Final report

Wastes to Profits

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Abstract

This project, led by Meat & Livestock Australia was funded under round three of the Australian Government Department of Agriculture, Fisheries and Forestry 's Rural Research and Development for Profit Program. The project brings together key stakeholders from across Australia's animal industries and technology, research and development providers to deliver advanced technologies to convert wastes from intensive animal production for example feedlots, food processing, and municipal water treatment into fertilisers, feeds, chemicals, and energy products for use in agriculture. The four areas of research were: Wastes assessments, business models and pathways to adoption; Development of technologies for improved waste management; Development of technologies for production of nutritionally-advanced feeds; and Development of technologies for production of fertilisers, chemicals, plastics and energy products. The benefits to the red meat industry include addressing key information gaps on waste composition and quantity, investigation of waste aggregation opportunities and development of novel pre-treatment and waste processing strategies (such as mechanical, chemical algal and enzymatic) to prepare wastes for value-adding.

Executive summary

Background

This project, led by Meat & Livestock Australia was funded under round three of the Australian Government Department of Agriculture, Fisheries and Forestry ’s Rural Research and Development for Profit Program. The project brings together key stakeholders from across Australia’s animal industries and technology, research and development providers to deliver advanced technologies to convert wastes from intensive animal production for example feedlots, food processing, and municipal water treatment into fertilisers, feeds, chemicals, and energy products for use in agriculture.

Australia’s animal industries produce significant quantities of wastes from on-farm production, intensive feed and processing sectors. The management of these wastes is a significant cost for these industries exceeding AUD$100 million per year [1]. In addition, primary production and processing costs are rising and there is an ongoing need to improve productivity to maintain future industry profitability. There are significant opportunities to create new business models for improved management of wastes, unlocking new revenue streams for Australia’s animal industries.

Objectives

The objective of the *Wastes to Profits* Project is to develop technologies and business models for the conversion of wastes from the red meat, dairy, pork and municipal waste industries into valuable products resulting in productivity and profitability improvements for primary producers. This was achieved through:

1. Assessing waste streams, developing business models and pathways to adoption;
2. Developing technologies for the improved management of wastes including advanced anaerobic digestion;
3. Developing technologies for the production of nutritionally-advantaged feeds; and
4. Developing technologies for production of fertilisers, chemicals, plastics, and energy products.

The project successfully met the objectives.

Methodology

The *Wastes to Profits* was established as a multi-party collaboration project that brought together key partners capable of delivering the project objectives.

The project was completed through research activities in four areas, that were developed corresponding to the Project objectives**:**

- Area 1 – Wastes assessments, business models and pathways to adoption
- Area 2 – Development of technologies for improved waste management
- Area 3 – Development of technologies for production of nutritionally-advanced feeds
- Area 4 – Development of technologies for production of fertilisers, chemicals, plastics and energy products.

Results/key findings

On-farm, intensive feeding and processing sectors in Australian red meat, dairy and pork industries produce substantial quantities of organic waste with biogas energy potential that can meet the majority of estimated onsite energy demand within these sectors. One of the key outcomes from the assessment of the various industry waste streams was the development of the ADAdvisor tool (https://adadvisor.info/) – an online tool that enables industry end-users to assess the economic feasibility of prospective anaerobic co-digestion projects that use livestock sector waste streams. Anaerobic digestion (AD) is a strong platform for technology integration and value-chain innovation to generate modern waste-to-value opportunities that go far beyond traditional AD products such as biogas and digestate. Intermediates can be captured and used as precursors in a range of commodity chemicals, anti-microbials, anti-fungals, novel fuels and bioplastics. A range of these products, such as production of nutritionally-enhanced animal feeds, organomineral fertilisers, chemicals and fuel, were explored. Technologies were developed at laboratory scale and transferred to pilot scale so that the processes could be assessed for economic feasibility and the products tested for safety and efficacy in livestock feeding trials. The feeding trials were focused on assessing the feed performance to build a business case for their use and provide initial data for regulatory approvals. The outcomes from the development of technologies for production of fertilisers, chemicals, plastics and energy products will be measured through profitability increases achieved using new technologies, reduced input costs, and improved productivity.

Benefits to industry

A significant project benefit has been the opportunity to collaborate on common issues for Meat and Livestock Australia, Australian Meat Processor Corporation, Dairy Australia and Australian Pork Limited. Red Meat 2030[1], which sets out the high-level strategic direction of the Australian red meat and livestock industry over the next decade lists under its commitment to carbon neutrality by 2030, to demonstrably reduce production, processing, and consumption waste. A strength of this project was the productive interactions with industry to address issues important to their business.

Future research and recommendations

There is an ongoing focus on wastewater treatment and solid organic waste management, partners have high interest in in-factory trials and pilots that can demonstrate the feasibility of novel technologies and accelerate adoption.

However, much of the project's impacts on industry may not be realised for several years due to the nature of the innovations and likely rate of adoption within the industry.

The research team is actively working together to develop opportunities for the next phase of *Wastes to Profits* and are looking out for ways to continue the research momentum and collaboration beyond this project.

[1] https://rmac.com.au/red-meat-2030/

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1. Background

This project was funded under round three of the Australian Government's Rural Research and Development for Profit Program. This project is supported by Meat and Livestock Australia through funding from the Australian Government Department of Agriculture and Fisheries and Forestry as part of its Rural R&D for Profit program and the partners Aduro Biopolymers, Australian Lamb Co, Australian Meat Processor Corporation, Australian Pork Ltd, Barwon Water, CSF Protein (Ridley AgriProducts Pty Ltd), Dairy Australia, Harvey Beef, JBS Australia, Meat and Livestock Australia, MLA Donor Company, Murdoch University, Queensland University of Technology, Queensland Urban Utilities, Teys Australia, University of Queensland, University of Southern Queensland and Zeolite Australia.

Australia's animal industries produce significant quantities of wastes from on-farm production, intensive feed, and processing sectors. The management of these wastes is a significant cost for these industries exceeding AUD$100 million per year (O'Hara 2016). In addition, primary production and processing costs are rising and there is an ongoing need to improve productivity to maintain future industry profitability. There are significant opportunities to create new business models for improved management of wastes, unlocking new revenue streams for Australia's animal industries.

The project brings together key stakeholders from across Australia's animal industries and technology, research and development providers to deliver advanced technologies to convert wastes from intensive animal production e.g. feedlots, food processing, and municipal water treatment into fertilisers, feeds, chemicals, and energy products for use in agriculture.

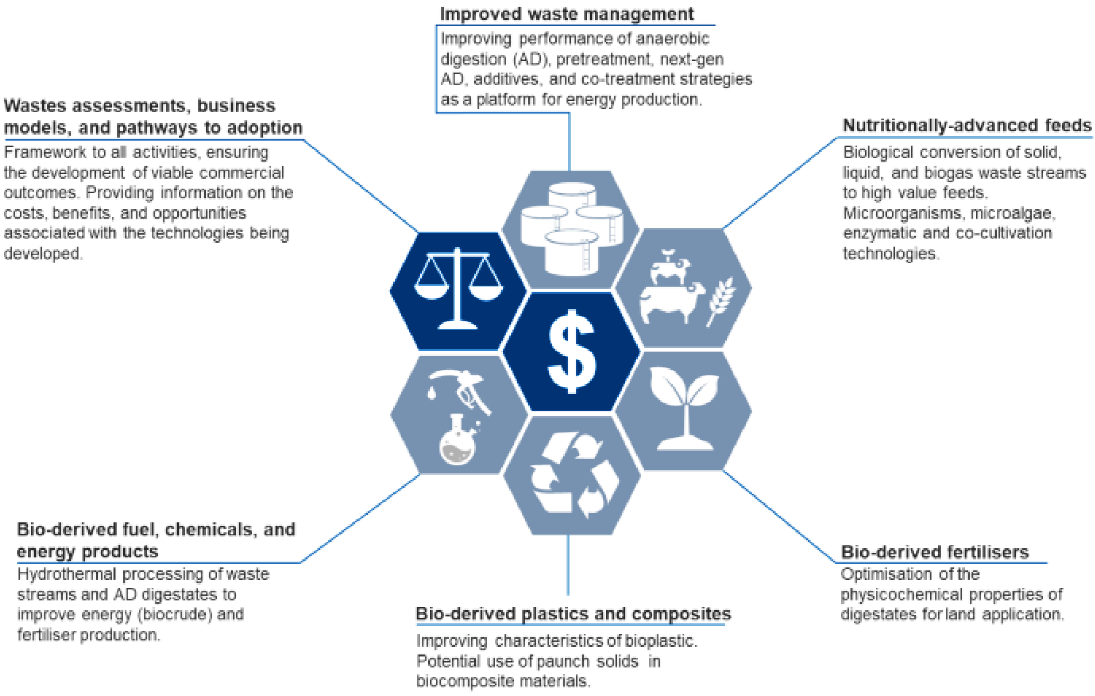
2. Objectives

The objective of the Project was to develop technologies and business models for the conversion of wastes from the red meat, dairy, pork and municipal waste industries into valuable products resulting in productivity and profitability improvements for primary producers.

This was successfully achieved through:

1. Assessing waste streams, developing business models and pathways to adoption;
2. Developing technologies for the improved management of wastes including advanced anaerobic digestion;
3. Developing technologies for the production of nutritionally-advantaged feeds; and
4. Developing technologies for production of fertilisers, chemicals, plastics, and energy products.

Figure 1. Framework to meet the objectives



3. Methodology

The Wastes to Profit project was established as a multiparty collaboration project that brought together key partners capable of delivering the project objectives. The project consisted of thirteen Activities in four major research Areas. Activity Leads were appointed to each activity and were responsible for the achievement of outcomes in each of these Activities.

Throughout the life of the project, the project activities were impacted by COVID-19 and resulting restrictions, particularly those activities that required access to partners sites to collect samples and/or conduct pilot and demonstration trials, and delays in procurement of pilot and demonstration items from international sources. A twelve-month extension to the Wastes to Profits project was approved by the Department of Agriculture, Fisheries and Forestry.

3.1 Wastes assessments, business models and pathways to adoption

The 'Wastes assessments, business models and pathways to adoption' project area provided information to industry partners on the costs, benefits and opportunities associated with the technologies being developed within the project through:

1. Analysing and identifying aggregate amounts of wastes produced from on-farm, intensive feed and related processing sectors and assessing waste aggregation opportunities across these industries; and
2. Undertaking research into the techno-economics of project technologies and exploring business models for adoption.

The 'Wastes assessments, business models and pathways to adoption' project area provided a framework for the project to ensure the development of commercially feasible outcomes from the *Wastes to Profits* research program. While on-farm, intensive feed and processing sectors from red meat, dairy and pork industries produce significant quantities of waste there are key information gaps on waste composition and quantities in these industries. The activities in the 'Wastes assessments, business models and pathways to adoption' area developed tools to better realise the opportunities in unlocking new revenue streams to produce energy products, fertilisers, feeds and chemicals for use in agriculture.

Further, common frameworks for analysing the economic viability of *Wastes to Profits* project technologies for evaluation and reporting were developed to meet the requirements of industry partners and project milestones. The analysis framework included techno-economic, business model, supply and value chain analysis progressing through identification, development and evaluation.

3.2 Development of technologies for improved waste management

The 'Development of technologies for improved waste management' project area focused on improving the economics of anaerobic digestion by targeting improvements in process rates (reduced capital), biogas yields (energy revenue), digestate quality (fertiliser revenue) and using smart process integration strategies to maximise plant wide benefits. The project targeted strategies including:

- pre-treatment technologies that transform the waste prior to anaerobic digestion, while also enabling direct recovery of high value compounds;
- next generation reactor technologies and process designs with improved efficiency;
- performance enhancing additives; and
- co-treatment strategies that leverage infrastructure to increase process output and promote industry cooperation.

To manage costs and improve industry sustainability, the Australian red meat industry aims to reduce waste with a long-term goal of zero waste discharge. In the Red Meat 2030 Strategic Plan, under the aim of moving to a Carbon Neutral Industry by 2030, the Australian red meat industry will demonstrably reduce production, processing and consumption waste. The “zero waste” concept revolves around redirecting material towards recycling, beneficial reuse or new value-adding by-product streams.

Many technologies contribute towards the "zero waste" goal, in particular anaerobic digestion. Anaerobic Digestion (AD) is an established technology that converts organic wastes, such as manure, paunch, fatty grease trap wastes or wastewater sludges into methane rich biogas, which is then burned as a source of renewable energy, and nutrient-rich fertiliser (digestate). This project focused on improving AD by maximising renewable energy production while reducing overall treatment costs. AD is a mature and successful commercial technology in many industries and regions; however, process performance and technology costs must be improved to enable widespread uptake in the Australian agriculture sector.

Anaerobic digestion is a strong platform for technology integration and value-chain innovation. The modern waste-to-value opportunities go far beyond traditional AD products such as biogas and digestate. Intermediates can be captured and used as precursors in a range of commodity chemicals, anti-microbials, anti-fungals, novel fuels and bioplastics. A range of these products, such as production of nutritionally-enhanced animal feeds, organomineral fertilisers, chemicals and fuel, were explored in the subsequent *Wastes to Profits* Project areas.

3.3 Development of technologies for production of nutritionally-advanced feeds

The ‘Development of technologies for production of nutritionally-advanced feeds’ project area included four activities focused on delivering cost-effective and scalable production processes for products that improve nutritional performance:

- Microbes to convert solid and liquid wastes to feed protein that is optimised for the co-production of other important nutrients, therefore significantly enhancing the value.
- Microalgae to convert liquid wastes, including from anaerobic digestion, into algal products and clean water that could be reused on site.
- Novel engineered co-cultures of microorganisms to convert crude biogas from anaerobic digestion into nutritional feed protein.
- Biological and enzymatic conversion processes to produce high value nutritionally enhanced feed protein and bioactive peptides.

In collaboration with the meat processing and animal feed industries, various solid, liquid, and gaseous waste streams will be converted using a range of processes based on different biological systems to produce animal feed products.

The 'Development of technologies for production of nutritionally-advanced feeds' project area developed technologies at laboratory scale and transferred to pilot scale so that the processes could be assessed for economic feasibility and the products tested for safety and efficacy in livestock feeding trials. The feeding trials were focused on assessing the feed performance to build a business case for their use and provide initial data for regulatory approvals.

Globally the demand for sustainable, lower cost and more effective animal feeds is growing. Nutritious animal feeds maximise animal performance and efficiency, influencing the sustainability of animal production. Animal health and performance are reliant on a targeted diet of carbohydrates, protein, fat, minerals, vitamins, and water as well as optimised supplements.

In Australia, drought is affecting the availability and costs of animal feed. The addition of protein, amino acids, vitamins, probiotics, enzymes, and other nutritional additives may be required to maintain productivity and health. This project area offers a suite of biological waste conversion processes to produce new sustainable nutritious animal feed products. The processes contribute towards "zero waste" goals in the industry and could provide potential new revenue streams in the order of $80 million per year (O'Hara 2016).

3.4 Development of technologies for production of fertilisers, chemicals, plastics and energy products

The 'Development of technologies for production of fertilisers, chemicals, plastics and energy products' project area sought to develop new commercial products that add value to anaerobic digestate and waste streams from the meat processing sector. These products will help underpin the long-term economic viability of meat production in Australia and reduce the environmental impact of the industry, thereby enhancing its domestic social 'license to operate' and its reputation internationally as a 'clean and green' industry producing safe, high-quality meat and meat products.

This project area consisted of four activities that targeted specific Waste to Value opportunities.

- Develop and demonstrate the performance of existing meat processing contamination control and general consumable products made from renewable, biodegradable, and safe to render materials; and further develop sheep and cattle weasand clip products for use in Australia;
- Develop and demonstrate hydrothermal liquefaction technology that can simultaneously generate crude bio-oil and secondary product streams from AD digestate and other animal waste streams; and provide relevant information to demonstrate technoeconomic assessment and optimisation of hydrothermal technology for value adding to AD digestate;
- Develop agricultural recycling of biodegradable wastes as a practicable option, including balancing the chemical composition of wastes to meet the nutritional requirements of crops and altering the physical properties of wastes to make them suitable for application using standard farm spreading equipment; and

- Assess the potential for using paunch as the fibre in biocomposites by extruding paunch fibres with both bio-based and fossil-fuel derived polymers and benchmarking the mechanical properties of the produced materials against commercial biocomposites.

As global demand for Australian livestock and meat products grows and production increases to satisfy that demand, the amount of wastes produced will increase. Most of these wastes are rich in organic carbon and valuable nutrients but are often disposed of in landfill. Recycling of these wastes will help address environmental concerns associated with livestock and meat production sectors, including greenhouse gas emissions and water and soil pollution, and decrease energy demand.

Results of each Activity are shown in the following section. Information in this report has also been published by the Project researchers in public scientific publications. The titles, authors, journal information and links to these articles are provided in the Appendix. For assistance in accessing the journal articles (where access is restricted by paywall), or if there are specific questions to the research teams, please contact Prof Ian O'Hara.

4. Results

4.1 Wastes assessments, business models and pathways to adoption

The demand for sustainably- and ethically produced meat and animal products is growing, hence, there is a need to develop technologies and approaches that can deliver significant economic, environmental and social impacts. For successful implementation of new technologies in well-established industries, there is a need to overcome barriers, which can be regulatory, cultural, or structural.

Understanding key information gaps on waste composition and quantities in on-farm, intensive feed and related processing sectors is a fundamental step to fully realising opportunities in unlocking new revenue streams from energy products, fertilisers, feeds and chemicals from waste.

One of the key strategies for ensuring the development of viable commercial outcomes from research is to underpin the work with research in the techno-economics of project technologies and explore new business models for adoption.

4.1.1 Results - Waste identification, analysis and assessment of waste aggregation and co-digestion opportunities for increased anaerobic digestion adoption

Activity team: Prof Bernadette McCabe, Dr Stephan Tait, Dr Peter Harris (University of Southern Queensland).

Summary

Activity 1.1 aimed to:

(1) identify and address data gaps related to waste quantities/composition from livestock industries to identify opportunities for aggregate processing of wastes;

(2) to develop a calculation tool to enable industry end-users to explore high-level economic feasibility of prospective biogas energy projects.

Data gaps were addressed via a comprehensive review and analysis of available literature, including past waste mapping studies and methods. Varied extents of information were found. However, analysis showed good biogas energy potential to meet significant onsite energy demands across partner industries. Biochemical methane energy potential was also measured directly for milk processing wastes, to address a key data gap identified via the review. A techno-economic assessment tool, called ADAdvisor (https://adadvisor.info/), was developed in a user-friendly online format. A waste characteristics database was attached to ADAdvisor to minimise inputs required from users. ADAdvisor was collaboratively developed with and steered by partner industry participants. The tool was extensively demonstrated and is now being increasingly used by partner industries to evaluate feasibility of prospective biogas projects. Overall, ADAdvisor has attracted significant interest, and feedback has indicated industry valued it as an important outcome from the project and supports its continued use and expansion into other feedstocks into the future.

The estimate and analysis of waste quantities showed good biogas energy potential (∼13.8 $PJ \cdot annum^{-1}$) to meet a significant onsite energy demand (∼18 $PJ \cdot annum^{-1}$) across partner industries. On-farm and intensive production appeared to have excess biogas energy potential, whereas off-farm processing was generally deficient in biogas energy potential. This suggested opportunities for synergistic aggregate anaerobic co-digestion across these sectors.

Anaerobic digestion and co-digestion are commercially mature technology which, if adopted, can value-add to wastes and displace fossil-fuel energy sources. Moreover, by enabling anaerobic digestion technology across Australian red meat processing, the sector can progress towards its goals of reductions in carbon dioxide equivalent emissions and decrease in fossil fuel-derived energy use intensity, relative to 2015 levels.

Objectives

To address related key information gaps, Activity 1.1 aimed to:

1. assess waste aggregation opportunities across partner industries by reviewing and analysing available data/information on aggregate waste amounts/characteristics; and
2. develop a techno-economics assessment tool (ADAdvisor) to enable industry users to document information on wastes amounts and characteristics relevant to anaerobic co-digestion and to assess high-level feasibility of site-specific anaerobic co-digestion prospects.

Active engagement with partner industries was a central focus of Activity 1.

Changes in objectives/methodology - Activity 1.1 originally aimed to data-share between *Wastes to Profits* and national public domain repositories such as the Australian Renewable Energy Mapping Infrastructure (AREMI) platform. This occurred to a limited extent, but a database was also fitted to ADAdvisor to enable voluntary data sharing amongst partner members. The data shared in ADAdvisor is anonymised.

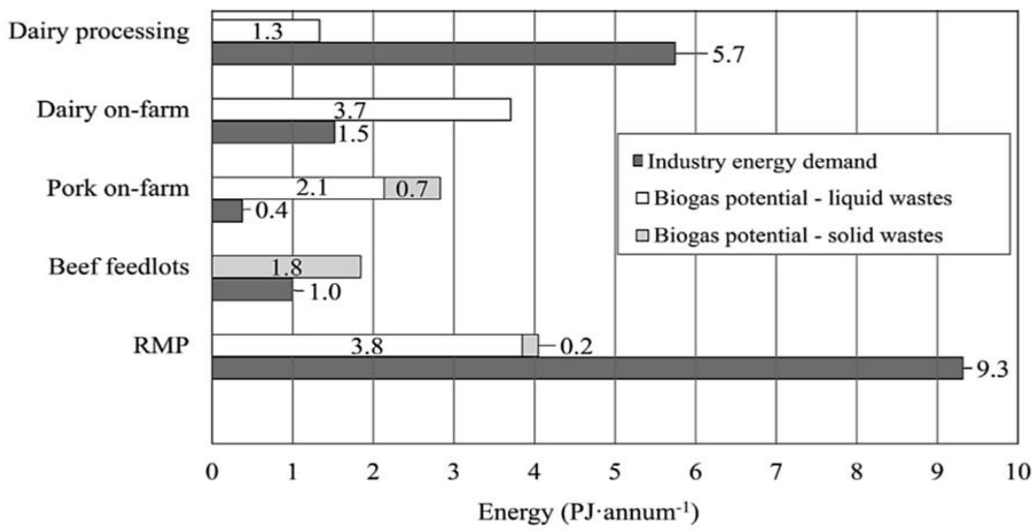
Results and Discussion

Review, information gaps analysis, and aggregate biogas energy potential estimates

A literature review was undertaken along with an information gaps analysis, and aggregate biogas energy potential estimates. The review showed on-farm, intensive feeding and processing in Australian red meat, dairy and pork industries produced substantial quantities of organic waste (~79 $gigalitres \cdot annum^{-1}$ liquid waste + ~2 million $tonnes \cdot annum^{-1}$ solid waste). Availability of this waste varied with industry sector and across various Australian states and territories, because of uneven geographical distribution of the various industries across Australia. For example, pork production is reasonably evenly distributed across Australia, whilst the majority of dairy and beef production occurs in Victoria and Queensland, respectively.

If converted into biogas energy, wastes from these industries had an estimated bioenergy potential (~13.8 petajoules·annum^{-1}) able to meet a large proportion of the onsite energy demands of these same industries (~18 petajoules·annum^{-1}). Moreover, when biogas energy potential was compared with onsite energy demand, on-farm and intensive feeding production appeared to have an excess of biogas energy potential, whilst off-farm processing was deficient in biogas energy potential. This is important because it suggests that there may be opportunities for synergistic aggregated processing of wastes sourced from production at processing sites, thereby maximising overall bioenergy benefits.

