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BEYOND WASTE-TO-ENERGY: BIOENERGY CAN DRIVE SUSTAINABLE AUSTRALIAN AGRICULTURE BY INTEGRATING CIRCULAR ECONOMY WITH NET ZERO AMBITIONS

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ABSTRACT

The race to meet net zero targets by 2050, while rapidly transitioning to a circular economy (CE) within the next decade, is shaping strategic Australian sustainability policy. While the success of integrating CE concepts relies on coordinating system-wide change, policies and strategies are still evolving under the traditional silos of waste and energy management. This presents multiple barriers to critical sectors, such as agriculture, which aims to become an $AUD100 billion industry by 2030. Agri-food systems face the challenge to meet growing global food demand, expected to increase by 70% by 2050, while decreasing emissions, resource use and waste production. Agriculture plays essential push and pull roles in meeting net zero targets and in developing a truly CE. Bioenergy, a critical part of the renewable circular bioeconomy, sits at the intersection of net zero and CE by producing renewable energy and recovering bioresources from waste biomass. By integrating agricultural end-users as key stakeholders, bioenergy can shift from a waste-to-energy process to a multi-resource generating process. These policy areas could be integrated via a similar approach to the Australian National Agricultural Innovation Policy Statement, with the goal of supporting agricultural production, while reducing emissions and maximising renewable resource use efficiency.

1. INTRODUCTION

1.1 The challenge of sustaining food production while reducing emissions and resource use

The calls to reach "net zero" greenhouse gas (GHG) emissions by 2050 has triggered one of the largest global transitions since the industrial revolution (IPCC, 2018). This transition is occurring in concert with moving from linear systems of production, consumption, and waste management towards a "circular economy" for material and biological resources (the bio-based or bioeconomy) (Arsic et al., 2022; Carus and Dammer, 2018; Stahel, 2016). However, with an estimated 8.5 billion people by 2030, and food demand rising by 70% by 2050, it will be challenging to reduce emissions and resource use while meeting the 2030 Sustainable Development Goals (SDG), notably SDG 2 "End hunger, achieve food security and improve nutrition and promote sustainable agriculture" (UNICEF, 2021). It is therefore critical to apply all three circular economy principles ("design out waste and pollution, keep products and materials in use, and regenerate natural systems") to ensure that valuable resources within organic biomass "wastes" are utilised to their full potential (Ellen MacArthur Foundation, 2015). From an Australian perspective, agriculture has an important role in international and domestic food security, supplying over 90 per cent of domestic food while exporting over 70 per cent of produce (ABARES, 2022). The sector aims to reach $AUD100 billion production value by 2030 to meet global food demands (Delivering Ag2030) (DAFF, 2022). However, growth must be aligned with strategic shifts for energy and resources.

1.2 Beyond waste-to-energy?

The bioenergy sector has valorised organic wastes for several decades through "waste-to-energy" technologies, which can be defined as "…any waste treatment process that creates energy in the form of electricity, heat or transport fuels (e.g., diesel) from a waste source" (World Energy Council, 2013). In addition, some waste-to-energy technologies such as anaerobic digestion (AD) and pyro-

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genic carbon capture and storage (PyCCS) can generate by-products that have reported beneficial properties as soil amendments and bio-based fertilisers (e.g., digestate, biochar) while reducing GHG emissions (carbon and methane) (Pivato et al., 2023). However, the development of these by-products into safe and effective agricultural inputs has been limited by a range of barriers, including technoeconomic (cost of transport, specialised machinery for land spreading, variability in volumes of production, elemental composition, presence of contaminants, and nutrient availability) (e.g., Antille et al., 2013), regulatory (variability in contaminant concentrations, emerging contaminants, variability in landfill levies, regional bans on thermal treatment, lack of waste reuse regulations), and policy (lack of national and state bioeconomy policies, policy "silos" between waste and energy). These barriers must be addressed to facilitate the development of viable novel circular value-chains and biomass value webs or networks, which are "…complex systems of interlinked value chains in which biomass products and by-products are produced, processed, traded, and consumed" (Callo-Concha et al., 2020). Waste-to-energy technologies should be utilised for their potential beyond waste valorisation for energy, as they sit at the energy-waste-food nexus with the potential to reduce emissions and return essential plant nutrients to agricultural soils, while keeping valuable resources out of landfill. This approach will also address some of the barriers currently limiting the expansion of the bioenergy sector in Australia, as it faces issues between energy and waste management regulatory and policy silos (Arsic et al., 2022).

