CSIRO PUBLISHING

Animal Production Science
https://doi.org/10.1071/AN20400

Perspective

Wastes to profit: a circular economy approach to value-addition in livestock industries

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Abstract. The livestock sector is a fundamental part of the modern global economy and provides food, clothing, furnishings, and various other products. So as to ensure its resilience to changes in consumer expectations, cost of production, and environmental sustainability, the sector must shift to a circular economy model. Current strategies to recover value from wastes and low-value co-products from livestock industries yield limited value; hence, new technologies are required to upgrade wastes and co-products, and generate high-value products that can feed into the livestock value chain. Anaerobic digestion can convert high organic-content waste to biogas for energy and a stable nutrient-rich digestate that can be used as fertiliser. Microbial technologies can transform wastes to produce nutritionally advanced feeds. New materials from waste can also be produced for livestock industry-specific applications. While aiming to add commercial value, the successful implementation of these technologies will also address the environmental and productivity issues that are increasingly valued by producers and consumers.

Keywords: adoption of technology, agricultural innovations.

Received 30 July 2020, accepted 18 January 2021, published online 15 February 2021

Introduction – the sustainability imperative

Animal-based products such as food, leather and wool are a significant part of the global bioeconomy and have an important role in society. Animal products are woven tightly into the fabric of modern life and, due to increasing global human population, demand for animal-based products has risen accordingly (Godfray 2011). The livestock sector depends on diverse and widely varying factors that are difficult to control or predict; livestock farming relies on environmental and climatic conditions such as rainfall and temperature, livestock health is affected by both external and internal factors, the efficiency of feed utilisation for animal growth productivity is complex, and livestock products are sold into a range of complex and dynamic global markets with variable supply and demand level and evolving consumer habits. The increasing costs and scarcity of key agricultural inputs including electricity, water, capital and labour provide additional challenges in maintaining agricultural profitability (Thornton 2010). To enhance economic sustainability, agricultural industries have worked to increase yields, enhance feed conversion efficiency, and reduce production costs while fulfilling market demands for high-quality and safe produce. Progress in animal science and production technologies have contributed to significant increases in productivity and enhanced understanding of the effects on animal health, welfare and the environment (Colditz and Hine 2016). This knowledge has benefitted the industry and provided greater access to information for consumers.

With increasing global population and, hence, increasing demand for food, energy and consumer products, ensuring sustainability of production systems is critical. Livestock industries around the world are developing strategies to enhance and demonstrate their environmental sustainability (FAO and New Zealand Agricultural Greenhouse Gas Research Centre 2019) such as the Carbon Neutral 2030 (CN30) initiative in the Australian red meat industry (Meat and Livestock Australia 2020). The sustainability principle outlined by Brundtland as part of the World Commission on

Economic Development defined sustainable development as 'development that meets the needs of the present without compromising the ability of future generations of people to meet their own needs' (Brundtland 1987, p. 16). This principle grounds the global agenda for sustainable development through the United Nations Sustainable Development Goals (SDG). While the Goals encompass many objectives, two targets, Zero Hunger (Goal 2) and Responsible Consumption and Production (Goal 12) relate closely to the animal production industries, while many others have indirect but important links (United Nations General Assembly 2015). Considering their ubiquity and close association to human development and the environment, livestock industries must play their part in contributing to achieving the targets of the SDGs by delivering significant positive economic, environmental, and social impacts.

Among the environmental aspects of livestock production, increasing volumes and yields of primary products while reducing fossil energy use, water use, and greenhouse-gas (GHG) emissions offers the opportunity to enhance sustainability while reducing costs. The environmental aspects of producing meat are already a key issue for many consumers (Vergunst and Savulescu 2017). For instance, ~15% of human-induced GHG emissions are attributed to the livestock sector, mostly from enteric fermentation by ruminants, feed production and manure processing (Gerber *et al*. 2013; Smith *et al*. 2014). Thus, measures that mitigate GHG emissions in alignment with the aim of the Paris Agreement to limit global temperature rise to below 2°C, along with other sustainability goals, needs to be thoroughly embedded in the animal production industries (Australian Pork Limited 2010; The Australian Beef Sustainability Framework 2017; Olmsted 2019). Recognising the global challenges of livestock production and processing, the environmental impacts of meat and milk production do vary considerably among regions and also on the basis of specific on-farm and processing practices, resource use and efficiency and location, as well as the type of livestock. For example, the differences in environmental impacts from the production or different livestock products in Australia are shown in Table 1 (Gollnow *et al*. 2014; Chen *et al*. 2015; Ridoutt and Hodges 2017; Wiedemann *et al*. 2017; Wiedemann 2018; Dairy Australia Limited 2019).

