composition of synthetic nutrient equivalents: Triple Superphosphate for P ($700 $/t – 20% P), Muriate of Potash for K ($650/t – 50% K), gypsum for S ($40/t – 18.6% S), and Urea for N ($750/t – 46% N).

4.1.2.3 Feedlot effluent use

Some feedlots reported that effluent was applied raw whereas others reported shandying effluent with clean water during the irrigation process with mixture rates ranging from 2.25% to 50% effluent. Only two feedlots gave information on the size of their effluent irrigation areas to enable calculation of effluent application rates. Calculated application rates for these sites were 0.14 and 0.30 ML/ha. At an application rate of 0.2 ML/ha, 44 kg N, 14 kg P and 218 kg K would be applied per hectare (based on the macronutrient concentrations in Table 15). Elevated K concentrations in feedlot effluent may limit higher application rates.

The lack of effluent composition data collected was a limitation of the study, and symptomatic of how feedlots typically sample soils in effluent irrigation areas rather than the effluent itself. The limited composition data and data on effluent irrigation rates mean that further investigation is required to determine an industry baseline for effluent application rates.

4.1.2.4 Barriers to further adoption

Lot feeders were asked to provide their opinions on the barriers to adoption and operational challenges of using feedlot effluent for irrigation. The top three challenges identified by lot feeders (n = 10) were: nutrient strength/irrigation area capacity (53%), government regulation (20%), and fresh irrigation water availability for shandying (13%). Barriers identified by lot feeders are presented in Figure 8.

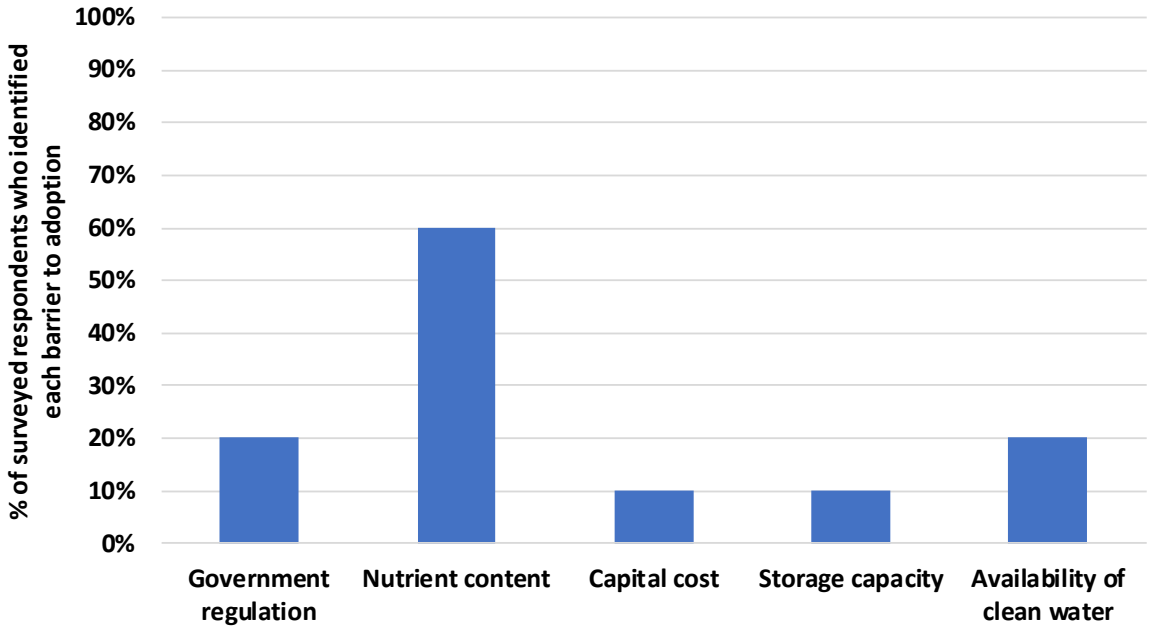

Figure 8. Reported barriers to further adoption and challenges faced by lot feeders utilising feedlot effluent

4.1.3 Feedlot cattle transport effluent

4.1.3.1 Transport effluent generation and use

An estimate of national effluent generation and capture from ingoing and outgoing feedlot cattle was calculated using an average effluent generation rate of 0.015 kg effluent/head/km (George et al., 2022), turnover and the weighted average (by turnover) of ingoing and outgoing transport distances from the survey (Table 17), and the assumption that only 36% of total truck effluent is captured (George et al., 2022).

Table 17. Effluent captured during transport of feedlot cattle

Region	Incoming distance (km)	Effluent captured - incoming (ML/year)	Outgoing distance (km)	Effluent captured – outgoing (ML/year)
NSW	444	6.17	333	3.77
QLD	525	14.30	287	8.74
SA	350	0.93	120	0.57
VIC/TAS	277	1.38	389	0.84
WA	100	1.10	200	0.67
National	**479**	**23.88**	**293**	**14.60**

Note: Assumed density of 1 kg effluent = 1 L effluent.

The results in Table 17 amount to a total of 38ML of truck effluent captured. This is equivalent to 107ML of truck effluent generated where, after George et al., 2022, 64% was assumed to be lost.

Assuming an average trip speed of 80 km/hr, these values align with the findings of (McGahan et al., 2010) where generation rates of 80 and 90 L/hr for different B-double configurations were used. The

generation rate of 0.015 kg effluent / head / km is approximated to 85 L/hr for a B-double travelling at 80 km/hr.

Effluent generated during the transportation of feedlot cattle accounts for 0.1% (38.4 ML) of total feedlot industry effluent generation. Over 60% of effluent is generated on the incoming leg of transportation where feeder cattle are transported across greater distances than from feedlot to abattoir.

B-doubles with capacity for 60-70 head are typically used to cart cattle to and from feedlots. Two transport companies were surveyed, and both reported a lack of facilities for disposal of effluent. Longer than average trips and/or trips with undulating terrain may be associated with a higher risk of overflow and spillage from effluent tanks. Dumping stations were typically at council facilities, if available. Truck washing was reported to be available once or twice a week at saleyards or privately operated facilities.

The trucking companies surveyed reported effluent tank capacity of 200 L for a B Double and 450 L for a road train. One recent study involving truck effluent volumes reported a B-Double effluent tank capacity of 600 L (George et al., 2022). It is therefore inconclusive as to whether cattle trucks have sufficient effluent storage capacity to allow for end-of-trip disposal at feedlots or abattoirs as the data reported here are from a very limited sample. For trucks with the 600 L capacity reported in (George et al., 2022) , there should typically be sufficient capacity to allow for end-of-trip disposal only. For trucks with lower storage capacity, this may not be feasible or may result in higher risk of spillage.

4.1.3.2 Transport effluent composition

Truck effluent is a highly concentrated source of nutrients. In comparison to feedlot effluent, macronutrient concentrations (except for K) are orders of magnitude higher in feedlot cattle truck effluent (Table 17; (George et al., 2022).Total nutrient volumes (also reported in Table 18) in captured feedlot truck effluent were determined using the concentrations and the total captured truck effluent volume for 2023.

Table 18. Macronutrient concentrations of captured feedlot cattle truck effluent at the midpoint of a 35km journey (George et al., 2022) and calculated totals produced by the feedlot industry in 2023

Parameter	Concentration (kg/ML)	Total produced in captured truck effluent (t/year)
Total Kjeldahl Nitrogen	3847	148
Total Phosphorous	357	14
Potassium	977	38

4.1.3.3 Effluent value

Transport effluent value (Table 19) was calculated from national feedlot cattle captured transport effluent volumes (Table 17), the typical composition of truck effluent (Table 18), and spot prices for corresponding synthetic fertilisers. The synthetic fertilisers used to represent each macronutrient were urea for N (48% N), triple superphosphate (TSP) for P (46% as P_2O_5 [converted to 20% as P]), MOP for K (50% K) and gypsum for S (19% S). Total theoretical nutrient values were determined as the sum of the values of all nutrients, however, as these values are highly unlikely to ever be realised,

reasonable discounted nutrient values were also determined. The discounted rates valued the effluent at 50% the value of the N, P and K contained in the product. This is a reasonable assumption given the challenges associated with handling, storing, transporting, and applying truck effluent.

Table 19. Macronutrient value of captured truck effluent

Parameter	Per megalitre	Industry total
N ($)	6,272	241,337
P ($)	1,250	48,077
K ($)	1,270	48,851
Total theoretical macronutrient value ($)	$8,791	$338,265
Total discounted macronutrient value ($)	$4,396	$169,133

Note: Price and composition of synthetic nutrient equivalents: Triple Superphosphate for P ($700 $/t – 20% P), Muriate of Potash for K ($650/t – 50% K), gypsum for S ($40/t – 18.6% S), and Urea for N ($750/t – 46% N).

4.1.3.4 Barriers to further adoption

Of the feedlots surveyed (n = 25), seven (or 28%) stated that they accepted truck effluent from incoming feeder cattle or supplied truck washing on-site. For three of these feedlots, the average distance travelled by incoming feeder cattle was 450km or more but one of these feedlots cited that the lack of dumping stations between the feedlot and abattoir (in a major metropolitan city) was the reason for accepting truck effluent.

Of the feedlots surveyed, over half stated that truck effluent not being the feedlots' responsibility was the major barrier to accepting and treating truck effluent (see Figure 9). Nearly a quarter cited biosecurity as a challenge to accepting truck effluent, with just over 10% raising cost as another issue. Three of the feedlots surveyed responded that truck effluent is not an issue or a focus as, at least in one case, nearby dumping options are available.

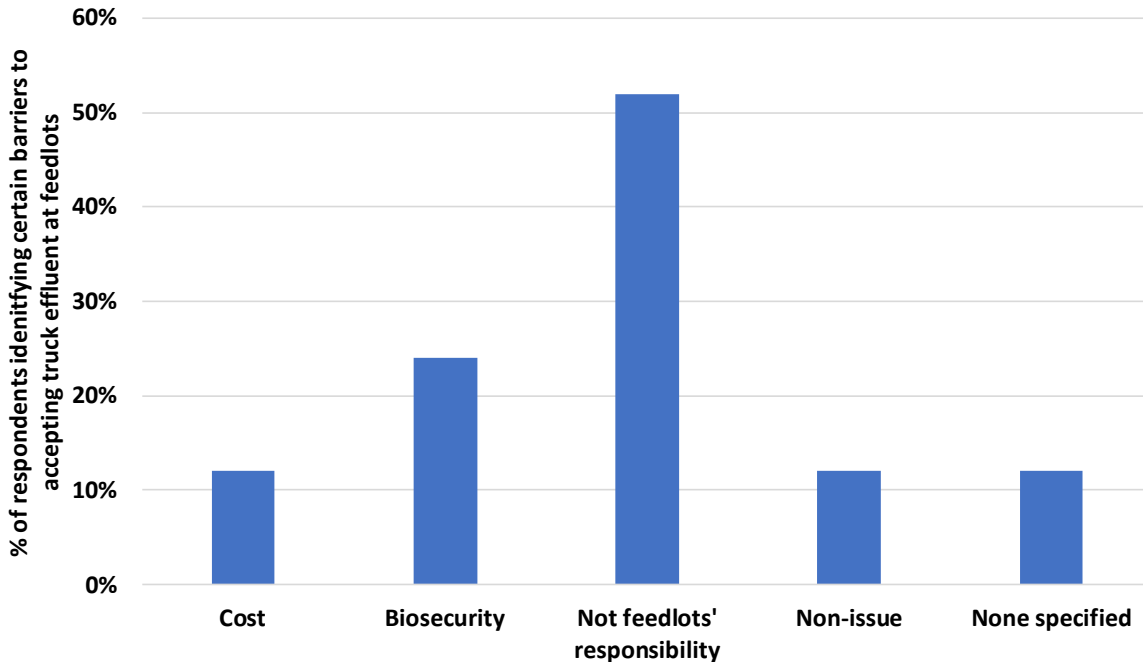

Figure 9. Reported barriers to further adoption and challenges faced by lot feeders accepting truck effluent

The findings relating to truck effluent in this study broadly align with those made previously by the feedlot industry (McGahan et al., 2010) although it should be noted that the previous study was focused on truck effluent and included more widespread consultation with local councils around spillage of truck effluent. The conclusions from the previous study are not repeated here but should be reviewed in detail by readers.

Fundamentally, both studies have found (through different means) that truck effluent is neither the sole responsibility of the transport industry or the feedlot industry. Road users are unlikely to make a distinction (or, in urban areas where the bulk of complaints regarding effluent are made (McGahan et al., 2010) have sufficient understanding of livestock production to draw a distinction), between the trucking industry, feedlot industry, and broader cattle or sheep production. At a minimum, truck effluent is a shared issue which must be addressed in partnership with the trucking companies, local council, State governments, and broader livestock industries (e.g., truck effluent is still generated between farms and abattoirs, and saleyards and farms or feedlots).

Based on the findings of both studies, and the variability in truck effluent storage capacity and transport distances, a targeted review of major transport routes should be conducted to identify locations for additional effluent dumping stations. Although this would not represent a value-adding opportunity, it would go some way to reducing the risk due to effluent spillage and avoid losses of truck effluent to the environment and major road networks. This is particularly relevant in areas where effluent spillage is enough of an issue that fines may well be issued in future should the risk not be mitigated.

4.1.4 Total nutrients and potential value produced in 2023

The total recoverable volumes (mass and macronutrients) produced by the feedlot industry in 2023 are reported in Table 20. The total discounted value of the macronutrients is reported in

Table 21, where all reported values are based on the discounted rates.

Table 20. Total recoverable nutrient volumes (N, P, K) produced in manure products, feedlot effluent, and captured truck effluent in 2023

	Mass/volume produced (t or ML/yr)	**N (t/yr)**	**P (t/yr)**	**K (t/yr)**
Manure products	2,151,184	32,849	21,185	22,727
Feedlot effluent	3,990	878	283	4,357
Truck effluent (captured)	38	148	14	38
Feedlot industry	**2,155,213**	**33,875**	**21,482**	**27,122**
	Mass/volume produced (% of total)	**N (% of total)**	**P (% of total)**	**K (% of total)**
Manure products	99.8%	97.0%	98.6%	83.8%
Feedlot effluent	0.2%	2.6%	1.3%	16.1%
Truck effluent (captured)	0.0%	0.4%	0.1%	0.1%

Table 21. Total discounted value of the recoverable macronutrients (N, P, K) produced in manure products, feedlot effluent, and captured truck effluent in 2023

	Total discounted value to the feedlot industry	% of total value
Feedlot manure products	$66,164,311	94%
Feedlot effluent	$4,043,422	6%
Truck effluent (captured)	$169,133	0%
Total	**$70,376,865**	**100%**

In 2023, manure represented 99.8% of the total volume of manure and captured effluent (truck and feedlot) produced by the industry. This equivalent value of the manure products was 94% of the total discounted value of recoverable N, P and K produced by the industry in manure and effluent. Therefore, efforts to improve the market value of manure will yield the greatest benefit as it represents almost all of the value of feedlot by-products, i.e., there is very marginal benefit to be gained from attempting to improve the value of feedlot or captured truck effluent. However, this does not preclude or negate the need for effluent produced at feedlots or from cattle transport to be carefully managing for environmental, licensing, and public perception reasons.

One limitation of this study was the uncertainty regarding the proportion of truck effluent lost. This analysis assumed a 64% loss rate after George et al. (2022). Depending on the effluent tank capacity of the trucks used and/or transport route (i.e., the relative availability of dumping stations), the actual loss rate may be higher. Whilst this would suggest that most of the truck effluent (and associated macronutrients) are lost to the environment (and therefore are not recoverable for economic purposes by the feedlot industry), there would be limited economic value in attempting to reduce loss rates. Even if 100% of truck effluent were captured in 2023, this would still have accounted for less than 1% of the total mass/volume of manure and effluent produced by the industry. This does not preclude, however, efforts to reduce loss rates for other reasons.

4.2 Phase 2

4.2.1 Global technology search bibliometrics

We found 3,434 entries that matched the search keys in Scopus. Within the search results there were 220 book chapters, 316 reviews and the remainder were peer reviewed articles. The waste type explicitly mentioned in title of the entries were Cattle (including feedlot and dairy), Piggery, Poultry and Urban (Table 22).

Table 22. **Count of each waste type in the title of the search results**

Waste type	Count
Cattle/Beef (Feedlot and Dairy)	1136
Poultry/Chicken	135
Piggery/Swine	211
Urban/Municipal	74

The bibliometric analysis of the results showed that between 2000 – 2024, >1000 articles were published in 10 journals, which are: Bioresource Technology, Journal of Environmental Quality, Journal of Environmental Management, Science of the Total Environment, Waste Management, Canadian Journal of Soil Science, Communications in Soil Science and Plant Analysis, Transactions of the ASABE, Agriculture, Ecosystems and Environment and Agronomy Journal (Figure 10). The number of publications increased steadily from 2000 (32 publications) to 2023 (249 publications) that is about 10 publications increase per year (Figure 11). The rise of publications on animal waste and its management and valorisation indicates the growing interest in the scientific community and industry stakeholders. More than 80% of the publications fall in agriculture (35%), environmental sciences (39%) and energy (8%) categories (Figure 12). The United States Department of Agriculture (USDA) is ranked as the top institute leading the waste management and valorisation research and extension (Figure 13).

Figure 10. Number of publications in different journals between 2000 – 2024.

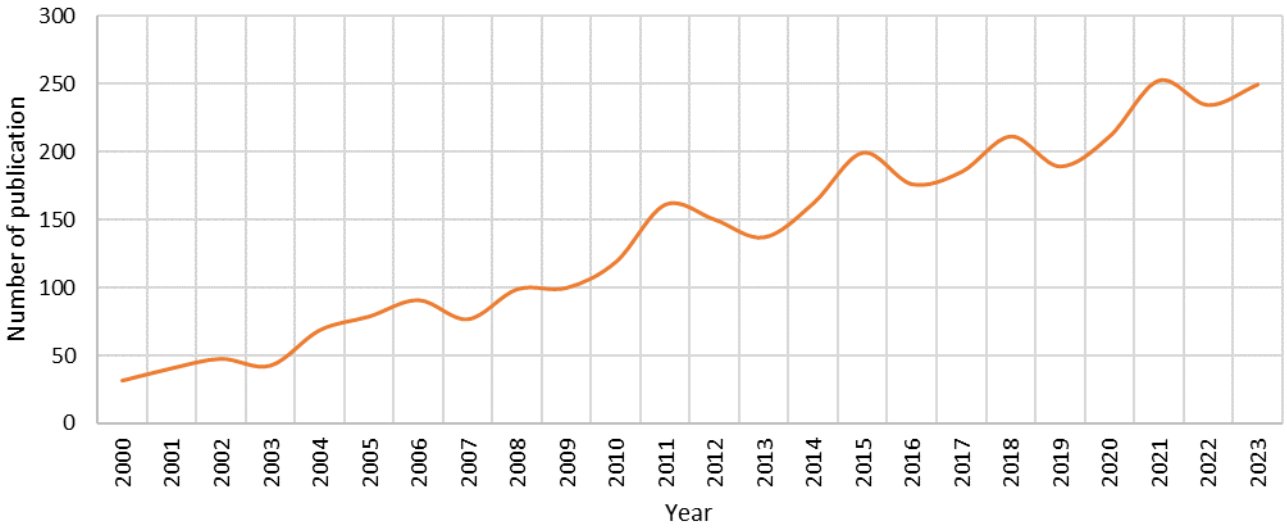

Figure 11. Number of publications in between 2000 – 2024.