This discussion paper aims to highlight the joint opportunities to sustainably utilise organic waste resources in Australia by exploring the synergies between bioenergy production and providing safe and effective inputs for agricultural systems. Key barriers preventing waste valorisation are outlined and high-level Australian and European Union (EU) governance structures across climate, waste management and agricultural policies compared. Based on this analysis, three key actions that could be readily implemented to address these barriers are suggested.

2. VALORISATION OF ORGANIC WASTES AND BIOMASS: AN AUSTRALIAN PERSPECTIVE

2.1 Bioenergy in Australia

This discussion piece is focused on the use of organic wastes and agricultural residues for bioenergy and circular fertiliser production, rather than purpose-grown bioenergy crops. The total energy supply in Australia is dominated by fossil fuels (5390 PJ), with oil (33 per cent), coal (32 per cent) and natural gas (27 per cent) contributing over 90 per cent in 2019 (CEC 2020). Bioenergy supplied 5 per cent of total clean energy production (394 PJ) and 1.4 per cent of total Australian electricity generation in 2020 (CEC, 2020). Technologies such as anaerobic digestion (AD) and thermal treatment (e.g., pyrolysis, gasification, incineration) have been used to process municipal, industrial, and agricultural wastes. In 2021, the Australian Renewable Energy Agency's (ARENA) Bioenergy Roadmap stated bioenergy could "reduce emissions by about 9 per cent, [and] divert an extra 6 per cent of waste from landfill by 2030" (ARENA, 2021). The report also notes, "Organic wastes and residues are the largest resource opportunity, for developing the industry in the short term, representing 37 per cent of Australia's current [bioenergy] potential." (ARENA, 2021).

2.2 Barriers to bioenergy sector development

There are two key barriers to sector development. Firstly, operational silos between energy and waste at policy, regulatory, and technological adoption levels must be addressed. The current focus in Australia is on identifying the mix of technologies that can most rapidly transition away from fossil fuels towards renewable energy sources, such as hydrogen, solar and wind power (CEC, 2020). Bioenergy systems have been primarily installed for waste management purposes to either replace or reduce the flow of organic materials to landfill, reduce odors, or to mitigate GHG emissions at landfill. While this diversion of materials is important and represents both cost savings for industry and reducing the volume of materials sent to landfill, bioenergy risks being viewed as a waste management solution, leading to a lack of recognition and investment from within the energy sector. Secondly, the full potential of bioenergy must be utilised beyond waste-to-energy towards "waste-energy-bioresources". There is recognition that the residues from bioenergy systems can have value as agricultural inputs, but there is a need for better engagement with fertiliser companies and end-users to create viable products (GHD, 2022). Similar technical and economic barriers faced by the development of organic waste fertilisers (e.g., sustainable feedstock sourcing, reliability, transport logistics, developing supply chains) are currently limiting the investment in and adoption of bioenergy as a renewable energy technology. Value chains need to be assessed from end-to-end to ensure that there is suitable feedstock, viable energy balance, value added fertiliser products and market demand. A lack of appropriate coordination across industry sectors risks fueling competition for feedstocks and organic waste resources, which may not consider their current value on-farm in terms of natural capital or productivity or may create new barriers that prevent the full valorisation of waste streams at their highest order use.

2.3 Beyond barriers: Valorising bioresources from organic wastes by integrating the agricultural sector

These barriers may be addressed by acknowledging the essential roles that the agricultural sector plays in the development of a viable bioenergy sector in Australia. Agriculture contributes both "pull" (energy and fuel demand, need for GHG offsets and waste management solutions) and "push" (historical acceptance of industrial organic waste by-products as a landfill diversion strategy, an increasing demand for organic or bio-based fertilisers) drivers for bioenergy technology adoption. Integrating the waste management service provision by bioenergy systems with their capacity to produce a range of bioresources is important, as the cost savings from improved waste management can be reinvested to explore circular resource recovery from other system by-products. New circular value chains and webs can be created by applying a biorefinery model to fully capture bioresources from organic wastes via "the sustainable processing of biomass into a spectrum of marketable products and energy" (Cherubini et al., 2009). For example, the application of organic carbon-rich products such as digestate and biochar to agricultural soils has the potential to increase soil carbon sequestration (Breunig et al., 2019). The possibility to generate income through carbon trading will help to offset the cost of utilising the organic residues from bioenergy systems at scale and create viable business models, while valuing the full range of products generated by bioenergy will require the development of new circular value chains (Verra, 2022). Developing an environmental monitoring and auditing system to measure, trace and ensure compliance of sustainability, contaminant limits and product agronomic effectiveness will be critical to producing safe and effective bioresources from waste-to-energy technologies.