Figure 2. Energy estimates for Australian agro-industry sectors. Source: Tait et al. (2021) https://doi.org/10.1016/j.jclepro.2021.126876



Waste management practices influenced waste amounts and characteristics. For example, in pasture-based dairies, only a fraction of daily manure output is captured, whereas in barn housing systems all daily manure output is captured. Also, the frequency of manure scraping and collection at beef feedlots strongly influences biodegradability and biogas energy potential, with fresher manure generally having a higher potential. This made interpretation and use of publicly available statistics (e.g. ABS) for waste mapping more challenging.

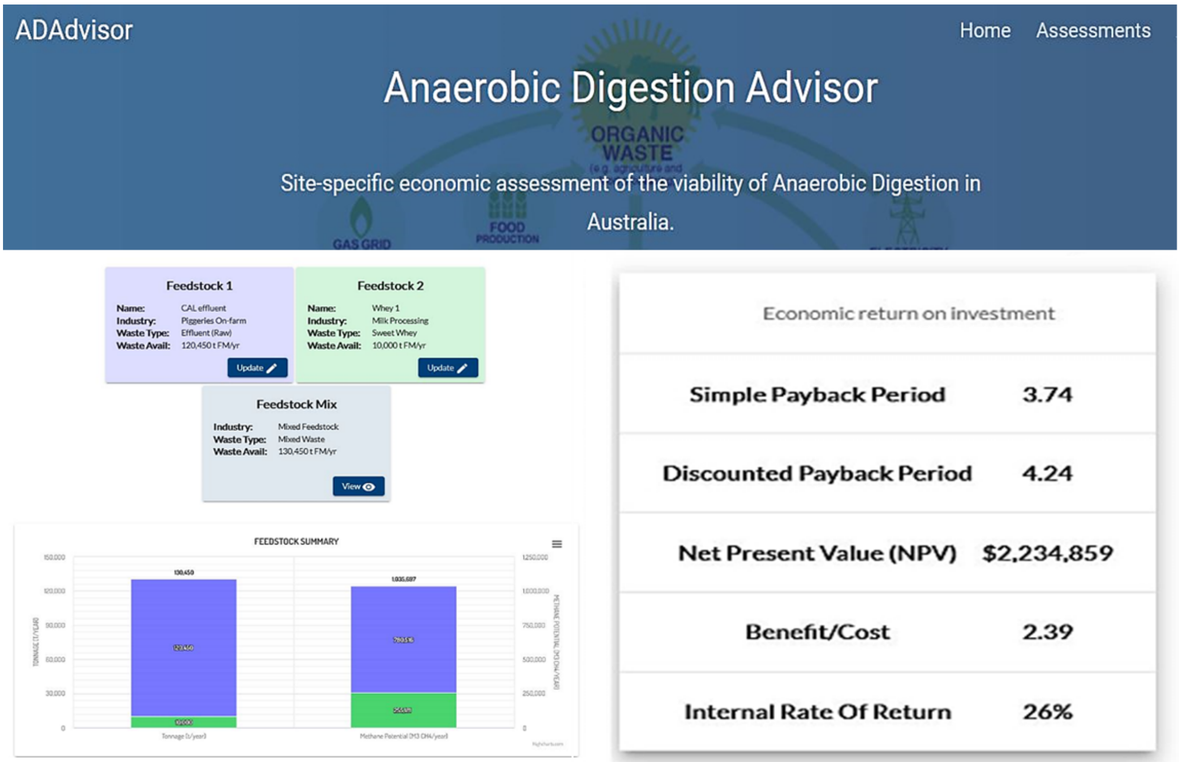
Accordingly, significant discrepancies were also noted in methods used by past state-based biomass mapping studies, largely due to differences in assumptions relating to waste management practices. Waste characteristics also influence materials handling, requirements for dilution water, and suitable anaerobic digestion technology types.

Data availability relating to the impact of waste management practices was generally good and meant their impact could be reasonably resolved when estimating waste amounts and characteristics on a site-by-site or region-by-region basis. This was demonstrated in the current work by estimating overall biogas energy potential across Australia (Fig. 2). Moreover, key considerations for anaerobic digestion technology selection were reviewed in the project. Information collated from this review was subsequently incorporated into a technology selection guide in ADAdvisor (See below) to help a user select an appropriate anaerobic digestion technology based on the characteristics of the waste input by the user.

ADAdvisor – A user-friendly tool for high-level techno-economic assessment of biogas projects

ADAdvisor guides users through an evaluation of potential business models and cost-effective concepts for aggregate biogas energy projects (Fig. 3).

Figure 3. Example analyses from ADAdvisor



The development of ADAdvisor was collaborative and consistently open to feedback from project partners and drew on the outcomes of the literature review detailed previously. Feedback received from project partners was promptly incorporated. ADAdvisor was collaboratively developed; and shared with, and steered by partner industry participants via webinars, workshops, and one-on-one hands-on demonstrations. These included: a live webinar 24th November 2020; Annual workshop panel presentation 17th March 2021; and a Circular Economy Workshop, Tessele Consultants, 9 November 2021, Albany, Western Australia. Since its launch, ADAdvisor has attracted significant interest (816 views to date), with partner feedback indicating industry valued it as an important outcome from *Wastes to Profits*.

The launch of ADAdvisor was also timely in terms of aligning with significant initiatives that were emerging within the project period of *Waste to Profits*, and to which ADAdvisor was highly relevant. These included: (1) the launch of the Emissions Reduction Fund (ERF), Animal Effluent Method, 6 December 2019; (2) the launch of a Draft End of Waste code for anaerobic digester digestate in Queensland; (3) A Western Australia, DPIRD, call for projects, for Collection Of Case Studies To Investigate Wastewater Management In Red Meat Processing, 11 August 2021; (4) and the Design and Construct project for a New Anaerobic Digester Facility at Agriculture Victoria Ellinbank Smartfarm, 18

February 2022, commissioned by DJPR Victoria. A recent tender call for Agricultural Waste for Biomethane from the Department of Industry, Science, Energy and Resources also builds on the viability of including agricultural wastes feedstocks that are not currently covered by ERF waste methods such as waste from sugar, cereal, rice and wine production. This represents an opportunity for the intensive livestock and related food processing sectors, including water utilities to cooperate with other agricultural sectors to help realise the full potential of co-digestion opportunities. It also reinforces the value of expanding ADAdvisor to include other feedstocks from the grains and horticulture sector post farm gate and other food waste post manufacturing.

Key Findings and Achievements

On-farm, intensive feeding and processing sectors in Australian red meat, dairy and pork industries produce substantial quantities of organic waste with biogas energy potential that can meet the majority of estimated onsite energy demand within these sectors. ADAdvisor has been set up as a user-friendly techno-economic assessment tool that will likely continue to be a future enabler in support of adoption of biogas technology across Australian red meat, dairy and pork industries, and their associated supply chains. ADAdvisor has also been set-up in a way to allow its on-going expansion (including voluntary data sharing inputs by users, being incorporated into the background waste characteristics database), and refinement, so that it can continue to be a useful tool to facilitate future biogas projects.

4.1.2 Results - Business models and techno-economics research for Wastes to Profits technologies

Activity team: Dr Jerome Ramirez and Prof Ian O'Hara (Queensland University of Technology)

Summary

The work within this Activity explored opportunities for enhancing commercial viability of project technologies by informing research within the program.

The activity achieved this aim by:

1. Assessing markets and identifying opportunities for potential products, including new opportunities identified during the Project, i.e., animal transportation truck effluent discharge and plastic silage wrap.

2. Understanding pathways to adoption through analysis of the context in which the technologies reside, using a modified PESTLE analysis approach and producing a set of one-page, plain language Path to Impact Analysis documents to provide information for Project partners.

3. Undertaking techno-economic assessments of technologies across the project by developing modelling frameworks for process and economic models. Techno-economic assessments were completed in this Activity for the dewatering of wastewater treatment sludge and digestate through hydrothermal carbonisation, anaerobic co-digestion of solid organic wastes, treatment of paunch waste to produce animal feed, and digestate drying and pelletisation.

Objectives

This Activity aimed to develop and implement a framework for techno-economic analyses to explore the factors impacting on economic feasibility of new waste to profit technologies. The models developed in this Activity provided information to assess how key technical, economic and market factors impact profitability of commercial application for the technologies within the Project. Economic factors such as product price and waste disposal costs were modelled to determine the conditions under which the implementation of these technologies may be profitable. The output of the Activity are assessments and business models that highlight potential pathways to technology adoption.

Results and Discussion

Market opportunities

The potential markets of the products from the technologies in this Project were assessed. Products assessed included biogas, biofertilisers, animal feeds for cattle and sheep, pigs, poultry and aquaculture, feed supplements and additives, animal nutrition products such as amino acids and carotenoids, liquid hydrocarbon-like fuels, and bioplastics and biocomposites.

The common characteristics among these markets are that they are typically large and mature, with established suppliers and supply chains. These markets are also sensitive to variabilities, such as weather conditions or global market movements, which are hard to control. Therefore, opportunities exist in using locally available materials such as wastes to generate products that can buffer the effects of variabilities. Many of the products have standard composition and quality requirements, which provide targets for novel products from waste. There is also emerging demand for sustainably-produced meat products, and the utilisation of waste enhances sustainability of the industry. Moreover, generating high value products from waste can be economically beneficial to meat production firms and the whole industry. This can potentially increase revenue or decrease production costs.

Truck effluent (waste captured during the transport of animals between farms, feedlots, and meat processing plants) was identified as a potential resource. The potential benefits in generating biogas from the anaerobic digestion of this wastewater stream were assessed. Key stakeholders have expressed an interest in capturing and enhancing the value of the transportation truck effluent.

Opportunities in improved silage wrap waste management were assessed as an issue identified by the dairy industry. The assessment shows potential to manage a significant waste stream that can improve environmental outcomes on farms but also add value to the region. The development of appropriate business models across various stakeholders in the value chain are essential ensure a feasible approach to the collection and recycling of silage wrap waste.

Path to Impact Analysis

“Path to Impact Analysis” documents were developed for each Activity in the project. These documents provide an overview of the research by presenting a short background and statement of research aims, a cost-benefit analysis, and a summary panel that highlights the broad classification of potential impacts of the activity, as well as a graphical representation of the “The Activity in Context” and the Activity Key Performance Indicators. These documents assist in organising information around the technologies in a way that can be readily communicated to current and potential partners.

Input from industry and Project Partners regarding drivers and barriers were considered to develop “The Activity in Context” panel, which has the following headings:

- Technology
- Pathways to Adoption
- Regulatory
- Health, Safety and Biosecurity
- Supply Chain
- Skills and Capabilities

This contextual analysis done with the Project researchers helped to identify barriers and limiters in adoption and include action plans to address these towards the completion of the Project. The initial assessment of potential pathways to adoption informed the development of business models and strategies to analyse opportunities.

Techno-economic assessment

Techno-economic assessments (TEA) were undertaken to facilitate the adoption of technology by generating information that can be assessed against goals and targets of companies, industry and governments. A techno-economic assessment framework was developed to present a consistent approach across the *Waste to Profits* project. A consistent method ensured a balanced and objective analysis, as well as provide assurance of the quality of the outputs.

The process models were developed in ASPEN Plus, SuperPro, and Excel. @Risk was used for stochastic modelling. Economic models were developed in Excel and report economic values such as costs, revenues, net present values, internal rate of return and payback period (when applicable). Analysis was also done to calculate target costs for cases when the cost of the processing is high.

A feasibility analysis of the energy and nutrient recovery pathways of red meat processing solid residues was conducted for a 1000 head/d meat processing plant. The residues considered were dewatered paunch, dissolved air flotation sludge and dewatered wastewater sludge amounting to 113 wet t/d. The scenarios modelled were in-vessel anaerobic digestion, drying and pelletisation to fuel pellets, drying and pelletisation to fertiliser pellets and AD and drying and pelletisation of the digestate. Over a process plant lifetime of 25 years, scenarios producing fertilisers present higher net present values. Production of fertiliser pellets as a co-product to biogas improved the economic feasibility of anaerobic digestion. Avoided disposal costs and the price of products affected the economic feasibility more than process-related parameters such as yields.

A feasibility analysis of the hydrothermal carbonisation of anaerobic digestion digestate was conducted for 137 wet t/d of digestate. The removal of 76% of moisture via hydrothermal carbonisation produced 52 t/d of hydrochar assumed to have a biofertilizer price of $50/t. Savings in transportation of wet digestate were assumed to be $65/t. Considering revenues from fertiliser sales and transportation cost savings, a capital cost of $5 million, and operational costs of $1 million/y, a Net Present Value (NPV) of $22 million can be achieved. Hydrothermal carbonisation with a waste biomass stream was also assessed. This is done to improve the properties of the hydrochar produced. Due to a higher input rate, the capital cost of the process increased, as well as operational costs, additionally because of the cost of transporting waste biomass from its source. However, higher amounts of hydrochar can be produced and sold, and alongside digestate transportation savings can generate moderate revenue. The NPV for hydrothermal carbonisation of digestate with sugarcane bagasse was $2 million. This scenario is highly sensitive to the cost savings in transportation of digestate for disposal.

A feasibility analysis of the solid-state fermentation of cattle paunch was conducted for 8,120 wet t/y of paunch. The fermentation process was modelled as a batch process taking in 40 t/batch. One batch is 22 days long, which means 203 batches can be run in a year. The fermented paunch was assumed to be similar to maize silage ($200/t) based on dry matter (35%) and protein (5%) composition. The NPV for this process was negative, and the minimum selling price was calculated to be $740/t. A reduction of capital costs by 25% brings the minimum selling price to $600/t. Further process optimisation can reduce costs and improve the economics of this process. Concurrently, a higher value product can be targeted so high processing costs can be justified.

Key Findings and Achievements

The opportunities presented by technologies to convert wastes from the livestock industries to high value products are driven by demand in the market for more sustainable animal-based products. Markets for new products from wastes exist and are large and mature. 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.

4.2 Development of technologies for improved waste management

Australia produces ~2.0 - 2.5 million tonnes of sludge and digestate from municipal and industrial wastewater treatment plants. The Australian animal industry is a major sludge/digestate producer. The industry also produces other high-water-content wastes, such as paunch. Paunch is comprised of partially digested cattle / sheep feed and contributes 20-70% of organic waste produced at red meat processing facilities. On average, 36 kg of paunch is generated per head of cattle, and approximately 200,000 tonnes are produced annually in Australia. Paunch has a high organic content, moisture content, microbial content and has an unpleasant odour, which makes treatment and disposal problematic. Disposal incurs significant costs and presents environmental impacts. The organic and moisture content make it unfavourable to dispose of by landfilling, due to gate fees and potential methane emissions. Reducing water content of solid wastes from 80% to 60% could reduce disposal costs by 50%. Dewatered paunch can be incinerated but the moisture and organic content hamper incineration due to inefficiency and generation of noxious SOx and NOx compounds.

Anaerobic digestion is a suitable technology for stabilisation of many organic wastes and allows energy recovery in the form of methane. AD is extremely flexible, making this a strong platform to build and integrate other higher value-add technologies. However, while AD has been successfully demonstrated for treatment of water streams in red meat processing facilities, many conventional forms are AD are currently not economically attractive when applied to red meat processing solid wastes (i.e., manure, paunch, wastewater sludge). Solid waste is an industry wide problem; therefore, the project has widespread potential benefit.

AD can be applied onsite by a wide range of businesses to generate methane that can be upgraded and added to natural gas grids or used onsite in boilers, engines or co-generation systems to generate renewable energy and offset onsite energy requirements. AD will simultaneously reduce the mass of waste requiring disposal, thereby reducing waste disposal fees. In some cases, the digestion residues may be converted into a form of organic fertilizer with revenue potential.

Another challenge currently faced with anaerobic digestion technology is that the process is sensitive to the inlet waste stream quality, for example, high ammonium concentrations will inhibit the biological processes which ultimately reduces gas yields. Research into the use of additives to anaerobic digestion can reduce the impact of stream-related limitations and have expanded the application of anaerobic digestion to challenging wastes.

4.2.1 Results - Treatments of animal industry wastes

Activity team: Dr Morteza Hassanpour, Dr Guiqin Cai, Dr Jerome Ramirez, Mr Majid Ebrahimi, Mrs Li Cao, A/Prof David Rowlings, A/Prof Zhanying Zhang (QUT)

Summary

In this activity, various treatment technologies were developed to treat animal industry wastes (sludge, digestate and paunch) to add value by reducing cost of disposal and developing or augmenting revenue streams. The outcomes explored by the treatment technologies are water and heavy metal removal to decrease disposal and transportation costs of digestate and new soil amendment and single cell protein products from digestate. These treatment technologies include bioleaching treatment, chemical treatment by $FeCl_3$ and hydrothermal treatment with the use of biomass (including paunch).

The results showed that the chemical treatment and hydrothermal treatment were both effective in improving waste dewaterability and reducing waste volume. The solid residues from the hydrothermal treatment could be used as soil amendments, which decreased nitrogen leaching rate and likely reduced greenhouse gas emissions. Techno-economic analysis showed that both treatment processes were economically viable for industrial application.

In addition, it was found that the hydrothermal treatment liquids could be used to produce single cell protein using *Yarrowia* yeast, which would generate revenue two times more than that from biomethane production. Pilot scale demonstration of these two treatments is recommended prior to industrialisation.

Objectives

The initial objectives of this activity were to develop bioleaching and hydrothermal treatments to reduce waste disposal costs by improving waste dewaterability and reducing waste volume, convert waste to valuable soil amendment, produce biomethane from treatment liquids as an energy source, and assess the economics of these treatment processes. In addition to methane production, the hydrothermal treatment liquids were also assessed to produce more valuable biofertiliser and single cell protein. During the implementation of this activity, a $FeCl_3$-assisted chemical treatment was also investigated.

Results and Discussion

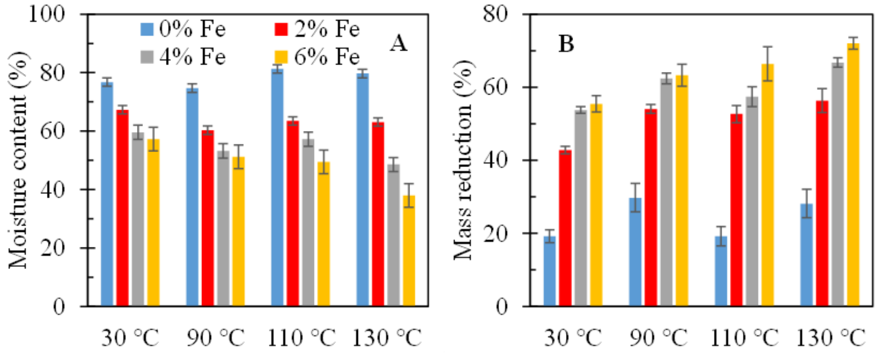
Bioleaching treatment

In this activity, a total of 12 *A. ferroxidans* strains were screened for bioleaching treatment of digestate. One strain *A. ferroxidans* ILS-2 was selected for further process optimisation and scale-up. The bioleaching treatment improved digestate dewaterability. However, the low internal return rate of -2% for the base scenario indicated that the bioleaching treatment was not economically viable. The major factor limiting the process economics was the high cost of ferrous sulphate due to the high ferrous ion usage for bioleaching treatment. Therefore, bioleaching treatment was not recommended for industrial application.

FeCl3-assisted chemical treatment

$FeCl_3$ is commercially used as a flocculant/coagulant and an odour control agent by wastewater treatment industry. Fig. 4 shows the effect of $FeCl_3$-assisted treatment on digestate moisture and mass reduction. Both treatment temperature and ferric ion loading affect moisture and mass reduction of digestate. Higher ferric loading and higher treatment temperature led to lower moisture and higher digestate mass reduction.

Figure 4. Effect of ferric ion loading on moisture (A) and mass reduction (B) of digestate treated at different temperatures. Treatment conditions: TS loading, 10%; time, 1 h.



The economics of the $FeCl_3$-assisted treatment was assessed. Table 1 shows the Techno-economic analysis results of $FeCl_3$-assisted treatment of digestate based on a wastewater treatment plant generating 50,000 wet tonnes of digestate (82% water content). For the base scenario, a Net Present Value (NPV) of $2.91 million was projected with an Internal Rate of Return (IRR) 23%. Sensitivity analysis showed that digestate transportation cost and $FeCl_3$ cost are the two most important factors affecting the process economics. Since $FeCl_3$ is already used at wastewater treatment plants, $FeCl_3$-assisted treatment of sludge and digestate is likely compatible with the existing facilities.

Table 1. Techno-economic analysis of $FeCl_3$-assisted treatment of digestate at 90 °C for 1 h (base scenario)

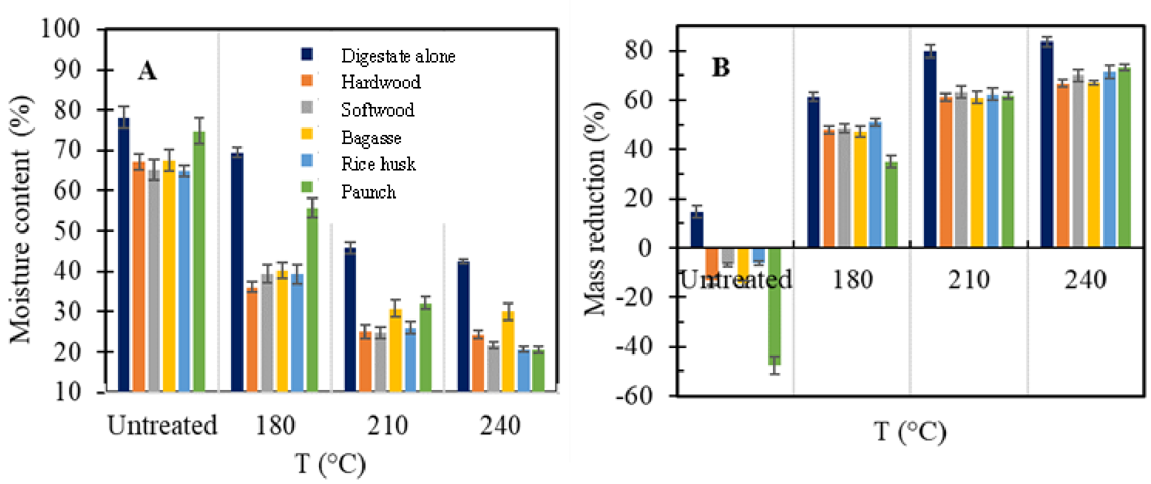
Digestate transportation cost for disposal, $, per wet tonne	65
$FeCl_3$ loading on total solids	12%
$FeCl_3$ price, $ per tonne	900
CAPEX, $million	2.50
OPEX, $million per year	1.42
Revenue (saved transportation cost), $million per year	1.92
Net present value (NPV), $million (20 years)	2.91
Internal rate of return (IRR, %) (20 years	23%

Note: inflation rate at 3% and discount rate at 10%

Biomass-assisted hydrothermal treatment

Biomass, such as sugarcane bagasse, rice husk and sawdust is abundant low-cost feedstock. Various biomass has been blended with sludge and digestate for hydrothermal carbonization, hydrothermal liquefaction and pyrolysis to produce solid biochar products and liquid fuels. However, the studies on the effects of biomass type on digestate dewaterability improvement, nutrient recovery and heavy metal removal from digestate are still very limited. Fig. 5 shows the effect of biomass type and hydrothermal temperature on the moisture and mass reduction after treatment and mechanical dewatering. The use of biomass in hydrothermal treatment led to more significant moisture reduction than those without biomass. Treatment of digestate alone led to more significant mass reduction than those with biomass because the use of biomass increased the total initial mass. Biomass type affected both moisture and mass reduction, especially at the low treatment temperature of 180 °C.