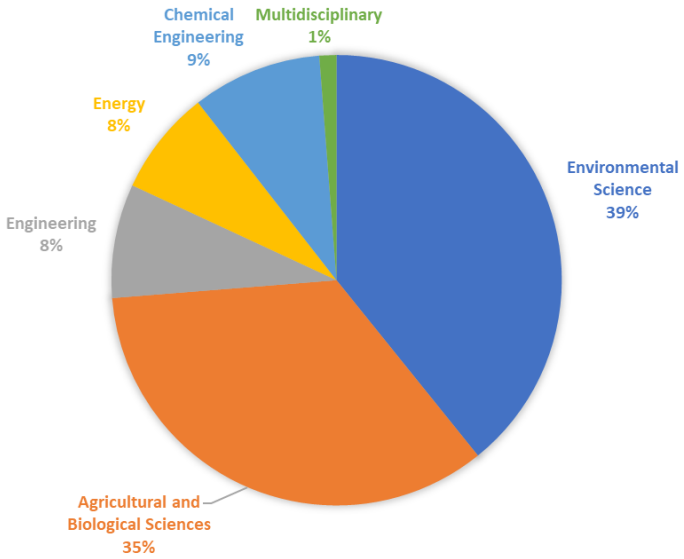

Figure 12. Grouping of the publications based on subject area.

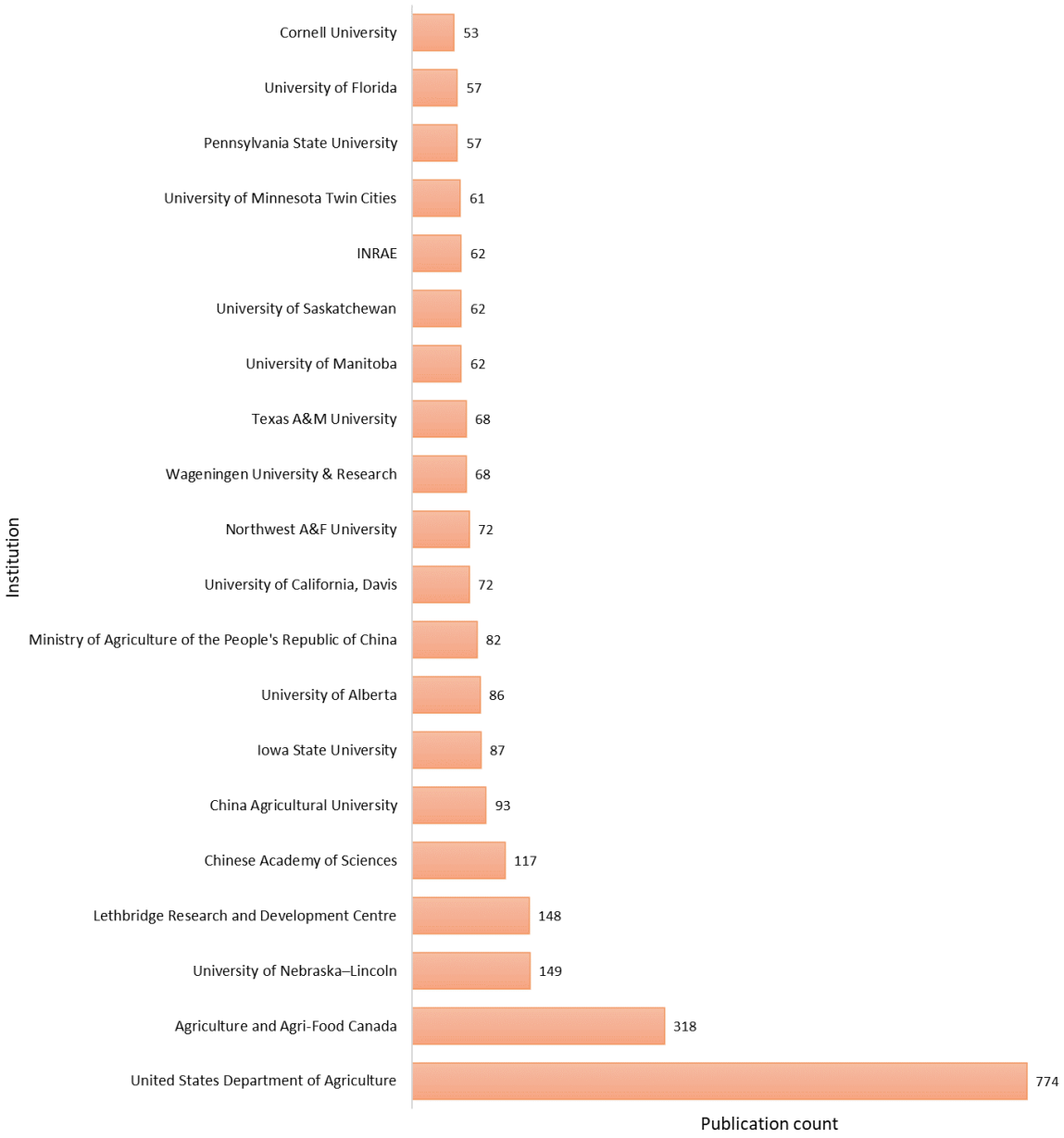

Figure 13. **Leading institutions for waste management and valorisation research and extension.**

4.2.2 Feedlot waste management and utilisation business as usual (BAU)

An extensive discussion on business as usual (BAU) for waste management in Australian beef feedlots can be found in Tucker et al. (2015). The survey result sections 4.1 summarises current BAU of manure management in the industry. Some additional information is presented here.

Pen cleaning and manure removal

Feedlot pens are cleaned regularly under moist conditions and transported to stockpiling and composting area. The interval between cleaning can be 13 weeks or less. Regular pen cleaning is essential for animal welfare and odour emission control. Pen cleaning is generally done at moist

condition (~34% moisture) using mechanical scrappers. About 80% of the total solid in excreted manure is volatile solid, and most of the volatile solid (60-70%) can be lost within 20 days (Davis et al., 2010). The volatile to total solid ratio of the harvested manure is 0.64 (Tucker et al., 2015).

Manure stockpiling

Manure stockpiling is best to done in long, low windrows (Tucker et al., 2015). The manure windrows are left months for aging to achieve a physically workable, friable and spreadable product. The stockpile manure contains seeds. Steam flaking (>55°C) can used to reduce the risk of weed seed in the stockpiled manure. About 18-33% of carbon, 20-50% of the nitrogen in the pen manure can be lost during the stockpiling (Davis et al., 2010; Tucker et al., 2015; Watts et al., 1994).

Composting

Manure composting is carried out using long, low windrows, which is less likely to get fire (Tucker et al., 2015). Composting is done to reduce volume of the manure (~60-70% of the raw manure) and to produce microbiologically and nutritionally stable workable product with possibility of value-addition. Aerobic composting is generally preferred over anaerobic composting as the former produces less odour, less greenhouse gas (low methane production) and heat that kills the weed seeds and pathogens. Typically, composted feedlot manure has 74% dry total solid, 2.11% N and 1.31% P (Tucker et al., 2015). The stable C in compost is mostly lignin, cellulose, and hemicellulose, with low microbial mineralisation potential (Lanery et al., 2006). Most of the Australian feedlots, part of their manure applied in feedlot owned land and other parts send off-side for land application (Tucker et al., 2015). The loss of carbon and nitrogen during composting are described in the section 4.2.3.1.

Effluent

The main liquid waste from cattle feedlots is the effluent resulting from storm water runoff from the pens. This waste must be properly contained. Typically, nitrogen concentration in feedlot holding ponds is 220 mg L-1 and total dissolved solid is 4915 mg L-1. Feedlots use part of the effluent for irrigation to grow hay or silage crops also used to produce grain (Tucker et al., 2015).

4.2.3 Brief description of valorisation technologies

The size of the Australian feedlot industry has grown 36% over the last decade and the growth of large feedlots (>10,000 cattle on feed) has risen about 5% (ABARES, 2024). In 2020 – 21 feedlot cattle turnoff was approximately 3 million head, with 520 kg liveweight and 13% retention of nitrogen intake (average of domestic, mid- and long-fed feedlot cattle) (DCCEEW, 2023; MLA & ALFA, 2024). Davis et al. (2010) estimated that the annual total solid manure production per 600 kg liveweight is 1861 kg. Extrapolating this estimate to the cattle population of 1 million in 2021 (DCCEEW, 2023) gives ~1.6 million tonnes of manure production in feedlots. This has been conferred by the survey as part of this project (see Table 7 and Figure 1), where we found in feedlots ~1.2 million cattle were on feed in financial year 2022-23 and manure yield was 1.7 t SCU^{-1} y^{-1}, which equates to ~2 million tonnes of annual manure yield. Considering total solid content of raw manure (~100 g kg^{-1}), feedlot effluent (~13 g L^{-1}) and transport effluent (~66 g kg^{-1}), it can be estimated that in 10,000 SCU (600 kg hd^{-1}), solid

manure consists 95% of the total waste produced in the feedlot and effluent types contributed only 5% (Bridle, 2011; George et al., 2022; Watts et al., 1994) (Figure 14). The value-addition of this large quantity of manure is an opportunity to create sustainable circular nutrient economy, which has potential to return nutrient to soil and reduce greenhouse gas emissions from feedlot sector. A brief list of technologies available for manure value-addition is given in Figure 14. The solids from the feedlot effluent (including transport effluent) can be separated and the extracted solids can be treated as solid manure (pathway 1 & 2) or can be managed to recover nutrients (pathway 3).

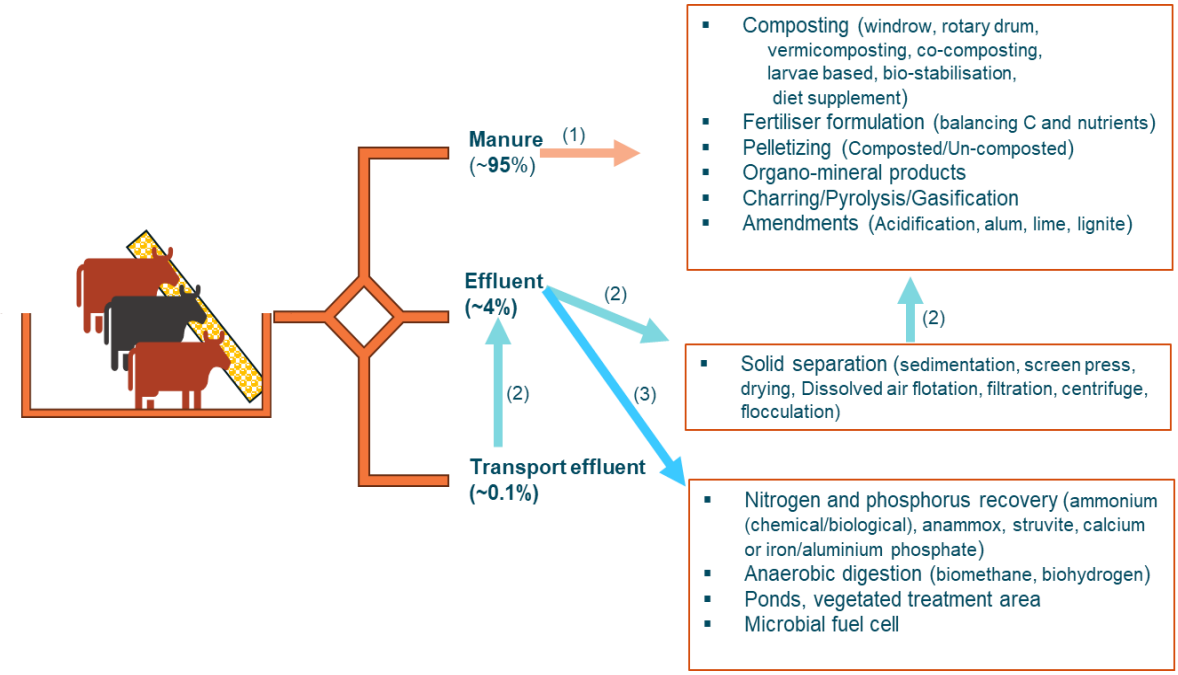

Figure 14. Overview of technologies for value addition of feedlot manure.

4.2.3.1 Composting

Description of the process

Composting is most commonly used technique to convert decomposable solid waste into soil-like product that is stable, free from pathogens and seeds by allowing microbes and meso-fauna to decompose organic matter in aerobic conditions (Haug, 1993). Ideally, for composting manure should have C:N ratio 25:1−30:1 and moisture 50−60% (Modderman, 2020; Pajura, 2024). Composting generally reduces the initial volume of material by 60–70% (Tucker et al., 2015). There are several key factors that regulate the composting process, nutrient retention and loss and greenhouse gas emissions that include oxygen concentration, temperature, pH, moisture content, porosity and C:N ratio (Bernal et al., 2009; Zeng et al., 2022). During composting the heat of the compost pile can raise up to 60°C which helps to eliminate the pathogenic microbes from the waste material. Depending on management it can take as little as one month or up to six months to produce stable compost. The cation exchange capacity, pH, organic matter quality, humification, microbial activity, phytotoxicity and pollutant concentration are the other parameters important to consider when assessing the quality of the compost (Bernal et al., 2009).

There are several major types of composting techniques that include (i) windrow composting (Eghball et al., 1997), (ii) compost bedded pack barns (Leso et al., 2020), (iii) vermicomposting using *Eisenia fetida* and *Eisenia Andrei* earthworms (Cestonaro et al., 2017; Enebe and Erasmus, 2023; Ferraz Ramos

et al., 2022), (iv) rotary drum reactor (Nayak and Kalamdhad, 2015), (v). Larve-based composting using black soldier fly, mealworm and cricket (Oonincx et al., 2015).

Addition of carbon rich materials as supplement or feedstock or bulking materials can change the quality of the finished compost (Modderman, 2020). Co-composting with sawdust, woodchips, straws, rice husk as supplement not only adds carbon for microbes, worms and larvae but also improve the aeration by increasing the porosity of the compost pile (Awasthi et al., 2023; Lim et al., 2023). Co-composting with biochar has potential to reduce the nitrogen loss and GHG emissions (Zubair et al., 2020). Adding bacterial consortium consisting of ammonifiers, Nitrobacteria and Azotobacter is considered useful to reduce ammonia emission from compost (Jiang et al., 2015). Application of alum (for example, aluminium sulphate salt) or acidification can reduce nitrogen loss from manure (Dadrasnia et al., 2021). Other amendments such as Aluminium chloride, sodium bisulphate, fly ash, gypsum, zeolite, and phosphoric acid can also be used to reduce ammonia emissions (Lim et al., 2023). However, chemical pre-treatment of manure is difficult and costly to implement at large scale (Dadrasnia et al., 2021).

Benefits

Reduce volume and moisture, less odorous, eliminate pathogens, good physical properties and workability, ease of storage and produce valuable soil amendment, steady market demand (Bernal et al., 2009).

Drawbacks

- High cost of installation and operation, require bulking agents, require large area, loss of ammonia, GHG (methane, nitrous oxide) emission, may contain heavy metals, soluble salts and xenobiotics (Bai et al., 2020; Bernal et al., 2009; Larney et al., 2006). Nitrogen and carbon loss, greenhouse gas emission are covered in detail in the following section, Nutrient recovery and GHG emission: recent R&D of this report.
- High initial cost. The cost of buying windrow composting equipment can be: compost windrow turner A$30-60K; Windrow water wagon A$25K; bagging machine A$ 30K (https://groundgrocer.com/categories/Commercial-Composting/?page=1).

Nutrient recovery and GHG emission: recent R&D

Aerobic composting releases 50–70% of total CO_2 and 75–80% of CH_4 emissions occurred within the first two weeks of composting (McGinn et al., 2016; Mulbry and Ahn, 2014). Approximately 62% of intake N is volatilised from the beef feedlot feed pad as ammonia, nitrous oxide and other N gases (Redding et al., 2017; Watts et al., 2011). Composting of livestock manure would produce a fertilizer with less N, as this would be lost through volatilization during the composting process (Dadrasnia et al., 2021). Many strategies have been applied to control the cost, time, avoid N volatilization, and improve the quality of compost. Generally, decreasing ammonia or nitrous oxide emission by retaining more NH4+ also improves the retention of N in the manure (Hao et al., 2007).

Chen et al. (2015) reported that it is possible to reduce nitrous oxide emission by carefully regulating the turning the compost pile during windrow composting. The authors showed that in the static

standing period in absence of O_2, NO_2^- was more likely to converted into N_2, whereas sudden flush of O_2 or aeration release N_2O during pile turning.

Longer delay in windrowing before manure piling reduces ammonia and methane (Arriaga et al., 2017). Lowering the ambient temperature has also shown to effectively reduce methane and nitrous oxide emissions in sewage-sludge composting (Han et al., 2018). The combination of aerated static windrow with GORE(R) cover membrane and an air-floor aeration system can reduce ammonia and methane emissions by 30-40% (Al-Alawi et al., 2019).

It has also been demonstrated that forced aeration and acidification of the composted manure can reduce both ammonia and methane emissions but not nitrous oxide (Tong et al., 2019). It has also been shown that regulating aeration during windrow composting can increase total nitrogen content of the compost by up to 33%.

Co-composting manure (poultry) with vinegar residue can reduce NH_3 and N_2O by 31 % and 45 % (Liu et al., 2022). Co-composting of cattle manure with biochar significantly reduce methane emissions by 91% and N2O by 56% (Castro-Herrera et al., 2023; Harrison et al., 2022).

Rotary drum composting has advantage of reducing the time of composting. This type of composting uses controlled aeration and temperature that greatly reduce the GHG emissions during composting process (Smith-Sebasto, 2024; Vuorinen and Saharinen, 1997).

Vermicomposting of cattle manure with straw supplement and biochar can increase the nitrogen retention 2 fold and also significantly reduce GHG gas emissions (Cao et al., 2021; Enebe and Erasmus, 2023).

The larvae based composting of various wastes including the cattle manure can significantly increase the retention of nitrogen (42-64%) and phosphorus (45-88%) (Liu et al., 2019). Black soldier fly larvae composting (entomo-composting) of a mixture of pig manure and corncob reduces methane, nitrous oxide and ammonia emissions up to 90% (Beesigamukama et al., 2023).

Addition of zeolite during sewage sludge composting can reduce 70% of methane and 50% of nitrous oxide emission (Wang et al., 2017). Diatomite addition in poultry manure composting piles reduces CH_4, N_2O and NH_3 by 18.27%−30.41%, 26.89%−84.16% and 10.41%−23.70%, respectively (Ren et al., 2019). Pratt et a. (2016) showed addition of 2:1 type aluminosilicate clays (vermiculite and bentonite) have potential to significantly decrease GHG gas and ammonia emission from livestock manures.

High fat grains diet (DDGS, Distiller's dried grains with soluble, plus chopped grass hay, dry-rolled corn grain, corn silage and a vitamins and minerals supplements) do not significantly reduce GHG emissions or increase nutrient recovery (%C, %P and %K) compared to control (Gautam et al., 2016). Lignite-coal in diet is not effective to reduce the methane or nitrous oxide emissions but has potential to reduce ammonia loss (Hao et al., 2007).

There are emerging techniques like manure bio-stabilisation by inoculating with effective microorganisms has potential to increase nitrogen recovery and reduce GHG emission (Hidalgo et al., 2022; Jiang et al., 2015). Application of alum and 0.5% Bacillus subtilis spray on feedlot surface material reduces ammonia emission and retain more carbon and nitrogen in the compost (Spiehs and Woodbury, 2024). Hyper-thermophilic composting by adding thermophilic bacterial inoculant during force aeration composting could reduce 90% of N2O emission (Cui et al., 2019).