3. OPPORTUNITIES AND BARRIERS FOR UTILISING WASTE BIOMASS IN AGRICULTURE

3.1 Opportunities for bioresources within agricultural and food systems

Applying organic wastes as soil amendments has long been practiced on-farm for improving plant nutrition, building soil carbon and fertility, and therefore enhancing soil physico-chemical properties and soil function (e.g., Quilty and Cattle, 2011). Farmers have accepted organic wastes for free with delivery costs (and sometimes field application costs) met by the waste producer, as this has historically been a cost reduction strategy to divert waste from landfill or incineration. Soil amendments include "by-products" from processes such as anaerobic digestion (digestate) and pyrolysis/gasification (biochar), which have been applied for sewage sludge treatment as well as bioenergy generation (Abbott et al., 2018; Nkoa, 2014). While current organic fertiliser production is small (16 Mt produced in 2020 compared to approximately 200 Mt of mineral fertilisers), market analyses project demand for nutrients will almost double by 2030 (Richardson, 2022; Technavio, 2020). Interest in bio- or organic-based fertiliser materials has been growing rapidly, partly in response to raising energy costs and partly due to increasing demand for carbon-rich products to build soil carbon and fertility (Richardson, 2022). Farmers are beginning to engage with financial incentives such as carbon farming methods, which are a subset of carbon trading initiatives and include increasing soil carbon sequestration by applying carbon-rich material to soils (CER, 2023). Similarly, biodiversity credits aim to stimulate private investment in agricultural stewardship, supported by the recent "Agriculture Biodiversity Stewardship Package" (DAFF, 2022). The Emissions Reduction Fund (ERF), Australia's national mechanism to stimulate investment in activities that store carbon and mitigate climate change, includes biochar as one of the approved inputs for the "Estimating soil organic carbon sequestration using measurement and models method" (CER, 2023).

3.2 Technoeconomic, social, regulatory and policy barriers

There are several types of barriers to uptake for farmers across geographical scales. Technical barriers include the availability and consistency of waste feedstocks, the location of feedstocks compared to the location of end-users, transportation costs and logistics, and the type of technology used to process organic wastes and the resulting "by-products". The variability in nutrient composition and nutrient availability compared with mineral fertilisers, makes it difficult to predict nutrient supply from organic materials (Quilty and Cattle, 2011). This has consequences for accurately estimating field application rates and optimising the timing of soil application to minimise environmental losses, and maximise agronomic efficacy and economic return (Antille et al., 2017). Similar barriers exist in terms of determining the presence, concentrations, and fate of contaminants such as trace metals, persistent organic pollutants, and microplastics. Further, the feasibility of spreading bulky organic products on-farm can pose additional costs compared to manufactured fertilisers. This includes increased energy use through fuel consumption, which was estimated to be up to three times higher for spreading organic materials such as cattle paunch, or through engaging external contractors to spread materials using specialised field equipment (Antille et al., 2018). Research is needed to substantiate the claims made about various products for farm productivity or carbon and natural capital sustainability metrics. For example, although many commercial products and services note the potential for biochar applications for soil carbon sequestration and improving soil fertility and physical properties (e.g., water holding capacity) or biochemically (e.g., improving nutrient cycling), positive results are highly dependent on a range of complex factors such as feedstock, pyrolysis conditions, biochar formulation, application rate, soil and crop type, the interaction with biological and environmental stress, and monitoring time (performance over years compared to decades and beyond) (Joseph et al., 2021).

Soft barriers such as social, policy and regulatory issues are also challenging. Social barriers include attitudes to waste products, willingness to pay versus accepting free residues, odor, concerns over soil contamination and risk of transfer of such contaminants to the food chain. Skepticism around product benefits, capacity to accept risks associated with changing management practices on-farm, and a lack of co-design practices between engineers, waste treatment processors and agricultural end-users to work towards generating enhanced-quality products for farmers have also been reported (e.g., Marchuk et al., 2023; McCabe et al., 2020). Policy and regulatory barriers include waste management regulations and the lack of clarity in emerging "end of waste codes" to allow the application of waste products in soils. There has also been stakeholder disagreement on acceptable contaminant levels for blended products such as composts (Australian Standard AS 4454-2012, Composts, soil conditioners and mulches), and reports of some industrial waste producers using blending processes to dilute contaminated waste streams into "clean" streams to avoid disposing of regulated wastes. While recent efforts have been made at the local, state, and federal government levels to facilitate the shift to CE models, developing CE frameworks and decision-making tools based on inorganic materials such as metal, glass and plastics risks missing opportunities for organic resources (Circular Australia, 2022). Additional barriers also include the administrative cost burden on farmers to access emerging carbon or natural capital markets, which otherwise is a significant opportunity as farmers manage over 55% of Australia's total land area (ABARES, 2022).