Figure 5. Effect of biomass type and treatment temperature on moisture (A) and mass reduction (B) of digestate. Reaction conditions: digestate/biomass total solid ratio, 1:1; treatment temperature, 180 °C; treatment time, 1 h



Moreover, the effect of biomass type and hydrothermal treatment temperature on nutrient recovery and heavy metal removal was also investigated. Fig. 6 shows the representative data after treatment with different types of biomass. The use of biomass improved nitrogen recovery in treated solids. The use of biomass also reduced heavy metal contents in treated solids especially at high treatment temperatures of 210 °C and 240 °C (except for those with rice husk). In addition to the treatment temperature, biomass type affected both nutrient recovery and heavy metal content in treated solids.

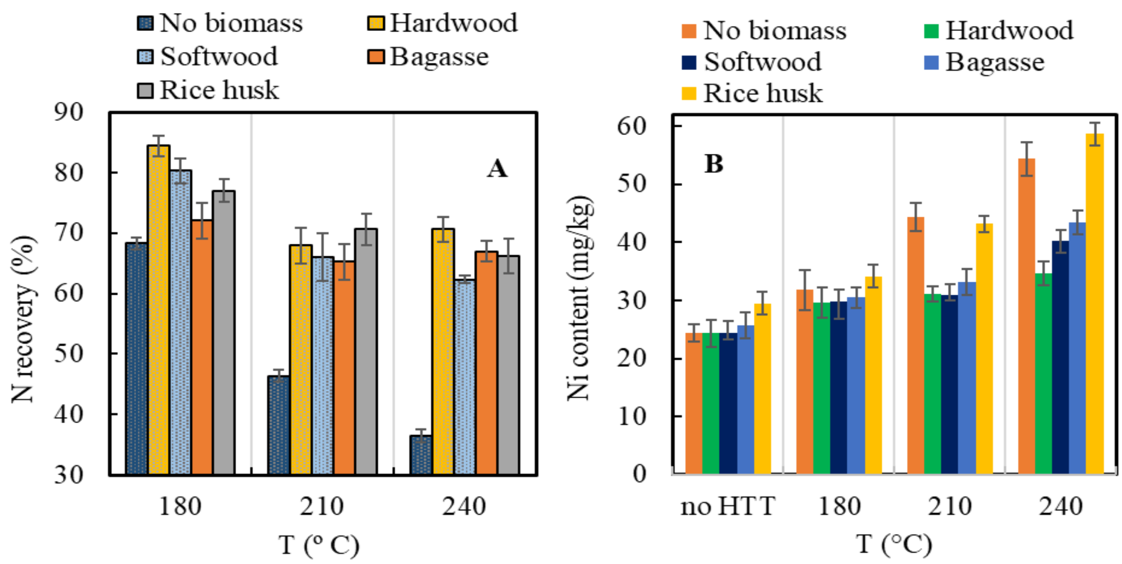


Figure 6. Effect of biomass type and treatment temperature on nutrient recovery (A) and heavy metal removal (B) from digestate.

The role of biomass in improving the dewaterability of digestate (especially at the low treatment temperature of 180 °C) was attributed to the skeleton effect of biomass and the hydrolysis of extracellular polymeric substances by organic acids generated from biomass. The different effects of biomass type on nutrient recovery and heavy metal removal were likely related to biomass composition, such as silica and oxygen-containing functional groups.

Table 2 shows the techno-economic analysis of biomass-assisted treatment of digestate based on a wastewater treatment plant generating 50,000 wet tonnes of digestate (82% water content). For the base scenario, a NPV of $10.60 million was projected with an IRR 22%. Depending on the geographic locations, various biomass, such as sawdust, sugarcane bagasse, rice husk and even green waste may be blended with digestate for hydrothermal treatment. Sensitivity analysis showed that biomass cost (affected by water content and transportation distance) and sludge transportation cost are the two most important factors affecting the process economics. Therefore, selection of biomass with low moisture contents and biomass close to the wastewater treatment plants will improve the process economics.

Table 2. Techno-economic analysis of biomass-assisted hydrothermal treatment of digestate at 180 °C for 1 h (base scenario)

Digestate transportation cost for disposal, $, per wet tonne	65
Biomass total solid leasing on digestate total solids	100%
Biomass total solid content	60%
Biomass cost, $ per wet tonne	100%
Selling price of treated sludge, $ per wet tonne	30
CAPEX, $million	10.50
OPEX, $million per year	2.10
Revenue (saved transportation cost+ product revenue), $million per year	4.06
Net present value (NPV), $million (20 years)	10.60
Internal rate of return (IRR), % (20 years)	22%

Note: inflation rate at 3% and discount rate at 10%

Value-added products from hydrothermal treatment of digestate

Hydrothermally treated digestate-biomass mixtures could be used as soil amendments. The use of treated digestate-biomass mixtures reduced the nitrogen (ammonium and nitrate) leaching than those with untreated digestate and treated digestate without biomass. Gas emission data indicated that the use of treated digestate-biomass mixtures likely reduce N_2O emission, a greenhouse gas having a Global Warming Potential 264-298 times of CO_2.

The hydrothermal treatment liquids contained 0.6%-1.5% acetic acid. The liquids were assessed to produce biofertiliser strains, single cell proteins by *Yarrowia* yeast and biomethane. The results showed some *Yarrowia* yeast strains could grow very well, rapidly consume acetic acid in the hydrothermal treatment liquids and produce single cell protein. It was estimated that for hydrothermal treatment of digestate-bagasse mixture, approximately 160 tonnes of *Yarrowia* cell biomass containing 67 tonnes of single cell protein could be produced from the hydrothermal treatment liquids. If all the cell biomass is sold as a pet feed additive at $2,000 per tonne, it will generate a revenue of $320,000, two times more than that from biomethane. These results indicated that single cell protein production is an attractive option for value-adding to the hydrothermal treatment liquids.

Key Findings and Achievements

The key findings and achievements from this activity are as follows:

- Bioleaching treatment was effective in improving digestate dewaterability and reducing digestate volume. However, the process was not economically viable.

- $FeCl_3$-assisted treatment at 90 °C was effective in improving sludge and digestate dewaterability and reducing waste volume. The process was economically feasible with a net present value of $2.91 million and internal return rate of 23% for the base scenario. Pilot scale demonstration of this process is recommended.

- Hydrothermal treatment of digestate with biomass at total solid ratio of 1:1 and treatment temperature of 180 °C was effective in improving digestate dewaterability. The treatment also improved nitrogen recovery and reduced heavy metal content in the treated digestate-biomass mixtures. The hydrothermal treatment process was economically feasible with a net present value of $10.6 million and an internal return rate of 22% for the base scenario. Soil incubation trial showed that the use of the treated digestate-biomass mixtures as soil amendments decreased nitrogen leaching and likely reduced greenhouse gas emission. In addition, the treatment liquids could be used as a carbon source to produce single cell protein by *Yarrowia* yeast, which has the potential for high-value pet feed additive application. Pilot scale demonstration of hydrothermal treatment, field trial with treated digestate-biomass mixtures and single cell protein production by *Yarrowia* yeast is recommended.

4.2.2 Results - Advanced anaerobic digestion - Enhanced efficiency of anaerobic digestion processes from animal wastes for increased biogas yields and lower costs (including co-digestion)

Activity team: A/Prof Paul Jensen, Dr Lisa Bai, and Dr Mario Rebosura (UQ)

Summary

This Activity undertook a systematic study including laboratory testing, process optimisation, and techno-economic analysis to transform multiple waste streams into methane energy and other resources. Advanced AD was considered as a modular approach where novel pre-treatments are used to transform wastes prior to AD.

More than 12 novel pre-treatments were assessed in this project and were able to improve methane production up to 100% when applied to compatible waste streams. Continuous process development was successful in validating results from laboratory screening experiments, but identified potential challenges associated with the variable nature of the solid waste streams. A demonstration facility has now been developed to test outcomes under real-world conditions using larger demonstration facilities. The demonstration facility is designed as a modular process train which has the capacity to serve as a platform to integrate multiple technologies including feedstock pre-treatment, co-digestion, pre-conditioning for value-add protein, and organic land conditioner development.

Objectives

This activity aimed to improve the economics of AD through research to: i) increase biogas revenue, ii) decrease capital requirements, and iii) reduce or eliminate disposal costs for post digestion residues (termed digestate). The approach was to develop Advanced AD technologies based around pre-treatment of waste, co-digestion of multiple waste streams, manipulation of reactor conditions and process additives. This was a systematic study including laboratory testing, process optimisation, and techno-economic analysis. Large-scale demonstration facilities are being developed to test the project outcomes under real world conditions and to serve as a platform for more integrated waste-to-value development and further progression of *Wastes to Profits* technologies – including to provide materials for protein production and fertiliser development.

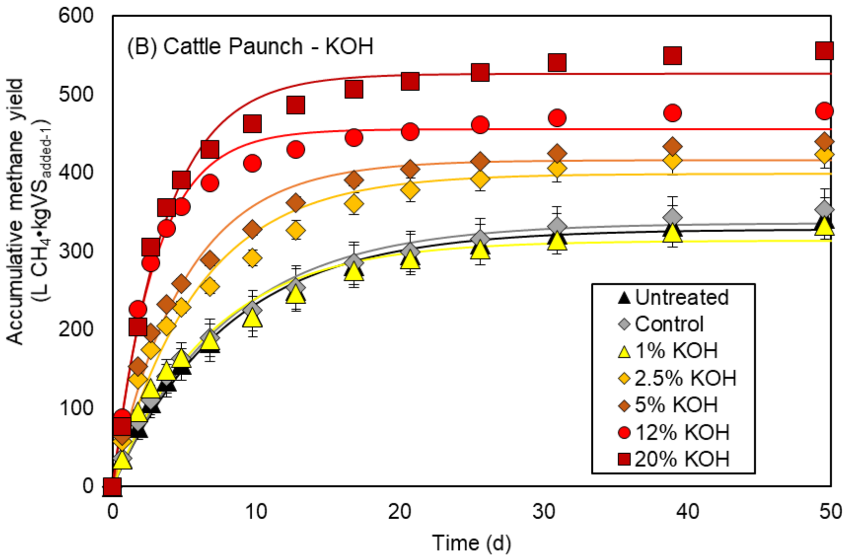
Results and Discussion

Laboratory batch tests were used to screen a broad range of pre-treatments for application to solid waste streams from agriculture and waste treatment applications. Pre-treatments were effective, but only when applied to compatible waste streams.

Alkaline pre-treatment was the most effective strategy for paunch solid waste, resulting in up to 60% improvement in methane production compared to conventional AD, a 50% reduction in residual disposal costs compared to conventional AD or a 75% reduction in disposal costs compared to existing dewatering only approaches. Example methane production results are shown in Fig. 7. Mild thermal pre-treatments were effective when applied to Waste Activated Sludge (WAS) but had no significant impact when applied to paunch.

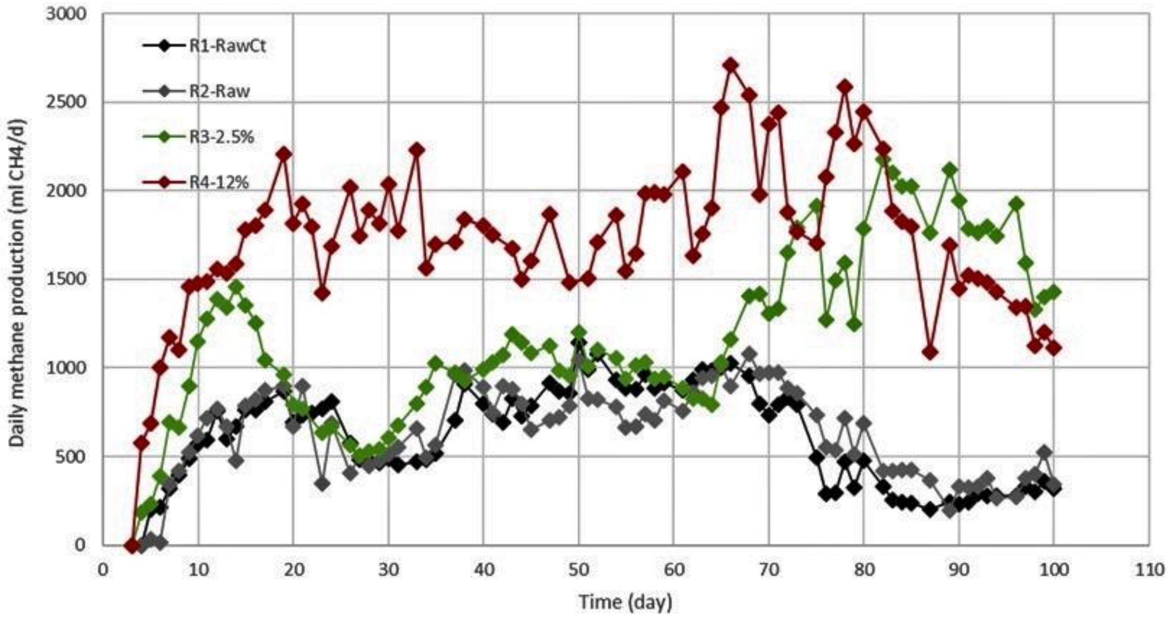
Alkaline pre-treatment was also effective when applied to high Fat, Oil & Grease (FOG) wastes, such as sludge from dissolved air floatation units at Red Meat Processing facilities. Alkaline Pre-treatment (Saponification) improved initial solubilisation of Dissolved Air Flotation (DAF) sludge (up to 20%), which results in minor improvements in methane production, but significant improvements in materials handling and significant reductions in process risks associated with lipid rich wastes (foaming issues, scum issues, process upset and inhibition). Alkaline pre-treatment of DAF sludge allows this material to be added to existing lagoons technologies or added to new developed paunch digesters with minimal risk.

Figure 7. Example methane production from initial screening experiments treating paunch solid waste after using alkaline pre-treatment.



Alkaline pre-treatment was selected for further process development. The next phase of the project aimed to progress the technology through development of a continuous process and then examine these outcomes under real-world conditions using larger demonstration facilities. Continuous process development at lab-scale was initially successful, with Fig. 8 showing 60-100% improvements in methane production in a continuous process (and similar reductions in residual solids for disposal). Continuous process operation identified some challenges in keeping the process stable, partly due to variations in waste composition and variations in process loading and operation. It is critical to continue process development under real world conditions to i) understand the impact of variable waste production on the process and ii) implement process management strategies to manage any risk.

Figure 8. Example methane production from continuous experiments treating paunch solid waste after using alkaline pre-treatment.



Demonstration facility progress

The demonstration facility design was based on a modular process skid with the capacity to test Advanced AD technologies, including pre-treatment (chemical dosing, mild-thermal, enzymatic, etc.), co-digestion, additive dosing regimens, etc. The skid was constructed with plumbing and power connections designed to be mobile and facilitate rapid deployment and redeployment. Construction of the skid experienced multiple delays related to supply chain and workforce limitations, however construction has now been completed and installation, systems checks and commissioning have commenced.

The key purpose of the demonstration is to move the Advanced AD technology along the TRL scale to validate the laboratory outcomes at an RMP under real-world conditions and improve the accuracy of the techno-economic assessment models with long-term operational parameters.

Figure 9. A Benchtop CSTR digesting paunch with the addition of chemicals or co-substrates and

KOH and B Pilot scale 3000 L.

Conventional AD is a mature commercial technology. Successful pilot testing of the Advanced AD pre-treatment would provide design information required to adapt existing and commercially available AD technology at full-scale or to construct new Advanced AD facilities. The technologies can be applied by a wide range of agricultural businesses, waste management businesses and water utilities, however the specific version of pre-treatment needs to be compatible with available wastes. Plants are able to utilise methane as a source of renewable energy within the plant. In generation, the methane will offset a portion of onsite energy requirements.

Key Findings and Achievements

More than 12 novel pre-treatments were assessed for application to RMP wastes, agri-industry wastes and other organic solid wastes. These pre-treatments were effective when applied to compatible waste streams.

Alkaline pre-treatment was effective when applied to paunch solid waste from either cattle or lamb processing facilities.

- Improved the methane yield from paunch up to 60% - the benefit was proportional to the alkaline chemical dose.
- Reduced residual solids, and therefore disposal costs by more than 50%
- Improved process rates up to a factor of 4.
- Preliminary economic assessments suggest a potential benefit of over $200,000 per year if applied at a large red meat processing facility.

Alkaline pre-treatment of DAF sludge (Saponification) had a clear impact on the waste properties.

- This technique increased solubilisation up to 20% and enhanced methane production up to ~16%. Alkaline pre-treatment allows DAF sludge to be treated in existing lagoons while reducing issues with crust and scum formation.
- Saponification may lead to other value-add opportunities, where the DAF sludge could become a carbon source for onsite nitrogen removal (which indirectly enhances onsite biogas production up to 20%) or as a precursor for waste-to-protein technologies based on PPB.
- Further optimisation is required to reduce chemical costs for alkaline treatment of DAF sludge to be economical.

Mild thermal pre-treatment is a form of pre-treatment that uses waste heat available when biogas is used to generate energy in go-generation engines.

- This technology seemed to increase methane production up to 20% when applied to DAF float and Waste Activated Sludge, but the results were variable.
- Mild thermal pre-treatment has no impact on Paunch or Cattle manure, mainly due to the robust lignocellulosic structure of these wastes.

Alkaline pre-treatment was selected for further development and optimisation in a continuous process. Initial continuous testing was positive, however, the highly variable nature of agricultural wastes was identified as a risk that needs to be assessed and managed under real world conditions.

4.2.3 Results - Utilisation of process additives to increase biogas yields and nutrient recovery during anaerobic digestion

Activity team: Prof Graeme J. Millar (QUT), Gerard Stephen (Zeolite Australia), A/Prof Paul Jensen (UQ), A/Prof Ilje Pikaar (UQ), Dr John Outram (QUT), Adrian Baker (QUT)

Summary

Powdered additives were examined in mesophilic BMP experiments which tracked the breakdown and mass balance of soluble content during anaerobic digestion. Common benefits were observed with respect to the nutrient (nitrogen and phosphorus) balance of the digestate, where nutrients were retained in the digestate and reduced in the liquid centrate proportional to the dosage of powdered additive used. This outcome was observed for anaerobic digestion of a range of waste streams including paunch, manure, red meat stream and liquid truck effluent. Gas modelling was used to better estimate the degradation parameters during the stages of anaerobic digestion. Current preliminary data indicated that the powdered additives had a positive impact in triglyceride degradation in fat, oil, and grease (FOG) containing streams, such as red meat processing. Destruction of soluble Chemical Oxygen Demand (COD) and volatile fatty acids were accelerated when powdered additives were used. The samples were further analysed for triglycerides and long chain fatty acid content.

Modified powder material, such as magnesium loaded, and magnetite coated material – were also prepared. These additives were designed to exploit the nutrient capture behaviour of original powdered additives with added activity for increased phosphate removal and fat, oil, and gas (FOG) degradation, respectively. The modified additives were not found to perform significantly different from the original powdered additive, under the conditions tested.

Collaboration with the ‘Advanced AD’ project activity for pilot demonstration was initiated, with experimental plans to evaluate the physical limitations of potential continuous designs in place.

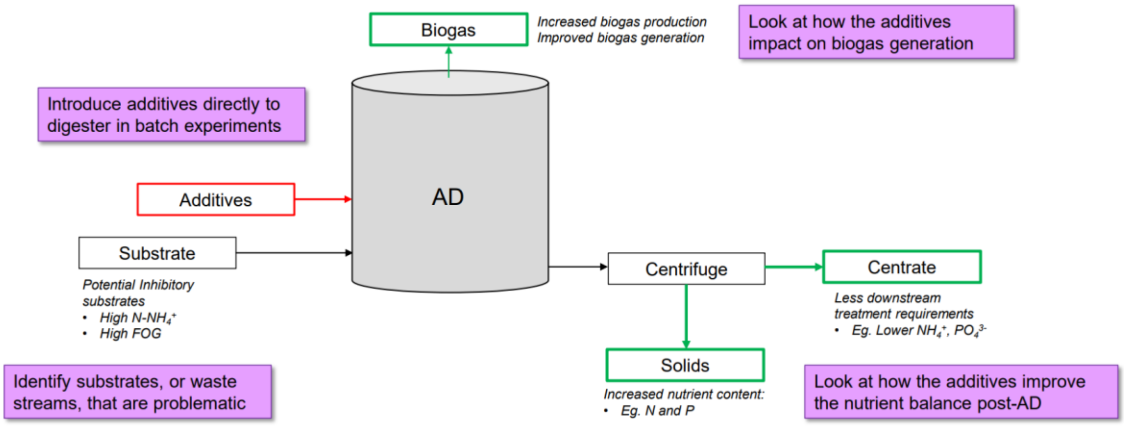
Objectives

The objectives for this Activity were to:

(1) identify problematic waste streams in collaboration with industry partners
(2) introduce additives that potentially impact on these streams
(3) understand how the additives impact the anaerobic digestion process, including gas generation and nutrient balance, and
(4) explore strategies to incorporate successful additives in existing infrastructure.

A graphical representation of the Activity objectives was reported in Fig. 10.

Figure 10. Strategy for introducing additives into the Anaerobic digestion process.



Additives to anaerobic digestion include zeolites, iron oxides (such as magnetite), magnesia, micro-nutrients (such as magnesium, molybdenum, ferrous iron, and nickel), and enzymes. The various additive types have different applications with respect to anaerobic digestion mechanisms. Zeolite materials are predominantly used to sequester ammonium and reduce ammonium inhibition. This is beneficial in high ammonium containing wastes, such as piggery wastes, where higher biogas yields are observed with zeolite additives. Magnetite (Fe_3O_4) and iron oxides are typically used for its redox properties where it acts as an electron shuttle which stimulates methanogenic activity in the digester (increased methane production). Magnesia (MgO), and magnesium-based additives, are used to sequester phosphate and ammonium in the digestate and precipitate as struvite; a valuable mineral for applications in fertilizers. Micronutrient addition supplements nutrient deficient wastes to stimulate methanogenic activity, and enzymes catalyse the biological processes; both additives work to increase the biogas yield of the digester.

Results and Discussion

Two key outcomes were identified in this Activity when powdered additives were used during anaerobic digestion:

1. Improved nutrient balance of the digestate in a range of problematic substrates, where increased nitrogen and phosphorus concentration in solid sludge and corresponding decrease in liquid centrate, was observed.
2. Improved degradation of fat, oil, and grease (FOG) containing streams in potentially inhibitory compositions, where the benefit was observed during the initial degradation period.