Implementation and Commercial application

- When considering setting up facilities for implementing composting operations the following should be considered (i) available space (ii) water supply (iv) run-off prevention (v) temperature and aeration monitoring (vi) reduction of compost fire (vii) reduction of odour and gaseous emission (viii) manure stockpile and composting areas are located sufficient distance from sensitive ecological and community areas (Skerman, 2000). The initial infrastructure, equipment and maintenance are the main cost for establishing manure compositing facility. Most of the large feedlots in Australia undertake composting in a windrowing facility. The number of composting lot feeders were 18 in 2010 (Tucker et al., 2015). A major economic advantage of composting is its proven penetration of the market, and existing profitable gross margin, despite the nutrient and carbon losses and recalcitrance of the carbon forms produced.
- The cost of operation of commercially available rotary drum aerobic composter is high. It is hard to get an estimate of cost from the manufacturers.
- Larvae based composting is still yet to be proved to be economically viable. The cost of installation, maintenance and rearing insects is hard to estimate. There are some commercial operators in this sector e.g. GoTerra (https://goterra.au/) and Fly farm (https://flyfarm.com/).

Evidence of performance

Compared to synthetic nitrogen fertilizers, beef cattle manure is less effective to increase crop productivity, with added benefits in that long-term application can increase soil carbon and soil health (Biala, 2011; Das et al., 2023; Zavattaro et al., 2017).

4.2.3.2 Pelletising, Organo-mineral fertilisers and fertiliser formulation

Description of the process

Pelletising is a process of mechanically compressing, extruding and tumbling of materials to form uniform size granules or pellets (Hao and He, 2020). The pelleted manure needs to be dried, cooled and stored. The moisture content of the manure or compost and drying of pelleted manure greatly influence the durability and bulk density of the pellets (Pampuro et al., 2017a). The quality of the pellets largely determined by machinery used, raw materials, pelleting temperature and pressure. Adding a bulking agent such as sawdust can preserve nitrogen in the pellets (Romano et al., 2014). Inorganic fertilisers are sometimes also added in the manure during the pelletising to produce organo-mineral fertilisers (Smith et al., 2020). Conventionally, manures are first composted then streamed, pelletised and dried to ~7% moisture and then mixed with inorganic fertiliser (Smith et al., 2020).

Benefits

Conventionally, pelletising is common in the poultry industry (Lim et al., 2023). Pelletising animal manure removes water content, reducing both weight, volume, and odour, and creates a product that is preferred over fresh manure for its reduced cost of storage, transportation handling, and application (Sharara et al., 2021). Thus, excess nutrients can be redistributed at less cost away from regions where large amounts of manure are being produced (Hao and He, 2020).

Pelletising un-composted (but sanitised) manure with organic carbon supplement/bulking agent can significantly avoid GHG emission during composting.

Pelletised composted manure sometimes has little agronomic value as the most of labile carbon and nitrogen are utilised by the microbes during composting process (Larney et al., 2006b). Adding labile carbon and nitrogen during pelletising can be useful to stimulate the microbial growth and nutrient release in the soil. The use of pre-defined and scientifically tested carbon to nitrogen ratio has potential to maximize nitrogen release from the pelletised manure and subsequent use by the growing plants (Farzadfar et al., 2021; Franklin et al., 2017).

The pelletisation or granulation process provides a convenient opportunity to significantly modify the composition and performance of the manure-based product during the process. One of the major failures of conventional nitrogen fertiliser products, like urea, is the immediate solubility of the entire mass of fertiliser nitrogen, resulting in losses to the environment. This contrasts strongly with the common time-profile of crop growth requirements. Initial plant requirements tend to be low, only maximising much later in the season at plant flowering (Chen et al., 2006). It has been proposed that the disparity between conventional fertiliser performance and the time-profile of plant nutrient requirements may be overcome by capitalising on native soil processes where the carbon and nitrogen cycles are re-coupled (Drinkwater and Snap, 2007). Given appropriate C:N ratios, addition of organic matter can promote microbial growth with the possibility of C sequestration and retention of N in microbial biomass. The N retained in the microbial biomass can be considered as 'transient storage', deferring availability of this N to later in the season. Building up this transient N storage in soil is critical to protect against N losses. Manure-derived materials provide this type of potential advantage with the correct formulation. Pelletisation or granulation also provides the opportunity for addition of other agri-chemicals, ameliorants, or inocculants.

A major advantage of pelletisation and granulation is that these particles can be formulated with sufficient structural integrity and appropriate size for application with conventional precision fertiliser application equipment. This enables nutrients to be delivered directly to the site of requirement, something that is not possible with raw, stockpiled, or disaggregated compost products.

Drawbacks

- Costly to implement, suitable for large to medium scale feedlots (Sharara et al., 2021).
- Power consumption of commercial pellet mills varies 48.9 –130.7 kJ t-1 of which 37-40% is required for pellet compression (Tumuluru et al., 2011).

Nutrient recovery and GHG emission: recent R&D

The nutrient recovery in pelletised manure is largely determined by machinery used, raw materials, pelleting temperature and pressure, and the pre-handling process applied to the manure (e.g. composting). Pampuro et al. (2017b) did not find any significant reduction in ammonia and methane emission compared to control when composted pig slurry pellets were added in soil, while nitrous oxide emission was significantly higher.

Implementation and Commercial application

To successfully pelletise manure, feedlots require investment in machinery, infrastructure and business model to make a profit. Pelletiser to granulate manure is in use in Australian feedlots. However, little is known about the production cost of pelletising manure in Australia.

Evidence of performance

The nutrient content of the pelleted manures is closely related to the source materials. The nutrient release from pellets not only depends on the size and bulk density of the pellets but also depends on pH, moisture, microbial activity and biophysical conditions of soil (Hao and He, 2020). Chiyoka et al. (2014) reported that pelletised anaerobically digested beef cattle feedlot manure significantly increase nitrogen immobilisation and reduce plant nitrogen uptake compared to raw and un-pelletised manure. The high nitrogen immobilisation in pellet treatments may offer opportunity to optimise the formulation of pellets to slowly release and synchronise nitrogen release with plant uptake. It has also been demonstrated that organo-mineral fertiliser increased plant growth and nutrient uptake of maize and wheat (Ojeniyi et al., 2009; Tejada et al., 2005). Tejada et al. (2005) also reported that organo-mineral fertiliser reduced the macro-nutrient leaching loss by 50% compared with control treatments.

While implementation of this technology is limited, the relative gross margin improvement related to composting compared to stockpiled or raw manure application, suggest that there is market appetite for improved product characteristics. It is an attractive prospect to investigate the potential of pelletising and granulation protocols to provide these improved characteristics without the large nutrient and carbon losses, and greenhouse gas emissions of composting.

4.2.3.3 Thermochemical techniques

Description of the process

Thermochemical treatment involves high temperature (200 – 900°C) conversion of the manure or waste biomass into bioenergy (synthetic gas and hydrocarbon fuels), ash and biochar (Cantrell et al., 2007). There are three types of thermochemical techniques, combustion, pyrolysis and gasification (Guo et al., 2020).

Combustion of the manure (cow and poultry) is usually done for energy (fuel source) (Lim et al., 2023). Combustion is a high temperature (>900 °C) ignition in presence of oxygen that generate light and heat in form of fire (Uma Rani et al., 2020). The lowest temperature for ignition of the biomass is between 190 and 260°C. The biomass materials burn into carbon dioxide (carbon monoxide in case of incomplete combustion), water and ash (Guo et al., 2020).

Pyrolysis is on the other hand heating or combustion at high temperature in absence of oxygen. The quick (20-40 min) mild-pyrolysis using low temperature (200 – 300 °C), low heating rate (~<1°C s-1) and limited oxygen is known as torrefaction. Liquefaction (hydrothermal pyrolysis or hydrothermal carbonisation (HTC)) of effluents (liquid waste) is a pyrolysis process under high temperature (250 – 374 °C), high pressure (4 –22 MPa) and in absence of oxygen. The process needs to run up to 1 hour to produce crude oil (hydrocarbon oil or hydrochar) (Toor et al., 2011). Liquefaction at very high temperature (>374 °C) and pressure (>22 MPa) produces syngas enriched in hydrogen. This technology also known as “super critical water gasification” or “hydrothermal gasification” (Cantrell et al., 2007; Toor et al., 2011). The conventional pyrolysis is also done without the presence of oxygen at high temperature (>350 °C). The brown liquid produced during pyrolysis is called bio-oil and the carbon dioxide and hydrogen enriched gas is called syngas. The biochar is the solid end product of the pyrolysis process. However, there are wide range of techniques available (e.g. slow, intermediate, fast pyrolysis) to produce biochar (Mašek, 2022). The biochar is widely considered ‘best option’ for long

term carbon sequestration in soil and the characteristic of the biochar is largely dependent on the feedstock quality and pyrolysis temperature (Sohi et al., 2010).

The aim of gasification is to maximise the production of syngas. It is usually done by heating the biomass at very high temperature (800 – 1000 °C) with controlled supply of oxygen (Sikarwar et al., 2017). This process is designed to minimise the production of solid char, which is in practice is very challenging (Mašek, 2022).

Benefits

- Waste volume reduction during combustion can be up to 90% (Uma Rani et al., 2020).
- Renewable energy generation (e.g. heat energy generated can be used for electricity generation). Combustion facility can produce 0.7 − 4 MW electricity (10K − 60K SCU feedlot) (Watts et al., 2013). Gasification facility can produce 0.2 − 2 MW electricity (10K − 60K SCU feedlot). The economic success of thermochemical conversion of feedlot manure depends on total solid (>65%) and moisture (<35%) contents of the manure feedstock (Watts et al., 2013).
- A feasibility study conducted by Bridle (2011b) concluded that for thermochemical conversion of abattoir waste (gasification and pyrolysis) can be economically feasible in Australia.
- Marketable products like biochar, ash, syngas and crude oil. A detailed assessment of the bioenergy potential of Australia can be found in the Australian Renewable Energy Agency (ARENA) website (https://arena.gov.au/projects/australian-biomass-for-bioenergy-assessment-project/) (Enea and Deloitte, 2021) and Australian Renewable Energy Mapping Infrastructure (AREMI) platform (https://nationalmap.gov.au/renewables/). A list of bioenergy projects in Australia is also be found in ARENA website.

Adoption challenges for Australian feedlots

Watts et al. (2013) wrote “The conclusions of this study are that thermal energy recovery systems may be viable at Australian feedlots, but pen manure management practices must be undertaken to maximise volatile solids content and minimise moisture content. If the manure is to be used for combustion, the correct design of the boiler is essential. The viability of gasification and pyrolysis technologies is highly dependent on the returns obtained from selling biochar.”

Drawbacks

- High installation cost
- Watts et al. (2013) estimated that capital cost of a combustion facility can be 20 − 23 million dollars for a large feedlot (value in 2023 is 26 − 29 million dollars, RBA inflation estimator, https://www.rba.gov.au/calculator/annualDecimal.html) with a payback time between 9 − 11 years. The estimated cost is about 3 times less for small feedlot, but the investment payback time can be 47 to 89 years.
- The gasification facility cost for a large feedlot can vary between 13 -14 million dollars (value in 2023 is 18 − 19 million dollars) with a payback time of 2 years. The estimated cost is about 2 times less for small feedlot with investment payback time of 6 years (Watts et al., 2013).
- The pyrolysis facility cost for a large feedlot can vary between 31 -33 million dollars (value in 2023 is 40 − 43 million dollars) with a payback time of 7−8 years. The estimated cost is about 3 times less for small feedlot with investment payback time of 23−29 (Watts et al., 2013) years.

- Watts et al. (2013) reported that gasification of feedlot manure generates ~4 g carbon monoxide and ~0.16 g nitrogen dioxide per second.
- Inefficiency of the thermochemical conversion process due to high moisture and gravel content in manure
- Production of fly ash during pyrolysis of manure
- The by-products of the thermochemical conversion are biochar and hydrocarbons. The economic value of these products determines the feasibility of installing pyrolysis or gasification units.

Nutrient recovery and GHG emission: recent R&D

GHG emissions, Emissions during gasification of wood waste varied from 3 to 9 g $CO_{2\text{-eq}}$ per MJ energy produced (Wu et al., 2013). Wu et al. (2013) estimated that application of biochar in land can achieve net reduction in GHG emissions. Watts et al. (2013) reported that about 6-25% of carbon and 9-36% of nitrogen can be lost during pyrolysis of feedlot manure.

Implementation and Commercial application

Environmental Solutions International Ltd (ESI), Perth
Renergi Pty Ltd, Collie, Perth
Pacific Pyrolysis, NSW
Black is Green Pty Ltd, Mackay
Chaotech Pty Ltd, Rocklea, QLD

Evidence of performance

Biochar has been considered as a tool to improve soil health, crop productivity and to sequester carbon in agricultural soils with varying degree of performance in different agroecosystem (Hossain et al., 2024; Lehmann and Joseph, 2015; Rabbi et al., 2021; Weng et al., 2022; Zhang et al., 2023).

4.2.3.4 Solid-liquid separation

Description of the process

Solid-liquid separation (SLS) is a commonly used technique for converting slurries into two easily manageable components (Møller et al., 2000). SLS can play an important role in nutrient management, as well as pathogen and odour control in feedlot systems (Zhang & Westerman, 1997). SLS aids in nutrient management by concentrating nutrients in the solid fraction which allows them to be recycled in other systems, for example broadacre cropping (Møller et al., 2000) (Hjorth et al., 2010). Liquid and gaseous components can also be collected and recycled during SLS which reduces likelihood of nutrient runoff into waterways as well as GHG emissions (Horacio et al., 2019; Xinxing et al., 2022). For SLS technologies to be used, an ideal slurry comprises of approximately 10-14% total solids (Carlos et al., 2012).

The most commonly used methods of SLS include centrifugation, filtration, dissolved air flotation (DAF), sedimentation, mechanical screen separators, screen presses, and drying (Ford & Fleming, 2002). Of course, each of these methods has benefits and drawbacks regarding financial, throughput

and nutrient recovery goals (Ford & Fleming, 2002). Nutrient recovery of SLS methods is measured in terms of total nitrogen, phosphorus and potassium which are the primary nutrients for plant growth and therefore determine if a method is worthwhile implementing to produce a fertiliser input (Hjorth et al., 2010). Additionally, total, and volatile solids retained are good indicators of efficiency of a technology (Xinxing et al., 2022). It is also important to acknowledge the GHG emissions generated through each method both in terms of environmental sustainability, and nutrient losses from these fractions (Xinxing et al., 2022). In some systems, GHGs can also be captured to recycle as an energy source, however, this technology comes with considerable financial input (Horacio et al., 2019; Xinxing et al., 2022).

Benefits

Liquid-solid separation allows for nutrient in slurries to be concentrated in the solid portion and therefore reduce total volume (Møller et al., 2000). In turn, this allows for cheaper transportation, and more efficient recycling in other systems (Lyons et al., 2021). Some methods of liquid-solid separation also reduce pathogen load in manure products, decreasing risk of biosecurity issues for application in other agricultural businesses (Zong et al., 2017).

Additionally, the liquid waste stream becomes easier to handle and therefore is more easily recycled to be used elsewhere (Lyons et al., 2021). The nutrient content of the liquid fraction is also reduced meaning there are less chances of negative environmental effects due to the minimal transport distance (Lyons et al., 2021).

Drawbacks

The separation of these fractions creates two waste streams that need to be managed and disposed/ recycled. There is also a high cost of initial investment to get these technologies up and running (Møller et al., 2000). Additionally, ongoing costs involved due to the replacement of parts e.g., membranes in filtration due to the wet and corrosive application could also be significant (Møller et al., 2000).

Nutrient recovery and GHG emissions: recent R&D

The primary reason for installing a separating mechanism is to enable the recycling of materials and nutrients for further use (Hjorth et al., 2010). Therefore, if the efficiency of this separation (and thus nutrient recovery) is low, the method is not worth investing in (Møller et al., 2000). Additionally, if GHG emissions of a method are high, nutrient retention is likely not reaching full efficiency (Xinxing et al., 2022).

Centrifuging is the process of removing liquid from a liquid-solid slurry by spinning at high speed (Zong et al., 2017). In this process, an internal auger moves solids and liquids towards separate discharge ports (Ford & Fleming, 2002). Centrifuging is considered the technology to have greatest GHG reductions (Xinxing et al., 2022). It also produces higher dry matter, and nutrient retention than other methods (Hjorth et al., 2010).

The process of filtration works by passing the slurry over a membrane which allows only particles of a certain size to pass through (Hjorth et al., 2010). A pressurised or vacuum based system can also be used to ensure liquids flow through the membrane (Hjorth et al., 2010).

In dissolved air flotation (DAF), microbubbles are used to increase buoyancy of particles in water (Féris & Rubio, 1999). The effluent is first treated with chemical flocculants such as organic polymers which bind solid particles together (Cocolo et al., 2012). Flocculated particles attach to the air bubbles and float to the surface (Ford & Fleming, 2002). Following which, they are skimmed off the top and dewatered (Féris & Rubio, 1999). DAF technologies, although efficient in separation of solid and liquid fractions and concentrating phosphorus in the solid portion, are highly inefficient in removal of ammonia and potassium (Féris & Rubio, 1999).

Sedimentation is likely the most common method of solid – liquid separation due to the ease of implementation (Hjorth et al., 2010). In sedimentation, effluent flows into a pond (usually during rain events) and solids settle to the bottom (Zhang & Westerman, 1997). The liquid portion is allowed to flow slowly into a lagoon or storage tank and the solid portion dries out through evaporation (Ford & Fleming, 2002; Zhang & Westerman, 1997). Following this, farm or earth moving machinery is used to empty the settling pond and this dry manure can be stockpiled, prepared for composting, or applied directly to a paddock (Ford & Fleming, 2002; Zhang & Westerman, 1997).

Screen separators and presses work in similar ways. Screen separators use gravity to pass the manure over a screen which allows only particles of a certain size to pass through, retaining the solid portion (Zhang & Westerman, 1997). Presses (belt, filter, and screw) on the other hand, add a significant force which presses the manure through the screen to squeeze out the liquid fraction (Møller et al., 2000; Zhang & Westerman, 1997).

Drying is often performed using rotary drum dryers which are set to high temperatures and rotate the manure to ensure even drying (Horacio et al., 2019). This process is efficient at removing moisture and can reduce pathogen load (Horacio et al., 2019).

Implementation and commercial application

When implementing these technologies, factors such as space requirements, capital investment, ongoing maintenance costs, electrical requirements and cost, and efficiency of the chosen method must be considered (Lyons et al., 2021; Møller et al., 2000; Xinxing et al., 2022). A settling pond might meet all other criteria, however, takes up significant land which cannot then be used for other purposes (Hjorth et al., 2010; Zhang & Westerman, 1997). Filtration and mechanical screen separators on the other hand are smaller, however have large costs involved in ongoing maintenance (Ford & Fleming, 2002). Whereas technologies such as centrifugation require more capital investment and higher electricity input to operate (Lyons et al., 2021).

Evidence of performance

The best way to determine the performance of a SLS method is to determine the separation efficiency of this method (Møller et al., 2000; Xinxing et al., 2022). Several studies have focused on evaluating these efficiencies, with most concluding centrifugation retains the highest proportions of total solids, nitrogen, potassium, and phosphorus (Cocolo et al., 2012; Møller et al., 2000; Xinxing et al., 2022). Additionally, GHG emissions are lowest using this method (Xinxing et al., 2022). Sedimentation was ranked second in separation efficiency, followed by filtration (Hjorth et al., 2010).