Table 1. Environmental impacts and resource use of meat and milk production in Australia (Gollnow *et al*. 2014; Chen *et al*. 2015; Ridoutt and Hodges 2017; Wiedemann *et al*. 2017; Wiedemann 2018; Dairy Australia Limited 2019)

GHG, greenhouse gases

Product	Fossil energy (MJ)	Water use (L)	GHG (kg CO_2-e)
Pork[A]	32	216	6.5
Lamb[B]	14–28	163–645	17–21
Beef[A]	34	442–598	30
Chicken[C]	25–30	53–155	2.5–3.1
Milk[B]	0.4–0.8 (on-farm) 0.7–2 (processing)	9–313	1.11

[A] per kg, boneless fat-corrected meat.
[B] per L fat and protein-corrected milk.
[C] per kg of boneless chicken portions.

Managing (treatment and disposal of) wastes and low-value by-products (herein also referred to as wastes) in the livestock industry is a high-cost activity that has become increasingly challenging due to changing community expectations, more stringent regulations, increasing compliance costs and increasing capital and operating costs for waste treatment (O'Hara *et al*. 2016). With the growth in demand for new bio-based consumer products, the development of new products from livestock industry wastes offers an opportunity to create new revenue streams of significant market value, underpin employment in the sector and contribute further to global sustainable development. Due to the nature and volume of waste produced at a single source, compared with distributed waste streams as in farms, the management of livestock processing waste presents viable opportunities to address life-cycle impacts, minimise footprint from landfilled waste and potentially improve economic outcomes. Extensive pastoral industries can also benefit from developing new products from waste; however, the applicability can be influenced by collection, transportation and the cost and complexity of appropriate technology that can handle wastes generated on farm.

Australia's animal industries produce significant quantities of wastes from the on-farm production, intensive feed, and processing sectors. On average, it is estimated that waste disposal is 0.7% of total red meat processing costs, including labour and transportation but excluding livestock purchase cost. Waste disposal makes up 12% of total utilities costs (Australian Meat Processor Corporation 2018). A recent report (O'Hara *et al*. 2016) has identified that the treatment and disposal of solid and liquid wastes from feedlots and red meat processing in Australia exceeds AU$100–200 million per year. Implementing technologies for the utilisation of wastes to generate products such as microbial protein and energy could realise new revenue streams exceeding AU$140 million (O'Hara *et al*. 2016).

A project currently underway known as the *Wastes to Profits* project is supported by Meat and Livestock Australia through funding from the Australian Government Department of Agriculture, Water and the Environment as part of its Rural R&D for Profit program and partners. The project is developing new technologies to convert livestock sector wastes from the red meat, dairy and pork industries into valuable products. The present paper describes the new sustainable approaches to waste management and processing that are being developed in the project and explores opportunities to create new valuable products for current and emerging markets.

Approaches to waste management and the circular economy

The broad range of organic wastes that result from animal processing are typically classified as either liquid waste (wastewater) or solid waste based on the water content and the materials handling properties. These properties often dictate the selection of waste handling and treatment options. Meat processing wastes consist of rumen waste (also referred to by the colloquial term, paunch solids), discarded meat, and offal from screens, settling tanks and dissolved air flotation. At many processing plants, offal and discarded material from the slaughter floor and boning room are directed to rendering, which further reduces wastes and creates co-products. However, there are still organic wastes generated from rendering and other co-product processing sections (e.g. tanning) such as hide cuttings, hair and hooves. Dairy processing has developed co-products, such as whey, thereby reducing waste; however, marginal amounts from spillages and rejected product still make it into waste streams. Wastewater with high organic content (and in some cases, high nutrient content) are generated from the washing of animals, pens, processing areas and equipment, and are usually directed to wastewater treatment facilities. These treatment facilities may generate solid wastes such as aerobic sludge. Across the livestock industries, single-use packaging and other plastic wastes are generated on-farm and off-farm. In meat processing, it is estimated that 5.9 kg/hot standard carcass weight is being sent to landfill. Packaging wastes such as cardboard and plastic are recycled in high rates (79% in 2009), although materials that come in contact with meat, blood or faeces are considered contaminated, and are landfilled (Australian Meat Processor Corporation 2016). Animal manure also constitutes a significant part of organic wastes in the context of total waste generation. The types of wastes from animal production are shown in Table 2.