The distribution of nitrogen and phosphorous concentrations in the centrate and sludge (referred to henceforth as nutrient balance) was monitored during Biomethane Potential (BMP) experiments. The centrate referred to the supernatant, or liquid, component of the digestate (<0.45 µm), and the sludge referred to the remaining solids fraction (>0.45 µm). Overall, it was found that powdered additives repeatably impacted on nutrient balance for a number of waste streams, whereby increased nitrogen and phosphorous were captured in the sludge with a corresponding decrease in the centrate was observed. The waste streams investigated focussed on red meat processing streams and included cattle manure, dewatered paunch, truck effluent, rendering stick and combined wastewater.

A simple cost benefit analysis of the additives was initially completed for a treatment process using ferric chloride as a precipitant for P-PO_4^{3-} removal and a Biological Nitrogen Removal (BNR) unit. Generally, the net value of the overall treatment was found to decrease with increasing additive dose. The cattle manure substrate attracted the greatest cost deficit associated with additive dose, which was due to the concentration of N-NH_4^+ in the substrate requiring an increased additive dose. Otherwise, the combined waste substate showed the lowest cost penalty with respect to additive dose due the reduced N-NH_4^+ concentration of the substrate.

Features of the simple cost-benefit of powdered additives were found to attract a range of economic improvements to treatment value. Additives reduced the energy cost attributed to nitrogen removal (BNR) and reduced precipitant cost were observed. Both of these benefits were a result of the reduced nutrients in the centrate which required less treatment downstream. The increased nutrients in the sludge simultaneously increased with additive dose, where the sludge value increased based on DAP price index (as of 2021). Despite these benefits, the cost associated with the additives appeared to overshadow the economic improvements observed when used as a direct additive to a digestor.

Kinetic anaerobic digestion Biochemical Methane Potential (BMP) tests of red meat processor combined wastes was developed and applied to investigate the mechanism in which additives impact digestion. It was found that additives increased the rate at which soluble FOG content degraded during the initial stages of digestion. This was hypothesised to be a result of increased rate of triglyceride destruction when additives were used during digestion. Samples for triglyceride and long chain fatty acid analysis have been submitted to measure the concentration of these components to further elucidate the mechanism.

Scaled Demonstration Plans

The kinetic experiments demonstrated that powdered additives had an impact on both the degradability and hydrolysis rate during the anaerobic digestion of combined wastewater under high FOG loading conditions. This impact was primarily observed during the first 3 days of digestion where increased rate of soluble Chemical Oxygen Demand (COD) destruction was detected, which aligned with an increased rate of Long Chain Fatty Acid (LCFA) catabolism.

Australian meat processors typically employ anaerobic lagoons as the treatment method for wastewater. The addition of powdered additives to covered anaerobic lagoons (CALs) has not been studied, however observations from the batch test can be used to predict potential operational issues within CALs. Firstly, the additive was found to settle with the sludge on standing. Within a CAL the additive would settle away from the grease and scum layer which may reduce the effectiveness of the additives. The premise of additive's beneficial action was that sufficient contact time between the LCFAs and additive was achieved.

In consultation with Activity 2.2, potential add-on unit operations were discussed which may incorporate additive media into the existing plant designs at either the anaerobic digestor stage, or post-digestion as a polishing unit.

Preliminary continuous trials were planned which evaluated the physical limitations of potential designs. This includes flow characteristics, back pressure and media performance in countercurrent/fluidised bed reactor, as well as performance of additive media when used as a polishing unit operation post digestion.

Further details on this research is available in this peer reviewed journal article published from this research on Purple phototrophic bacteria.

Stegman, S., Batstone, D.J., Rozendal, R., Jensen, P.D. and Hülsen, T., 2021. Purple phototrophic bacteria granules under high and low upflow velocities. *Water Research*, *190*, p.116760. https://doi.org/10.1016/j.watres.2020.116760

Key Findings and Achievements

- Powdered additives improved the nutrient balance of digestate by lowering nutrient load in downstream centrate and increasing the potential value of sludge (based on diammonium phosphate (DAP) index))

- Powered additives appeared to improved degradation of triglycerides during the initial stages of anaerobic digestion, however further analyses is required to confirm this.

Further studies to include investigating the application of additives to existing infrastructure and the impact of additives as a polishing media for post digestive treatment and scrubbing residual nitrogen from effluent to reduce disposal costs.

4.3 Development of technologies for production of nutritionally-advanced feeds

This project area developed technologies in using purple phototrophic bacteria, microalgae, a biogas co-cultivation, fungal protein production and treatment of keratin wastes to higher value products.

Purple phototrophic bacteria (PPB) is a Waste-to-Value technology that captures carbon, nitrogen (N), and phosphorus (P) in wastewater and converts these resources into a protein-rich biomass product. PPB grow anaerobically in the presence of infra-red light. The biomass is characterized by up to 65% protein on a dry weight basis, with potential applications as an organic fertilizer, feed additive or substitute in livestock, poultry and aquaculture feed formulations. Removing organics, nitrogen and phosphorous wastewater saves discharge costs, while recovering and upgrading these components into protein-rich biomass has the potential to add value and provide alternative feed and fertilizer products that reduce supply chain pressures.

The integration of microalgae cultivation as a tertiary treatment procedure for the removal and recovery of waste nutrient does not only allow for the generation of reclaimable water but also valuable algal biomass, thus, establishing a circular economy. The cultivation of microalgae on AD effluent can be highly profitable for local industries as it combines the simultaneous treatment of an otherwise untreatable waste stream with the production of valuable algal biomass (waste to profit).

The biogas co-cultivation technology consists of a phototrophic-methanotrophic co-culture that can potentially convert both CO_2 and CH_4 into microbial biomass, in a system that does not require the addition of exogenous O_2. Both components of biogas can be utilised, as the phototroph assimilates CO_2, while the methanotroph assimilates CH_4 using the O_2 produced by the phototroph. This concept has been demonstrated previously.

A process that included pre-treatment and fermentation was developed to use paunch as a substrate for fungi that generate high-value chemicals. Paunch can be converted to crude protein, or to a feed material with increased amounts of amino acids, vitamins, micronutrients and enzymes, which can enhance animal productivity. Options included conversion to edible fungi such as mushrooms, production of probiotic spores, growing fungi to produce enzymes, fatty acids and organic acids, and insect cultivation as an alternative protein- and lipid-rich feed supplement. Paunch contents were considered as a suitable substrate since it is generated as a by-product of meat processing. It is a macerated fibrous solid residue consisting of partially digested feed from the stomachs of processed cattle and has a high organic and moisture content that can support fungal growth.

The recalcitrant by-products of animal production and meat processing are cattle hairs from tails and those removed in leather manufacturing, waste wool streams in wool processing, horns and hooves in meat processing and feathers from poultry processing. The amount of waste is significant considering 9 million hides, and 36 million hooves produced in Australia. These are all keratin-containing materials, which are by nature and intended purpose, hard to break down. These materials can be treated with chemicals and processed with enzymes to break down keratin proteins and produce peptides. Such processes can unlock the value of these streams as a processed livestock or poultry feed product to improve anti-microbial/antipathogen activity, gut microbiome modulation, flavour profiles and antioxidant activity. Peptides produced through this process also have potential as supplements to improve nutrition.

4.3.1 Results - Technologies for nutritionally advantaged feeds

Activity team: A/Prof Paul Jensen (UQ), Dr Tim Huelsen (UQ), Maria Grassino (UQ), Samuel Stegman (UQ), Prof Susanne Schmidt (UQ), Dr Harshi Gamage (UQ), Prof Andrew Barnes (UQ), Zuo Meng Gan, Glen Cornish

Summary

Purple phototrophic bacteria (PPB) are a type of bacteria that can be used to transform organics, nitrogen and phosphorus from agri-industrial wastewater into microbial protein that can be used as a sustainable new animal feed, an organic fertilizer or a feedstock for energy production. The value in PPB biomass comes from the high protein content (~60% by weight) and presence of high value compounds. During this project PPB were successfully growth in granular form for the first time; this outcome reduces the cost of producing and harvesting PPB biomass for industry. Further, growth conditions were used to successfully augment the composition and value of the PPB biomass, specifically lycopene, which is a high value carotenoid with immuno-nutritional properties. PPB was grown successfully on various forms of agricultural and industrial wastewater.

The value of the PPB biomass as i) animal feed or ii) organic fertilizer was assessed at a proof-of-concept level. In feed trials, PPB biomass was successfully used as a substitute for fishmeal (valued at ~$1,970 tonne^{-1}) as part of aquaculture feed formulations used to grow tiger prawns. In organic fertilizer trials PPB biomass was used successfully to grow tomato, silverbeet, spinach, sorghum, and watermelon. These outcomes demonstrate proof-of-concept for using PPB as value-added material in a circular economy. However, the PPB technology is still in its infancy and on-site, outdoor pilot units have to translate the findings into real world applications. Wastewater source and the regulatory environment impacts the end-use and value add strategies.

Objectives

This research aimed to develop PPB technology using liquid agro-industrial wastes as a raw material. Core objectives were to develop strategies to enhance the composition of PPB biomass, to establish a continuous process design, to progress process optimisation and technology scale up, and to conduct proof-of-concept product testing. The aim was to deliver robust production systems and scalable processes supported by techno-economic analyses, including technology integration, bioreactor engineering, harvesting, compound extraction and feed production.

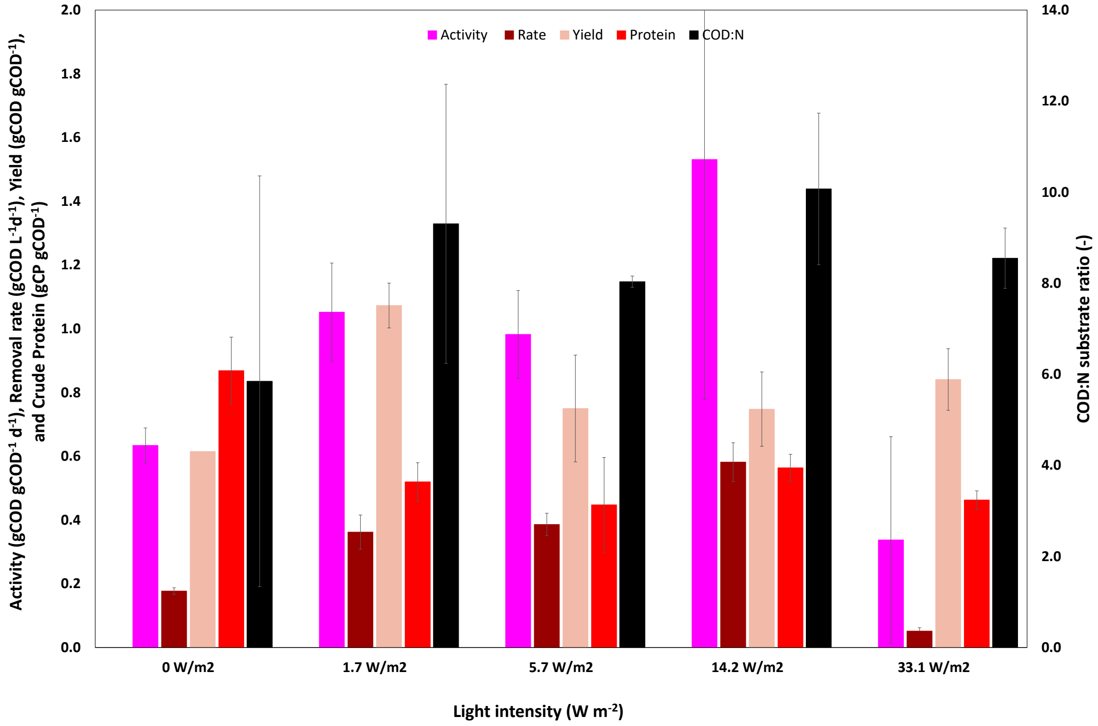
Results and Discussion

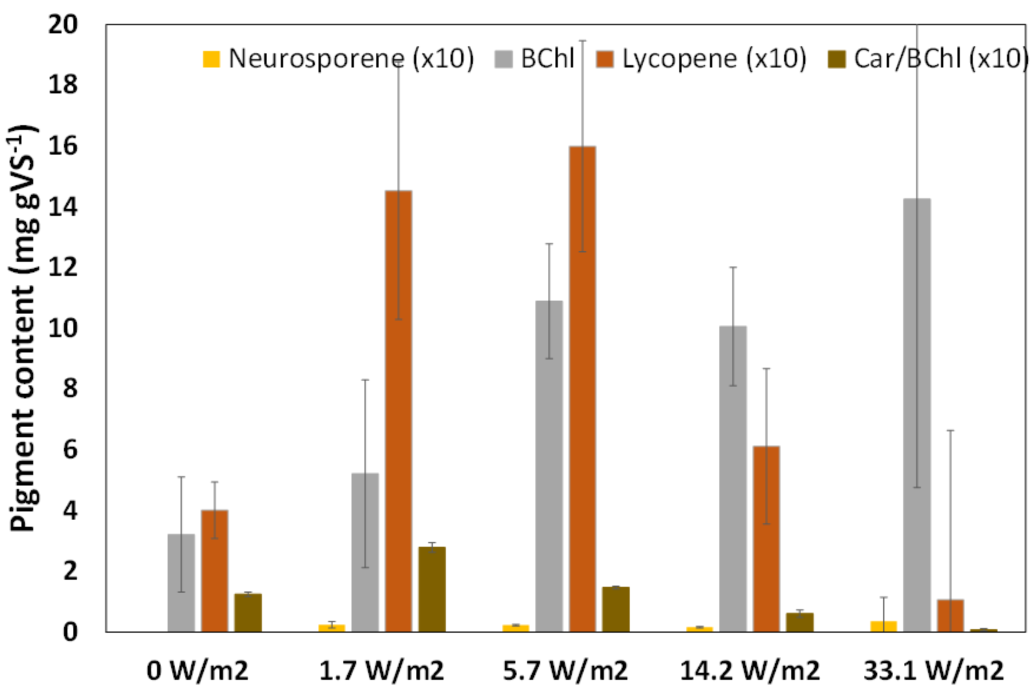
Experiments were performed to assess the impact of light on the growth and composition of PPB biomass. Results in Fig. 11 showed that light intensity has a clear impact on the growth and composition of PPB biomass. Growth rates and protein production were highest at moderate light intensities of 14.1 W.m^{-2}, increasing the light to 33 W.m^{-2} significantly decreased performance due to photo inhibition, at lower light intensities the light became a limiting factor that also reduced performance. Interestingly, production of lycopene, a high value pigment with immuno-nutritional properties was highest at lower light intensities (1.7 and 5.7 W.m^{-2}). The results suggest lycopene concentrations of 160 mg.L^{-1} could be achieved, which is a commercially relevant concentration. However, optimising the growth conditions of PPB biomass appears to present a trade-off between maximising biomass production rates and maximising biomass product value.

Experiments were performed to develop and compare the performance of PPB biomass grown in granular and flocculant forms. Liquid upflow velocity was applied as the driving force for granulation. Separate reactors were operated at either low (2-5 m h^{-1}) or high (6-9 m h^{-1}) upflow velocities, with sludge retention times (SRTs) ranging from 5-15 d. Reactors produced anaerobic, photo-granules within ~50 d. The sludge volume index (SVI30) of the granules was 10 mL g^{-1} and average settling rates were greater than 30 m h^{-1}, both metrics being similar to existing granular technologies and indicating excellent settling properties, which translate into effective low-cost biomass harvesting. Figure is an example of granular PPB biomass in an upflow-photobioreactor.

The efficacy of the PPB biomass product was tested in feed trials to establish the value of PPB -based feeds, which informs the value proposition of the process. PPB could potentially substitute fishmeal as a protein source in commercial aquaculture feeds, while also adding immune-nutritional components such as carotenoids to the feed. Preliminary trials confirmed proof-of-concept, but to date there is no large-scale system, and the capital costs are still to be determined.

Figure 11. TOP: Activity (gCODremoved gCODbiomass-1 d-1) Rate (gSCOD L-1 h-1), yield (gCOD gCOD-1), COD:N and crude protein (mgCP gCOD-1) at different light intensities. BOTTOM: Pigments contents of PPB biomass at different light intensities.

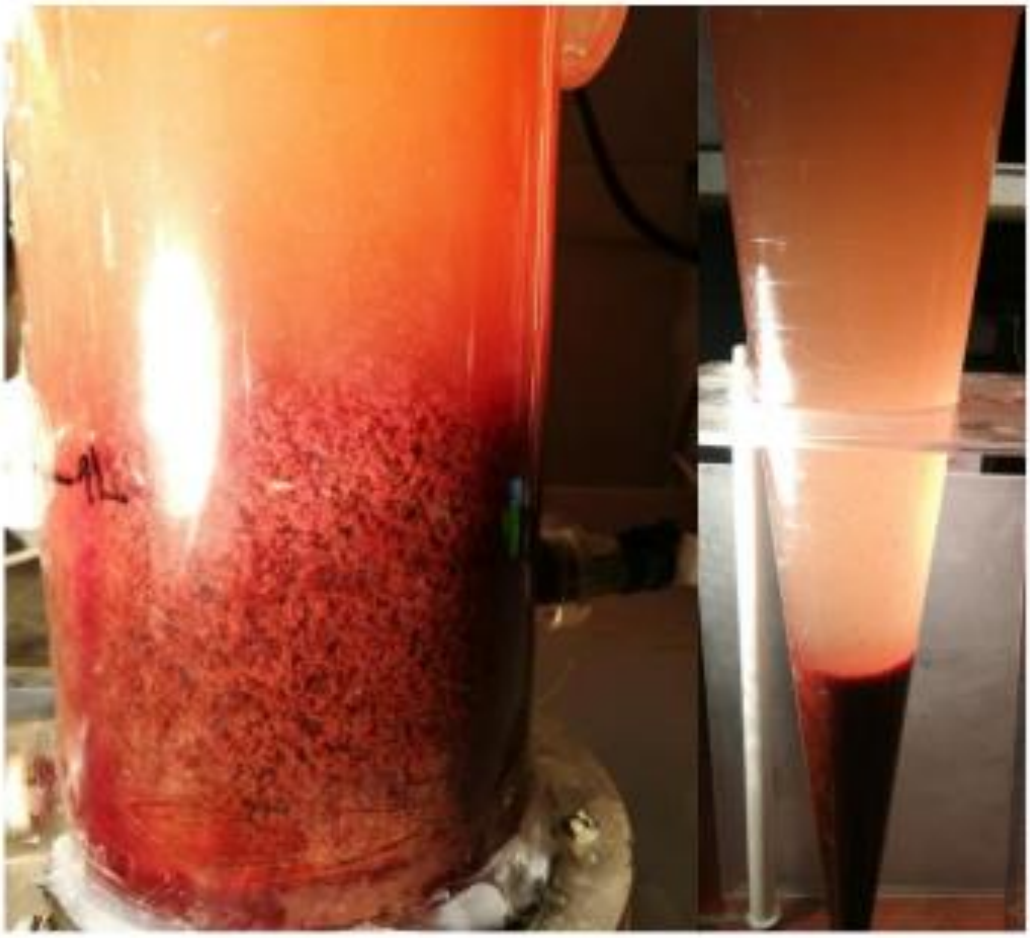




This technology could be adopted by agricultural businesses as an addition or an alternative to existing wastewater treatment operations. In these applications, modelling by the project researchers demonstrates that significant savings in trade waste charges. This technology could be adopted by wastewater utilities, however additional treatment steps would be important to reach environmental discharges standards for the treated water. A modular, scalable PPB system would allow for flexible installation based on different needs and available space. With regard to skills and capabilities the PPB is very robust and a minimum of sensors are required to run the process.

Business models for implementation are expected to require agreement between the wastewater producers, that runs the process and generates the PPB and end users such as a feed manufacturer or fertilizer company to purchase the product.

Figure 12. Aggregated PPB biomass in a lab reactor and settled PPB biomass in an Imhoff cone.



Key Findings and Achievements

The application of purple phototrophic bacteria for agri-industrial wastewater enables the recovery of organics, nitrogen, and phosphorus as protein-rich biomass, applicable as animal feed or fertiliser.

The growth and composition of PPB biomass can be manipulated using light intensity. However, optimising the growth conditions of PPB biomass is a trade-off between maximising biomass production rates and maximising biomass product value.

- Low light intensities limit the growth rate of PPB biomass, however, these conditions enhance production of Lycopene, a valuable carotenoid with immuno-nutritional properties.

- Moderate light intensities maximise the growth rate of PPB biomass, but result in lower production of pigments, including Lycopene.

- High light intensities reduce the production of pigments and photo-inhibit PPB growth.

A high-throughput microplate method to grow PPB under anaerobic photoheterotrophic conditions was developed. This method is expected to find widespread application to test and optimise PPB growth and biomass characteristics.

PPB can be grown in the form of aggregated granules with excellent harvesting properties. Both, low and high upflow rates can be applied. Lower upflow velocities reduce the recycle flow and lower the operational costs. The potential of lowering harvesting costs due to substantially improved settling velocities needs to be confirmed in a scalable outdoor reactor under real conditions.

Harvested PPB biomass was transformed into prawn feed at different inclusion rates. Up to 100% of fishmeal might be substituted with PPB biomass generated from wastewater. The trials are ongoing. These trials are crucial to determine the real value for the feed manufacturer (e.g., aquafeeds) and enable a complete cost benefit analysis.

PPB were successfully tested as organic fertiliser e.g., for sorghum and watermelon and the results underline the use of recovered nitrogen and phosphorus from wastewater to generate plant material and protein. The final value as fertiliser still needs to be defined by a fertiliser producer.

4.3.2 Results - Microalgae cultivation for treatment of waste streams in the meat processing industry

Activity team: Professor Parisa Bahri, Professor Navid Moheimani, Dr Ashiwin Vadiveloo, Pooya Darvehei, Arsalan Alavian, and Hajar Shayesteh (Murdoch University*)*

Summary

This project activity assessed the techno-economic feasibility of integrating microalgae cultivation as a tertiary wastewater treatment procedure for Anaerobic Digestion (AD) effluent produced by red meat processors. The aim of this project was to develop a sustainable microalgal treatment system to convert the nutrients in AD effluent into profitable algal biomass that can be valorised into multiple end-products as well as the production of cleaner water. In addition, we critically evaluated the techno-economic and environmental impacts of the developed process. The first key achievement of this project was the successful bioprospecting and isolation of local microalgae species (i.e., *Chlorella* sp. and *Scenedesmus* sp.) that could effectively treat AD effluent sourced from the local meat processing industry. Subsequently, multiple growth optimization studies (i.e., pH, culture depth and CO_2 addition) were conducted to maximize the efficiency of the overall microalgal wastewater treatment process. A major milestone of this project was the successful 13-month continuous pre-pilot operation of this process on-site at a meat processing facility with minimum maintenance. Various dewatering methods such as electrocoagulation, flocculation, and pH induced flocculation were also evaluated to identify the most efficient method for de-watering microalgae. Pathogen and biochemical composition of biomass grown in AD effluent was also characterized to assess its suitability for product developments (i.e., animal & aquaculture feed and biofertilizers). The effect of culture scaling-up (up to 50 m^2) and the hydrodynamics of mixing in open raceway ponds at different scales were also evaluated as part of this study to validate the performance of the developed microalgal wastewater treatment system at large scale.

Another major milestone of this project was developing the techno-economic and lifecycle models to evaluate the technical and environmental aspects of the process in large scale. The results of the design can be summarized as the total cost of the process in terms of both wastewater treatment and microalgae production, the effect of operational variables on the cost of the process (i.e. AD effluent flowrate, biomass productivity, ammonia volatilization and water evaporation), the profitability of the process in terms of net present value (NPV) or internal rate of return (IRR) considering the value of microalgae and treated water produced, and calculation of environmental impact of the whole process in terms of greenhouse gas emission (GHG), nitrogen, and phosphorus emissions.