4.2.3.5 Anaerobic digestion

Description of the process

According to IEA (2020) the potential of converting global feedstocks (crop residues, animal manure, municipal solid waste, wastewater) to biogas is about 16 times more than that is in production now. Anaerobic digestion is a process of converting organic waste into biogas (a mixture of methane (55–65%), carbon dioxide (30–35%) and small quantities of hydrogen sulphide) (Harrison and Ndegwa, 2020; IEA, 2020). The anaerobic digestion system can be upgraded to produce near pure methane, which is also known as biomethane (IEA, 2020). Acidified cattle manure can be used to produce biohydrogen by modifying the anaerobic digester (Leong et al., 2024; Xing et al., 2010). Methanogens, a group of archaea, can produce methane during anaerobic decomposition of the organic matter. The methanogens use CO_2 and H_2 and/or small organic molecules and convert it to methane. Methanogens are quite diverse group of archaea and can be found in many anerobic environments. Some methanogens are: Methanococcales, Methanobacteriales, Methanosarcinales, Methanomicrobiales and Methanopyrales (Enzmann et al., 2018).

The anerobic digestion takes place in stages (Meegoda et al., 2018; Uddin and Wright, 2023) (i) hydrolysis, is a process of conversion of carbohydrate, lipids and proteins into sugars, amino acids, long chain fatty acids by bacterial extracellular hydrolytic enzymes. This a rate-limiting step and the optimum temperature is 30-50 °C and pH between 5-7 (ii) Acidogenesis, is also microbial process where acidogenic microbes produce volatile fatty acids (VFA) such as acetates, propionic acid and butyric acid. These VFS are substrates for the methanogenic bacteria to produce methane. Acidogenesis is considered to be fast process, often can be completed with 36 hours, (iii) Acetogenesis, is also a microbial process of converting VAFs into acetate and hydrogen and (iv) Methanogenesis, is the final stage where methanogenic microbes produce methane by utilising acetate. At this stage methanogenic microbes require pH between 6.5 – 7.5 for optimal functioning. In batch reactors, the production of methane usually ceases within 40 days.

In addition to pH and temperature, organic loading rate, hydraulic retention time, substrate composition, C/N ratio and stirring condition inside the reactor are the important factors to consider for successful anaerobic digestion (Ali et al., 2023). The efficiency of the methane production is also dependent on the biological (fungal inoculation, thermophilic digestion, enzymes), chemical (acid and alkali), mechanic (particle size, ultrasonic, microwave) and thermal (high temperature and pressure) pre-treatments (Meegoda et al., 2018). Among the inhibitory factors, concentration of ammonia and VFS are most important as they are critical to maintain favourable pH during anaerobic digestion (Chen et al., 2008).

There are many types of digesters are available depending on the feedstock feeding method (batch and continuous digester), feedstock type (High solid (20-40%), low solid (<20%), dry and wet digesters) process complexity (single and multistage digesters), operating temperature (mesophilic, thermophilic and psychrophilic digesters) and scale of the digester (farm based, centralized digesters) (Nizami et al., 2013; Pullen, 2015). Covered anaerobic lagoon and contract digesters are two suitable types of digesters for Australian intensive livestock industry (Bridle, 2011a).

Recent developments in small-scale and modular digester (i.e. in containers, mobile units) units can also be useful for in farm energy generation (Biogas World, 2024; INOPLEX, 2024).

Benefits (Nutrient recovery and GHG emission)

- Anaerobic digestion/biogas industry offer multiple opportunities of energy, environmental, agricultural and economic benefits. Australia has 242 biogas plants (as per 2017 estimates), mostly in the landfill/waste management industry and 50% of the methane produced is flared (Carlu et al., 2019).
- Energy generation- biogas can be used to generate electricity and heat. The covered anaerobic lagoons for example can produce 41- 256 KW electric energy depending on the size of the feedlot (10K – 60K SCU feedlot) (Bridle, 2011a).
- Capture N, P and K in the sludge. The N, P and K are not lost during anaerobic digestion, which may increase the concentration of the nutrients in the digestate. Some reports suggested that ammonia-N and P concentrations were 37% and 26% higher in the digestate than the pre-digested manure (Harrison and Ndegwa, 2020). However, the final concentration of the nutrients in the digestate also depends on the pre-digestion management and storage of the manure and effluents.
- Reduces GHG emissions (methane and nitrous oxide) to the atmosphere compared to stored and/or land applied raw or composted manure. Herrera et al. (2021) using carbon footprint analysis showed about 84% reduction in GHG emission from an anerobic digestion plant. Reduction in CO2 emissions by 6000 tonnes per annum for a 1000 kW plant (Pullen, 2015). It has been reported that storage of digestate can also cause ammonia and nitrous oxide emission (Herrera et al., 2021). However, it is important to do life cycle analysis to estimate GHG emissions to get the better understanding because manure management may account for 65% (Nizami et al., 2013; Pullen, 2015). It has also been reported that methane emission from digestate is about 59% less than the raw manure (VanderZaag et al., 2018). Reduction of methane and hydrogen sulphide odour from manure is also an advantage of using an anaerobic digester.

Drawbacks

- Capital cost of installation either covered anaerobic lagoon or industrial scale biogas plant is high (Bridle, 2011a; Carlu et al., 2019). For example, construction cost of covered anaerobic lagoon for 10K SCU feedlot was estimated about 700K in 2011 (i.e. 900K in 2023; https://www.rba.gov.au/calculator/annualDecimal.html) and simple payback time is 61 years (Bridle, 2011a). The Jandakot Bioenergy Plant in WA had a capital investment of 8-10 million A$, while the capital cost for the Yarra Valley Water biogas plant was 27 million A$ (Carlu et al., 2019).
- While the investment for covered anaerobic lagoon for >60K SCU feedlot is 3 times more than the investment for 10K SCU feedlot, the payback time is about 7 years (Bridle, 2011a).
- Upgradation of existing biogas plant to produce 100 Mtoe (mega tonne of oil equivalent) biomethane require large investment, about 15 US$ per MBtu (million British Thermal Unit) (1 MBtu = 0.29 MWh) (Carlu et al., 2019). Economics of upgradation or co-production of biohydrogen and methane requires assessment (Zappi et al., 2021).
- Construction and operation of anaerobic digester require skilled personnel (Lim et al., 2023; Pullen, 2015)

- Consistent feedstock supply. Not only do anerobic digesters require constant feedstock supply, the quality of feedstock also influence the methane output. Maximum biological methane potential of animal manures can vary widely. Feedlot manure exhibit low to moderate hydrolysis rate, which affects its methane production potential (Gopalan et al., 2013). According to IPCC (2006) the maximum methane-producing capacity of beef feedlot manure (0.17 m^3 CH_4 Kg /VS) is about 2.6 times less than the swine manure (0.45 m^3 CH_4 Kg /VS) and 1.4 times less than poultry manure (0.24 m3 CH_4 Kg /VS). Among the feedstock methane potentials, cattle/dairy manure is the lowest, about 15-25 m^3/tonne biogas yield (Pullen, 2015). Poultry manure has relatively higher biogas potential (30-100 m^3/tonne biogas) than the cattle slurry (Pullen, 2015).
- No/limited reduction in the volume of the feedstock. The end product, digestate should be managed. Cannot be utilised in full potential due to socio-economic condition (Lim et al., 2023)

Nutrient recovery and GHG emission: recent R&D

Co-digestion of cow manure with vegetable/fruit waste or bone meal/crude glycerol can improve the methane production (Andriamanohiarisoamanana et al., 2018; Aravani et al., 2023; Dias et al., 2014; Miramontes-Martínez et al., 2021). Li et al. (2021) reviewed a range of strategies to improve methane output from anaerobic digestion of cow manure. Among the reviewed processes, co-digestion of cow manure with corn stover and switchgrass. Municipal waste can also be a suitable substrate for co-digestion. The authors also summarized that shredding, mixing, blending, ultrasound, thermal and thermochemical pre-treatments and additions of additives (trace metal mixture, minerals, etc.) have positive influence on the methane production. Ding (2021) showed that electrochemically assisted anaerobic digestion can remove 65% of phosphorus from the dairy manure and increase methane yield by 11%. Ammonium and methane emission is likely during storage and application of digestate (solid and liquid). Acidification of the digestate can be an option to reduce ammonium and methane emissions (Tompkins et al., 2023).

Implementation and Commercial application

A detailed assessment of the bioenergy potential of Australia can be found in the Australian Renewable Energy Agency (ARENA) website (https://arena.gov.au/projects/australian-biomass-for-bioenergy-assessment-project/) (Enea and Deloitte, 2021) and Australian Renewable Energy Mapping Infrastructure (AREMI) platform (https://nationalmap.gov.au/renewables/). A list of bioenergy projects in Australia is also be found in ARENA website.

Evidence of performance (digestate)

Digestate may have higher nutrient content than compost but microbially unstable Digestate can be used as fertiliser and soil conditioner similar to the compost (Harrison and Ndegwa, 2020; Möller et al., 2008; Pullen, 2015). However, digestate solid needs to be either dried or composted before agricultural application. The liquid separated from solid can also undergo valorisation process to produce nitrogen-rich or -reduced solution and struvite (Mg/K ammonium phosphate) (Tompkins et al., 2023).

Adoption challenges for Australian Feedlots

- Pen manure is usually mixed with soil, gravel, hair or other contaminants that might clog/ the digester. (Tucker et al., 2015; Watts and McCabe, 2015). Regular pen cleaning and avoiding stockpiling is necessary to maximise methane production potential. Davis et al. (2010) and Tate et al. (2021) reported that about 60-70% of the volatile solid of the excreted manure can be lost within 20 days and thus reduces its methane production potential to about 60% (Gopalan et al., 2013).
- Requires at least 10,000 head or more and to be run at high occupancy. Feedlot manure management machineries should be fit for use to run anaerobic digester or digester should be designed so that existing machinery can be used. Need to have a steam flaker and boiler system to use the biogas (Watts and McCabe, 2015).
- >95% of the feedlot manure is solid. The feedstock for the digester is slurry and some digester can operate with maximum of 40% solid. It worth to mention, water availability will be one of the vital issues for converting manure to slurry. A mixing pond should be established to process the manure for the digester, which can be operationally challenging (Tait et al., 2021).
- The biological methane potential of feedlot manure is quite low compared to other manures or crop based feedstocks (Pullen, 2015). To maximise the methane potential, the manure needs to be co-digested with other wastes. Even if the co-digestion is economically possible, the maintenance and monitoring the feedstock for the digester offers significant challenges.
- There is opportunity to transport feedlot manure to existing biogas plants (https://nationalmap.gov.au/renewables/). The cost involved in transporting manure to biogas plants can be costly and poses risk of GHG emissions during handling and transportation.
- De-sludging and de-watering of the digestate and use of it will be challenging.
- The key geographical considerations for establishing anaerobic digesters are climate (require stable and warmer climate), transport network, regional cost of energy and regional network and distribution charges (ReNU Energy, 2017).
- O'Hara (2022) summarises the barrier for adoption of technologies including anaerobic digester as "the cost of processing wastes to high value products may hinder the adoption of technologies, however, rising costs of transportation and disposal of wastes encourage the valorisation of wastes. Aside from economic barriers, firms in the livestock industries are aware of drivers and barriers to adoption such as new business models that include the pathways to adoption, regulatory barriers, health, safety and biosecurity concerns, changes to the supply chain and the availability of skills and capabilities to support these new technologies."

4.3.2.6 Nitrogen and phosphorus recovery

Description of the process

Air scrubbers are used to capture ammonia from the air in the dairy farms and feedlots (Hristov et al., 2011; Van der Heyden et al., 2015). The air from the exhaust is passed through the air scrubbing system, consisting of inert porous bed or biofilters and washing liquid or water spraying system. The

basic principle is to capture water soluble ammonia (NH_3) gas as ammonium ion (NH_4^+) into liquid phase.

In a chemical air scrubber acidifying chemical is used (such as aluminium sulphate, sodium/potassium bisulphate and ferric sulphate/chloride) to maintain the pH of the washing liquid below 4 because higher pH (≥7) favours ammonia formation (Moore et al., 2018). Ammonium oxidizing nitrifying bacteria is used in biological air scrubber or in the biofiltration system to produce nitrate from the ammonium (Melse, 2009; Philippe et al., 2011). The efficiency of the ammonium capture from air is dependent on the scrubber configuration, temperature, air-liquid flow rates and pH.

The biofiltration system also requires optimal concentration of oxidizable carbon to function properly (Van der Heyden et al., 2015). Ammonium from effluent (solid separation is required to done before ammonium recovery) can also be recovered by acidifying the effluent and maintaining pH around 4. Using a gas-permeable membrane can also be used to recover ammonia from the effluent (Al-Juboori et al., 2023; Munasinghe-Arachchige et al., 2021; Tompkins et al., 2023). By design the gas-permeable membrane is a micro-porous hydrophobic system that allows ammonia to pass through the pores into an acidified aqueous solution to be converted to ammonium. Besides gas-permeable membrane nano-filter (MWCO 150 − 300 Da, high rejection of polyvalent cations and organics) and cation exchange zeolite (hydrated aluminosilicates) can also be used to separate ammonium from the aqueous solution (Pinelli et al., 2022; Zarebska et al., 2015).

Biological nitrogen removal process is also an effective way of recovering ammonium from the solid separated effluents. The basic idea is the same as the nitrification and denitrification of the ammonium in the effluent into N_2 gas ($NH_4^+ \rightarrow NO_2 + NO_3^- \rightarrow N_2$) (Vanotti et al., 2020). As nitrifying bacteria requires less oxidizable carbon than the denitrifies, biological nitrogen removal system, the effluent goes in the denitrification and then into an aerated nitrification tank. The effluent from the nitrification tank is recycled to the denitrification tank continuously until it recovers most of the ammonium as N_2 gas (Vanotti et al., 2009). The success of this recovery process is dependent on the presence of high-performance nitrifying organisms in the sludge (Ducey et al., 2010). Anammox (Anaerobic ammonium oxidation or de-ammonification) is an alternate pathway to oxidizing ammonium into N2 gas in anaerobic condition using Planctomycetes-like bacteria, including five species *Candidatus Scalindua, Candidatus Brocadia, Candidatus Kuenenia, Candidatus Anammmoxglobus*, and *Candidatus Jettenia* (Meng et al., 2017). This process is suitable for the effluent contains high ammonium and low organic carbon (C: N ~0.8), such as digestate from anaerobic digester (Pekyavas and Yangin-Gomec, 2019).

Dairy and piggery effluents contain high concentration of phosphorus and are suitable for recovery as magnesium ammonium phosphate or struvite ($MgNH_4PO_4$) (Prabhu and Mutnuri, 2014). Struvite contains both nitrogen and phosphorus and the phosphorus in struvite is less mobile than monoammonium phosphate or triple super phosphate that makes it better choice as a fertiliser (Ryu et al., 2012). Struvite can be precipitated from the effluent at a between 7 and 7.5 with a specific molar ratio between magnesium, nitrogen and phosphorus (Vanotti et al., 2020). It has been demonstrated that struvite precipitation is maximum at Mg^{2+}:NH_4^+: PO_3^- molar ratio of 1.2:1:1. For successful struvite precipitation, magnesium salt must be applied either as $MgCl_2$ or other suitable magnesium compounds. The concentration of calcium in the effluent has an influence on the struvite precipitation. When the concentration of calcium in effluent is high, maximum struvite precipitation occurs at pH between 7 and 7.5, whereas pH range can be varied between 7.5 and 9 if the calcium concentration is low. However, 99.7% pure struvite can be produced at pH 7-7.5. Struvite produced in higher pH values can be 30 to 70% pure because of precipitation of calcium and magnesium phosphate. Ethylene diamine tetra acetic acid (EDTA), a chelating agent and oxalic acid can be used to prevent calcium from forming calcium phosphate during struvite precipitation from dairy effluent.

Aeration plays a critical role in struvite precipitation. Optimal aeration can increase the rate of CO_2 production, may increase the pH of the effluent that favours struvite formation.

Alternative to extraction of struvite from the effluent, depending on the ammonium and calcium concentration, calcium or Fe/Al phosphates can also be extracted (Vanotti et al., 2020). The precipitation of calcium phosphate required large amounts of hydrated lime to increase the pH of the effluent >9.0. However, presence of bicarbonate (produced during hydrolysis of urea from urine present in the effluent, $CO(NH_2)_2 + H_2O \rightarrow 2NH_4^+ + CO_3^-$) and ammonium in the effluent buffer the pH against a quick rise after addition of lime or $Ca/Mg(OH)_2$. The increase in pH of the effluent produces NH3 gas that can be easily lost to the environment if sufficient care has not taken. The challenges with high ammonium in the effluent can be tackled by using a in nitrification bioreactor to produce effluent with nitrate. Calcium hydroxide can be added to this nitrate-rich effluent to precipitate phosphates ($Ca_5OH(PO_4)_3$). Alum (Al_2SO_4), aluminium chloride ($AlCl_3$), ferric sulphate ($Fe_2(SO_4)_3$) and ferric chloride ($FeCl_3$), alone or in combination can be used to precipitate phosphate from effluent in acidic or alkaline conditions. However, the precipitated phosphorus when applied to arable soil remains less available to plants as it is more soluble in acidic pH.

Microbial fuel cell (MFC) in which microorganisms work as catalysts for electrochemical reactions can be utilized to remove nitrogen and phosphorus from wastewater or effluent (Chen et al., 2021; Zubair et al., 2020). Algae is another option for recovering nitrogen and phosphorus from effluents. Microalgae Chlorella species may recover 20-100% of nitrogen and phosphorus (Khan and Yoshida, 2008).

Benefits

When implemented in the poultry and piggery systems, the air scrubbers can remove 70 − 80% of the ammonia from the air in the barn. Depending on the process involved up to 90% of N can be recovered from the effluent/aqueous solution. Up to 80-98% P can be recovered as struvite from poultry and piggery manure (Vanotti et al., 2020).

Drawbacks

- Requires high implementation cost, trained personnel, significant chemical handling.
- *Nutrient recovery and GHG emission: recent R&D*
- At the theoretical level ammonium and phosphorus recovery techniques aim to reduce emission of ammonia, methane and nitrous oxide (Tompkins et al., 2023).
- *Implementation and Commercial application*
- In USA, UK and some EU countries they have nitrogen and phosphorus extraction commercial plants for liquid digestate (Tompkins et al., 2023).

Evidence of performance

The agronomic performance of struvite is dependent on the climate, soil types and crop grown. There is evidence of increase crop yield with application of struvite but may not have influence on increasing phosphorus utilisation efficiency (Hertzberger et al., 2020; Talboys et al., 2016; Thiessen Martens et al., 2022).

4.2.4 Technology assessment

Based on the discussion in section 4.2.3, the technologies for value-adding solid manure and effluent are assessed. The technology assessment and evaluation can be found in Table 23 and in the embedded excel file in the Appendix. It is important to note here that, manure slurry is required to run the anaerobic digester. When solid feedlot manure is used as anaerobic digestion feedstock, a considerable volume of water is needed to prepare the solids for the digester (see section 4.2.3.5). This the why anaerobic digestion is grouped with technologies relevant for both solid and effluent.