The waste hierarchy (shown in Fig. 1) applies to livestock industries and provides a strategy to reduce the quantities of materials disposed to landfill or municipal water treatment and to make material use efficient so as to obtain the most value from the material resources. Waste avoidance cannot be achieved for many activities and processes within livestock industries without significant implications to productivity and/or animal health. For example, the generation of manure is an unavoidable consequence of animal production. However, waste reduction has been practised extensively. An example of effective and long-standing waste minimisation strategies within animal industries is the generation of co-products, including hide and tallow. In fact, these co-products predate industrialised food production and have been used throughout human history (Ockerman and Hansen 1988). Due to increasing costs, technologies to recover the maximum value from the carcass and reduce waste are being continuously developed (Anderson 2007; Drummond *et al*. 2019). For example, collagen, which is typically used for gelatin production, has been investigated for the production of bioactive peptides (Drummond *et al*. 2019). Further, waste reduction offers the opportunity to increase efficiency,

Table 2. Organic wastes and co-products generated in meat processing
HSCW, hot standard carcass weight

Waste type	Amount produced	Notable properties	Reference
Manure, cattle in feedlots	27 kg/day.animal (450 kg liveweight)	Moisture content of 20–78% harvested, up to 90% in excreted manure. Amount varies based on size (larger animals produce more).	Department of Agriculture and Fisheries Queensland Government (2011); Kissinger *et al*. (2007)
Manure, cattle in meat processing	4–13 kg/t HSCW[A]		Australian Meat Processor Corporation (2010)
Manure, sheep	5–12 kg/t HSCW[B]		Australian Meat Processor Corporation (2010)
Manure, pig	108 kg/year.standard pig unit total solids	Manure and waste feed.	Tucker (2018)
Litter, broiler chickens	0.035 kg/day.bird	Mixture of manure, bedding materials and feathers.	Forde and Sticklen (2016)
Rumen waste/paunch solids, cattle	25–70 kg/t HSCW[A]	Rumen contents: undigested feed (grass and grain) and nutrients 40–50% total solids.	Australian Meat Processor Corporation (2010)
Solids from primary treatment	150–300 kg/t HSCW[A]	Screenings, DAF float, bottom solids. Variable quality prevents rendering.	Australian Meat Processor Corporation (2010)
Hair, hooves and horns, cattle	<50 g/animal hide hair, 8 kg/animal hooves	Keratinaceous waste. Some feet/tendons are edible.	Meat and Livestock Australia (2009)
Feathers, chicken	86 000–111 000 t/year	Keratinaceous waste. Rendered to feather meal.	PoultryHub (2020)
Blood[C]	15 L/head cattle, 2–3 L/pig	Rendered as bloodmeal.	Bah *et al*. (2013)
Hide, cattle[C]	28 kg/animal	Processed in tanneries. Waste hide processed to gelatine.	Meat and Livestock Australia (2009)
Waste flesh and tallow, cattle[C]	48 kg meat meal/animal, 52 kg tallow/animal	Weights are rendered product from a 270 kg HSCW.	Meat and Livestock Australia (2009)

[A] HSCW of 270 kg from a 465 kg (liveweight) steer (Meat and Livestock Australia 2009).
[B] HSCW of 20–26 kg (Lamb carcase weights up despite dry; Anon 2019).
[C] Considered co-products with established processing routes and markets.

although these waste production measures can be associated with significant increases in capital and operating costs, thereby reducing profitability.

Livestock industries are increasingly moving to align with the global industrial trend to transition from the traditional 'linear consumption' approach to a new 'circular economy' (see Box 1). The circular economy concept aims to address risks around volatile resource prices and supply, inefficiencies in production that drive up costs, and the flattening growth of agricultural productivity (World Economic Forum 2014). Demand for sustainably and ethically produced goods is growing, creating opportunities for 'green' products in new markets. These opportunities also exist for livestock industries; hence, the development of technologies and approaches that can deliver sustainable production is identified as a key strategy.