Objectives

The main aim of this project activity was to develop, establish and optimize an innovative microalgal system for the treatment of effluent post AD. Also, as part of this activity, a detailed techno-economic assessment of the developed algal wastewater treatment system for different scenarios as well as a Life Cycle Assessment (LCA) to realise the environmental benefits of the system were successfully carried out.

Results and Discussion

Bioprospecting of local microalgae species capable of growth in raw AD effluent

The first key step of this project activity was the successful bioprospecting and isolation of multiple local microalgae species (i.e., *Chlorella* sp. and *Scenedesmus* sp.) that were not only capable of growth in raw AD effluent from red meat processors but efficiently treat it (Fig. 13A). The growth, biomass productivity, and nutrient removal efficacy of the isolated microalgae strains in AD effluent were evaluated under local outdoor conditions, establishing *Scenedesmus* sp. as the preferred and most efficient candidate.

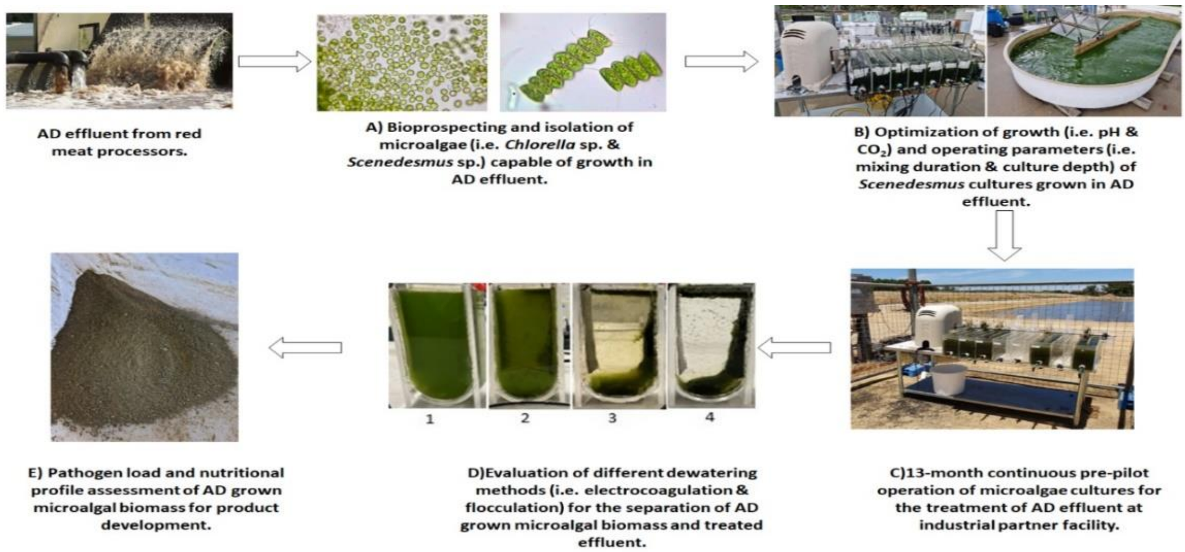
Optimization of growth conditions and nutrient removal rates of Scenedesmus sp. cultivated in AD effluent

Various algal growth factors and operating conditions (i.e., pH, CO_2 addition, mixing duration, culture depth and the recycling of culture media) were successfully optimized under outdoor conditions to maximize the removal of nutrients and the production of algal biomass in the targeted AD effluent (Fig. 13B). In summary, pH of 6.5, the addition of CO_2, 24-hour paddle wheel mixing and the culture depth of 14 cm were found to be ideal for maximizing the performance and output of the developed microalgal wastewater treatment system, resulting in biomass productivity values of up to 18 $g.m^{-2}.d^{-1}$ as well as 100% ammoniacal nitrogen and 92% phosphate removal efficiency.

Pre-pilot experimental assessment of reliable long term (13-month) microalgae cultivation in AD effluent under local outdoor climatic conditions.

The major landmark of this activity was the 13-month continuous pre-pilot growth of microalgae in AD effluent for both wastewater treatment and microalgal biomass production at a local meat processing facility under local climatic conditions (Fig. 13C). The average biomass yield of cultures after one week of growth during summer and winter trended between 0.83-1.16 g L^{-1} and 0.4-0.78 g L^{-1}, respectively. Irrespective of the climatic season, almost all the available ammoniacal nitrogen (NH_3-N) in the AD effluent was found to be depleted (≈100% removal efficiency) within one week of the microalgae cultivation period. Addition of CO_2 can increase the biomass productivity by over two times.

Figure 13. Summary of experimental activities undertaken as part of this project



Evaluation of different dewatering methods for harvesting microalgae biomass grown in AD effluent

In this study, the performance of three different dewatering/separation methods namely electrocoagulation, flocculation, and pH induced flocculation on microalgae was investigated to identify the most efficient procedure for biomass production and the generation of reclaimable water (Fig. 13D). Biomass recoveries of microalgae cultures in electrocoagulation was found to be significantly higher at a shorter time period when compared to those in flocculation and pH induced experiments.

Nutritional profile and pathogen load of AD effluent grown microalgal biomass.

The aim of this activity was to assess the suitability of AD effluent grown algal biomass for product development (i.e., animal or aquaculture feed ingredient) based on its nutritional profile and pathogen load (Fig.13E) The pathogen load of the biomass produced was found to be favourable for use as animal feed based on the absence of *Salmonella* spp. and *Listeria* spp. In terms of nutritional value, the crude protein content (44.7%) of biomass was highly promising as it was comparable to soybean meal. The high content of essential fatty acids such Omega-3 and Omega-6 and hydrolysed fat (9.6%) is another major advantage for the application of the biomass as animal feed.

Techno-economic and lifecycle analysis of the process at large scale.

The results of the technical analysis showed that considering the design target of 99 wt% of total nitrogen removal from red meat processing wastewater, the microalgae would also be able to remove 94 wt% of total phosphorus from AD effluents in red meat processing industry. The results also show that 63 wt% of total wastewater entering the process would be treated to the final quality of 2 mg N/L and 3 mg P/L. it is also possible to produce 2 kg high value microalgae out of 1 m^3 wastewater from red meat processing facilities which might not only cover the cost of treatment, but also make the process of converting wastes to value added products profitable. Finally, the average value of specific design loading rate for the treatment of the wastewater using open ponds in large scale is calculated to be 11.3 L/m^2.day.

The total cost of wastewater treatment to remove nitrogen and phosphorus with a capacity of 1700 m^3 per day is AU $ 2.6 /m^3 of AD effluent. Considering the credits of the non-potable recycling water which can be reused in the red meat processing facilities and carbon dioxide removal, the net cost of treatment would reach AU $ 1.8/m^3. If the microalgae paste (20 wt% dry microalgae) derived from the wastewater treatment process is dried to 95 wt% dry microalgae product, and it could be sold with a minimum value of AU $ 1.8 /kg, the net present value of the whole process would be almost zero. Considering the possibility of selling the dry microalgae product as animal feed (AU $2.3 /kg), the calculated internal rate of return for the project would be 10%. Considering the highest possible feed value in the market such as aquaculture feed (AU $4/kg), the internal rate of return can even reach 26%, and the total investment cost could be returned after 3.5 years of operation.

The lifecycle analysis shows that the Greenhouse Gas emissions of the whole process in terms of carbon dioxide equivalent are negative which is a great advantage for this process. The mass ratio of direct carbon dioxide removal of microalgae based on the experimental analysis is reported to be 1.76 kg CO_2 per 1 kg of dry biomass. In terms of phosphorus and nitrogen emissions, some of the nitrogen is emitted directly from the open pond cultivation unit; however, this issue can be solved by keeping the pH around 6.5 during cultivation. Despite the possibility of complete removal of nitrogen from the wastewater, small amount of phosphorus components might be left in the treated wastewater which should be considered as the possible emissions to the environment.

Further details on this research are described in the seven papers published from this work (Matos et.al. 2021, Raeisossadati et.al. 2021, Shayesteh et.al. 2021, Shayesteh et.al. 2022, Vadiveloo et.al 2020, Vadiveloo et.al 2021, Vadiveloo et.al 2022). The list of papers included in the Appendix.

Key Findings and Achievements

1) Isolation of robust local microalgae species (i.e., *Scenedesmus* sp. and *Chlorella* sp.) capable of growth and treatment of raw AD effluent from red meat processors.
2) Optimization of growth of the developed microalgal wastewater treatment system resulted in *Scenedesmus* sp. biomass productivities up to 18 $g.m^{-2}. d^{-1}$ as well as 100% ammoniacal nitrogen and 92% phosphate removal efficiency.
3) A major achievement was the 13-month continuous pre-pilot operation of the developed microalgae-wastewater treatment system at a local meat processing facility under local environmental conditions.
4) Pathogen load and nutritional assessment (i.e., protein content) of AD effluent grown microalgal biomass establish its suitability for use as animal or aquaculture feed.
5) Scaling up microalgae cultures grown in AD effluent from $0.1m^2$ to $50m^2$ in open raceway ponds illustrated no significant difference in the biomass productivity obtained for the different sized ponds.
6) Analysing the possibility of using microalgae in open ponds as an advanced wastewater treatment process in large scale and the possibility of making the whole process of converting waste to value added products economically feasible and environmentally friendly.

4.3.3 Results - Biological conversion technologies for valorisation of biogas

Activity team: Prof Alexander Beliaev (QUT/PNNL), Prof Robert Speight, Dr James Strong, Dr Alexander Gissibl, Marius Jessen, Wenshao Li and Raveendra Anangi (QUT)

Summary

To enable valorisation of waste treatment through anaerobic digestion, we have developed a technology for converting gases into nutrient-enhanced biomass. The biogas co-cultivation technology has a significant biological advantage for productivity because it concurrently consumes carbon dioxide and methane, which are the most potent greenhouse gasses. Furthermore, the co-cultivation platform represents a sustainable route for the use of both large and small scattered sources of biogas, and the technology can be deployed for effective production of high-value products, nutritionally enhanced feeds, and feed additives as an economical alternative to biogas combustion.

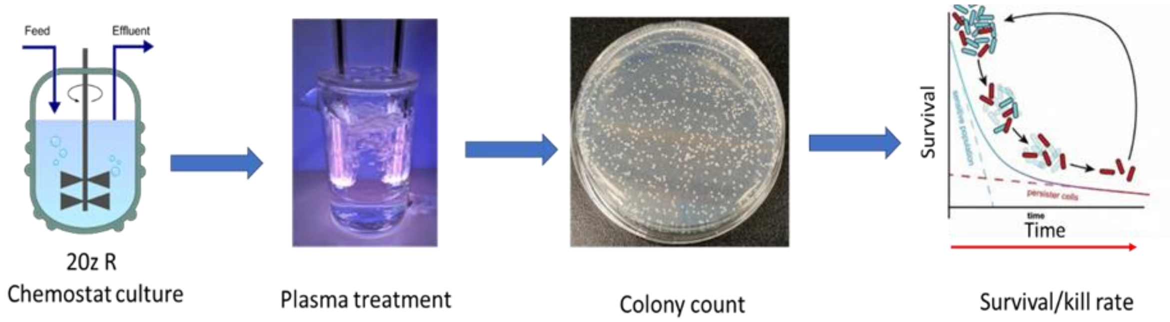
Objectives

While anaerobic digestion is an attractive technology at large scale, the relatively small digestors used for agriculture and food industry residues and wastewater treatment typically result in biogas that is generally burnt to generate value as heat, but also result in CO_2 emissions. The aim of this study was to use a phototrophic-methanotrophic co-culture to convert both CO_2 and CH_4 into microbial biomass, in a system that does not require the addition of exogenous O_2. Both components of biogas can be utilised, as the phototroph assimilates CO_2, while the methanotroph assimilates CH_4 using the O_2 produced by the phototroph. This concept has been demonstrated previously.

Results and Discussion

An important advancement is that the process did not require any external base or acid added for pH control; instead, the pulsed additions of the biogas countered the pH increase resulting from metabolic activity of the phototroph. This work demonstrated growth of the phototroph and methanotroph in a bioreactor while using biogas to provide a carbon for both microbes while simultaneously controlling pH. Feed and nutrient replacement strategies were investigated which are critical to stable growth. Methanotroph and phototroph cultures were run in the bioreactor independently, as well as a co-culture. Pure methane was used to establish initial methanotroph growth. This project also established a platform for use of cold plasma, which is a novel mutagenesis technique requiring no genetic manipulation. Baseline exposure required to generate mutants was established, which may be used subsequently to generate mutants capable of surviving specific conditions – such as inhibitory compounds, low pH or high salt content.

Figure 14. Workflow for cold plasma exposure and survival of Ma20Z® at different growth rates



Key Findings and Achievements

Various operational and control systems were assessed with respect to biogas addition into a photobioreactor at QUT to control pH. Innovative Cold Plasma technology is being explored for effective mutagenesis. The combined approach will allow for development of non-transgenic methanotrophic strains.

4.3.4 Results - Proteins and high value products from solid wastes

Activity team: Activity team: Juan Martinez, Yiman Sun, Dr Guiqin Cai, Dr Remya Nair, Dr Jerome Ramirez, Dr Zhanying Zhang, Adj Prof Karen Robins, Prof Robert Speight, and Dr James Strong (QUT)

Part A Fungal protein production from paunch waste

Summary

The aim of this work was to biologically convert paunch residues into a feed supplement – as this has higher value if protein-enriched. Majority of the research focussed on filamentous fungi to generate mycelial protein. Cost-benefit analysis indicated that sterilisation and the speed of biological transformation limited the commercial viability of a fungal transformation process, while laboratory research indicated that contamination by bacteria and yeast would limit scale up in an open environment.

Various yeasts were assessed because they grew quicker and yielded more biomass in paunch liquor, indicating that they were a better choice for rapid protein synthesis. While yeast did grow on the material, the conversion did not allow for a viable process. Yeast growth did not remove odour to the same extent as filamentous fungi. An alternative is to use mushroom-producing fungi that generate high-value edible mushrooms that offset the cost of stringent sterilisation. Here smaller quantities of paunch may be diverted.

Objectives

Part A of this activity aimed to develop a solid-state fermentation (SSF) process that converts paunch to potential animal feeds and productivity-enhancing compounds or high-value chemicals. Depending on the composition of paunch, the best-suited organisms to produce the highest value products need to be identified. The optimum process conditions also need to be determined to maximise yield and quality. The robust production system would have to be scalable and supported by techno-economic analyses. If viable, the efficacy and palatability of the products would have to be assessed in feeding trials.

Results and Discussion

Filamentous fungi and yeast conversion of paunch

Paunch is particularly complex because it contains a solid material that can be degraded, as well as soluble compounds in the liquor that are used for growth and metabolism. This is further compounded when the solid material is composed of material that the fungi may degrade – and then convert into biomass. It is therefore difficult to determine the true extent of microbial growth on solid substrates. Because the soluble components in the liquor are the most easily accessible, these are likely the first compounds that will be utilised for cell growth and metabolism. Therefore, growth of yeast and filamentous fungi were compared in paunch liquor.

Fermentation of paunch to produce high-value waste

Figure 15. Raw paunch before (top left) and after fungal solid-state fermentation

Initial cost-benefit analysis modelling showed the capital costs of the process depend largely on the selection of reactor for the fermentation. Due to the residence time of fermentation, processing large amounts of paunch need reactors of large volumes. The cost and configuration also depend on the required mixing, aeration, heat, and product removal.

While the composition of paunch varied between different red meat processors, a standard requirement was the need for sterilisation to allow a monoculture of filamentous fungi or yeast to colonise the material. Process challenges that impact mycelial protein synthesis include the relatively fast growth rates of yeast and bacterial contaminants and need for a lower moisture content than typically occurs in paunch. Economic challenges resulting from this were substrate sterilisation costs and the kinetics of substrate conversion. The challenge of microbial competition and stringent sterilisation could be lessened by using a yeast that was faster-growing than filamentous fungi. When assessed, the fastest-growing yeast in paunch liquor grew three times faster than filamentous fungi. Yeast did grow in paunch at full moisture content, which removed the need to partially dewater the substrate. However, the final product after yeast solid state fermentation was not improved to the point where it would be a viable process, as heat inactivation of the material (even if less stringent) was a major barrier.

Key Findings and Achievements

Fermentation of paunch to produce high-value waste

- Scale-up of the yeast growth from screening in 96-well plates (200 µL) to shake flask cultures (100 mL) yielded data indicating equivalent trends. Yeast growth was much quicker and greater biomass concentrations were obtained than for filamentous fungi.
- The change in free-fatty acids indicated the consumption of these compounds by fungal growth on paunch solids. This consumption was considerably less for the yeast culture.
- Yeast growth was assessed in paunch that was not dewatered. There were positive changes in the sterilisation requirements, equipment footprint, and operational costs due to improved speed of bioconversion and lack of dewatering required.

Part B Keratin wastes to higher value products

Summary

This work has developed and refined a process for the treatment of keratins, specifically cattle hair and more recently poultry feathers. These co-products from livestock processing are composed of hard proteins that would have more nutritional value if they could be made more digestible. Although feather meal is a current feed product, it is of lower value than other proteins due to its lower digestibility, and no feed products have been developed directly from cattle hair. Collaboration with industry partners within the project has targeted the process towards generating nutritional peptides with enhanced bioactivity (e.g., antioxidant properties) and controlling the processes to modulate product characteristics (i.e., degree of keratin solubilisation, peptide molecular weight and degree of amino acid chemical modification).

The process was scaled to multi-kilogram batches to generate sufficient material for livestock feeding trials that evaluated the digestibility and market opportunity for these products. The scaled processes also provide valuable information for techno-economic analyses and commercialisation planning. We have also been in discussions around integrating our process with existing and future commercial scale feather meal processes. Process deployment would contribute to a future reduction in waste for the livestock industry and the generation of more valuable products.

Objectives

The project developed and optimised pre-treatments for enhanced enzymatic breakdown of these keratin proteins to shorter peptides. The project developed and optimised the enzymatic breakdown process through the choice of enzyme or combinations of enzymes as well as process conditions to both reduce costs and control the specific peptide lengths and amino acid modifications that are generated. The peptide products were tested for biological activity to understand their relevance as feed additives (e.g., as antioxidants). Chemical modification of the amino acids within the peptides during processing was explored. Modification of amino acids to unnatural amino acids reduces the nutritional value of the peptides and so mild pretreatments were investigated that also could lead to suitable levels of keratin breakdown.

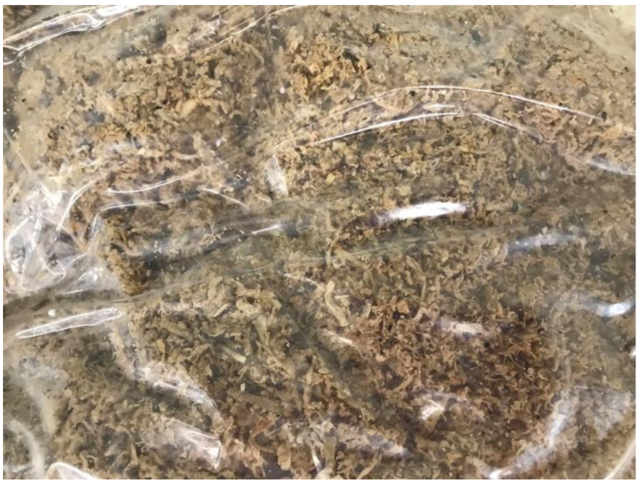
Results and Discussion

This research has designed, developed, and tested processes aimed to be scalable and economic and that synergise with available material streams. The availability consideration has led us to include feathers as a material input as well as the cattle hair that was in the initial focus.

The development work throughout the research considered the effects of changing process parameters, such as the severity of the thermochemical pretreatment, on the efficiency of the process (as judged by the degree of breakdown of the solid keratin to soluble peptides). This efficiency must be balanced with the characteristics of the product and the estimated cost of the process. We have sought to maximise the value of the peptides that are generated by assessing their antioxidant potential for when they are used as a feed supplement. We have found that the cheaper higher severity pretreatment process leads to more chemical modifications of peptide amino acids, which in turn negatively affects antioxidant activity and nutritional value. We have also considered the effects of pretreatment conditions on peptide molecular weight (which also affects antioxidant activity) and the enzyme loading that is required to reach an acceptable level of solubilisation (which affects the process cost). Different processes in different industrial scenarios (different keratin substrates, different peptide market applications for example) have different considerations, so we have focused on understanding the process so that it can be readily adapted to specific industry partner needs.

Figure 16. Tail hair (left) and hide hair (right) being prepared for treatment.

Figure 17. The appearance of the hydrolysed feathers (left) and moisture and ash content data (right), with values being the mean and standard deviation of three replicates.



	Hydrolysed feather	
	Ice cold	Frozen
Appearance	Similar	
Moisture	55.7% ± 0.6%	55.3% ± 0.1%
Ash	1.6% ± 0.0%	1.8% ± 0.0%

Further details on this research are available in this peer reviewed journal article: Cai, G., Moffitt, K., Navone, L., Zhang, Z., Robins, K. and Speight, R., 2022. Valorisation of keratin waste: Controlled

pretreatment enhances enzymatic production of antioxidant peptides. Journal of Environmental Management, 301, p.113945. https://doi.org/10.1016/j.jenvman.2021.113945

Key Findings and Achievements

The process has been developed and characterised now to a point where kilogram scale processes are possible and where there is sufficient understanding to control the process to modulate the product characteristics. These scaled processes generated peptide products for feeding trials that tested hypotheses around feed performance and digestibility.

- Higher enzyme loadings and reaction times increased keratin degradation as well as improving desirable characteristics such as low molecular weight peptides and antioxidant activity.
- However, these improvements were not proportional to enzyme loading and so the optimal enzyme loading for particular partners and situations should be determined by techno-economic modelling that considers enzyme cost contribution and the value of the product. Lower enzyme loadings could deliver product at much lower cost but would require increased severity pretreatments that reduce the value of the product through chemical modification of the amino acids.
- Hydrolysed feathers collected part way through the feather meal production process are a viable substrate that is available at large scale for future commercialisation of the process. We developed specialised proteomic methods for determining amino acid composition and chemical modifications that can be now used throughout the industry to understand the influence of feather meal production processes on product quality.
- The feeding studies showed the products were safe and contributed to a business case and cost-benefit analyses that considered whether more severe, cheaper processes that lead to higher levels of solubilisation are preferred over less severe processes that generate slightly less solubilisation but lead to less damage (amino acid modifications) to the peptide product.

4.4 Development of technologies for production of fertilisers, chemicals, plastics and energy products.

This project area developed technologies to produce biodegradable plastics, energy products through hydrothermal conversion, organomineral fertilisers (OMF), and biocomposite materials using waste fibres.

Petroleum-based plastic extraneous matter in rendered protein meal has increased because of introduction of national livestock identification system tags, improvements in hygiene standards in RMP facilities, and decreased rendering temperatures. Replacing existing products with starch- or protein-based bioplastics is an opportunity to eliminate petroleum-based plastic from the extraneous matter contamination of rendered products. Aduro Biopolymers is considering the commercialisation of Novatein®, a blood-meal based bioplastic which is safe to render and is biodegradable. Aduro Biopolymers currently has a range of contamination control products at different technology readiness levels including cattle throat plugs, and sheep and cattle weasand clips. The use of weasand clips in red meat processing (RMP) is critical to prevent unwanted microbial contamination of meat by stomach contents but removal of the weasand clip on the viscera table is a manual process and can be challenging to undertake with 100% efficiency.