Table 23. Manure and technologies assessed

Solid manure	Feedlot effluent	Transport effluent
Co-composting	Screen, sedimentation and holding Pond	Screen, sedimentation and holding Pond
Organo-mineral fertiliser (Pelletised)	Anaerobic digestion	Waste water treatment plant
Windrow composting	Filtration	Anaerobic digestion
Composting with amendments	Phosphorus recovery	Nitrogen recovery
Pelletising	Nitrogen recovery	Phosphorus recovery
Compost bedded pack barns/ Feedlot covered housing	Waste water treatment plant	Liquefaction
Anaerobic digestion	Liquefaction	Presses (belt/filter/screw)
Pyrolysis	Presses (belt/filter/screw)	Filtration
Rotary drum composting	Centrifuge	Centrifuge
Gasification	Drying	Drying
Larvae based composting		
Vermicomposting		

The technologies were assessed based on the eight criteria and each of the criterion had equal weight (Table 24).

Table 24. Technology assessment criteria and weights

Criteria	Weight
Benefits	10
Drawbacks	10
Biomass volume reduction	10
Nutrient loss/recovery	10
Ammonia & GHG emission	10
Capital and operation cost	10
Operational volume	10
Operation for manure per 10000 head feedlot	10
Science based innovation potential for feedlots	10
Technology readiness level for feedlots	10

Based on the scoring of the technologies is summarised in Table 25. A detail scoring can be found in Appendix.

Table 25. Ranking of the technologies

Solid manure	Feedlot effluent	Transport effluent	Ranking
Co-composting	Screen, sedimentation and holding Pond	Screen, sedimentation and holding Pond	1
Organo-mineral fertiliser (Pelletised)	Anaerobic digestion	Waste water treatment plant	2
Windrow composting	Filtration	Anaerobic digestion	3
Composting with amendments	Phosphorus recovery	Nitrogen recovery	4
Pelletising	Nitrogen recovery	Phosphorus recovery	5
Compost bedded pack barns/ Feedlot covered housing	Waste water treatment plant	Liquefaction	6
Anaerobic digestion	Liquefaction	Presses (belt/filter/screw)	7
Pyrolysis	Presses (belt/filter/screw)	Filtration	8
Rotary drum composting	Centrifuge	Centrifuge	9
Gasification	Drying	Drying	10
Larvae based composting			11
Vermicomposting			12

4.2.5 Laboratory testing

The technology assessment demonstrated that composting and pelletising were two of the most feasible value-addition technologies for solid manure.

We performed a short-term laboratory incubation to assess the extractable soil mineral nitrogen (NH_4^+ and NO_3^-), CO_2 emission (proxy for soil microbial activity) and N_2O emission from soil after application of composted pelletised beef manure and composted manure. We also added raw manure and stockpile manure in soil to compare with composted pelletised and unpelletized manure. A no manure addition control was also maintained. The rate of nitrogen application from each type of manure was 115 kg ha^{-1} based nitrogen requirement for 2.5 t ha^{-1} wheat yield (grain protein 13%) in Australian conditions. The required amount of manure was mixed with 400 g air-dried sieved (0.5 – 2.0 mm) Vertosol. The soil water content was maintained at 70% of field capacity (field capacity water content was 52%).

The incubation experiment was performed in sealed 2L glass vessels connected to computer controlled solenoid channels that control the flow of gas from glass vessels to the CO_2 and N_2O gas analysers (ABB LGR, USA). The soils were incubated for 16 days at 25°C. All the treatments (i.e., control, raw manure, stockpile manure, composted manured and pelletised composted manure) had 3 replications. After the incubation period, soil samples were destructively harvested to measure the concentration of 2M KCl extractable mineral nitrogen in soil. The concentration of NH_4^+ and NO_3^- were measured using Shimadzu TOC/L-TN analyser.

The CO_2 and N_2O emissions during the incubation period was highest in raw manure. Raw manure produced ~1.5 and ~2-fold more CO_2 and N_2O, respectively than the composted manure, which

indicated higher microbial activity and mineral nitrogen release in soil, when raw manure was added. While stockpile manure did not produce higher CO_2 than the stockpile manure, the N_2O emission from stockpile manure was about 2-fold lower than the raw manure. There was no clear difference between pelletised compost and compost in CO_2 and N_2O gas emissions (Figure 15).

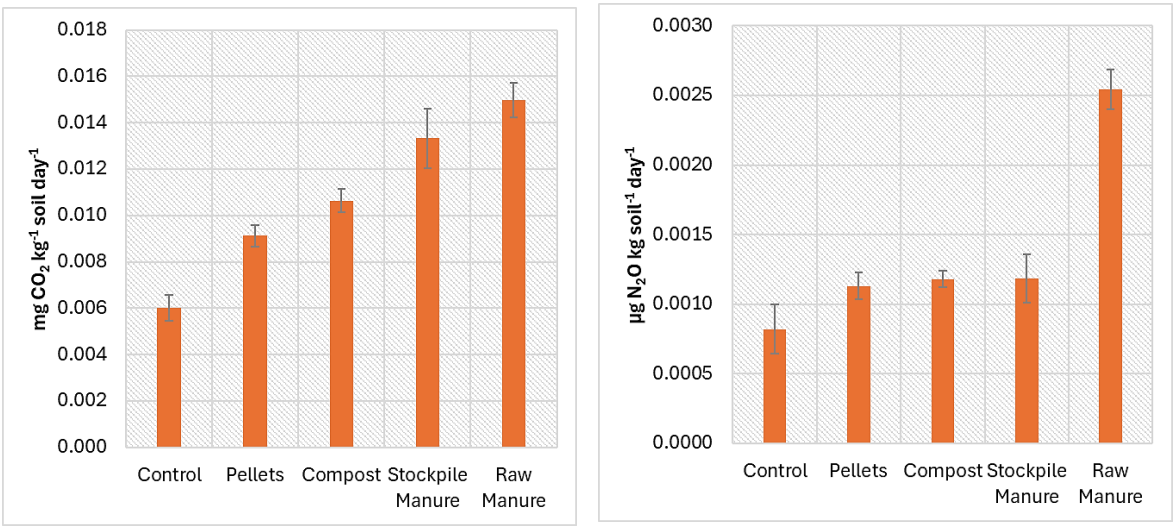

Figure 15. CO_2 and N_2O gas emissions from manure treated soil

Despite the changes observed in gas emissions, the extractable mineral nitrogen was on 54 mg kg $^{-1}$ soil across all manure treatments (Figure 16). The mineral nitrogen concentration in all manure treatments were not significantly higher than control, which implies blending synthetic fertiliser with manure is essential to formulate effective organo-mineral fertiliser.

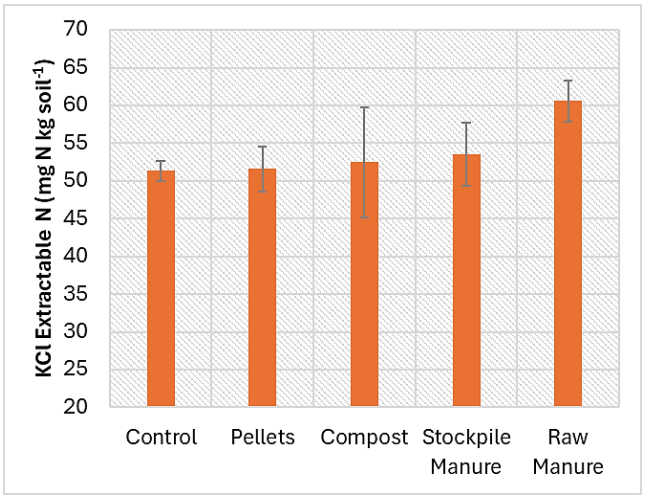

Figure 16. Concentration of extractable mineral N in soils treated with manure

4.2.6 Life cycle assessment and cost-benefit analysis

The results and implications of the LCA and CBA of the shortlisted technologies are outlined in the following sections. For the purposes of the LCA and CBA, the shortlisted technologies are abbreviated as follows:

- BAU: Stockpiling of feedlot manure
- S1: Co-composting of feedlot manure
- S2: Pelletised feedlot manure (not representative of organo-mineral fertiliser in Table 25)
- S3: Windrow composting of feedlot manure
- S4: Filtration of feedlot effluent
- S5: Anaerobic digestion of feedlot effluent
- S6: Screening of feedlot effluent (screw press separator)
- S7: Treating truck effluent at feedlot in the existing wastewater treatment train
- S8: Treating truck effluent at abattoir in the existing wastewater treatment train
- S9: Co-digestion of truck effluent with feedlot effluent at abattoir.

The additional theoretical scenario (a feedlot with anaerobic digestion of effluent and manure) is denoted as S5A. Production and cost assumptions which underly the LCA and CBA analysis are outlined in the Appendix.

4.2.6.1 Model 10,000 SCU Feedlot

Total greenhouse gas emissions associated with the nine shortlisted technologies/strategies are reported in Table26 (alongside BAU emissions) disaggregated by scope and source for the model 10,000 SCU feedlot. A summarised version is reported in Table27, outlining greenhouse gas emissions by scope for the 10,000 SCU feedlot and comparing to the BAU emissions.

Table 26. Greenhouse gas emissions (disaggregated by Scope and source) for a model 10,000 SCU feedlot under the BAU scenario and S1 – S9 for a twelve-month period

	Units	BAU	S1	S2	S3	S4	S5	S5A	S6	S7	S8	S9
Scope 1	**t CO_2-e**	**19,792**	**20,760**	**20,400**	**20,400**	**19,792**	**19,429**	**15,240**	**19,643**	**19,795**	**19,792**	**19,792**
Enteric methane	t CO_2-e	14,943	14,943	14,943	14,943	14,943	14,943	14,943	14,943	14,943	14,943	14,943
Manure methane	t CO_2-e	1,307	1,436	1,194	1,194	1,307	988	48	1,157	1,307	1,307	1,307
Feedpad	t CO_2-e	714	714	714	714	714	714	-	714	714	714	714
Stockpiling	t CO_2-e	227	-	-	-	227	227	-	231	227	227	227
Composting	t CO_2-e	-	356	113	113	-	-	-	-	-	-	-
Effluent pond	t CO_2-e	366	366	366	366	366	48	48	213	366	366	366
Irrigation	t CO_2-e	-	-	-	-	-	-	-	-	-	-	-
Manure nitrous oxide	t CO_2-e	2,407	3,021	3,021	3,021	2,407	2,385	-	2,408	2,409	2,407	2,407
Feedpad	t CO_2-e	1,771	1,771	1,771	1,771	1,771	1,771	-	1,771	1,771	1,771	1,771
Stockpiling	t CO_2-e	614	-	-	-	616	614	-	618	-	614	614
Composting	t CO_2-e	-	1,229	1,228	1,228	-	-	-	-	614	-	-
Effluent pond	t CO_2-e	-	-	-	-	-	-	-	-	-	-	-
Irrigation	t CO_2-e	21	21	21	21	20	-	-	19	24	21	21
Feedlot services	t CO_2-e	249	472	356	356	249	249	249	249	249	249	249
Feedmill	t CO_2-e	886	886	886	886	886	864	0	886	886	886	886
Scope 2	**t CO_2-e**	**73**	**73**	**627**	**73**	**78**	**73**	**73**	**74**	**73**	**73**	**73**
Feedlot services	t CO_2-e	73	73	627	73	78	73	73	74	73	73	73
Feedmill	t CO_2-e	0	0	0	0	0	0	0	0	0	0	0
Scope 3	**t CO_2-e**	**171,707**	**171,438**	**171,632**	**171,409**	**171,708**	**171,701**	**170,951**	**171,707**	**171,708**	**171,707**	**171,707**
Indirect nitrous oxide	t CO_2-e	461	498	498	498	461	455	-	461	462	461	461
Feedpad	t CO_2-e	394	394	394	394	394	394	-	394	394	394	394
Stockpiling	t CO_2-e	61	-	-	-	62	61	-	62	5	61	61
Composting	t CO_2-e	-	98	98	98	-	-	-	-	61	-	-

Effluent pond	t CO_2-e	5	5	5	5	4	-	-	4	-	5	5
Irrigation	t CO_2-e	2	2	2	2	2	-	-	2	2	2	2
Land application	t CO_2-e	1,737	1,376	1,485	1,376	1,737	1,737	1,737	1,737	1,737	1,737	1,737
Feedlot services	t CO_2-e	76	131	216	103	77	76	76	76	76	76	76
Feedmill	t CO_2-e	295	295	295	295	295	295	0	295	295	295	295
Feed	t CO_2-e	12,128	12,128	12,128	12,128	12,128	12,128	12,128	12,128	12,128	12,128	12,128
Transport	t CO_2-e	456	456	456	456	456	456	456	456	456	456	456
Feeder cattle emissions	t CO_2-e	156,553	156,553	156,553	156,553	156,553	156,553	156,553	156,553	156,553	156,553	156,553
Total	**t CO_2-e**	**191,572**	**192,271**	**192,659**	**191,882**	**191,578**	**191,204**	**186,263**	**191,424**	**191,576**	**191,572**	**191,572**

Table 27. Greenhouse gas emissions (disaggregated by Scope) for a model 10,000 SCU feedlot under the BAU scenario and S1 – S9 for a twelve-month period

	Units	**BAU**	**S1**	**S2**	**S3**	**S4**	**S5**	**S5A**	**S6**	**S7**	**S8**	**S9**
Scope 1	t CO_2-e	19,792	20,760	20,400	20,400	19,792	19,429	15,240	19,643	19,795	19,792	19,792
Scope 2	t CO_2-e	73	73	627	73	78	73	73	74	73	73	73
Scope 3	t CO_2-e	171,707	171,438	171,632	171,409	171,708	171,701	170,951	171,707	171,708	171,707	171,707
Total	**t CO_2-e**	**191,572**	**192,271**	192,659	**191,882**	**191,578**	**191,204**	**186,263**	**191,424**	**191,576**	**191,572**	**191,572**
Change from BAU	t CO_2-e		699	1,086	310	6	-369	-5,309	-148	4	-	-
Change from BAU	%		0.36%	0.57%	0.16%	0.003%	-0.19%	-2.77%	-0.08%	0.002%	0.00%	0.00%

At a whole-of-business level, no substantial change in greenhouse gas emissions (relative to the BAU scenario) was achieved through the adoption of S1 – S9 (see Table 26 and Table 27). Only two shortlisted technologies (S5 and S6) achieved any reduction in greenhouse gas emissions. The greatest reduction in emissions was associated with scenario S5A, however, this was achieved using a system design never yet adopted (and perhaps never to be adopted) in Australia. The value in analysing and reporting S5A is to demonstrate that the methane potential and volume of feedlot effluent alone is very small and, even in systems where the manure is also anaerobically digested and used to generate biogas, there is limited emission reduction potential for the feedlot industry. No change in greenhouse gas emissions was achieved by S8 and S9 as emissions arising from BAU truck effluent disposal (dumping, spillage etc) arose outside the emission boundary of the feedlot and the LCA and were treated outside the boundary of the feedlot and the LCA under S8 and S9.

Isolating manure and effluent-related methane and nitrous oxide emissions (as in Figure 17) demonstrates that the manure scenarios (S1 – S3) resulted in an increase in these emissions relative to the BAU. The greatest increase was associated with S1 (co-composting). Compost generates higher nitrous oxide which is a primary factor in the higher emission rates reported here. S6 (screening feedlot effluent to remove some N and VS) achieved a slight reduction relative to BAU emissions as emissions from effluent ponds were reduced.

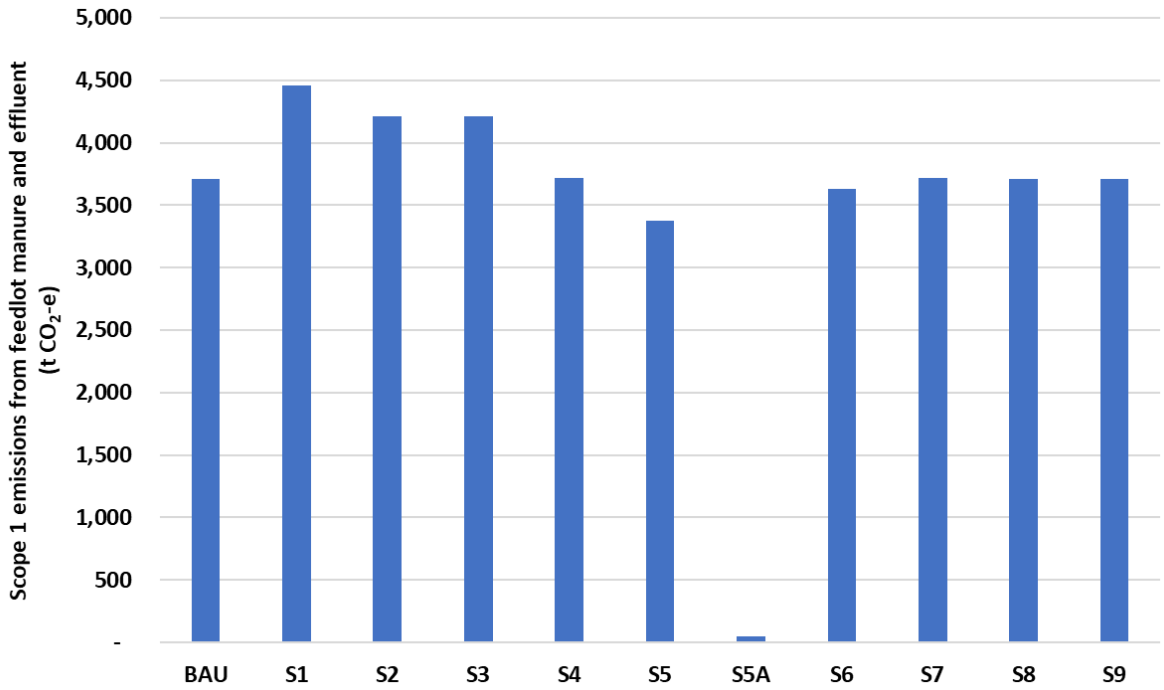

Figure 17. Scope 1 emissions from manure and effluent (generation and management) under the BAU and S1 – S9 scenarios for a model 10,000 SCU feedlot. Note livestock and fuel use related emissions were excluded.

Although S1 – S3 resulted in higher emissions from manure at the feedlot-level, the only true comparison between greenhouse gas emissions is made at the field-level due to variability as to where emissions arise in the treatment train for the BAU and S1 – S3 technologies. Scope 3 emissions from field application of the manure products were approximately 20% lower in S1 and S3 compared with the BAU and 15% lower in S2 than in the BAU (due to urea added in the pelleting process, i.e., higher N) (see also section 4.2.5 for laboratory comparison of gas emission). Despite this, the treatment processes in S1 – S3 ultimately led to higher total emissions (compared with the BAU scenario) as,

although there were lower Scope 3 emissions in S1 and S3, these were not large enough to offset the higher emissions from composting relative to stockpiling. The windrow composting process, followed by the high input palletisation process (including the addition of urea) contributed to higher Scope 1 and Scope 3 emissions under S2 compared with the BAU.