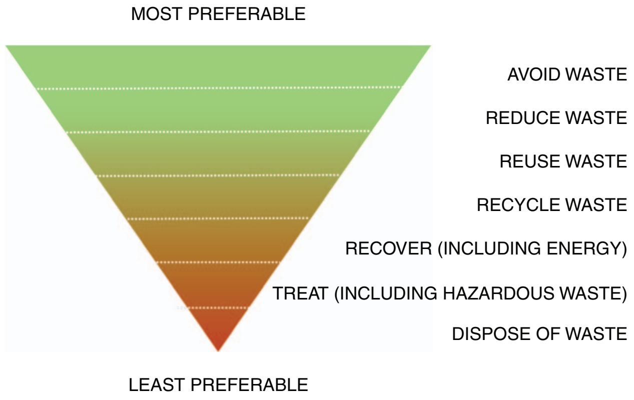

Fig. 1. The waste hierarchy demonstrating the priority of waste management measures. The pyramid area represents the waste volume, which is reduced from top to bottom by the management methods in order of preference. Redrawn from Commonwealth of Australia 2018.

Livestock processing wastes may contain pathogens and/or components that affect food safety. Requirements for hygienic production so as to avoid the contamination of meat products limit the direct re-use of these waste materials within the existing production chains. The opportunities, therefore, lie in new processes for the recycling and recovery of waste that do not rely on significant modifications to current operations but present ways to maximise existing value chains. At present, there are processes used to recycle and recover waste with established supply chains as part of the bioeconomy. Composting, anaerobic digestion, lime stabilisation and vermiculture are employed to stabilise animal processing wastes and manure with residues being re-used through land application. Land application of treated organic wastes is considered as a recycling method. The use of methane produced in anaerobic digestion for energy is considered as recovery (Commonwealth of Australia 2017). Waste offal and hides, which are inedible, are processed through rendering to recover valuable products such as animal feed ingredients, tallow, and gelatine. Organs and glands are also used in producing pharmaceuticals and medicines (Alao *et al.* 2017).

Waste valorisation technologies and markets

Figure 2 shows a circular economy approach to livestock industries, including a broad range of opportunities to convert waste materials from livestock industries into high-value products (Fig. 2). The development of new technologies can result in positive economic, environmental and social

Box 1. The circular economy

The circular economy concept was initially conceived as a way to maintain the sustainability of human life considering a finite pool of resources on Earth. This came about as an expansion of industrial ecology, which is typically applied to an industrial system and its immediate environment (Ghisellini *et al.* 2016). The concept is implemented as a set of methods that achieve a circular flow of materials or energy within a production system. In the 'linear economy', raw materials are processed into products, which are then used to extract value. The residual value of the product is considered 'waste' and is written off. In the circular economy, the residual value is recovered or enhanced and fed back into the value chain to achieve circularity (Van Buren *et al.* 2016). Strategies such as 'reduce, reuse and recycle' are the most common ways to implement circularity, although the application of these strategies can be limited by the particular waste characteristics, the quality or condition of the wastes, and the suitability of the resulting product streams to be returned into the main material flows. Due to this gap, other strategies (such as recover, repurpose, repair) have been developed in more comprehensive frameworks, which aim ultimately to minimise the amount of waste for disposal.

The implementation of circular economy strategies is not without challenges. Many linear economy systems that manufacture cheap goods in high volumes will need to change drastically to allow materials to be cycled back. Examples of these changes are designing for products to be reusable or recoverable, implementing business models that assist consumers to maximise the life of a product (e.g. a repair service), or integrating residual product processing in main manufacturing streams (Stahel 2016). Even when linear processes are adapted for recycling and reuse, the properties of wastes dictate how such circular economy strategies can be applied. Some materials can be recycled a limited number of times due to a progressive deterioration of the material. For example, cellulose fibres, from pulp and paper, can be recycled only four to six times. However, different strategies, likely recovery (as energy), can then be applied to extend the value of the material (Reh 2013). Some materials cannot be recycled in this manner due to a more rapid physical and biological degradation. This is particularly relevant for streams with high organic and moisture content such as those generated from animal industries. However, biological degradation also allows opportunities for further processing. So as to use appropriate waste materials (e.g. food waste) in animal feed, proper handling, sterilisation, and decontamination will be required at the minimum to ensure the safety of the feed, and to remove the image that animals are being fed with refuse (Dou *et al.* 2018).

While the development of processing technologies and products are vital, the impacts of a shift to the circular economy can be fully realised only with systemic changes (Kirchherr *et al.* 2017). Businesses have a role in this, especially as a 'social licence to operate' is increasingly promoted to encourage businesses to create social and environmental value in the communities in which they operate (Joyce and Paquin 2016). Socio-institutional changes are also important to accomplish the implementation of the circular economy. This can be realised with further understanding of the perspectives from law, ethics, economics and sociology (Blomsma and Brennan 2017) and preparing policies that remove the barriers and support circular economy strategies.