The hydrothermal technologies of interest were, from the onset, hydrothermal liquefaction (HTL) and hydrothermal gasification (HTG). HTL converts organic wastes (*e.g.*, a solid and/or liquid) to bio-oil, which is a fuel precursor, and water-soluble organics. HTG produces gaseous products of methane and hydrogen, which have considerable energy content. HTL conditions are typically 200 to 350 °C and because the process is performed in a sealed vessel, pressures are typically 700 to 2500 psi. HTG conditions can be up to 400 °C and at higher pressures. HTL can be performed with or without the addition of a catalyst, however, HTG is typically considered (at least in the literature) to require catalysts for gas-forming reactions to occur. One benefit of gas production from these technologies is that the gas is pressurised and contained in a sealed apparatus, making its capture and repurposing much easier than gas emissions that occur in atmosphere. These hydrothermal technologies have the potential to treat animal production wastes in shorter processing times compared to anaerobic digestion.

Agricultural recycling is sustainable from the resource (carbon and nutrients) recovery perspective and considered to be the best practicable environmental option for disposal of organic wastes. There are several logistic and practical difficulties that need to be overcome before organic wastes can be efficiently used as bio-fertilisers. Some of the limitations for agricultural use, as identified by this work, include unbalanced chemical composition (which makes them unsuitable for specific crop and soil applications), physical and mechanical properties being unsuitable for storage and transport, and incompatible with standard farm spreading equipment, and little understanding of heavy metals dynamics following soil application and their potential transfer to the food chain as a result of plant uptake. Optimisation of the physico-chemical properties of biosolids and digestates is, therefore, a pre-requisite to ensure land application as an organomineral fertiliser (OMF) is environmentally safe and agronomically efficient, and it is a requirement for increased acceptability by farmers.

Paunch solids also has the potential of being re-directed into potentially high value biocomposite materials with values that can exceed $3000/t. With a global wood plastic composites (WPCs) market volume stood at almost 4,260 kt in 2016, the market size of WPCs has the potential to absorb the large volume of paunch from low-value waste streams and transform to high-value composite products.

4.4.1 Results - Development and validation of biodegradable bioplastics for the Australian Meat Processing Industry

Activity team: A/Prof Mark Harrison (QUT), Dr Lalehvash Moghaddam (QUT), Mr Graham Shortland (Aduro Biopolymers), Dr Rachel Self, Dr Willsen Wijaya and A/Prof Johan Verbeek (University of Auckland)

Summary

Single-use, petroleum-based plastic products are used extensively in meat processing to make sure that the meat that we eat is clean and safe. Hygiene aids, like weasand clips, are used to prevent contamination by microorganisms that can cause disease and reduced product shelf life. While these hygiene aids play an important role in keeping our meat safe to eat, the meat processing sector is seeking to reduce the use of petroleum-based plastics in food processing. Novatein® is a renewable, protein-based plastic made from bloodmeal, a by-product of red meat processing. The Activity has developed new Novatein® formulations with the physical properties needed to make hygiene aids, scaled-up production of sheep and beef weasand clips made from these new renewable, biodegradable materials, and successfully trialled sheep weasand clips made from Novatein® in a commercial meat processing plant operated by a Project Partner. The results of the trials demonstrated that Novatein®-based hygiene aids could replace those made from petroleum-based plastics, thereby reducing petroleum-based plastic use in red meat processing.

Objectives

This project was undertaken to demonstrate the design, manufacture, and commercial testing of red meat processing hygiene aids made from new Novatein® blends that could improve the environmental sustainability of meat processing, enhance social 'license to operate', and reduce the likelihood of extraneous matter contamination of meat and rendered products.

Results and Discussion

The Activity Team developed three novel Novatein® formulations each incorporating a biodegradable co-polymer and one of two compatabilisers. These formulations were devised based on extensive experience in biopolymer chemistry and knowledge of the mechanical requirements of RMP hygiene aids. The formulations were manufactured, and their mechanical properties evaluated in a series of industry-standard tests for tensile strength at maximum load, modulus, and impact strength. The elite, novel Novatein® formulation was selected for subsequent prototype manufacture of sheep weasand clips.

A laboratory-scale simulation of the low temperature (wet) rendering process was established and deployed by the Activity Team to produced meat and bone meal and tallow with increasing incorporation rates of the elite, novel Novatein® formulation. The inclusion of Novatein® in rendering at 5% or less produced meat and bone meal that was indistinguishable by Fourier-transform infrared spectroscopy and carbon, nitrogen, and sulphur content analysis from meat and bone meal containing no Novatein® (noting that the average inclusion rate of Novatein® in wet rendering is <0.01%).

A review of the existing Novatein® sheep weasand clip design was carried out and the design was modified to improve production efficiency and end-user comfort and reduce stress in the clip during application. A single-cavity, prototype injection mould was manufactured and prototype Novatein® sheep weasand clips using the elite, novel formulation was produced and evaluated. The design of the prototype injection mould was modified to address the issues identified with the prototype clips and two additional cycles of design, prototype production, and testing were undertaken, with testing being undertaken in a RMP facility in New Zealand.

A multi-cavity tool for the finalised Novatein® sheep weasand clip design was manufactured and used to produce more than 5,000 clips for two in-factory trials in a Project Partner RMP facility. The results of the preliminary, 500 clip trial demonstrated that Novatein® sheep weasand clips can replace the incumbent made from petrochemical-based plastic, but additional development is required. The larger, full shift (6,000 unit) trial was unexpectedly terminated prior to completion and the results indicated that additional work (including the design and testing of a cannister system for Novatein® lamb weasand clips) was required for integration of the renewable, safe to render hygiene aid into a commercial RMP facilities operating at high processing rates.

Factory trials of Novatein® sheep weasand clips were a challenge to the successful delivery of Phases 1 and 2 of this Activity because of restricted access to Project Partner sites arising from the COVID-19 pandemic. Despite this challenge, the Activity Team successfully transitioned the concept for both sheep weasand clips made from a new Novatein® formulation from Technology Readiness Level 2 to Technology Readiness Level 6. Based on the successful outcome of the Novatein® sheep weasand trials one and two, Aduro Biopolymers is seeking support for the continued development of sheep weasand clips made from the new Novatein® formulation.

The Activity Team responded to requests from the Project Partners and undertook parallel development of the Novatein® beef weasand clip. The existing design of the Novatein® beef weasand clip was reviewed, updated based on learnings from its sheep counterpart, and 3D-printed using nylon. Two cycles of design, prototype production using nylon, and testing were undertaken, with testing being undertaken in a RMP facility in New Zealand. Based on these small-scale in-factory tests, the design of the Novatein® weasand clips was finalised, a single-cavity prototype injection mould was manufactured and prototype Novatein® beef weasand clips using the elite, novel formulation were produced and evaluated. Based in the results of a preliminary in-factory trial in New Zealand, the single-cavity tool was modified to accommodate design changes, and a second preliminary trial in a New Zealand RMP facility has been scheduled. As a result, the Activity Team successfully transitioned the concept of the beef weasand clips made from a new Novatein® formulation from Technology Readiness Level 2 to Technology Readiness Level 6.

Key Findings and Achievements

The key findings from the Activity are as follows:

- The elite novel Novatein® formulation is safe to render and sheep weasand clips made from this blend are unlikely to be affected by production stoppages in RMP facilities;
- Novatein® sheep weasand clips can perform as well as the incumbent, petroleum-based product in a commercial RMP facility; and
- Novatein® sheep and beef weasand clips design, prototypes, and performance requirements must be informed by feedback from the RMP sector and the results of in-factory trials.

4.4.2 Results - Development of technologies for the hydrothermal processing of animal wastes and anaerobic digestion digestates

Activity team: Prof William Doherty, Dr Lalehvash Moghaddam, Dr John Outram, Dr Jerome Ramirez, Mr Adrian Baker, and Ms Isha Sharma (QUT)

Summary

This project has confirmed that hydrothermal processing (Hydrothermal Liquefaction (HTL) and Hydrothermal Gasification (HTG) technologies can be applied to red meat processing as well as municipal wastewater treatment industry wastes. The project moved from Technology Readiness Level (TRL) 3 and 4 and is now positioned ready to demonstrate the technologies at large scale (TRL 5). The HTL technology can produce a variety of energy products including bio-oils which can be upgraded or polished to fuel (that meets ASTM specifications of diesel) or fuel blending stock. The HTG technology convert these wastes to fuel gasses of hydrogen and methane in high concentrations. These technologies will therefore allow partner industries to reduce direct CO_2 emissions by alternate waste management strategies. The project demonstrated that the wastewater from the processing of these wastes can be used for anaerobic digestion to produce methane, while the solid residue can be used as adsorbents for the removal of N and P in wastewater streams.

Objectives

The *Wastes to Profits* Activity 4.2 project focused on development of hydrothermal processing technologies with red meat processing wastes and wastewater treatment plant wastes.

The HTG work has focused on the development catalysts for gas production, and this has been a key focus of PhD student work embedded in this project.

Aside from small- and large-scale laboratory assessments of the hydrothermal technologies, technoeconomic assessments of the HTL technology have been performed. In some cases, these were assisted or directed based on the laboratory trials performed at QUT. QUT also collaborated with an oil refinery located in Australia to evaluate the quality of the produced bio-oils from HTL, and to assess their potential for upgrading into fuel for use as transportation fuels.

Results and Discussion

Novel HTL catalyst developed

Given the relatively low cost of crude oil and fuel gasses (methane and hydrogen), it is imperative to produce bio-crude with as low cost as possible, and to be a viable commercial alternative. For this reason, the use of catalysts is often avoided in HTL, due to the added expense associated with the commercially available noble metal-based catalysts. An alternative explored in this work is the application of low-cost mineral catalysts, specifically, derivatives of a synthetic zeolite (H-USY zeolite).

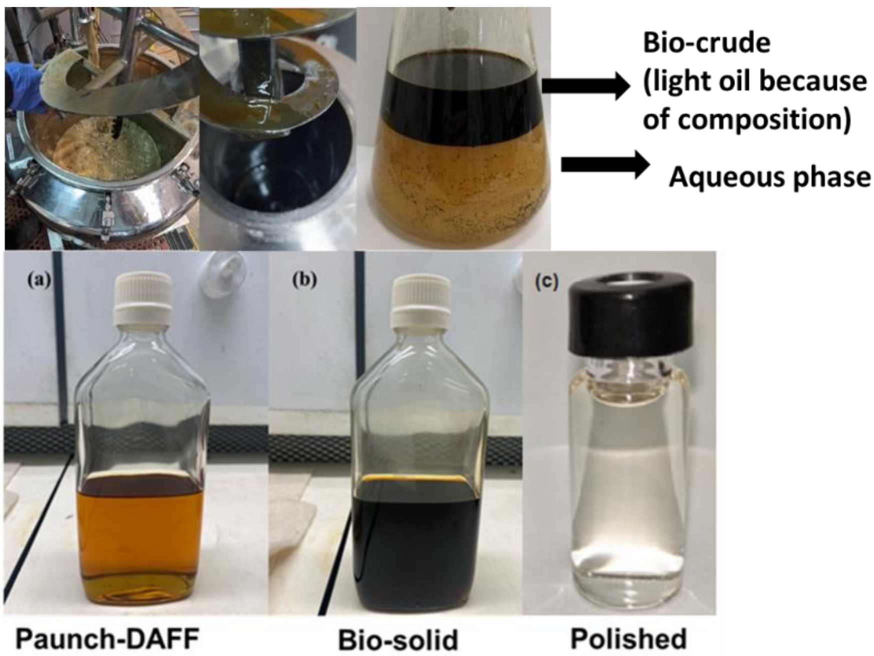
Studies on red meat processing wastes showed that the liquefaction of paunch and dissolved air floatation float (DAFF) mixtures in the presence of the developed catalysts has a higher bio-oil yield (77 % on a volatile solids basis) than that obtained using the best-performing ruthenium-carbon (Ru/C) commercial catalyst (70 %). The higher heating value (HHV) of the bio-oil produced in the presence of our catalyst was 39 MJ/kg (cf. diesel 45 MJ/kg) and consisted mainly of saturated methyl esters with the potential to be upgraded to renewable diesel, jet fuel and marine fuel.

A mixture of primary sludge (PS) and waste activate sludge (WAS) from wastewater treatment plants was processed using HTL in the absence of catalyst, resulting in the production of bio-oil with a HHV of 40 MJ/kg at a yield of 69 % (volatile solids basis). There was no benefit from the addition of any of the catalysts tested to HTL of the mixture of PS and WAS, which reduces the cost of any commercial process developed using the technology.

Scale up of HTL trials and subsequent bio-oil upgrading at refinery

In late 2020 and early 2021, wastes including a mixture of paunch and DAFF from red meat processors was processed by HTL in the presence of a co-solvent. Also studied was biosolids from a municipal wastewater treatment plant, again with the use of a liquefaction co-solvent. While normal HTL trials at QUT were routinely conducted on a small scale (~0.12 kg), these trials were conducted at larger scale in batches (~ 1.4 kg of each type of wastes were processed) in much larger hydrothermal reactors. Most of the bio-oil produced at this larger scale Fig. 18 was then used for chemical analysis and bio-oil upgrading tests conducted at an oil refinery.

Figure 18. Processed wastes by HTL and polished bio-solid

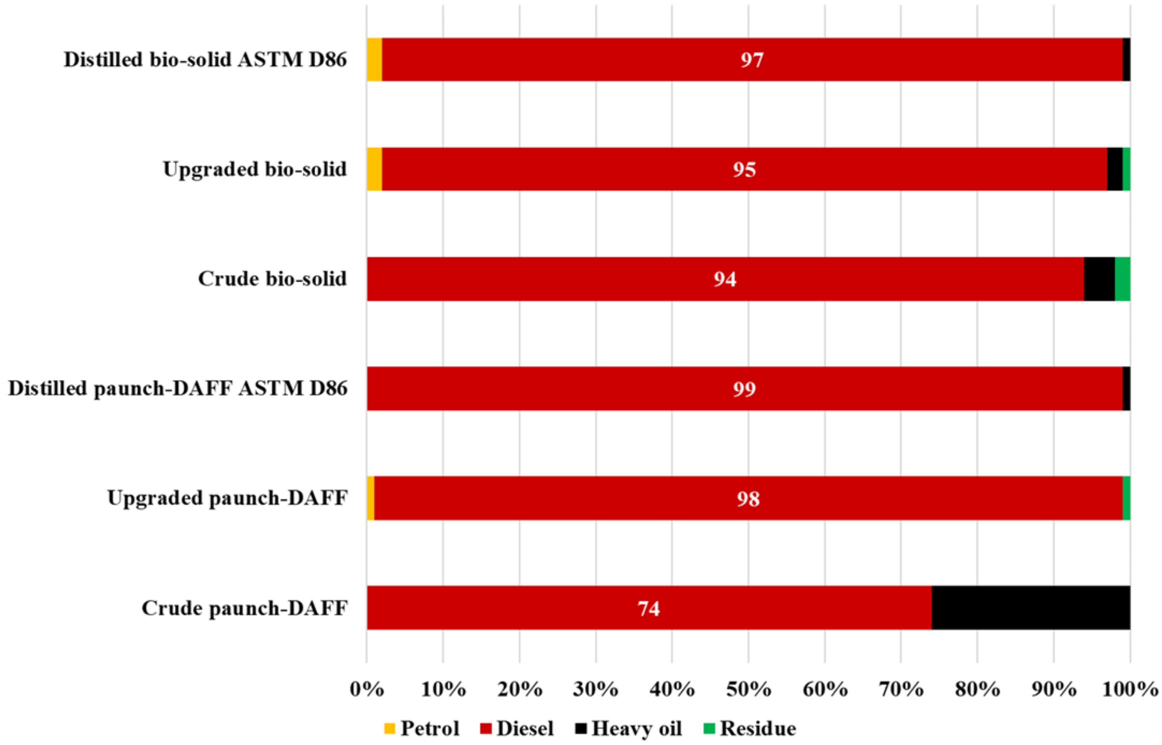


The results of the trials are given in Fig. 19 and the key outputs are:

- Diesel equivalent oil is produced (ASTM D86)

- Oil yield 67 - 98.5 % (volatile solids basis), energy content equivalent to diesel
- Biosolids derived oil contains 94 % diesel eq. – hydrotreating not required
- Paunch-DAFF oil upgraded contains 89 % diesel eq.
- Preliminary investigation showed that the degradation of perfluorooctanoic acid (PFOA), which belongs to the group of per- and poly-fluoroalkyl substances (PFAS), using HTL technology, was markedly reduced to below the limit of reporting (LOR 0.01 ppb).

Figure 19. Results of the analysis of crude and upgraded bio-oil



Results of the preliminary techno-economic assessment of the wastes are given in Table 3. It shows that upgraded paunch and DAFF gives best value for money.

Table 3. Animal waste and biosolids converted to drop-in diesel fuel

Feedstock/condition	Bio-oil yield (per t dry feed)	HHV (MJ/kg)	Fuel Value (A$/t feed)
Biosolids	676 kg	42	$324*
Biosolids - – With Upgrading	656 kg	45	$435**
1DAFF: 1 Paunch	865 kg	42	$415*
1 DAFF: 1 Paunch - With Upgrading	839 kg	46	$564**

*value based on A$67bbl crude oil price (AIP); ** value based on A$0.56L diesel price (ex tax)

Hybrid HTL-HTG thermal processing technology

We suggested a hybrid HTL-HTG technology where HTL is performed in a first step to produce bio-oil primarily, while the water layer from the HTL is further subjected to HTG to convert dissolved organic material in the water to gases. Lab testing of this generated relatively high proportions of hydrogen (41.4% (v/v)) and methane (9.1% (v/v)) in the resulting gas mixture. For this work, initially a range of commercial catalysts were assayed for their HTG effectiveness, and a commercial Ru/C catalyst was superior to all other commercial catalysts trialled.

HTG catalyst design and testing

As part of a PhD program, heterogeneous catalysts specifically for use in HTG are being tested, synthesised, and optimised at QUT. The recyclability or life span of the catalyst, cost, and effects on the other HTG by-products were also assessed.

Anaerobic digestion as a part of a hybrid AD-HTL technology

The conversion of the aqueous phase by-products (produced in larger-scale HTL trials) to methane by anaerobic digestion (AD) was successfully demonstrated in small scale lab trials. The aqueous phase was obtained initially from the HTL of biosolids, and separately from HTL of a paunch-DAFF mixture. The results showed an initial inhibitory behaviour for methane production before an accelerated rate of production (up to 800 mL CH_4/g VS by day 42). The outcome of this work shows potential for a hybrid of AD-HTL-AD technology for the processing of animal and wastewater treatment plant wastes. In such a process, AD digestate or biosolids would be subjected to HTL to rapidly convert organic material into HTL bio-oil. The resulting water fraction could then be processed in a relatively low energy consuming AD process to further produce methane and to reduce COD/BOD of the resulting water.

Production of an adsorbent from HTL solid by-product

The solid residues obtained from the larger-scale liquefaction of biosolids, and paunch-DAFF mixture, were converted to high-performance adsorbents that showed good uptake of phosphate and ammonia/ammonium in synthetic wastewater.

Technology readiness level (TRL) for hydrothermal processing

The work in the *Wastes To Profits* program has helped us take this project concept from a TRL of 3 (on the 9 step scale) which is "proof of concept" through TRL 4 "technology validated in lab" and is now ready for TRL 5 where we can demonstrate the technology in an industrially relevant environment (e.g., a site which generates waste, or at a dedicated pilot scale facility designed to accept such waste for HTL/HTG processing).

Key Findings and Achievements

A relatively cheap catalyst was developed that enhanced HTL by improving bio-oil yield or its properties. The catalyst does not contain expensive precious metals.

Crude bio-oil was produced from liquefaction of several wastes, and these bio-oils were upgraded to diesel-like fuel. The feedstocks of greatest interest and promise are red meat processing wastes including paunch solid waste, dissolved air floatation float, and manure. Municipal wastewater treatment plant biosolids were also converted to good quality bio-oil. Biosolids can be liquefied without a co-solvent to produce bio-oil with a gross energy content of 37 MJ/kg.

Biomass wastes can be more effectively converted to bio-oil of high energy content by using a co-solvent that was identified and evaluated during the project.

Hydrothermal gasification (HTG) can be performed on wastes to produce gas mixtures rich in hydrogen and methane. The gas stream is contained and compressed by the process. CO_2 is also captured in the same stream so it can be utilised or controlled. The water layer obtained from HTL trials was shown to be suitable for use in anaerobic digestion, and after some initial inhibition the trials showed significant production of methane. This could support hybrid technologies such as HTL-AD, or AD-HTL-AD.

Studies have shown the breakdown of PFOA (a type of PFAS) with the novel HTL process to a concentration below the limit of reporting (0.01 ppb). Carbonised solid residue from HTL of biosolids, and also paunch-DAFF mixtures, have been shown to be effective adsorbents for the removal of N and P from wastewater. Catalysts are being developed specifically for enhancing HTG, which could be employed as a process on its own, or as a hybrid in HTL-HTG waste processing.

4.4.3 Results - Development of biosolids and digestate-derived organomineral fertilisers (OMF)

Activity Team: Prof Bernadette McCabe (USQ-CAE), Dr Diogenes L. Antille (CSIRO and USQ-CAE), Dr Serhiy Marchuk (USQ-CAE), Dr Jochen Eberhard (USQ-CAE).

Summary

This research was conducted to help overcome some of the challenges presented by the physico-chemical properties of biosolids to assist in securing the agricultural route for the disposal of biosolids. A three-year multi-scale experimental work that included glasshouse and field-based studies has demonstrated the fertilising potential of biosolids and organomineral fertilisers (OMF) for use in Australian arable and grass cropping systems. The product specifications for novel fertiliser materials have been established, and if appropriate product quality control procedures could be implemented, acceptability by farmers should not be a barrier to increasing the amount of biosolids (and derived fertiliser materials) currently being recycled to agriculture. This represents a clear opportunity for both the wastewater (reduced cost of disposal) and farming (reduced fertiliser costs and improved productivity) industries, particularly in the current scenario with abnormally high fertiliser prices.

Effort should be spent on upscaling and improving the granulation technology and ensuring the physical and mechanical properties of biosolids and OMF are such that they meet the requirements of modern farm spreading equipment. The assessment of such fertiliser properties, as documented in this work, may be used as guidance to improve, and standardise, the quality of biosolids-derived fertilisers. The knowledge gained through this project, coupled with novel lab-scale granulation equipment installed at the Centre for Agricultural Engineering at the University of Southern Queensland, can be used to inform and test organic-based fertiliser technology.

A conservative monetary value in relation to the sale of the product may be made based on the overall urea fertiliser market in Australia, which is estimated at AU$1 billion; if, for example, all the sludge produced in Australia (about 350,000 Mg) was converted to biofertiliser, it would represent about 2.5% of urea fertiliser (or about AU$21 million per year).