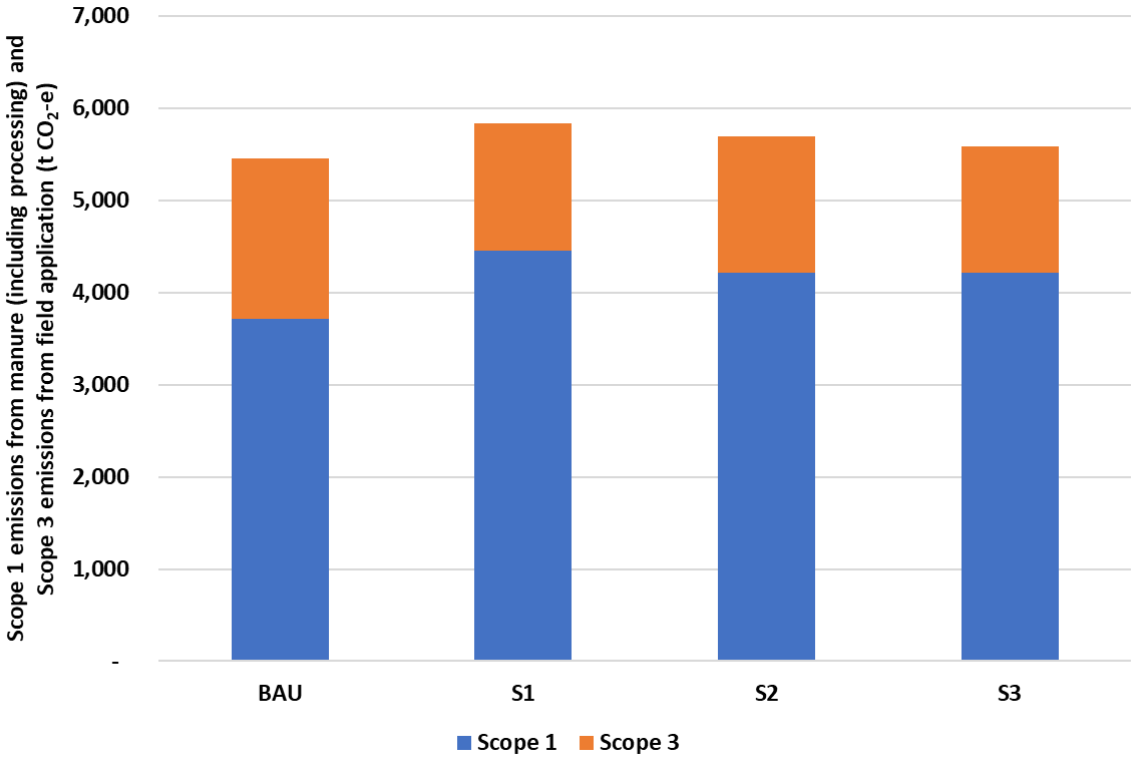

Figure 18 Scope 1 emissions from manure (including processing) and Scope 3 emissions from field application of manure products for a 10,000 SCU feedlot under a BAU scenario and S1 – S3

The CBA results also indicated that the adoption of S1 – S9 would not necessarily result in economic benefits for the model feedlot (see Table 28). The majority of the technologies resulted in negative economic outcomes. All except S2 had negative net present values (NPVs), indicating that the projects/investment was unprofitable. In addition, most never achieved a positive cashflow over the 10-year project life (indicated by N/A under the Internal Rate of Return (IRR)). As only three technologies (S5, S5A, and S6) achieved a reduction in greenhouse gas emissions, only three marginal abatement costs (MACs) could be determined. Based on the MACs, even if the Safeguard Mechanism were extended to agriculture and the feedlot were required in future to purchase ACCUs from the Clean Energy Regulator's (CER) Cost Containment Mechanism (the price floor of which was set at $75/t in FY24), the feedlot would be better placed purchasing ACCUs for some time, noting that the ACCU price set by the CER will be indexed by the Consumer Price Index (CPI) plus 2% each year (Australian Government, 2024).

Table 28. Results from the cost-benefit analysis of the BAU scenario and S1 – S9 for model 10,000 SCU feedlot

	Total benefits ($ PV)	Total costs ($ PV)	Net present value ($)	Change from BAU ($)	Internal Rate of Return (%)	Marginal abatement cost ($/t CO2-e)
BAU	$428,683	$964,800	-$536,117		N/A	
S1	$1,999,055	$6,164,067	-$4,165,012	-$3,628,895	N/A	N/A
S2	$21,316,296	$11,157,434	$10,158,862	$10,694,979	108%	N/A
S3	$825,162	$1,702,494	-$877,332	-$341,215	N/A	N/A
S4	$2,480	$585,663	-$583,184	-$47,067	N/A	N/A
S5	$127,346	$1,983,889	-$1,856,543	-$1,320,426	N/A	$538
S5A	$5,110,441	$14,525,239	-$9,414,798	N/A	-23%	$387
S6	$-	$2,420,188	-$2,420,188	-$1,884,071	N/A	$1,635.50
S7	$428,683	$964,800	-$536,117	$-	N/A	N/A
S8	$428,683	$964,800	-$536,117	$-	N/A	N/A
S9	$428,683	$964,800	-$536,117	$-	N/A	N/A

Breakeven prices for manure products (BAU, S1 – S3) were calculated (Table 29) to compare the average of the surveyed/reported selling prices (used in the CBA reported in Table 28) and the price required to achieve a NPV of zero or above. For stockpiling and composting, lot feeders would have to be able to sell the end-products for approximately double the current industry average to breakeven on these activities. Co-composting would require nearly three times the current industry average selling price for compost (although this value may not be reflective of the selling price for co-composted material). For S2, the breakeven price was nearly half the average of the reported selling prices, indicating that producers of pelletised manure products may be attempting to sell these products at a premium to a niche market.

Table 29. Comparison of average surveyed/reported selling prices for manure products versus calculated breakeven prices

	Units	BAU	S1	S2	S3
Average of surveyed/reported selling prices	$/t	$12.71	$25.26	$700.00	$25.26
Breakeven prices – product	$/t	$28.61	$77.9	$401.78	$52.13

Despite these findings, there are a number of reasons why adoption of some technologies covered in the LCA and CBA may be worthwhile.

Manure (either stockpiled, co-composting or traditional windrow composting), for example, produces a product that contributes to soil carbon sequestration in the short-term. This has not been quantified in the present study as it is nearly impossible to do so theoretically and over a wide area. Due to the additional carbon added during the process, co-composted material should generally be superior in this respect as the amount of carbon applied to the soil (per tonne of compost applied) will generally be higher than pure feedlot manure compost. More of the carbon in stockpiled manure (BAU) may well degrade when land applied (as less carbon in lost in the stockpiling process than in the composting) but there is no conclusive evidence as to whether there is a greater long-term soil carbon benefit from stockpiling or composting. In addition to soil carbon sequestration potential, there may be regulatory or social licence issues (e.g., odour) that necessitate composting.

The fundamentals determined elsewhere in this study do not support a high valuation for feedlot compost unless sold into select industries that require the benefits from low weed seeds, low pathogens and low odour (see 4.1.1 Feedlot manure). However, the analysis does indicate that there may be marginal growth in the selling price possible. The principle means of obtaining this is to market the product to users with the greatest potential gain from it (e.g., high margin crops with high nutrient demand and requirements for the added benefits, such as vegetables), although this niche opportunity will likely only be available to feedlots located proximate to major growing regions given the high transport costs associated with moving feedlot manure products.

Given the very large capital costs (and the additional labour and infrastructure requirements) associated with pelletisation, it could likely only achieve a maximum theoretical adoption equivalent to approximately 17% of the industry capacity. However, the feedlots would likely end up selling into the same concentrated markets (e.g., QLD/NSW) and therefore may be unlikely to achieve current reported selling prices which would have a significant effect on the viability of the investment.

4.2.6.2 Australian feedlot industry

The 10,000 SCU feedlot LCA was extrapolated to whole-of-industry level and results are reported in Table 30. The industry-level results represent greenhouse gas emissions under theoretical 100% adoption of the strategies and technologies. Fundamentally, the results of the LCA and CBA at the feedlot level did not support or justify a targeted extrapolation to industry-level as, based on the current prices, adoption is likely to be very low (if it occurs at all, e.g., for feedlot or truck effluent technologies).

Table 30. Greenhouse gas emissions (disaggregated by Scope and source) for the Australian feedlot industry under the BAU scenario and S1 – S9 for a twelve-month period

	Units	BAU	S1	S2	S3	S4	S5	S6	S7	S8	S9
Scope 1	**t CO_2-e**	2,413,616	2,531,646	2,487,772	2,487,772	2,413,678	2,369,425	2,403,714	2,413,963	2,413,616	2,413,616
Enteric methane	t CO_2-e	1,822,359	1,822,359	1,822,359	1,822,359	1,822,359	1,822,359	1,822,359	1,822,359	1,822,359	1,822,359
Manure methane*	t CO_2-e	159,366	175,179	145,550	145,550	159,366	120,484	149,312	159,366	159,366	159,366
Feedpad	t CO_2-e	87,049	87,049	87,049	87,049	87,049	87,049	87,049	87,049	87,049	87,049
Stockpiling	t CO_2-e	27,631	-	-	-	27,631	27,631	27,899	27,631	27,631	27,631
Composting	t CO_2-e	-	43,444	13,816	13,816	-	-	-	-	-	-
Effluent pond	t CO_2-e	44,685	44,685	44,685	44,685	44,685	5,803	34,363	44,685	44,685	44,685
Irrigation	t CO_2-e	-	-	-	-	-	-	-	-	-	-
Manure nitrous oxide	t CO_2-e	293,484	368,424	368,391	368,391	293,546	290,869	293,636	293,831	293,484	293,484
Feedpad	t CO_2-e	215,962	215,962	215,962	215,962	215,962	215,962	215,962	215,962	215,962	215,962
Stockpiling	t CO_2-e	74,907	-	-	-	75,086	74,907	75,347	-	74,907	74,907
Composting	t CO_2-e	-	149,847	149,814	149,814	-	-	-	74,907	-	-
Effluent pond	t CO_2-e	-	-	-	-	-	-	-	-	-	-
Irrigation	t CO_2-e	2,615	2,615	2,615	2,615	2,498	-	2,327	2,962	2,615	2,615
Feedlot services	t CO_2-e	30,306	57,584	43,371	43,371	30,306	30,306	30,306	30,306	30,306	30,306
Feedmill	t CO_2-e	108,101	108,101	108,101	108,101	108,101	105,407	108,101	108,101	108,101	108,101
Scope 2*	**t CO_2-e**	8,902	8,902	76,417	8,902	9,463	8,902	9,004	8,902	8,902	8,902
Feedlot services	t CO_2-e	8,902	8,902	76,417	8,902	9,463	8,902	9,004	8,902	8,902	8,902
Feedmill	t CO_2-e	-	-	-	-	-	-	-	-	-	-
Scope 3	t CO_2-e	20,939,723	20,906,903	20,930,546	20,903,361	20,939,822	20,938,956	20,939,704	20,939,825	20,939,723	20,939,723
Indirect nitrous oxide	t CO_2-e	56,250	60,747	60,745	60,745	56,234	55,482	56,210	56,352	56,250	56,250

	Units	**BAU**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Feedpad	t CO_2-e	47,992	47,992	47,992	47,992	47,992	47,992	47,992	47,992	47,992	47,992
Stockpiling	t CO_2-e	7,491	-	-	-	7,509	7,491	7,535	634	7,491	7,491
Composting	t CO_2-e	-	11,988	11,985	11,985	-	-	-	7,491	-	-
Effluent pond	t CO_2-e	560	560	560	560	535	-	498	-	560	560
Irrigation	t CO_2-e	208	208	208	208	199	-	185	236	208	208
Land application	t CO_2-e	211,851	167,811	181,087	167,774	211,851	211,851	211,851	211,851	211,851	211,851
Feedlot services*	t CO_2-e	9,302	16,024	26,394	12,522	9,417	9,302	9,323	9,302	9,302	9,302
Feedmill*	t CO_2-e	36,034	36,034	36,034	36,034	36,034	36,034	36,034	36,034	36,034	36,034
Feed	t CO_2-e	1,479,036	1,479,036	1,479,036	1,479,036	1,479,036	1,479,036	1,479,036	1,479,036	1,479,036	1,479,036
Transport	t CO_2-e	55,650	55,650	55,650	55,650	55,650	55,650	55,650	55,650	55,650	55,650
Feeder cattle emissions	t CO_2-e	19,091,600	19,091,600	19,091,600	19,091,600	19,091,600	19,091,600	19,091,600	19,091,600	19,091,600	19,091,600
Total	**t CO_2-e**	23,362,242	23,447,452	23,494,735	23,400,035	23,362,963	23,317,283	23,352,422	23,362,690	23,362,242	23,362,242

**Based on Queensland methane conversion factors and Queensland grid electricity emission factors.*

4.2.6.3 Adoption rates

Although not used in the whole of industry analysis due to the lack of incentive to adopt, predicted peak adoption levels and time to near peak adoption is reported in Table 31 for S1 – S9.

Table 31. Adoption rates and timeframes for S1 – S9 determined using ADOPT

	S1	S2	S3	S4	S5	S6	S7	S8	S9
Peak adoption level (%)	1%	3%	1%	1%	1%	2%	6%	6%	6%
Time to near peak adoption (years)	13	14	8	16	16	13	3	7	7

The adoption rates outlined in Table 31 may well be higher in practice. Note that the key underlying assumptions (e.g., environmental outcomes, effect on business profitability, and which are reported in the Appendix) were informed by the LCA and the cost-benefit analysis (which relied on current selling prices for manure products). If higher prices could be achieved in the future (leading to higher potential for financial return on the investment), adoption rates would likely be higher. In addition, the calculated adoption rates are based on a standardised set of questions and do not reflect (nor can the model readily be altered to reflect) the nuances as to why individual lot feeders may adopt a technology or strategy even if there are additional cost, environmental, or management challenges to doing so, e.g., for regulatory or social licence reasons.

Even though the adoption rates outlined in Table 31 are theoretical, they align with the broader findings of this study that there is very limited (and may well be negative) marginal utility from adopting certain technologies or strategies. Essentially, the majority of the Australian feedlot industry is already operating low-cost, low environmental impact, and low input (labour etc) by-product management, and there are various disadvantages to changing practices.

4.2.7 Case study of pelletised organo-mineral fertiliser

Pelletised organo-mineral fertiliser was not found to be a viable alternative to synthetic fertiliser in either conventional maize silage (Table 32) or wheat (Table 33) production, with negative gross margins returned under multiple estimates of nitrogen use efficiency (NUE). To return a gross margin equivalent to that of BAU production, the selling price for the organo-mineral fertiliser would have to be approximately $200/t which is approximately half the breakeven selling price needed by the feedlot (see Table 29). Given that the product cannot be viable in either broadacre scenario, the potential market for pelletised organo-mineral fertiliser within the agricultural industry is likely to be very small.

There is also no definitive indication that organo-mineral fertiliser would achieve a better environmental outcome (from a product carbon footprint perspective) than synthetic alternatives. Where emissions associated with composting the raw manure were attributed to the product (rather than the feedlot), the result was a significantly higher impact for maize silage and wheat under both the optimistic and conservative NUE scenarios (see Table 36 and Table 37) due to high application rates required and the associated field emission factors. Even if the emissions associated with composting the raw material were attributed to the feedlot, and hence the marginal product carbon footprint (difference between composting and stockpiling raw manure, and the emissions associated with pelletising) used, a significant environmental benefit was only achieved in the optimist scenario of a 74% NUE. However, adjustment to feedlot manure stockpiling and composting duration or method would maximise nutrient retention and minimise emission of GHG (Bai et al., 2020) and thus

allow to modify the N_2O and CH_4 emission factor to better reflect the 'adjusted' feedlot manure management (Maciel et al., 2021).

The justification for allocating impacts from stockpiling of manure to the feedlot (as opposed to the end-product) is relatively clear, as this practice forms the industry standard practice, and all manure cannot reasonably be sold raw at point of harvest. As composting represents an additional emission source, however, allocating these emissions to the feedlot (and not to the product) is less justifiable, particularly as the process is intended to value add the manure product and creates emissions additional to the BAU operating case for industry.

No conclusive statement as to there being an environmental benefit from using pelletised organo-mineral fertiliser (as opposed to synthetics) can be made, particularly as the BAU scenarios for both maize silage and wheat were associated with very high application rates of synthetic fertilisers to meet the N, P and K demand of the crops (accounting for losses and utilisation efficiencies) which may be atypical to standard operating practices. However, even under this scenario, the organo-mineral fertiliser (at 74% NUE) resulted in 50% less P being applied to the wheat crop than when the synthetic fertiliser was used (see Table 35). Conservatively, application of organo-mineral fertiliser could achieve 0.5 t of removals in CO_2-e terms per hectare; optimistically, this may be 1.5 t CO_2-e per hectare (data not shown). This would theoretically reduce reportable emissions associated with the technology but would still not be viable from a financial perspective.

4.2.8 Pelletised organo-mineral fertiliser: Alternative scenarios and recommendations

The case study presented in section 4.2.7 was based on considering NUE of 74% and 14:1 mixture of composted pelletised feedlot manure and urea. The target composition of the organo-mineral fertiliser in the case study was to provide ~50% of the applied N from composted feedlot manure. Since the gross margin reported in the case study was not economically feasible, there are few other alternatives to consider because organo-mineral fertiliser has NUE, soil health and environmental benefits (Burak et al., 2023; Quan et al. 2021).

- Davis et al. (2010) reported that 70% of N excreted on feedlot pen surface is lost as NH_3, N_2O or other N gases. Adjustment to feedlot manure stockpiling and composting duration or method would maximise nutrient retention and minimise emission of GHG (Bai et al., 2020 & see section 4.2.3.1). Shortening the stockpiling and composting duration may reduce the emission factor that is used for accounting N_2O and CH_4 emission from the manure management. Any modification to the emission factor would potentially alter the GHG emission from Australian feedlot industry. Maciel et al. (2021) and Davis et al. (2010) questioned the validity of using a fixed N_2O emission factor for feedlot manure. Nevertheless, future research is required to determine emission factor for any manure management technique aiming at improving nutrient value of the feedlot manure.
- Adjustment of the mixing ratio of composted pelletised feedlot manure with synthetic N fertiliser to achieve NUE higher than 50% (i.e. BAU). On-going research in Queensland DPI (formerly QDAF) is suggesting that even at mixing ratio of 7:1 — 2:1 higher NUE can be achieved compared to BAU in experimental situations resembling high rainfall conditions. At this mixing ratio it is likely to achieve positive gross marginal return as the quantity of the pelletised manure has substantially reduced (note: approximation was done based on the gross marginal budget for wheat in Table 33 Table 35). For example, using the gross margin

budget for wheat (see Table 33), if mixing ratio in pelletised organo-mineral fertiliser is 2:1 and NUE target is 74% then the positive gross margin will be $357/ha, whereas positive gross margin is $385/ha for BAU with 46% NUE. A more conservative NUE target of 46% for pelletised organo-mineral fertiliser will also achieve positive gross margin of $205/ha.

- Alternative cost-effective way of pelletising or granulating feedlot manure can be considered to lower the price of commercially available pelletised feedlot manure. Comparing the with urea ($750/t with 46% N), the current price of pelletised manure product ($700/t with ~3% N) is very high and shrinks the market for the product. Any engineering solution to make the palletisation cost-effective may potentially increase the demand for the product.
- The main advantage of the pelletised product is its compatibility with conventional fertiliser spreaders. However, un-pelletised composted feedlot manure can also be used for formulating organo-mineral fertiliser to get higher NUE, soil health and environmental benefits than the synthetic N fertilisers. Using the gross margin budget for wheat (see Table 33) and end-user cost of applying composted manure in paddock (i.e. $55/t, see Table 14), if the mixing ratio in pelletised organo-mineral fertiliser is 14:1 (as in Table 35) and NUE target is 74% and 46% (as in BAU) then the positive gross margin will be $500/ha and $434/ha, respectively compared to $385/ha in BAU. Comparing the N concentration in composted pelletised and un-pelletised manure and total cost of spreading of composted manure (see Table 14), it can be suggested that there are research and development opportunities to formulate organo-mineral fertiliser with un-pelletised composted manure to provide better economic outcome than pelletised manure. However, this entails and additional challenge to devise a 'precise method' of applying the un-pelletised organo-mineral fertiliser near the seed in the paddock.