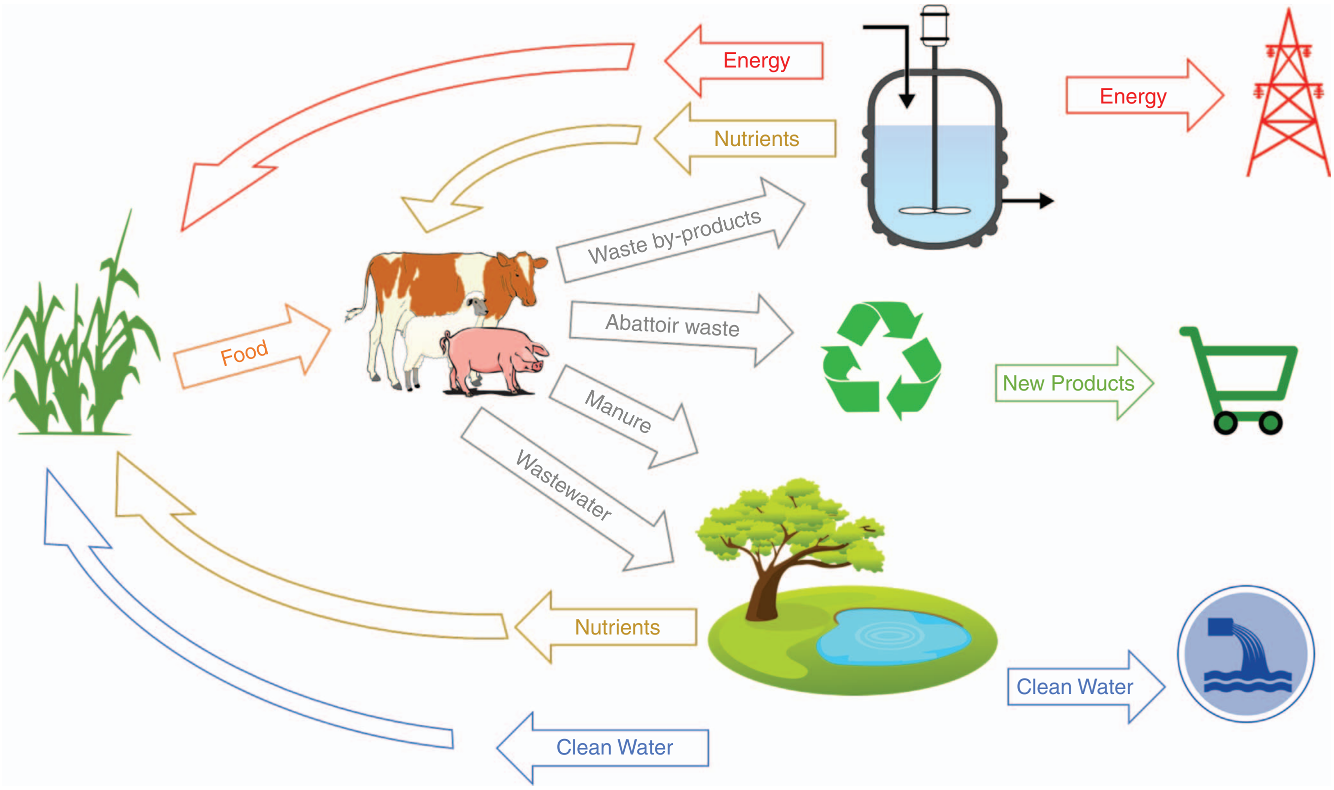

Fig. 2. A circular economy approach to livestock industry wastes. Technologies that take waste streams as input can produce materials that can be used within the livestock supply chain.

impacts. Previous innovations to extend the value derived from livestock, such as the use of offal, mechanically removed meat, and protein hydrolysates, have enabled the industry to improve revenues and produce high-quality, nutritious protein despite increasing costs, production variability and market volatility. With the introduction of these technologies, what has been identified in the past as 'waste' has evolved because opportunities to upgrade low-value by-products have been developed (Drummond *et al*. 2019).