Objectives

A three-year multi-scale experimental work that included glasshouse and field-based studies was conducted to:

- Develop the specifications for novel, enhanced-value anaerobic digestion digestate-derived products (OMF) that meet the requirements for field application using standard farm equipment (physical and mechanical properties) and nutritional needs of crops (chemical composition),
- Evaluate the proposed product formulation and product format, determine the fertilising value of OMF, and
- Develop a set of practical management guidelines for the use of OMF and biosolids on arable and grass crops.

Results and Discussion

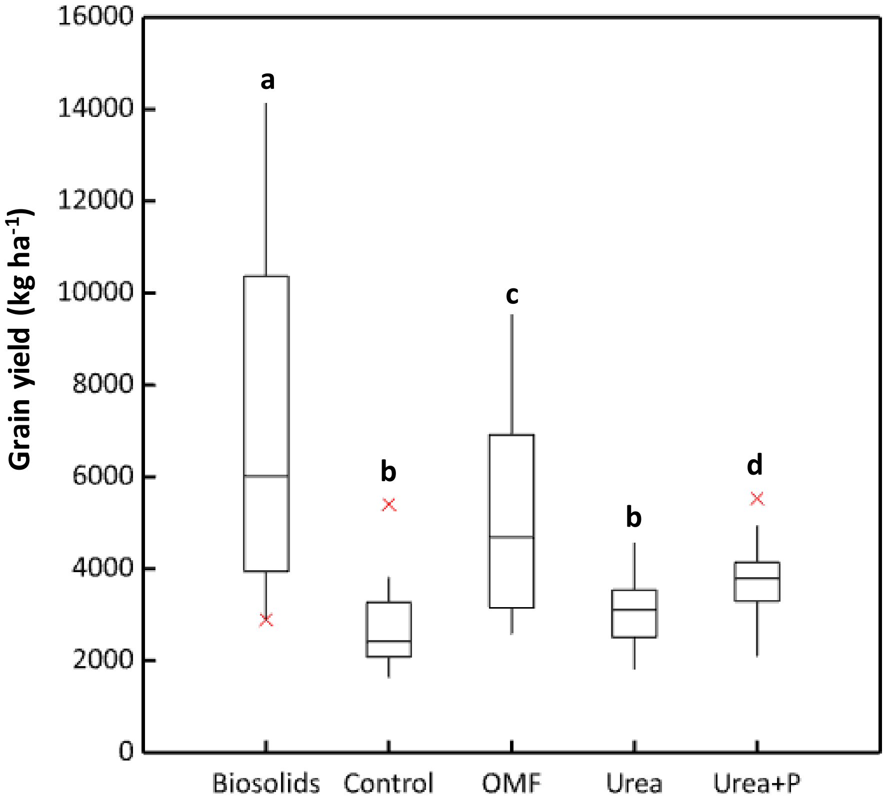
Product specification: formulation and physical characteristics of organomineral fertilisers

Biosolids from wastewater treatment plants were converted to organomineral fertilisers (OMF) by adding nitrogen (N) from urea (46% N) to increase the concentration in the raw material from an average of 6% N to 15% N (w/w). The content of phosphorus (P) was not modified, which therefore enabled the N:P ratio in OMF to be increased from 1:1 to about 3:1. The OMF formulation was approximately 15% N and 5% P. An increase in the N:P ratio was needed to avoid application of P in excess of crop requirement while being able to match crop demand for N. Measurements of physical/mechanical properties of OMF indicated that fertiliser particles (median diameter: 4.05 mm) need to be able to withstand vertical loads greater than about 20 Newton to avoid significant particle deformation (compression) or particle fracture (shattering) during handling, transport, and field spreading. Particle deformation and shattering modify the particles' aerodynamic properties (because of changes in particles' shape or diameter), affect spreading patterns, and consequently, the uniformity of distribution during field application. Uneven fertiliser distribution with coefficient of variation (CV ≥12%) can have adverse effects on crop yield and result in financial penalties (these penalties increase in a nonlinear fashion with an increase in the CV). Given the particle densities of OMF and biosolids (range: 750-1000 kg m^{-3}), the particle size range should be between 1.30 and 6.80 mm in diameter, with about 80% (w/w) of particles between 3.10 and 5.20 mm in diameter. The recommended particle size distribution will allow achieving similar spreading performance to urea with a particle size range between 1.00 and 5.30 mm. The moisture content of OMF should be maintained at less than 10% (w/w) to ensure particle strength is not adversely affected. Field application of OMF may be possible with twin-disc fertiliser spreaders. For this, disc designs and settings should provide a small upward particle trajectory angle (e.g., 10°) instead of increasing the discs' rotational velocity to achieve a specified bout width. Application of OMF with spinning discs applicators may be restricted to tramlines spaced at a maximum of 24 m, as this would maintain the CV below the 12% threshold and allow for some degree of overlap between adjacent bouts to ensure adequate uniformity of distribution perpendicular to the direction of travel is achieved. The same recommendations as for OMF may be made for biosolids granules, given that both fertiliser materials have similar physical and mechanical properties.

Fertilising value of organomineral fertilisers: field studies

Grain yields of wheat recorded at the experimental site over three consecutive seasons (2019-2021) are summarised in Figure20. There were significant fertiliser type and N application rates effects on grain yield across all years (*P*-values <0.05). Grain yields decreased in the order: Biosolids > OMF > Urea + TSP > Urea >> Control (zero-fertiliser). Application of triple superphosphate (TSP) at a rate of 100 kg ha^{-1} together with urea increased the response to applied N compared to urea applied alone, which suggested strong N×P interaction. Yield responses to biosolids demonstrated the legacy effect from previous years' applications and confirmed the hypothesis formulated prior to this study that the use of biosolids may be better justified to meet crop requirements for P of the entire crop rotation and not for a crop in a given year. The residual effect of the P-containing fertilisers used in these experiments meant that P could be recovered in subsequent crops over several years, and for biosolids and OMF, this could be up to 5 years post-application.

Figure 20. Grain yield of wheat for Control (zero-fertiliser) and treatments (Biosolids, OMF, Urea, and Urea + P) as recorded at the experimental site over three consecutive seasons (2019, 2020, 2021)



n = 27 (Control) and *n* = 36 (Treatments, except for Urea + P, *n* = 15). For 'Urea + P', phosphorus (P) was applied as triple superphosphate (TSP, 46% P_2O_5) at a rate of 100 kg TSP ha^{-1}. The box spans the interquartile range of the values in the variate (Q_3-Q_1), with the middle line indicating the median (Q_2). Whiskers extend to the most extreme data values within the inner 'fences', which are at a distance of 1.5 times the interquartile range beyond the quartiles (or the maximum value if that is smaller). Individual outliers are identified with a red cross, and 'far' outliers (beyond the outer 'fences') are at a distance of three times the interquartile range beyond the quartiles.
Different letters indicate that mean values are significantly different at a 5% probability level, LSD: 1174 kg ha^{-1}).

From the yield-to-N response relationships Table 4), it was possible to derive the N application rate (N_{MAX}) required for maximum yield (Y_{MAX}) and the most economical rate of nitrogen (MERN), which was subsequently used to obtain the optimum yield (Y_{MERN}), based on the approach of Antille and Moody (2021, https://doi.org/10.1016/j.indic.2020.100099). The analysis assumed a price ratio (P_R) of 5, that is, the ratio between the price of N and the price of grain. The MERN value reflects the N rate at which the economic return from applied fertiliser N is maximised. The agronomic efficiency (AE) of applied fertiliser N is the ratio between the differential yield (that is, the increase in grain yield due to an increment of applied N of a specified fertiliser form) and the N application rate. The estimation of MERN for urea in 2021 returned a negative value, which meant that the use of this N source was not economical (except when used together with triple superphosphate). By substituting MERN into the AE-to-nitrogen response, the AE_{MERN} is obtained. This value is useful to compare the agronomic efficiency of different fertiliser sources when the N application rate has been optimised (given the assumed price ratio). For example, it can be seen that biosolids returned, on average, 24 kg grain for every kg of biosolids-N applied and that the average MERN (170 kg ha^{-1} N) would deliver a yield of about 7620 kg ha^{-1}. If biosolids were to be supplied by wastewater operators at no cost to farmers, they could afford to apply the N_{MAX} to target the maximum yield (Y_{MAX}). The use of biosolids and OMF will attract a 3- to 5-time higher cost of field application compared with urea, depending upon the MERN and in-field logistics (spreading time, fuel and equipment loading). Therefore, these products will need to be competitively priced (e.g., partially subsidised by the wastewater industry), which may be still economical for the industry compared to other disposal options. Despite this, the application of biosolids and OMF may be still an economic proposition for farmers, as implied by the differential yields reported in Table 4. For biosolids and OMF, it was suggested that approximately 40% to 50% of the full rate (MERN) be applied between planting and tillering, and the balance before and up to early stem extension. However, the optimum timing of application for biosolids and OMF requires investigation.

Table 4. Parameters derived from the yield-to-nitrogen response relationships obtained at the experimental site. Averages over three (2019-2021) consecutive seasons; except for urea, which shows the average of the 2019 and 2020 seasons.

Parameter	P_R	Average Yield Response	Y_{MAX}	N_{MAX}	Y_{MERN}	MERN	AE_{MERN}
Unit	\$ \$$^{-1}$	-		kg ha^{-1}			kg kg^{-1}
Biosolids	5	$Y = 3204 + 43.93N - 0.108N^2$	7730	214	7618	170	24
OMF	5	$Y = 2648 + 23.27N - 0.042N^2$	6098	281	5916	208	14
Urea	5	$Y = 2840 + 7.33N - 0.018N^2$	3587	203	3238	63	6
Urea + P	5	$Y = 2650 + 14.51N - 0.028N^2$	4485	253	4267	166	10

Recovery of heavy metals (Cd, Pb and Zn) in grain

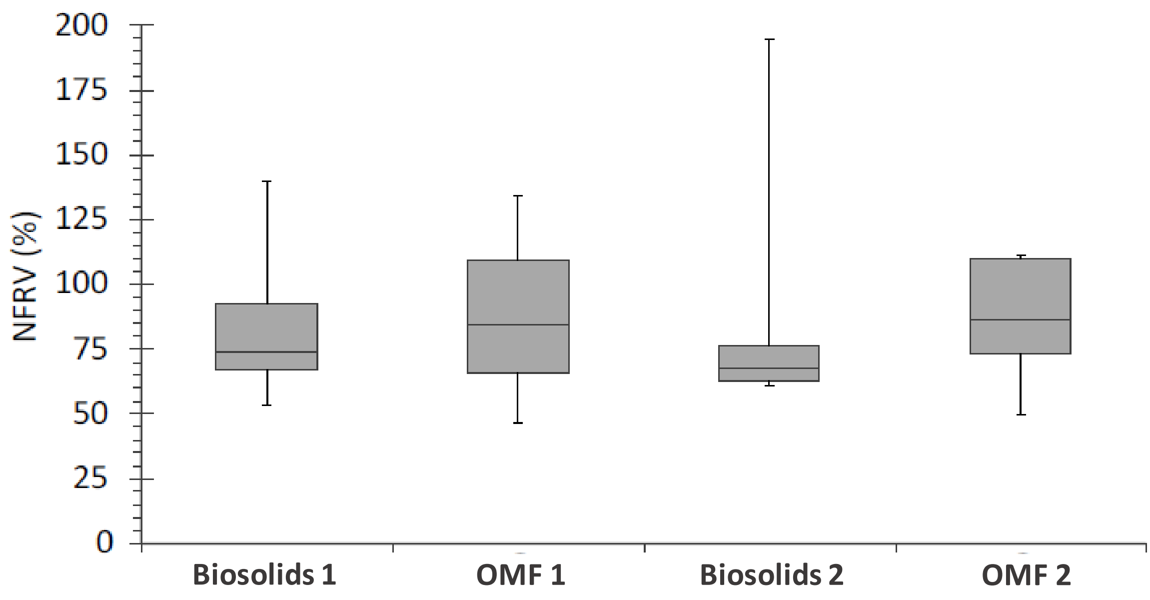
Under the conditions of this study (fertiliser rates, placement and timing of application, and soil pH), soil application of biosolids and OMF did not increase the recovery of selected heavy metals (Cd, Pb, and Zn) in grain. The concentration of these heavy metals in grain was within the range found in crops treated with mineral fertilisers (urea, urea + TSP), and it was not significantly higher than controls (zero-fertiliser). Based on these results, the risk of transfer of the selected heavy metals to the food chain was regarded as low. However, if the soil was to be routinely applied with either biosolids or OMF, soil analyses should be conducted at regular time intervals (e.g., annually or every two years prior to crop establishment) to assess potential longer-term build-up. Important practical considerations for soils receiving biosolids and OMF are to maintain soil pH above the cut-off value of 5 (equally avoid application to soils with pH lower than 5), observe maximum permissible concentrations of heavy metals in soil (in relation to soil pH), and observe limit values for their concentration in the fertiliser material (State-specific guidelines).

Fertilising value of organomineral fertilisers: glasshouse studies

Results derived from the glasshouse studies using ryegrass established in pots were fairly consistent with those from the field experiments and further demonstrated the potential for future development of OMF technology. The main observations derived from this work were: (1) mean (cumulative) dry matter yield (DMY) after six consecutive cuts, conducted at regular time intervals of 30 days, were between 13% and 21% lower with urea (6370 kg DM ha^{-1}) than with biosolids and

OMF (range: 7220-7745 kg DM ha^{-1}); (2) the agronomic optimum N application rate for urea was significantly lower (113 kg N ha^{-1}) than with biosolids and OMF (range: 214-273 kg N ha^{-1}). sFertiliser responses for biosolids and OMF showed that about of 90% of maximum DMY can be achieved with the optimum N application rate or about 50% of the N rate required for maximum yield whereas for urea about 80% of the maximum DMY could be achieved with the optimum N application rate or 35% of the N rate required for maximum yield; (3) agronomic efficiency calculations (all in kg DM kg^{-1} N) at the optimum N application rates were 13.6 for biosolids, 16.2 for OMF, and 20.4 for urea, respectively; (4) N sfertiliser replacement values (NFRV) of biosolids and OMF were between 74% and 82% when N inputs were optimised Fig.21; (5) soil extractable P levels increased in biosolids and OMF-treated soils, and decreased a little in urea-treated soil ($P<0.05$), and there was a significant N × P effect on DMY, and (6) the overall fertiliser type or fertiliser rate effects on selected heavy metals (Cd, Pb, Cu, and Zn) content in soil were not significant, and so their concentration in soil remained closed to background levels. As reported in results from the field studies, the risk of transfer of the selected heavy metals to the food chain (e.g., through animals grazing on biosolids or OMF-treated pastures) was regarded as low. Similar recommendations in terms of soil chemical assessment apply to grassland soils routinely receiving these materials.

Figure 21. Nitrogen fertiliser replacement values (NFRV, %) of biosolids and organomineral fertilisers (OMF) as derived from cumulative (six cuts at regular 30-day intervals) dry matter yields-to-nitrogen response relationships.



Box-plots show: Min, Q_1, Med, Q_3, and Max, respectively; $n = 8$, $P>0.05$ (fertiliser treatments), $P<0.05$ (fertiliser rate). Biosolids 1 and 2 were from two different wastewater treatment plants in Queensland, and these materials were used to produce OMF 1 and 2, respectively. The chemical composition of the two biosolids and OMFs was reported by Antille et al. (Antille et.al. 2020).

Further details on this research are available in the conference presentations listed below.

Antille, D. L., McCabe, B. K., Marchuk, S., Eberhard, J., Baillie, C. P. 2020. Glasshouse study of the value of biosolids-derived organomineral sfertilisers for perennial ryegrass growth. ASABE Paper No.: 2000326. St. Joseph, MI.: 2020 Annual International Meeting, American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/aim.202000326.

McCabe, B. K., Antille, D. L., Marchuk, S., Tait, S., Lee, S., Eberhard, J., Baillie, C. P. 2019. Biosolids-derived organomineral sfertilisers from anaerobic digestion digestate: Opportunities for Australia. ASABE Paper No.: 1900192. St. Joseph, MI.: 2019 Annual International Meeting, American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/aim.201900192.

Key Findings and Achievements

Future agronomic studies should consider investigating options for improving nutrient use efficiency through adjustments to the timing of fertiliser application and fertiliser placement and the longer-term (>3 years) effects of routine fertiliser applications on potentially toxic elements (both heavy metals and organic contaminants). The use of biosolids and OMF for the production of non-food crops (e.g., cotton) may be an attractive alternative as this may remove concerns associated with the transfer of heavy metals to the food chain. Despite this, our work has shown that, in the shorter term (3 years), the risk of heavy metals accumulation in soil and plant material was low and that such risk can be managed by controlling soil pH.

There is also a need to perform further and more detailed economic analyses when the actual cost of production of biosolids and OMF to the required quality are known. Fertiliser N replacement value data and the yield-to-nitrogen response relationships produced by this study can be used to inform such economic analyses. Biosolids and OMF will need to be competitively priced to compensate for the increased (3 to 5-time higher) cost of application and in-field logistics compared with synthetic fertilisers. For this, it is necessary to undertake a willingness to pay study based upon the methodologies developed by the authors in earlier work.

4.4.4 Results - Utilisation of waste fibres for the development of novel biocomposite materials

Activity team: A/Prof Steven Pratt, Prof Bronwyn Laycock, A/Prof Paul Jensen, and Dr Clement Chan, Dr Emilie Gauthier (UQ)

Summary

This activity utilises paunch as a low-cost but valuable source of fibres for the production of sustainable biocomposite material with applications such as packaging and panelling. Exploration of the potential of paunch wastes as the reinforcement for wood plastic composite (WPC) materials in a range of commercially available biodegradable polymers was investigated. A range of biodegradable polymers were selected for their diverse properties. Polyhydroxyalkanote (PHA), polylactic acid (PLA) and polybutylene adipate terephthalate (PBAT) biocomposites with paunch fibres and wood flour were successfully extruded and their mechanical properties were characterised. It was shown that paunch fibres could be used in biocomposites and present mechanical properties comparable with wood composites. In addition, the variation in mechanical properties from the batch-to-batch differences in paunch from different facilities is less than anticipated.

Overall mechanical testing showed that the properties of biocomposites with 30 wt% paunch from different RMP facilities are comparable to the products in the current WPCs market. Initial commercialisation development activities included scientific research on processing aspects, preliminary engagement with partners and simple techno-economics estimations. Finally small ear-tag shaped keychain demonstrators were produced by compression moulding followed by laser cutting/engraving to the desired shape.

Objectives

The potential use of paunch wastes as the reinforcement for wood plastic composite (WPC) materials was explored. To assess this a variety of commercially available biodegradable polymer matrices were chosen. Composites of commercially available biodegradable polymer matrices with increasing fibre loading from 0 to 50 wt% of untreated paunch were manufactured using extrusion. Their mechanical properties were characterised and were benchmarked against in-house biopolymer/wood fibre composites and commercial WPC products. In addition, the effects of five different treatments on the properties of the paunch fibres and their resulting biocomposites were investigated aiming to further optimise the composite mechanical properties and investigate the effect of batch-to-batch variation on the final biocomposite mechanical properties. Another processing method, namely compression moulding, was also explored with a view to produce demonstrator products for proactive engagement with partners. Finally, a techno-economic estimation was scoped to include a simple process flow diagram alongside with CAPEX estimations.

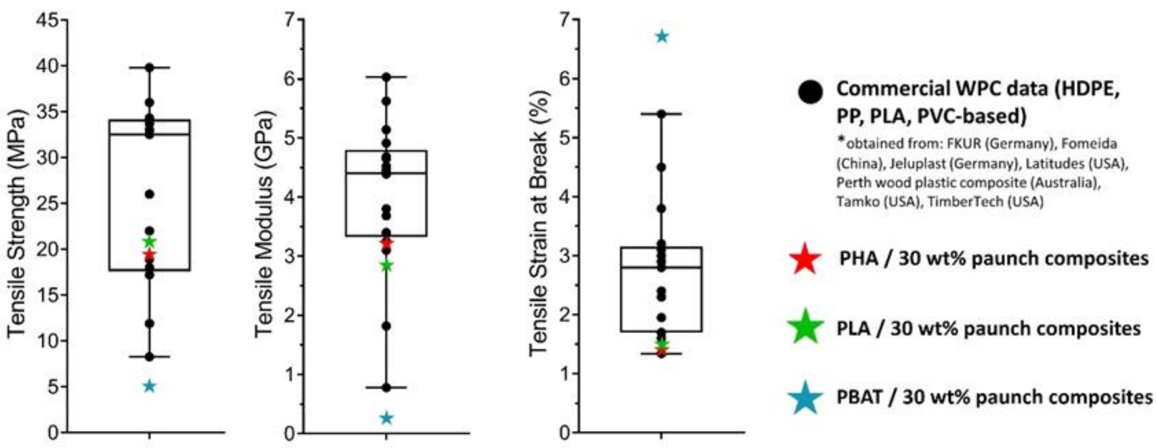
Results and Discussion

Paunch composites properties

The activity commenced with post-collection processing of paunch to generate short fibres that are suitable for composite applications. Paunch was collected as a wet fibrous solid (70% moisture content) containing short digested lignocellulosic fibres at red meat processors from the pile after separation from the red stream (blood and offcuts) and pressing to remove water. The as-developed procedure involved washing the fibres twice with water and dried in a conventional oven at 80°C over 3 days. The dried paunch was then grinded for 2 min then sieved through a 1 mm mesh. The fibre characteristics of paunch were benchmarked against wood flour fibres as an established cheap fibre for biocomposites.

Paunch shows fibre-like characteristics such as rough surface and comparable aspect ratios, which makes it attractive as a low-cost fibre for composite applications. These high aspect ratio fibres are beneficial for achieving good composite properties through more effective load distribution when stress is applied. Without any treatment and refinement, extrusion processing was able to produce composites of common biopolymers (PHA, PLA and PBAT) and paunch up to a 50 wt% paunch loading. Biocomposites with 30 wt% paunch showed potential as an engineered material. As can be seen in Fig.22, the window of mechanical properties of biocomposites with 30 wt% paunch is comparable to the data from commercial WPCs. It is also worth noting that the paunch biocomposites properties can be tailored for target applications by changing the polymer matrix. For example, PBAT composites give a higher flexibility but lower strength material whereas PHA and PLA composites yield a stiffer and stronger material.

Figure 22. Tensile strength, Young's modulus and strain at break of 30 wt% paunch biocomposites benchmarked against commercial WPC products



Batch-to batch variations and fibre pre-treatment

To verify the batch-to-batch differences in terms of composite properties Paunch from three different Red Meat Processing facilities (RMP B, RMP C and RMP D), and RMP B at three different time period were procured and their biocomposite properties at 30 and 50 wt% paunch were compared. Results showed that the variation in composite properties from the batch-to-batch differences in paunch is less than we anticipated, as well as revealed good reproducibility of biocomposite manufactured with paunch collected from the same facility but at a different time. The combination and balance of different effects including fibre morphology, distribution, composition, the presence of other components etc. contribute towards the final mechanical properties. This is a piece of evidence showing that the standard post-processing procedure is able to minimise the variation by narrowing the distribution of fibre properties. The effects of five fibre treatments (water, acid, alkali, H_2O_2, NaOCl) on the fibre morphology and composite properties were also investigated to further improve the composite properties. Preliminary results showed that acid and

NaOCl bleaching treatments were effective in washing out extractives and enhancing surface roughness of paunch fibres and gave the most significant improvement in the mechanical properties of the paunch biocomposites. The fibre refining process through chemical treatments showed potential to further improve the composite properties.