Table 32. Gross margin budget for maize silage under BAU (synthetic fertiliser) and pelletised organo-mineral fertiliser scenarios with varying nitrogen use efficiencies

	Units	**BAU**	**Pelletised organo-mineral fertiliser**	
Nitrogen use efficiency	%	50%*	74%**	50%
Income				
Expected yield	t DM/ha	16.7	16.7	16.7
Selling price***	$/t DM	$324	$324	$324
Total income	$/ha	$5,416.2	$5,416.2	$5,416.2
Variable costs				
Pre-planting	$/ha	$187.7	$187.7	$187.7
Seed	$/ha	$812.5	$812.5	$812.5
Contract - Planting	$/ha	$187.0	$187.0	$187.0
Fertiliser	$/ha	$1,940.0	$6,181.9	$9,134.1
Herbicide	$/ha	$367.9	$367.9	$367.9
Insecticide	$/ha	$51.5	$51.5	$51.5
Irrigation	$/ha	$216.0	$216.0	$216.0
Total variable costs	$/ha	$3,762.5	$8,004.3	$10,956.6
Gross Margin	**$/ha**	$1,653.8	-$2,588.1	-$5,540.4

**Based on GRDC (2014). **Based on* Kaupa & Rao (2014)*. ***Based on a selling price of $120/t standing wet and a dry matter content of 37%. Note that costs associated with contract harvesting, carting, and covering are not included as these costs would typically be borne by the purchaser (total estimated cost to purchaser for product: ~$160/t wet at silage pit).*

Table 33. Gross margin budget for wheat under BAU (synthetic fertiliser) and pelletised organo-mineral fertiliser scenarios with varying nitrogen use efficiencies

	Units	BAU	Pelletised organo-mineral fertiliser	
Nitrogen use efficiency	%	46%*	74%**	46%
Income				
Expected yield	t DM/ha	2.4	2.4	2.4
Selling price	$/t DM	350.0	$350	$350
Total income	$/ha	$840.0	$840.0	$840.0
Variable costs				
Seed	$/ha	$48.5	$48.5	$48.5
Fertiliser	$/ha	$222.6	$749.9	$1,180.5
Herbicide	$/ha	$84.4	$84.4	$84.4
Harvesting	$/ha	$81.5	$81.5	$81.5
Levies	$/ha	$8.6	$8.6	$8.6
Insurance	$/ha	$8.7	$8.7	$8.7
Wetter	$/ha	$1.1	$1.1	$1.1
Total variable costs	$/ha	$455.2	$982.6	$1,413.2
Gross Margin	**$/ha**	$384.8	-$142.6	-$573.2

**Based on* Angus & Grace (2017)*. **Based on* Kaupa & Rao (2014)*.*

Table 34. Maize silage case study fertiliser application

	Units	BAU	Pelletised organo-mineral fertiliser	
Nitrogen use efficiency	%	50%	74%	50%
N applied	kg/ha	735	496	735
P applied	kg/ha	83	83	123
K applied	kg/ha	167	174	257
Urea application	kg/ha	1,116	-	
Easy N application	kg/ha	346	-	
DAP application	kg/ha	413	-	
MOP application	kg/ha	334	-	
Organo-mineral pellets*	kg/ha		8,810	13,044
N application as % of removal	%	200%	135%	200%
P application as % of removal	%	165%	165%	245%
K application as % of removal	%	50%	52%	77%

**Composition of organo-mineral fertiliser pellets: 6.7% urea and 93.3% composted feedlot manure.*

Table 35. Wheat case study fertiliser application

	Units	BAU	Pelletised organo-mineral fertiliser	
Nitrogen use efficiency	%	46%	74%	46%
N applied	kg/ha	95.0	59	95
P applied	kg/ha	14.5	10	16
K applied	kg/ha	11.0	21	33
Urea application	kg/ha	193	-	-
Easy N application	kg/ha	-	-	-
DAP application	kg/ha	73	-	-
MOP application	kg/ha	22	-	-
Organo-mineral pellets*	kg/ha	-	1,055	1,686
N application as % of removal	%	216%	135%	216%
P application as % of removal	%	165%	113%	180%
K application as % of removal	%	100%	189%	302%

**Composition of organo-mineral fertiliser pellets: 6.7% urea and 93.3% composted feedlot manure.*

Table 36. Product carbon footprint of maize silage produced BAU (synthetic fertiliser) and organo-mineral fertiliser scenarios

	Units	BAU	Pelletised organo-mineral fertiliser	
Nitrogen use efficiency	%	50%	74%	50%
*Cradle-to-grave product carbon footprint of organo-mineral fertiliser**				
Carbon footprint of maize silage	t CO_2-e/t DM	0.39	0.54	0.77
*Marginal product carbon footprint of organo-mineral fertiliser***				
Carbon footprint of maize silage	t CO_2-e/t DM	0.39	0.32	0.45

**Emissions associated with composting the raw manure are attributable to the product, as well as emissions from the pelleting process.*

***Product carbon footprint is based on the emissions from the pelleting process, and the marginal difference between composting and stockpiling the raw manure.*

Table 37. Product carbon footprint of wheat produced BAU (synthetic fertiliser) and organo-mineral fertiliser scenarios

	Units	BAU	Pelletised organo-mineral fertiliser	
Nitrogen use efficiency	%	46%	74%	46%
*Cradle-to-grave product carbon footprint of organo-mineral fertiliser**				
Carbon footprint of wheat	t CO_2-e/t	0.38	0.52	0.74
*Marginal product carbon footprint of organo-mineral fertiliser***				
Carbon footprint of wheat	t CO_2-e/t	0.38	0.34	0.44

**Emissions associated with composting the raw manure are attributable to the product, as well as emissions from the pelleting process.*

***Product carbon footprint is based on the emissions from the pelleting process, and the marginal difference between composting and stockpiling the raw manure.*

5. Conclusion

5.1 Key findings

Twenty-five Australian feedlots covering 615,000 head of capacity were surveyed to determine the baseline volume and value of manure and effluent products to the Australian feedlot industry in the 2023 financial year. It was found that 2.1 million tonnes of manure products are generated and sold each year and an additional ~4,000 ML of liquid effluent is generated and utilised on site at feedlots.

Despite large volumes of product being moved each year, the sale of manure cost the industry $0.57 for every tonne sold in FY23. Feedlots are under significant pressure to move product under the constraints of space and a continuous stream of manure. This often leads to the lot feeder being in the position of price taker at the point of sale of manure products.

Manure is currently marketed as one of three products: raw, stockpiled, or composted manure. Granulated (e.g., pelleted) compost is also available to a lesser extent. The sale of stockpiled manure products accounts for roughly 70% of all manure sold with raw and composted manure making up 15% of the market each. Around 35% of manures are used on feedlot owned land.

The primary barrier to further adoption of manure by end-users outside the feedlot industry was cost but product consistency and characteristics (particularly high moisture levels) were also reported as challenges. The high concentration of feedlot effluent and insufficient access to clean irrigation water for shandying was the key barrier to further adoption of effluent irrigation on farm. Effluent data quality was generally low. Data reliability for volume generated at feedlots was low and no useful data could be collected on costs of applying effluent.

In most cases, N and P were found to be the only macronutrients valued in the decision-making process for the use of manures vs synthetic fertilisers. N and P constitute nearly 65% of the total macronutrient value of the product. Manure products also contain high concentrations of other macronutrients such as K and organic carbon, which can be highly beneficial to many farming systems, particularly where soil fertility is naturally low or has been degraded over time. Creating financial incentives within local economies and supply chains may increase demand for feedlot manure products and contribute to the development of circular economy principles between feedlots and local farms.

In addition to the analysis relating to manure and feedlot effluent, the total volume of captured truck effluent from feedlot cattle across the industry was quantified and found to be very low (38.4 ML of effluent generated per year, <1% of total industry effluent generation) which aligned with expectations. Notwithstanding, the main issue related to feedlot cattle transport effluent is spillage from trucks in built up areas. This continues to pose a risk to the livestock industry.

At a whole-of-business level, no substantial change in greenhouse gas emissions (relative to the BAU scenario) was achieved through the adoption of any of the nine technologies investigated. Only two shortlisted technologies (anaerobic digestion and screening of effluent) achieved any reduction in greenhouse gas emissions. The greatest reduction in emissions was associated with the scenario of a feedlot where all manure is collected fresh and digested to produce biogas, however, this was achieved using a system design uncommon in Australia.

The CBA results indicated that the adoption of any of the shortlisted technologies would not necessarily result in economic benefits for the model 10,000 SCU feedlot. The majority of the technologies resulted in negative economic outcomes and had negative net present values (NPVs), indicating that the projects/investment was unprofitable. Pelletised organo-mineral fertiliser containing feedlot manure was the exception, returning a positive NPV for the feedlot based on the reported selling price of $700/t for the organo-mineral fertiliser. As demonstrated by the case study, the end-products are not financially viable for end-users in cropping at the current selling prices and the product would have to be sold at a loss by the feedlot in order for end-users to achieve expected gross margins. It is also uncertain whether the product would yield any environmental benefit from a product carbon footprints perspective for the end users. However, there are opportunities to transform existing compositing and composted pelletised and un-pelletised manure into superior or high-efficiency hybrid or organo-mineral fertiliser for use in broadacre and horticultural cropping systems, which requires further research investment.

5.2 Benefits to industry

This research set out to examine benefits from treating feedlot manure and effluent to deliver better environmental or economic outcomes. These outcomes were difficult to demonstrate from the technical perspective, but other learnings were established and are summarised here.

Manure continues to be undervalued, but it was not clear that the technologies studied would increase this value proposition to users. Treatments invariably add cost, and without very clear market signals and high-value markets in close proximity, the market research presented here indicates this cost will be difficult to recoup. The conclusion from this is that technology adoption should be very targeted, based on careful evaluation of nearby markets with a high capacity to pay.

Considering the above, the best opportunity for supporting value may come through targeted and industry supported field trials that demonstrate the value of manure to high-value users. This would best be done by focusing on feedlots close to areas that have high value crops in close proximity and demonstrating value. Testing high-efficiency hybrid or organo-mineral fertiliser for high value crop can also demonstrate the potential of circular nutrient economy to deliver high crop yield and as well as maintain healthy productive soil for generation to come. This has been done periodically over the years in most industries and has generally delivered value by boosting awareness and demand.

Some benefits in the study may arise from ideas shared by survey participants that were tangential to the original objectives. For example, one feedlot operator developed a strategy for supplying manure in exchange for discounted grain, which helped increase demand, and helped return manure to grain growing country supporting the feedlot. This local approach may be extended to feeder cattle supply, particularly if this was combined with supply chain decarbonisation efforts. Utilising manure is likely to assist carbon sequestration (though benefits have been inadequately researched) and this strategy could therefore have multiple benefits. This would warrant further research.

With respect to the original objectives, the principal benefits to industry from this research are:

- The quantification of current industry values for feedlot manure, effluent, and feedlot cattle truck effluent, demonstrating that the greatest opportunity lies in manure valorisation and that truck effluent accounts for a very small proportion of the industry's total nutrient management volume.

- With the volume of truck effluent attributable to the feedlot industry being so low, it demonstrates that no one industry is responsible for the production and management of it and that shared responsibility and solutions are required .
- Confirmation that business-as-usual operations in relation to feedlot manure (i.e., stockpiling) is the lowest cost, lowest input, and lowest environmental management strategy of those shortlisted in this assessment. While this may surprise some, it indicates that the market has largely 'got it right' and that adjusting prices for manure will need to focus on marketing to high value users with capacity to pay. Fortunately, the longer-term trend suggested there has been positive movement in the value of stockpiled manure over 20 years suggesting modest recognition of manure as a fertiliser replacement.
- Demonstration that there is limited to no benefit (environmental, financial) from attempting to value-add feedlot effluent confirming that investment is better placed in other areas of the business. However, keeping research investment opportunities to improve composting technique, minimise feedlot greenhouse gas emission and find solutions to make manure pelletising cost-effective would further increase the possibility of converting feedlot manure to superior hybrid or organo-mineral fertiliser with environmental and financial benefits.
- Identification of the major barriers to further adoption of feedlot manure by end-users, helping to prioritise future research to reduce contamination and better understand nutrient supply vs demand at the local level. Research on hybrid or organo-mineral fertiliser may help to alleviate manure adoption barriers in broadacre and horticulture farming systems.

While this study did not directly establish the value proposition of manure treatment, further work in this area is needed. Manure management will continue to be an environmental challenge for industry as feedlot sites have been in operation for longer, and nutrient loading rates reach and exceed original design criteria. In the future, the focus may have to shift to nutrient concentration technology or other means to make sure feedlots can continue to operate without negatively impacting nutrient levels at the site. While not the original focus, understanding the risk perspective would be beneficial for building awareness and getting ahead of potential compliance problems. This could be done by confidentially surveying the industry regarding current nutrient levels. As noted in this survey, regulatory concerns are growing in this space, and consideration of risks, alongside opportunities would be timely.

With all these points noted, perhaps the greatest opportunity that can arise from a renewed focus on the value of manure could be stimulated by focusing on building soil carbon. This is a new and attractive opportunity, but work may be needed to establish the best way to unlock the opportunity. This could focus on utilising new land nearby feedlots for manure application or creating supply chain connections to utilise this on land used to supply feeder cattle. This would ultimately provide the greatest benefit by deliver better nutrient management outcomes, by distributing manure to larger areas of land, while also having an attraction element by reducing the carbon footprint of the supply chain.

6. Future research and recommendations

Based on the findings of this study, there are several recommendations to industry, including in relation to future research.

6.1 General recommendations

- To maximise the potential selling price of manure products, lot feeders should identify the key nutrient demands or soil quality deficiencies locally and then market the products accordingly, e.g., as a soil carbon amendment to highly degraded cropland.
- Co-composting or otherwise value adding manure products (as opposed to selling it raw) may increase their utility (available nutrients) and improve the ease of application.
- Focus and investment should be directed towards measures that improve the collection rate of effluent from feedlot cattle in transit and assist industry implementation of the Effluent Code (NHVR, 2022) across the entire Chain of Responsibility from feeder cattle origin to feedlot and feedlot to processor. This should include a considerable effort to increase the accessibility of transport effluent disposal locations on major transit routes. Value adding opportunities could be researched at a broader livestock sector level where improved consolidation of volumes and value would result in better economies of scale.
- End-users will typically only preference manure products where these can be purchased, transported, and applied for less than $50/t. Improving product consistency may reduce the costs of application incurred by the end-user but enable the products to be sold at a higher price.
- Circular economy partnerships between feedlots and grain producers or backgrounding farms received highly positive feedback and create a good news story for the industry/the business. Lot feeders should work within their supply chains and local areas to investigate opportunities for this.

6.2 Future research

- Further investigation is required to determine an industry baseline for effluent application costs.
- The composition of feedlot manure products is expected to have changed over time as industry has moved to more frequent pen cleaning and maintenance. Further efforts should be made to collect and consolidate laboratory analyses of manure products from feedlots to track changes in composition and nutrient value over time and identify best practice pen cleaning and maintenance to limit contamination of feedlot manure to improve the consistency and value of the end-product.
- The feedlot industry produces large volumes of beneficial nutrients (N, P and K). Further research is required to map nutrient demand (from broadacre cropping, horticulture, etc) against organic nutrient availability (reflecting volumes produced from feedlots, piggeries, and the poultry industry) to understand the potential market at a local level. This may strengthen opportunities for lot feeders to market manure products to particular industries or locations, maximising the value of the manure, and keeping transport costs to a minimum.
- There are opportunities to transform existing compositing and composted pelletised manure into superior or high-efficiency hybrid or organo-mineral fertiliser for use in broadacre and horticultural cropping systems, which requires further research investment. This work has a

concurrent focus on decreasing processing costs and emissions relative to conventional composting and pelletising.

- Field emission factors and viable application rates for feedlot manure are two areas requiring further research. Current emission factors and manure application rates may result in nine times the field level emissions as synthetic fertiliser (data not shown). However, application of nitrification inhibitor with manure can potentially reduce the nitrous oxide emission to soil background level requiring further research (Unpublished data, Queensland DPI).

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8. Appendix

8.1 Appendix A – Survey Questionnaire

Survey - excel spreadsheet - 4 April

8.2 Appendix B – Technology Assessment

Technology assessment_Milestone

8.3 Appendix C – Technology scoring

Technology assessment_Milestone

8.4 ADOPT Assumptions for each strategy

Table A1. Assumptions for each technology/strategy as entered into ADOPT to determine peak adoption level and time to peak adoption

		S1 - Co-composting	**S2 - Pelletisation**	**S3 - Composting**	**S4 - Filtration**	**S5 - AD**	**S6 - Screening**	**S7 - Treat at feedlot**	**S8 – Treat at abattoir**	**S9 - Co-digest at abattoir**
Relative advantage for the population										
1. Profit orientation	What proportion of the target population has **maximising profit** as a strong motivation ?	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all
2. Environmental orientation	What proportion of the target population has **protecting the natural environment** as a strong	A majority	A majority	A majority	A majority	A majority	A majority	A majority	A majority	A majority

		S1 - Co-composting	**S2 - Pelletisation**	**S3 - Composting**	**S4 - Filtration**	**S5 - AD**	**S6 - Screening**	**S7 - Treat at feedlot**	**S8 – Treat at abattoir**	**S9 - Co-digest at abattoir**
	motivation ?									
3. Risk orientation	What proportion of the target population has **risk minimisation** as a strong motivation ?	A majority	Almost all (risk averse)	A majority	A majority	Almost all (risk averse)	Almost all (risk averse)	A majority	Almost none (risk takers)	Almost none (risk takers)
4. Enterprise scale	On what proportion of the target farms is there a **major enterprise that could benefit** from the innovation ?	A majority	About half	A majority	A minority	A minority	Almost none	Almost none	Almost none	Almost none

		S1 - Co-composting	S2 - Pelletisation	S3 - Composting	S4 - Filtration	S5 - AD	S6 - Screening	S7 - Treat at feedlot	S8 – Treat at abattoir	S9 - Co-digest at abattoir
5. Management horizon	What proportion of the target population has **long-term (greater than 10 years) management horizon** for their farm?	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all
6. Short-term constraints	What proportion of the target population is under conditions of **severe short-term financial constraints** ?	A minority	A minority	A minority	A minority	A minority	A minority	A minority	A minority	A minority
Learnability characteristics of the innovation										

		S1 - Co-composting	**S2 - Pelletisation**	**S3 - Composting**	**S4 - Filtration**	**S5 - AD**	**S6 - Screening**	**S7 - Treat at feedlot**	**S8 – Treat at abattoir**	**S9 - Co-digest at abattoir**
7. Trialable	How **easily** can the innovation (or significant components of it) **be trialled on a limited basis** before a decision is made to adopt it on a larger scale?	Moderately trialable	Not trialable at all	Easily trialable	Difficult to trial	Not trialable at all	Difficult to trial	Easily trialable	Moderately trialable	Moderately trialable
8. Innovation complexity	Does the **complexity** of the innovation **allow the effects of it use to be easily evaluated** when it is used?	Not at all difficult	Not at all difficult	Not at all difficult	Not at all difficult	Not at all difficult	Not at all difficult	Not at all difficult	Not at all difficult	Not at all difficult