Significant sustainability benefits from the recycling and recovery of waste can be realised if these are performed within the animal production value chain. The organic wastes generated can be used to close agricultural nutrient loops, decrease inorganic fertiliser requirements, decrease carbon dioxide emissions, and enhance organic content in soil (Ellen Macarthur Foundation 2018). The use of manure and effluent in farms illustrates this. As a result, the overall nutrient use efficiency can be higher, since nutrients in residual fractions are put back into the system and additional inputs from elsewhere are minimised (e.g. mineral fertilisers; McCabe *et al*. 2016). Similarly, biogenic energy produced from wastes reduces fossil fuel-based carbon dioxide and methane emissions. Mature technologies such as composting and anaerobic digestion are employed to recycle and recover wastes (McCabe *et al*. 2020). Composting is used for solid wastes, while anaerobic digestion is used in wastewater treatment, although anaerobic digestion has also been demonstrated to treat a variety of solid wastes from meat processing (Tait *et al*. 2009; Jensen *et al*. 2014). The benefits are known for these processes, although conversion rates and cost efficiency can still be improved. Both composting and anaerobic digestion generate products with high organic contents, which might be more stable for land application but still have a low value. Considering the operational and transportation costs required for these products, there can be challenges in developing commercially viable applications.

Recovery of energy and nutrients from waste

Anaerobic digestion is a biological process that occurs in both natural environments and engineered reactors. The process is able to convert the organic content of waste streams into methane-rich biogas. From a treatment perspective, anaerobic digestion will stabilise wastes and reduce pathogens and odours. From a circular economy perspective, the biogas generated in anaerobic digestion is mostly composed of a mixture of methane and carbon dioxide; burning the biogas can generate heat or electricity.

Anaerobic digestion is a highly flexible and broadly applicable technology. However, the performance and economics of an anaerobic digestion process are highly dependent on the feedstock characteristics and environmental conditions. Feedstock characteristics will determine the speed that material digests, and, therefore, the treatment time/reactor size. Feedstock characteristics will also determine the volumes of methane that can be produced (energy recovery) and the potential for generation of by-products that are toxic or inhibitory to the essential microorganisms. For example, animal processing wastes can be high in lipids, proteins and urea. Lipids have an extremely high methane potential. However, if lipid loading is not carefully managed, long-chain fatty acids can accumulate and inhibit methanogenesis (Arvanitoyannis and Ladas 2008; Harris and McCabe 2015). The production of ammonia from the breakdown of proteins, urea or nucleic acids can inhibit reactions in the digester at high concentrations (Rajagopal *et al*. 2013; Astals *et al*. 2014).

Lagoon-style anaerobic digesters are widely applied in livestock industries due to low-cost construction and a perception of low ongoing maintenance requirements. However, the performance of lagoons is affected by climate variations. For example, seasonal temperature variations can affect both the biogas production rates in lagoons (Schmidt *et al*. 2019) and the organic loading limits of the process. Lagoon-style digesters are not suitable for all wastes, with more complex and more expensive in-vessel reactors being appropriate for rumen waste, manure, and other higher solid-waste streams from livestock industries. Unfortunately, these wastes tend to require long treatment times and produce lower volumes of biogas; as a result, the economic viability of anaerobic digestion can be reduced. There are opportunities to improve the economics of anaerobic digestion through co-treatment of high-energy wastes (to offset the cost of treating low-energy wastes) or through larger centralised treatment facilities that benefit from economy of scale. Selection and design of co-treatment mixtures and co-treatment loading rates will depend on waste characteristics (particularly carbohydrates/lipids/proteins present), operating temperature, and digester configuration (covered pond vs mixed heated digester). Waste composition can be quite different, but still complementary and, therefore, well suited for co-treatment. From an economic perspective, co-treatment needs to balance improvements in biogas revenue with increased residue disposal costs and increased nutrient management costs.

The economic value of biogas is primarily based on its heating value. With minimal treatment, the biogas produced through anaerobic digestion can be burnt onsite at a processing facility to offset heating and electricity requirements of the plant. Generally, the biogas that can be produced at a red meat processing plant can offset 20–50% of onsite heating requirements. This translates to a reduction of Scope 1 carbon emissions[1] of up to 83% (Fredheim *et al*. 2017) and energy cost savings estimated at up to AU$1.66/head (Fredheim *et al*. 2017). Similar results can be expected at animal production facilities, where a modelled scenario producing biogas from piggery effluent showed 25% reduction in fossil energy use (Wiedemann *et al*. 2018). The value of biogas is not restricted to onsite energy generation. Biogas can be processed to upgrade the methane content, and sold into the natural gas grid as biomethane or compressed and stored in bottles as an alternative to compressed natural gas or liquified natural gas. Compressed biomethane could then be used within the livestock industries as an alternative vehicle and machinery fuel (O'Hara *et al*. 2016). This can lower the fossil energy footprint of livestock industries significantly, since on-farm fuel use for vehicles and machinery make up a large part of fossil energy use for both lamb and grass-finished beef production (Wiedemann *et al*. 2016*a*, 2016*b*). Aside from fossil fuel reductions, the 'behind-the-meter' use of energy produced onsite also enables production to be less sensitive to fuel and electricity supply and price changes. Alternatives to anaerobic digestion for energy production include combustion or pyrolysis, both of which benefit from the use of dry inputs (Bridle 2011). Hydrothermal liquefaction of wet wastes for the production of liquid fuels is an emerging technology with significant potential for application at commercial scale (Skaggs *et al*. 2018). There is potential for thermochemically treated products to be introduced as drop-in fuels to meet fuel standards (Ramirez *et al*. 2017). Both pyrolysis and liquefaction processes produce biochar as a by-product, which can be used as a valuable soil conditioner (Løes *et al*. 2018; Maroušek *et al*. 2019).