Simple technoeconomic assessment

A simple process flow diagram (PFD) for the production of paunch bioplastics composites was constructed and presented in Fig. 23. The process can be broken down into the following steps:

i. Paunch fibre treatment and washing

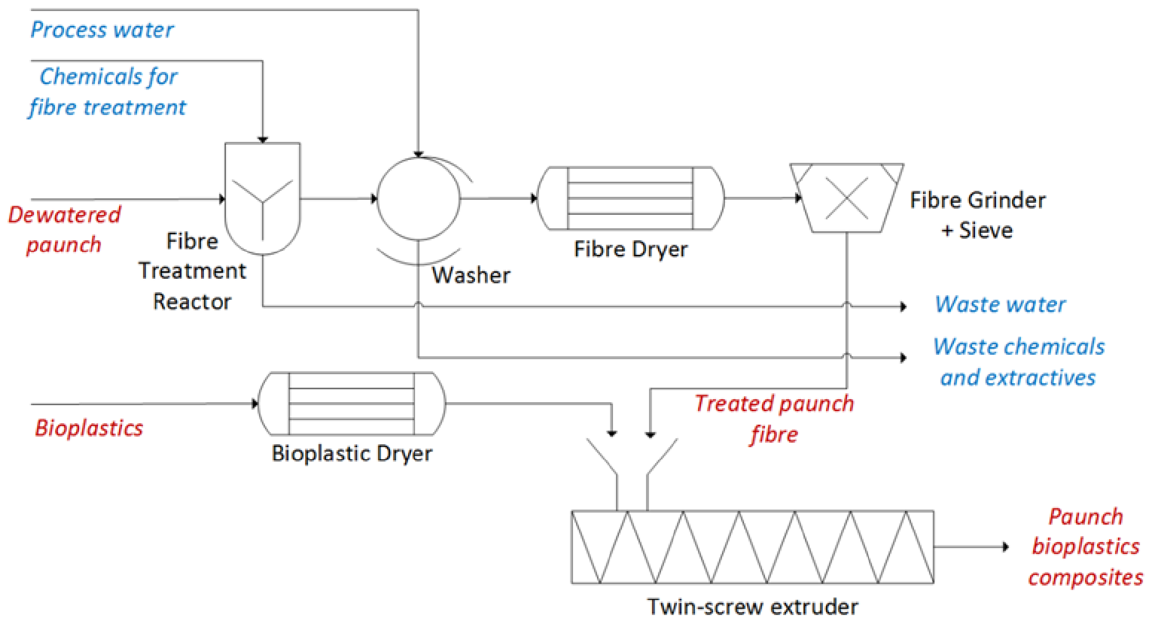
ii. Paunch fibre drying and grinding

iii. Bioplastics procurement and drying

iv. Extrusion processing

v. Chemical / solvent recovery (if necessary)

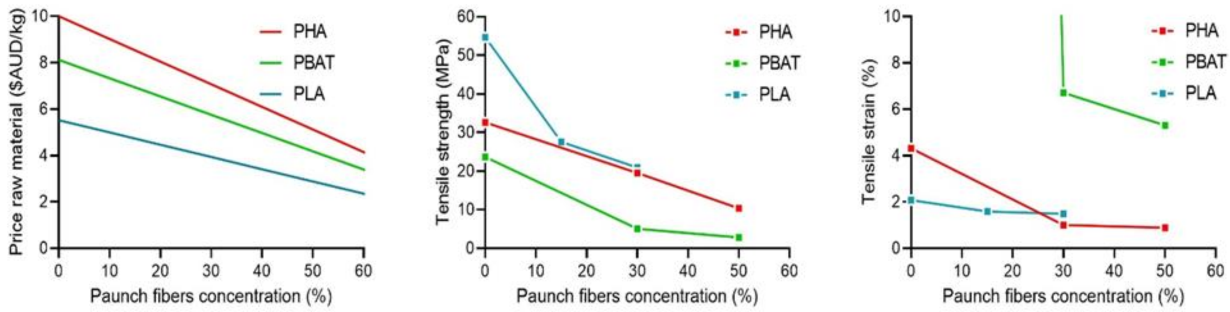
Figure 23. Simple process flow diagram for the manufacturing of paunch bioplastics composites



CAPEX estimation

Simple equipment cost and CAPEX estimations were made to provide the estimated range of investment needed for adopting this technology. The numbers on equipment cost were extracted and updated from a previous in-house techno-economic assessment on composites referenced as “personal communications with supplier”. The capital expenditure was estimated using a basis of 30000 tonnes/annum composite, thus 9000 tonnes/annum paunch assuming a 30 wt% content (Fig. 23). The equipment cost and CAPEX were estimated to be $5.3 million and $15 million, respectively, at that scale. In terms of raw material costs, the price of fibre is negligible; the main driver is the biopolymer price, hence the interest of adding paunch fibres to the raw material would drastically decrease the end product price with the biopolymer being the more expensive ingredient. Fig. 24 presents the price in $AUD/kg of biocomposite against the fibre concentration with their corresponding tensile strength (MPa) and tensile strain (%), which could help to decide which material to be use depending on the final mechanical properties required.

Figure 24. Biopolymer composite raw material price ($AUD/kg), tensile strength (MPa) and tensile strain (%) are presented against the Paunch fibres content (wt%)



Product forming and demonstrators

PHBV/paunch composite sheets with 30 wt% fibre content were successfully produced via compression moulding with flat plates as shown in Fig. 25. A thickness range of 1 mm and 2 mm was achieved. The mould was fully filled, demonstrating the potential processability of paunch composites. Furthermore, ear tag-shaped keychains were produced using laser cutting and engraving as demonstrators, also shown in Fig. 25.

Figure 25. Compression moulded PHBV/30 wt% paunch composite sheets (left); Ear tag-shaped keychain produced via laser cutting and engraving (right).

Further details on this research are available in the following journal: Chan, C.M., Martin, D., Gauthier, E., Jensen, P., Laycock, B. and Pratt, S., 2022. Utilisation of Paunch Waste as a Natural Fibre in Biocomposites. Polymers, 14(18), p.3704. https://doi.org/10.3390/polym14183704

Key Findings and Achievements

- Current composite market size has the potential capacity to absorb the large volume of paunch wastes from meat processing facilities in Australia.

- Extrusion processing of composites with polyhydroxyalkanoate (PHA), poly lactic acid (PLA) and polybutylene adipate terephthalate (PBAT) and untreated paunch was successful with up to 50 wt% paunch contents. Biocomposites with 30wt% untreated paunch showed properties comparable to current Wood Plastic Composite (WPC) products. The mechanical properties could be tailored by using a different biopolymer matrix and difference paunch content depending on the aim of the final application.
- Post-processing procedure was developed to reduce the batch-to-batch differences of paunch across different facilities. The variation in composite mechanical properties from the batch-to-batch differences is less than anticipated.
- The fibre refining process through chemical treatments showed potential to further improve the composite properties
- Small ear-tag shaped keychain demonstrators were produced by compression moulding followed by laser cutting/engraving to the desired shape. The aim is to use those demonstrators to start discussions on the use of industrially relevant processes such as injection moulding for making demonstrators with more complex geometry and to further understand their processability.
- A graph including the raw materials price per kg and the mechanical properties of paunch composite was established in order to assist in selecting the best biocomposite to be manufactured following the targeted end product mechanical properties
- A process flow diagram for the manufacturing of paunch bioplastics composites was constructed, alongside with the description of each process. Simple equipment cost and CAPEX estimations were made to provide the range of capital investment needed for commencing this technology.
- Paunch solids are the largest solid waste stream at meat processing facilities across Australia. Overall, this activity explores the potential of re-directing paunch into potentially high value biocomposite materials. The resulting paunch biocomposites produced using industrially relevant extrusion process showed mechanical properties that are comparable to current wood plastic composite products in the market. The use of fibre refining and treatment strategies further improved the mechanical performance of the biocomposites. A simple process flow diagram was constructed to layout the process units and estimated costs required for the adoption of this technology. Small ear-tag shaped keychain demonstrators were produced by compression moulding followed by laser cutting/engraving to the desired shape. The aim is to use those demonstrators to start discussions on the use of industrially relevant processes such as injection moulding for making demonstrators with more complex geometry and to further understand their processability.

5. Conclusion

5.1 Key findings

Wastes assessments, business models and pathways to adoption

- **Waste identification, analysis and assessment of waste aggregation and co-digestion opportunities for increased anaerobic digestion adoption**. On-farm, intensive feeding and processing sectors in Australian red meat, dairy and pork industries produce substantial quantities of organic waste with biogas energy potential that can meet the majority of estimated onsite energy demand within these sectors. ADAdvisor has been set up as a user-friendly techno-economic assessment tool that will likely continue to be a future enabler in support of adoption of biogas technology across Australian red meat, dairy and pork industries, and their associated supply chains. ADAdvisor has also been set-up in a way to allow its on-going expansion (including voluntary data sharing inputs by users, being incorporated into the background waste characteristics database), and refinement, so that it can continue to be a useful tool to facilitate future biogas projects.
- **Business models and techno-economics research for Wastes to Profits technologies**. The opportunities presented by technologies to convert wastes from the livestock industries to high value products are driven by demand in the market for more sustainable animal-based products. Markets for new products from wastes exist and are large and mature. 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.

Development of technologies for improved waste management

- **Treatments of animal industry wastes** Bioleaching treatment was effective in improving digestate dewaterability and reducing digestate volume. However, the process was not currently economically viable. $FeCl_3$-assisted treatment at 90 °C was effective in improving sludge and digestate dewaterability and reducing waste volume. The process was economically feasible with a net present value of $2.91 million and internal return rate of 23% for the base scenario. Pilot scale demonstration of this process is recommended. Hydrothermal treatment of digestate with biomass at total solid ratio of 1:1 and treatment temperature of 180 °C was effective in improving digestate dewaterability. The treatment also improved nitrogen recovery and reduced heavy metal content in the treated digestate-biomass mixtures. The hydrothermal treatment process was economically feasible with a net present value of $10.6 million and an internal return rate of 22% for the base scenario. Soil incubation trial showed that the use of the treated digestate-biomass mixtures as soil amendments decreased nitrogen leaching and likely reduced greenhouse gas emission. In addition, the treatment liquids could be used as a carbon source to produce single cell protein by Yarrowia yeast, which has the potential for high-value pet feed additive application. Pilot scale demonstration of hydrothermal treatment, field trial with treated digestate-biomass mixtures and single cell protein production by Yarrowia yeast is recommended.

- **Advanced anaerobic digestion - Enhanced efficiency of anaerobic digestion processes from animal wastes for increased biogas yields and lower costs (including co-digestion).** More than 12 novel pre-treatments were assessed for application to RMP wastes, agri-industry wastes and other organic solid wastes. These pre-treatments were effective when applied to compatible waste streams. Alkaline pre-treatment was effective when applied to paunch solid waste from either cattle or lamb processing facilities. Alkaline pre-treatment of dissolved air flotation (DA)F sludge (Saponification) had a clear impact on the waste properties. Mild thermal pre-treatment is a form of pre-treatment that uses waste heat available when biogas is used to generate energy in go-generation engines. Alkaline pre-treatment was selected for further development and optimisation in a continuous process. Initial continuous testing was positive; however, the highly variable nature of agricultural wastes was identified as a risk that needs to be assessed and managed under real world conditions.
- **Utilisation of process additives to increase biogas yields and nutrient recovery during anaerobic digestion.** Powdered additives improved the nutrient balance of digestate by lowering nutrient load in downstream centrate and increasing the potential value of sludge (based on diammonium phosphate (DAP) index). Powered additives appeared to improved degradation of triglycerides during the initial stages of anaerobic digestion, however further analyses is required to confirm this. Further studies to include investigating the application of additives to existing infrastructure and the impact of additives as a polishing media for post digestive treatment and scrubbing residual nitrogen from effluent to reduce disposal costs.

Developing technologies for the production of nutritionally-advantaged feeds

- **Technologies for nutritionally advantaged feeds.** The application of purple phototrophic bacteria for agri-industrial wastewater enables the recovery of organics, nitrogen, and phosphorus as protein-rich biomass, applicable as animal feed or fertiliser. The growth and composition of PPB biomass can be manipulated using light intensity. However, optimising the growth conditions of PPB biomass is a trade-off between maximising biomass production rates and maximising biomass product value. Low light intensities limit the growth rate of PPB biomass; however, these conditions enhance production of Lycopene, a valuable carotenoid with immuno-nutritional properties. Moderate light intensities maximise the growth rate of PPB biomass, but result in lower production of pigments, including Lycopene. High light intensities reduce the production of pigments and photo-inhibit PPB growth.
- **Microalgae cultivation for treatment of waste streams in the meat processing industry** Isolation of robust local microalgae species (i.e., Scenedesmus sp. and Chlorella sp.) capable of growth and treatment of raw AD effluent from red meat processors. Optimization of growth of the developed microalgal wastewater treatment system resulted in Scenedesmus sp. biomass productivities up to 18 $g.m^{-2}$. d-1 as well as 100% ammoniacal nitrogen and 92% phosphate removal efficiency. A major achievement was the 13-month continuous pre-pilot operation of the developed microalgae-wastewater treatment system at a local meat processing facility under local environmental conditions. Pathogen load and nutritional

assessment (i.e., protein content) of AD effluent grown microalgal biomass establish its suitability for use as animal or aquaculture feed. Scaling up microalgae cultures grown in AD effluent from 0.1m^2 to 50m^2 in open raceway ponds illustrated no significant difference in the biomass productivity obtained for the different sized ponds. Analysing the possibility of using microalgae in open ponds as an advanced wastewater treatment process in large scale and the possibility of making the whole process of converting waste to value added products economically feasible and environmentally friendly

- **Biological conversion technologies for valorisation of biogas**. Various operational and control systems were assessed with respect to biogas addition into a photobioreactor at QUT to control pH. Innovative Cold Plasma technology is being explored for effective mutagenesis. The combined approach will allow for development of non-transgenic methanotrophic strains.
- **Fermentation of paunch to produce high-value waste.** Scale-up of the yeast growth from screening in 96-well plates (200 µL) to shake flask cultures (100 mL) yielded data indicating equivalent trends. Yeast growth was much quicker and greater biomass concentrations were obtained than for filamentous fungi. The change in free-fatty acids indicated the consumption of these compounds by fungal growth on paunch solids. This consumption was considerably less for the yeast culture. Yeast growth was assessed in paunch that was not dewatered. There were positive changes in the sterilisation requirements, equipment footprint, and operational costs due to improved speed of bioconversion and lack of dewatering required.
- **High Value Products from Keratin waste.** The process has been developed and characterised now to a point where kilogram scale processes are possible and where there is sufficient understanding to control the process to modulate the product characteristics. These scaled processes generated peptide products for feeding trials that tested hypotheses around feed performance and digestibility. Higher enzyme loadings and reaction times increased keratin degradation as well as improving desirable characteristics such as low molecular weight peptides and antioxidant activity. However, these improvements were not proportional to enzyme loading and so the optimal enzyme loading for particular partners and situations should be determined by techno-economic modelling that considers enzyme cost contribution and the value of the product. Lower enzyme loadings could deliver product at much lower cost but would require increased severity pretreatments that reduce the value of the product through chemical modification of the amino acids. Hydrolysed feathers collected part way through the feather meal production process are a viable substrate that is available at large scale for future commercialisation of the process. We developed specialised proteomic methods for determining amino acid composition and chemical modifications that can be now used throughout the industry to understand the influence of feather meal production processes on product quality. The feeding studies showed the products were safe and contributed to a business case and cost-benefit analyses that considered whether more severe, cheaper processes that lead to higher levels of solubilisation are preferred over less severe processes that generate slightly less solubilisation but lead to less damage (amino acid modifications) to the peptide product.

Development of technologies for production of fertilisers, chemicals, plastics and energy products.

- **Development and validation of biodegradable bioplastics for the Australian Meat Processing Industry**. The elite novel Novatein® formulation is renderable and sheep weasand clips made from this blend are unlikely to be affected by production stoppages in RMP facilities; Novatein® sheep weasand clips perform as well as the incumbent, petroleum-based product in a commercial RMP facility; and Novatein® sheep and beef weasand clips design and prototype must be informed by feedback from the RMP sector and the results of in-factory trials.
- **Development of technologies for the hydrothermal processing of animal wastes and anaerobic digestion digestates**. A relatively cheap catalyst was developed that enhanced hydrothermal liquefaction by improving bio-oil yield or its properties. The catalyst does not contain expensive precious metals. Crude bio-oil was produced from liquefaction of several wastes, and these bio-oils were upgraded to diesel-like fuel. The feedstocks of greatest interest and promise are red meat processing wastes including paunch solid waste, dissolved air floatation float, and manure. Municipal wastewater treatment plant biosolids were also converted to good quality bio-oil. Biosolids can be liquefied without a co-solvent to produce bio-oil with a gross energy content of 37 MJ/kg. Biomass wastes can be more effectively converted to bio-oil of high energy content by using a co-solvent that was identified and evaluated during the project. Hydrothermal gasification (HTG) can be performed on wastes to produce gas mixtures rich in hydrogen and methane. The gas stream is contained and compressed by the process. CO_2 is also captured in the same stream so it can be utilised or controlled.
- **Development of biosolids and digestate-derived organomineral fertilisers (OMF).** Future agronomic studies should consider investigating options for improving nutrient use efficiency through adjustments to the timing of fertiliser application and fertiliser placement and the longer-term (>3 years) effects of routine fertiliser applications on potentially toxic elements (both heavy metals and organic contaminants). The use of biosolids and OMF for the production of non-food crops (e.g., cotton) may be an attractive alternative as this may remove concerns associated with the transfer of heavy metals to the food chain. Despite this, our work has shown that, in the shorter term (3 years), the risk of heavy metals accumulation in soil and plant material was low and that such risk can be managed by controlling soil pH.
- **Utilisation of waste fibres for the development of novel biocomposite materials**. Current composite market size has the potential capacity to absorb the large volume of paunch wastes from meat processing facilities in Australia. Post-processing procedure was developed to reduce the batch-to-batch differences of paunch across different facilities. The variation in composite mechanical properties from the batch-to-batch differences is less than anticipated. The fibre refining process through chemical treatments showed potential to further improve the composite properties.

5.2 Benefits to industry

A significant benefit has been the opportunity to bring together a diverse range of partners to collaborate on common issues across the red meat, dairy and pork sectors including increasing collaboration between the relevant Research Development Corporations. This collaboration addressed a key element of Red Meat 2030 (Red Meat Advisory Council 2019), which sets out the high-level strategic direction of the Australian red meat and livestock industry over the next decade including its commitment to carbon neutrality by 2030, to demonstrably reduce production, processing and consumption waste.

Additionally, the project brought a significant number of researchers together to address sectoral issues, many of which had never worked with the sector before, which will leave a legacy of research capability and experience.

Key benefits to industry from project Activities include:

- The production of an online tool (ADAdvisor) which will assist industry proponents to readily and cost-effectively define, analyse, and refine potential anaerobic digestion projects across the livestock sector. The utilisation of this tool should result in lower cost economic evaluations of anaerobic digestion projects and increased likelihood of commercialisation.
- Development of economic information relating to waste valorisation processes which supports red meat processing and other livestock companies in making better decisions about which potential projects to pursue.
- Development of a hydrothermal carbonisation process for biosolids and AD digestates that reduces transportation costs of these materials. While this process is currently not economic, with future increases in disposal costs this technology may be cost-effective in the future.
- Development of a process for anaerobic digestion of solid wastes (paunch) and readiness for demonstration of that technology at pilot scale. This development will facilitate the readiness of the technology for commercialisation at a red meat processing facility which would reduce paunch disposal costs and improve environmental outcomes.
- Development of additive technologies for anaerobic digestion processes increases the potential value of AD sludge which, if successfully introduced, would reduce the costs of waste treatment at red meat processing sites.
- Purple phototrophic bacteria (PPB) and algae have been demonstrated to be novel mediators for wastewater treatment with potential to reduce nutrients in industry wastewater streams and also then be used as animal feeds with the potential to reduce costs across the sector.
- Development and demonstration of a process for producing animal feed from hair and feathers has advanced the technology readiness of this technology and increasing likelihood of commercial application across livestock industries.
- The factory scale trials of renderable processing aids have advanced the commercial readiness of the technology and again increased the likelihood of adoption in Australian red meat processing facilities.
- The demonstration and assessment of biosolids based biofertilisers has provided information to further support the commercial application of this technology which has the potential of reducing costs in wastewater treatment.

- The development of technology for directing paunch into potentially high value biocomposite materials using industrially relevant extrusion process and evidence that the mechanical properties are comparable to current wood plastic composite products in the market has advanced this technology's commercial readiness.

6. Future research and recommendations

This project explored several potential opportunities and technologies for addressing waste management across livestock industries. While the project advanced the technology readiness for all the technologies investigated, for many technologies further research and / or demonstration will be required to provide industry with the confidence needed to invest. This is particularly the case for technologies with larger capital investment requirements. The ability to undertake pilot scale studies within the project was valuable and a key benefit of the program.

During the project, industry partners identified other issues that were not explored in detail in the project. These may form the basis of future work and include:

- Animal transport truck effluent was identified as a significant waste challenge for some livestock industries. Initial investigations indicate that animal transportation wastes may be suitable for treatment using Anaerobic digestion, either at Red Meat Processing facilities or at offsite facilities along the transport route.
- Silage wrap on farm contributes significantly to on-farm plastic wastes with limited alternative disposal options available.
- Reduction in water usage on-sites can reduce the costs of wastewater treatment, however, limitations currently exist in the ability to re-use water for some on-site applications.

The project identified that advanced AD of solid wastes, particularly paunch, are key opportunities for the industry. Co-digestion of wastes to balance the nutrient profile of the waste streams requires further development to enhance economics. Red meat processing streams with high nitrogen, such as red screenings, thickened WAS (waste activated sludge) or cattle manure are key co-digestion targets. The purpose of co-digestion strategy is to provide a balanced feed in terms of C/N/P as well as other micronutrients to further boost the reactors performance and further work is required taking into account site specific factors is needed to achieve this.

There is also a need to perform further and more detailed techno-economic analyses on these and new and emerging technologies. To ensure that the industry is at the forefront in sustainable production, the development, demonstration and economic assessment of technologies will be important and ongoing.

The Research and Development Corporations have a critical role in ensuring the project has medium- and long-term impacts in both industry and research sectors. The two primary strategies that can be deployed to address this include: (1) to invest directly, with industry, in further research, development and extension activities to maintain and enhance current capacity and capability and (2) entice commercialisation/extension entities to take up the knowledge, products, services and personnel to ensure the industry sees medium- and long-term benefit from this investment.

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8. Appendix

8.1 List of Publications from Wastes to Profit Project

8.1.1 Refereed journal Articles

Cai, G., Moffitt, K., Navone, L., Zhang, Z., Robins, K. and Speight, R., 2022. Valorisation of keratin waste: Controlled pretreatment enhances enzymatic production of antioxidant peptides. Journal of Environmental Management, 301, p.113945. https://doi.org/10.1016/j.jenvman.2021.113945 https://eprints.qut.edu.au/214306/

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8.1.2 Published Conference Papers

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