		S1 - Co-composting	**S2 - Pelletisation**	**S3 - Composting**	**S4 - Filtration**	**S5 - AD**	**S6 - Screening**	**S7 - Treat at feedlot**	**S8 – Treat at abattoir**	**S9 - Co-digest at abattoir**
9. Observability	To what extent would the innovation be **observable to farmers who are yet to adopt it** when it is used in their district?	Very easily observable	Moderately observable	Very easily observable	Not observable at all	Moderately observable	Difficult to observe	Easily observable	Easily observable	Moderately observable
Learnability of the population										
10. Advisory support	What proportion of the target population **uses paid advisors capable of providing advice** relevant to the project?	Almost none	Almost all	Almost none	Almost all	Almost all	Almost all	Almost none	Almost none	Almost none

		S1 - Co-composting	S2 - Pelletisation	S3 - Composting	S4 - Filtration	S5 - AD	S6 - Screening	S7 - Treat at feedlot	S8 – Treat at abattoir	S9 - Co-digest at abattoir
11. Group involvement	What proportion of the target population **participates in farmer-based groups** that discuss farming?	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all	Almost all
12. Relevant existing skills & knowledge	What proportion of the target population will **need to develop substantial new skills and knowledge** to use the innovation?	A majority	Almost all	About half	Almost all	Almost all	Almost all	Almost none	Almost none	Almost none

		S1 - Co-composting	S2 - Pelletisation	S3 - Composting	S4 - Filtration	S5 - AD	S6 - Screening	S7 - Treat at feedlot	S8 – Treat at abattoir	S9 - Co-digest at abattoir
13. Innovation awareness	What proportion of the target population would be **aware of the use or trialling of the innovation** in their district?	A majority	A majority	Almost all	Never used or trialled in district	About half	Never used or trialled in district	Almost all	Almost all	Almost all
Relative advantage of the innovation										
14. Relative upfront cost of the project	What is the size of the **up-front cost of the investment relative to the potential annual benefit** from using the innovation ?	Large	Very large initial investment	Moderate	Very large initial investment	Very large initial investment	Moderate	No initial investment required	No initial investment required	No initial investment required

		S1 - Co-composting	**S2 - Pelletisation**	**S3 - Composting**	**S4 - Filtration**	**S5 - AD**	**S6 - Screening**	**S7 - Treat at feedlot**	**S8 – Treat at abattoir**	**S9 - Co-digest at abattoir**
15. Reversibility of the innovation	To what extent is the adoption of the innovation **able to be reversed**?	Easily reversed	Moderately difficult to reverse	Easily reversed	Moderately difficult to reverse	Difficult to reverse	Moderately difficult to reverse	Very easily reversed	Very easily reversed	Very easily reversed
16. Profit benefit in the years that it is used	To what extent is the innovation **likely to affect the profitability of the farm** business in the years that it is used?	Moderate disadvantage	Large advantage	Small disadvantage	Small disadvantage	Large disadvantage	Small disadvantage	No advantage or disadvantage	No advantage or disadvantage	No advantage or disadvantage
17. Future profit benefit	To what extent is the innovation **likely to have additional**	No advantage or disadvantage	No advantage or disadvantage	No advantage or disadvantage	No advantage or disadvantage	No advantage or disadvantage	No advantage or disadvantage	No advantage or disadvantage	No advantage or disadvantage	No advantage or disadvantage

		S1 - Co-composting	S2 - Pelletisation	S3 - Composting	S4 - Filtration	S5 - AD	S6 - Screening	S7 - Treat at feedlot	S8 – Treat at abattoir	S9 - Co-digest at abattoir
	effects on the future profitability of the farm business?									
18. Time until future profits are likely to be realised	**How long** after the innovation is first adopted would it take for **effects on future profitability to be realised**?	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
19. Environmental costs & benefits	To what extent would the use of the innovation have **net environmental benefits or costs**?	Small disadvantage	Moderate disadvantage	Small disadvantage	Small advantage	Small advantage	Small advantage	Small disadvantage	Not net effects	Not net effects

		S1 - Co-composting	S2 - Pelletisation	S3 - Composting	S4 - Filtration	S5 - AD	S6 - Screening	S7 - Treat at feedlot	S8 – Treat at abattoir	S9 - Co-digest at abattoir
20. Time to environmental benefit	**How long** after the innovation is first adopted would it take for the **expected environmental benefits or costs to be realised**?	Immediately	Immediately	Immediately	Immediately	Immediately	Immediately	Immediately	Not applicable	Not applicable
21. Risk exposure	To what extent would the use of the innovation **affect the net exposure** of the farm business **to risk**?	Moderate increase	Large increase in risk	Small increase	Small increase	Large increase in risk	Small increase	No increase	No increase	No increase
22. Ease and convenience	To what extent would the use of the	Moderate decrease	Large decrease in ease and convenience	Small decrease	Moderate decrease	Large decrease in ease and	Small decrease	No change	No change	No change

		S1 - Co-composting	S2 - Pelletisation	S3 - Composting	S4 - Filtration	S5 - AD	S6 - Screening	S7 - Treat at feedlot	S8 – Treat at abattoir	S9 - Co-digest at abattoir
	innovation **affect the ease and convenience of the management of the farm** in the years that it is used?					convenience				

8.5 Production & cost assumptions for the BAU & S1 – S9 scenarios

Table A2. Key production assumptions and mass flows for BAU scenario

Manure volume	**Units**	**10,000 SCU**	**Source/notes**
Manure VS	t/yr	6,639	
Manure TS	t/yr	8,298	
Manure ash	t/yr	1,660	
Moisture	%	90%	
Total manure excreted	t/yr	82,984	
	t/head	8.30	
Harvested to stockpiling			
Fraction VS lost in pen	%	55%	Tucker et al. (2015)
VS harvested	t/yr	2,987	
TS harvested	t/yr	4,647	
VS/TS		64.3%	
Moisture in harvested manure		35%	
Total manure harvested	t/yr	7,149	
Contamination	%	10%	Estimate of best that can be achieved (from industry survey)
Total product harvested from pen	t/yr	7,944	
Total clean manure harvested	t/SCU	0.71	
Total product harvested from pen	t/SCU	0.79	
Reduction in dry matter from stockpiling	%	35%	Tucker et al. (2015)
TS out	t/yr	3,021	
	t/SCU/yr	0.30	Tucker et al. (2015): 0.26t/SCU/yr
Ash out	t/yr	1,660	
VS/TS ratio		45%	
Moisture	%	27%	From industry survey
Total stockpiled manure OUT	t/yr	4,158	
Total stockpiled manure OUT	t/SCU/yr	0.42	(Tucker et al., 2015) 0.35t/SCU/yr

Table A3. Key cost assumptions and mass flows for BAU scenario

Costs			**Source/notes**
Manure harvesting cost (from pen)	$/t	$9.86	Industry survey
Stockpiling processing cost	$/t	$3.76	Industry survey
Tractor	$	$100,000	Average of list available for sale new.
Front end loader	$	$75,000	Average of list available for sale new.
Revenues			
Selling price for stockpiled manure - sold off-site	$/t	$12.71	Industry survey

Table A4. Key production assumptions and mass flows for S1

	Units	10,000 SCU	Source/notes
Total manure harvested	t/yr	7,149	
Density of harvested manure	t/m3	0.715	Calculated from range given in Tucker et al. (2015)
Total manure harvested	m3/yr	9,999	
Moisture of harvested manure	%	0.35	R. J. Davis et al. (2010)
TS harvested	t	4,647	
Moisture in harvested manure	t	2,502	
C to N ratio (x:1) for composting		30	Tucker et al. (2015)
C in harvested manure	%	27%	From industry datasets
C in harvested manure	t	1,916	
N in harvested manure	t	179	Calculated from Tucker et al. (2015)
Actual C:N ratio		11	
Additional C required to achieve close to target C:N ratio	t	3,500	
C in straw	%	45%	DPIRD (2017)
Straw required	t	7,778	
C:N ratio of wheat straw		120	DPIRD (2017)
N added by straw	t	65	
VS in straw	%	86%	Rani et al. (2021)
VS added by straw	t	6,707	
Total C composted	t	5,416	
Total N composted	t	244	
C:N ratio		22	
Moisture in straw	t	15%	
Added moisture from straw	t	1,167	
Total moisture of composting material	%	25%	
Optimum moisture content for composting material	%	55%	Tucker et al. (2015)
Additional moisture (water) required	t	4,541	
Density of straw	t/m3	0.38	
TS lost in composting process	%	35%	Tucker et al. (2015)
Compost TS out	t	7,318	
Moisture in final product	%	25%	Tucker et al. (2015)
Compost out	t	9,757	
Operations			
No. of turns required		6	Tucker et al. (2015)
Material to turn	m3/week	2,562	
	m3/day	512	Assume operates 5 days/week
Hours operation	hrs/day	4	

Diesel required	L/t feedstock	5.53	UNSW (2006)
	total L/yr	82,547	

Table A5. Key cost assumptions and mass flows for S1

Costs			**Source/notes**
Manure harvesting cost (from pen)	$/t	$9.86	Industry survey
Composting processing cost	$/t	$12.51	Industry survey
Co-composting material	$/t	$75	Based on price of straw
Compost turner	$	$108,982	Average of list available for sale new.
Slurry tanker	$	$118,047	Average of list available for sale new.
Tractor	$	$100,000	Average of list available for sale new.
Front end loader	$	$75,000	Average of list available for sale new.
Water	$/kL	$0.10	Wiedemann & McGahan (2017)
Revenues			
Selling price for compost - sold off-site	$/t	$25.26	Industry survey

Table A6. Key production assumptions and mass flows for S2

	Units	**10,000 SCU**	**Source/notes**
Total manure harvested	t/yr	7,149	
Density of harvested manure	t/m3	0.715	Calculated from range given in Tucker et al.(2015)
Total manure harvested	m3/yr	9,999	
Moisture of harvested manure	%	0.35	R. J. Davis et al. (2010)
TS harvested	t	4,647	
Moisture in harvested manure	t	2,502	
Moisture in harvested manure	t	2,502	
Optimum moisture content for composting material	%	55%	Tucker et al.(2015)
Moisture (water) required	t	1,430	
TS lost in composting process	%	35%	Tucker et al.(2015)
Compost TS out	t	3,021	Tucker et al.(2015)
Moisture in final product	%	25%	
Compost out	t	4,028	
	t/SCU/yr	0.40	Tucker et al.(2015): 0.46t/SCU/yr
Operations			
No. of turns required		6	Tucker et al.(2015)

Material to turn	m3/week	833	
	m3/day	167	Assume operates 5 days/week
Hours operation	hrs/day	4	
Diesel required	L/t feedstock	5.53	UNSW (2006)
	total L/yr	39,536	

Table A7. Key cost assumptions and mass flows for S2

Costs			**Source/notes**
Manure harvesting cost (from pen)	$/t	$9.86	Industry survey
Composting processing cost	$/t	$12.51	Industry survey
Compost turner	$	$108,982	Average of list available for sale new.
Slurry tanker	$	$118,047	Average of list available for sale new.
Tractor	$	$100,000	Average of list available for sale new.
Front end loader	$	$75,000	Average of list available for sale new.
Water	$/kL	$0.10	Wiedemann & McGahan (2017)
Pelletiser – capital cost	$	$908,669	Calculated from Alege et al. (2021)
Pelletiser – operating cost	$/yr	$517,968	Calculated from Alege et al. (2021)
Electricity	$/yr	$244,644	Calculated from Alege et al. (2021) and average electricity price Australia 2024
Urea	$/t	$880	
Revenues			
Selling price for pellets - sold off-site	$/t	$700	From reported values

Table A8. Key production assumptions and mass flows for S3

	Units	**10,000 SCU**	**Source/notes**
Total manure harvested	t/yr	7,149	
Density of harvested manure	t/m3	0.715	Calculated from range given in Tucker et al. (2015)
Total manure harvested	m3/yr	9,999	
Moisture of harvested manure	%	0.35	R. J. Davis et al. (2010)
TS harvested	t	4,647	
Moisture in harvested manure	t	2,502	

Moisture in harvested manure	t	2,502	
Optimum moisture content for composting material	%	55%	Tucker et al. (2015)
Moisture (water) required	t	1,430	
TS lost in composting process	%	35%	Tucker et al. (2015)
Compost TS out	t	3,021	Tucker et al. (2015)
Moisture in final product	%	25%	
Compost out	t	4,028	
	t/SCU/yr	0.40	Tucker et al. (2015) 0.46t/SCU/yr
Operations			
No. of turns required		6	Tucker et al. (2015)
Material to turn	m3/week	833	
	m3/day	167	Assume operates 5 days/week
Hours operation	hrs/day	4	
Diesel required	L/t feedstock	5.53	Tucker et al. (2023)
	total L/yr	39,536	

Table A9. Key cost assumptions and mass flows for S3

Costs			**Source/notes**
Manure harvesting cost (from pen)	$/t	$9.86	Industry survey
Composting processing cost	$/t	$12.51	Industry survey
Compost turner	$	$108,982	Average of list available for sale new.
Slurry tanker	$	$118,047	Average of list available for sale new.
Tractor	$	$100,000	Average of list available for sale new.
Front end loader	$	$75,000	Average of list available for sale new.
Water	$/kL	$0.10	Wiedemann & McGahan (2017)
Revenues			
Selling price for compost - sold off-site	$/t	$25.26	Industry survey

Table A10. Key production assumptions and mass flows for S4

	Units	**10,000 SCU**	**Source/notes**
Effluent generated	kL/d	115	Bridle (2011)
	ML/yr	42	
Total dissolved solids in effluent	mg/L	4915	Tucker et al. (2015)
	g/L	4.92	
	t/yr	206	

Product recovery - water	%	95%	Singh (2011)
TDS elimination	%	98%	Zolfaghari & Kargar (2019)
TDS removed	t	202	
Total nitrogen in effluent	mg/K	220	Tucker et al. (2015)
Total nitrogen in effluent	% of TDS	4%	
N removed (not to pond or irrigated. So added to stockpile)	t	0.71	
Freshwater consumption that can be avoided	% of total	1.5%	R. Davis & Watts (2016)
	kL/yr	3,057	Tucker et al. (2015)
Operations			
Energy demand	kWh/m3	0.15	Singh (2011)
Energy demand	kWh/yr	6,296	

Table A11. Key cost assumptions and mass flows for S4

Costs			**Source/notes**
Microfiltration system	$	$419,463	Samco (2024)
Engineering costs	$	$34,375.00	Assumes cost of installation ranges from 10-15% of capital cost (Samco, 2024).
Installation costs (labour)	$	$115,352	Assumes cost of engineering ranges from 10-15% of capital cost (Samco, 2024).
Grid electricity costs	$/yr	$2,031	Based on demand from Singh (2011) and average Australian electricity price 2024
Revenues			
Freshwater cost	$/kL	$0.10	Wiedemann & McGahan (2017)
Avoided freshwater consumption	$/yr	$306	

Table A12. Key production assumptions and mass flows for S5

	Units	**10,000 SCU**	**Source/notes**
Effluent generated	kL/d	115	Bridle (2011)
	ML/yr	42	
N in effluent	t/yr	15.8	
VS in effluent	t/yr	72.3	
MCF		0.77	
Bo	m3/kg VS	0.19	
p	kg/m3	0.6784	
Total methane produced	m3	10,570	

Energy density methane	MJ/kg	55.6	
	MJ/m3	37.7190	
Boiler efficiency	%	90%	Tucker et al. (2023)
Energy potential	MJ	358,831	
Total heat demand at feedlot	MJ	14,400,000	
Fossil energy-dervied heat (LPG) avoided	MJ	358,831	
Energy density of LPG - Propane	MJ/L	25.3	

Table A13. Key cost assumptions and mass flows for S5

Costs			**Source/notes**
Anaerobic digester	$	$1,500,000	Assumes small-scale digester designed for a maximum inflow daily event and 40 days short hydraulic retention time.
Operating cost	$	$59,659	Based on ratio OPEX to CAPEX from Watts & McCabe (2015)
Revenues			
Avoided heat energy (LPG)	$/yr	$15,701	Based on price per litre of $1.11

Table A14. Key production assumptions and mass flows for S5A

	Units	**10,000 SCU**	**Source/notes**
VS in effluent	t/yr	5700	Tucker et al. (2023)
MCF		0.75	
Bo	m3/kg VS	0.17	
p	kg/m3	0.6784	
Total methane produced	m3	541,500	
Energy density methane	MJ/kg	55.6	
Density of methane		0.6784	
Energy density methane	GJ/m3	0.0377	
Boiler efficiency	%	90%	Tucker et al. (2023)
Energy potential	GJ	18,382	
	MJ	18,382,374	Tucker et al. (2023)
Total heat demand at feedlot	MJ	14,400,000	
Fossil energy-dervied heat avoided	MJ	14,400,000	

Table A15. Key cost assumptions and mass flows for S5A

Costs			**Source/notes**
Anaerobic digester	$	$10,982,400	Based on McCabe and Watts (2015) and adjusted for inflation
Operating cost	$	$436,800	Based on McCabe and Watts (2015) and adjusted for inflation
Revenues			
Avoided heat energy (LPG)	$/yr	$630,071	Based on price per litre of $1.11

Table A16. Key production assumptions and mass flows for S6

	Units	**10,000 SCU**	**Source/notes**
Effluent generated	kL/d	115	Bridle (2011)
	ML/yr	42	
N in effluent	t/yr	15.8	
VS in effluent	t/yr	72.3	
Screw press separator - efficiency	VS removal	42%	Larson et al. (2022)
	N removal	11%	Larson et al. (2022)
VS removed (i.e., goes to stockpiling)	t	30	
VS to pond	t	42	
N removed (i.e., goes to stockpiling)	t	2	
N to pond	t	14	
Operations			
Electricity requirement	kWh/hr	0.13	Watts et al. (2001)
WTotal operating hours	hrs/yr	8760	
Grid electricity requirement	kWh/yr	1,139	

Table A17. Key cost assumptions and mass flows for S6

Costs			**Source/notes**
Screw press separator	$	$257,543	From Watts et al. (2001)and adjusted for inflation
Operating cost – grid electricity	$/yr	$367	Based on demand from Watts et al. (2001), and Australian average electricity price 2024
Maintenance costs	$/yr	$7,726	Based on 3% of capital cost
Revenues			

N/A			

Table A18. Key production assumptions and mass flows for S7

	Units	**10,000 SCU**	**Source/notes**
Average travel distance	km	479	Industry survey
Turnover	times per year	2.54	
Effluent produced and captured	kg/head.km	0.02	George et al. (2022)
	kg/year	542,708	
	ML/year	0.54	
VS in captured truck effluent	g/L	28.70	George et al. (2022)
	kg/L	0.03	
	t/year	15.58	
N in captured truck effluent	mg/L	3,847	George et al. (2022)
	kg/L	0.0038470	
	t/year	2.09	

Table A19. Key cost assumptions and mass flows for S7

Costs			**Source/notes**
N/A			
Revenues			
N/A			

Table A20. Key production assumptions and mass flows for S8

	Units	**10,000 SCU**	**Source/notes**
N/A			

Table A21. Key cost assumptions and mass flows for S8

Costs			**Source/notes**
N/A			
Revenues			
N/A			

Table A22. Key production assumptions and mass flows for S9

	Units	**10,000 SCU**	**Source/notes**
N/A			

Table A23. Key cost assumptions and mass flows for S9

Costs			**Source/notes**
N/A			
Revenues			
N/A			