The solid and liquid residues that remain after anaerobic digestion are called digestate, which is emerging as a co-product from anaerobic digestion with many opportunities for value-addition. Digestates can be more uniform in consistency than are untreated organic wastes, and they can have higher proportions of nutrients that are more available to plants, which enhances the utility of digestate as a fertiliser product (Risberg *et al*. 2017). The application of digestate as an organic fertiliser fits well with re-use strategies within the animal production value chain, because of the potential to enhance crop yields with minimal use of external nutrients. However, the use of digestates comes with some complexity in ensuring that the correct nutrient balance needed by crops is supplied, minimising contaminants and impurities, and dewatering and processing the fertiliser product to a form that can be easily transported, stored and applied (McCabe *et al*. 2019). The ability of microbial biomass to recover nitrogen and carbon from wastewater and transform them into a plant-available form makes them highly suitable for use as biofertilisers (Zarezadeh *et al*. 2019).

Producing nutritionally advanced feeds

While anaerobic digestion provides one viable technology for effectively treating wastes and producing fertiliser products, liquid and solid wastes can also be used for the propagation of microorganisms to produce nutrient-rich biomass and bio-based products of higher value. These biological treatments can have the added advantage of removing nutrients such as nitrogen and phosphorus from wastewater streams, which are typically difficult and costly to remove in conventional wastewater treatment processes. The growth of microorganisms in wastes enables the production of a variety of value-added products including energy, protein-rich

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[1] The Australian NGER Act Technical Guidelines 2017–18 define 'scope 1' emissions as greenhouse gas emissions released by the facility as a direct result of an activity that constitute the facility.

livestock feed, fertiliser, and high-performance livestock feed supplements; the selection of optimal species is key for developing an economically viable process. A focus on producing high-protein biomass from microbes can also enable the industry to diversify into new protein products to be commercialised in the growing microbe-based protein market (Tubb and Seba 2019). Microbial species being explored for their role in wastewater systems are microalgae such as *Chlorella* sp., *and Scenedesmus* sp. (Duong *et al*. 2015; Vadiveloo *et al*. 2019), macroalgae such as *Lemna minor* (Schenk 2016), *Cladophora* sp. (Vadiveloo *et al*. 2019), *Rhizoclonium* sp. and *Ulothrix* sp. (Nwoba *et al*. 2017), and purple phototropic bacteria *Rhodopseudomonas* sp. and *Rhodobacter* sp. (Hülsen *et al*. 2014; Dalaei *et al*. 2019). Preferred species are selected on the basis of their productivity, lipid and protein content, their ability to thrive in wastewater, and their effectiveness in extracting nutrients from wastewater. Combinations of these species in the same biological treatment process may also be possible. Moreover, these microorganisms are photosynthetic and although wastewater may be nutrient-rich, these species need additional carbon to support growth. This presents capital and operational costs in adding carbon through aeration or chemical addition; however, it is also an opportunity for CO_2 sequestration. Microbial biomass can also be produced using solid wastes. Rumen waste, which are mainly lignocellulosic plant fibres from partially digested feed removed in processing of cattle or sheep carcasses, can potentially be used as a substrate in solid-state fermentation to produce a protein-rich product with direct application as an animal feed ingredient.

Protein for animal feeds can also be provided by plant- or insect-based alternatives, although some of these sources contain anti-nutritional components that can make them less digestible and hinder their application in feed (Delamare-Deboutteville *et al*. 2019). Microbial biomass products are seen as an alternative to both animal- and plant-based feed ingredients due to higher protein content, smaller land footprint, and higher conversion efficiency in a wider range of climates, soil conditions and available land (Matassa *et al*. 2015). Moreover, these products can deliver not just protein but added nutritional value from essential amino acids or vitamin content, or probiotic potential to improve animal gut health and productivity. For instance, microalgae have been suggested as a promising biomass for energy, animal feed and food products, predicated by its development in the past few decades and its use in wastewater treatment. Other microbes such as purple phototropic bacteria have been looked at more recently to explore viable alternatives to algae (Hülsen *et al*. 2014; Delamare-Deboutteville *et al*. 2019).

A key consideration in producing alternative protein sources for animal and aquaculture feed is to replace high-priced and unsustainably harvested ingredients such as fishmeal (US$2/kg), which costs more than soybean meal (US$0.5/kg; IndexMundi 2019). A cheaper protein feed component that can be produced reliably can also lower feed costs and make production less sensitive to price fluctuations and climate effects. It is important that the raw materials and processes used to produce compounded bulk feed are cheap and simple. The resulting feed should also be able to provide a wide range of nutritional needs, so as to limit the use of other ingredients and supplements that can elevate costs. Several emerging bioprocesses such as enzymatic processing can potentially use solid wastes such as cattle hairs or waste wool to produce peptides or amino acids, which can supplement feed (Navone and Speight 2018). The production of essential amino acids from waste materials through fermentation is a key pathway for recovering the nutrients in waste within the animal production cycle.

Waste to new materials

Liquid and solid wastes can also be used to produce bio-based plastics and biocomposites. Blood, which is typically rendered into bloodmeal for animal feed or fertiliser, can be processed into a 'safe to render' biodegradable bioplastic (Verbeek and van den Berg 2011). The importance of reducing traditional petroleum-based plastics is underscored by the comingling of plastics with the rendered co-product streams used in making animal and pet food. This contamination has recently been made visible as pet welfare and safety have been increasingly important to the public (Donnellan and Burns 2018). Aside from this, plastic wastes from packaging and worker protection are abundant in meat processing and represent a significant share in total solid wastes produced. Waste plastics usually go to landfill due to contamination that prevents reuse and recycling. For packaging applications, high-performance plastics are required to maintain freshness and prevent contamination of products. New biodegradable or compostable polymers have been developed that may be suitable for some applications in meat processing if essential physical properties are met. For instance, some types of polyhydroxyalkanoates can be used in food packaging (Philip *et al*. 2007). The inclusion of additives such as natural fibres can increase strength of the biocomposites and decrease costs (Chan *et al*. 2018). The further development of food grade and biodegradable plastic alternatives is imperative to reduce plastic contamination and reduce total landfilled waste. Animal production wastes such as rumen waste/paunch solids can also be potentially processed to produce bioplastics or biocomposites, which can be used in farms and processing plants.

Policy and regulations

The success of developing a sustainable animal production industry embedded in the circular economy depends largely on the creation of robust and fit-for-purpose technology that minimises environmental impact and maximises value. However, the influence of policy and regulations should not be understated. As technologies are being demonstrated at commercial scale, policies relevant to renewable energy, waste management and sustainable production should enable quick uptake and adoption. For instance, economic incentives that place a value on the environmental cost of using land for waste disposal support the economic viability of management systems higher in the waste hierarchy. Regulations that support the use of animal production wastes in feed and fertiliser are also needed in many jurisdictions. In conjunction with the development of new processing technologies, further research that demonstrates the safety and efficacy of animal waste-derived products is needed.

Conclusions

The development of an industry based on converting livestock wastes to high-value products addresses complex issues facing the meat and livestock industries. The availability of cutting-edge technology will enable the industry to expand not only existing markets, but also enter those that are emerging. By making use of wastes, the total economic value for the sector can be increased, even just considering the additional revenues from the increased price of typically low-value co-products. Moreover, developing products that can cycle back into the value chain amplify these benefits. Environmental values such as nutrients, water and land are enhanced by the efficient use of resources through the circular economy. This also introduces some resilience to the industry, which is already sensitive to climate change effects. Most importantly, as a major part of sustainable food systems and a steward of the landscape, the industry will be able to continuously support sustainable development, ensuring that people have access to healthy diets and an environment where animals and humans sustainably co-exist.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgements

This project is supported by Meat and Livestock Australia through funding from the Australian Government Department of Agriculture, Water and the Environment as part of its Rural R&D for Profit program and the partners.

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Handling editor: Wayne Bryden