4. TOWARDS A NATIONAL CIRCULAR BIOECONOMY FOR ENERGY AND AGRI-FOOD SYSTEMS

Developing a holistic approach towards a circular bioeconomy could address the range of barriers identified earlier by moving towards full valorisation of biological resources, from virgin feedstocks to organic wastes. Effective implementation of circular strategies will likely deliver positive economic, social, cultural, and environmental outcomes (Burggraaf et al., 2020; 2022). Bioeconomy can be defined as "the production, utilisation, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy" (IACGB, 2020). Circular bioeconomy integrates CE principles into this definition, by "aim[ing] to provide sustainable wellbeing through the provision of ecosystem services and the sustainable management of biological resources (plants, animals, micro-organisms, and derived biomass, including organic waste). These [resources] are transformed in a circular manner into food, feed, energy, and biomaterials – within the ecological boundaries of the ecosystems that it relies on." (Palahi et al., 2020).

To identify potential actions that could be taken, relevant climate, waste management and agricultural policies were compared between Australia and the EU. The European Commission has pioneered both the strategic development of the bioeconomy (2012 Strategy "Innovating for Sustainable Growth: A Bioeconomy for Europe, Action Plan in 2018) and the CE (2015 Action Plan for the Circular Economy), which are now both key elements in the 2019 EU Green Deal. From an Australian perspective, policies and legislative drivers include the recent Climate Change Act 2022, which confirms Australia's commitment to reduce GHG emissions by 45% by 2030 and to reach net zero by 2050. The National Waste Policy 2018 (NWP) and National Waste Policy Action Plan 2019 (NWPAP) aim to "…embod[y] a circular economy… [to] maintain the value of resources for as long as possible…" (DEE, 2018; 2019). The NWP and NWPAP include strategies for municipal organic waste but not agricultural wastes, likely due to their large volumes and dispersed nature. A National Waste Roadmap for the agricultural, forestry and fisheries sectors in Australia has been drafted and is currently under review (AgriFutures, 2022). However, proposed strategies for agricultural waste reuse must consider feasibility (e.g., large farm sizes and distances from processing centers or customers) and must weigh the competition between new proposed processes and products from collecting wastes (e.g., stubble) with their current provision of natural capital (e.g., providing habitat for biodiversity) and productivity values (e.g., bedding, soil cover, returning carbon and nutrients to soils) (Brady et al., 2015). While CE policies have recently been adopted federally and by most states, there is currently no national bioeconomy policy. While three states have specific bioeconomy policies, other states have developed policy documents for aspects of the bioeconomy such as waste-to-energy, biotechnology, or "organics" more broadly (Arsic et al., 2022).

By comparing the relevant high-level governance structures between Australian and the EU, there are three key gaps from an Australian perspective (Iriarte et al., 2021) (Figure 1). Firstly, while Australia is participating in international bioeconomy forums (as an observer), the lack of a national policy means there is a gap in addressing complex institutional co-ordination and actor cooperation across the waste-energy-bioresources nexus. Secondly, the EU system of governance includes two critical instruments that are missing from the Australian context: the system underpinning the creation of new circular value chains, the Eco-Management and Audit (EMA) Scheme (EC, 2022), and the Circular Economy Package Fertiliser Regulation (Regulation (EU) No 2019/1009) for production and tracing of "circular" fertilisers (EU, 2019). Finally, cross-sectoral key research, development and extension priorities need to be identified that would allow for the expansion of these emerging industries and products supported by sustainability metrics. These actions could be incorporated into a framework such as the National Agricultural Innovation Policy Statement, which outlines a vision, the priorities needed to achieve the vision, current and future reforms, the key participants in the system and their strategic roles and relationships, and outlines how to monitor and evaluate success (DAWE, 2021). There is a resurgence of interest in industrial policy, beyond innovation policy, particularly as a means of addressing environmental challenges; an approach that is appropriate to issues that involve inter-industry linkages and clusters of technological innovations (Aiginger and Rodrik, 2020). In addition, by coordinating this policy through the Federal Department of Agriculture, Fisheries and Forestry, the importance of returning nutrient or carbon-rich inputs to support growing productivity in agricultural systems would support the sector's ambitious $AUD100 billion production value goal by 2030 (Ag2030), as well as supporting natural capital in agroecosystems. The development of these governance tools would leverage Australian agriculture's emerging potential for supporting global food security, as well as investing in bioenergy technologies and international sustainability markets (Figure 2).

5. CONCLUSIONS

The sustainable utilisation of biomass derived from organic waste in sectors such as bioenergy and agriculture

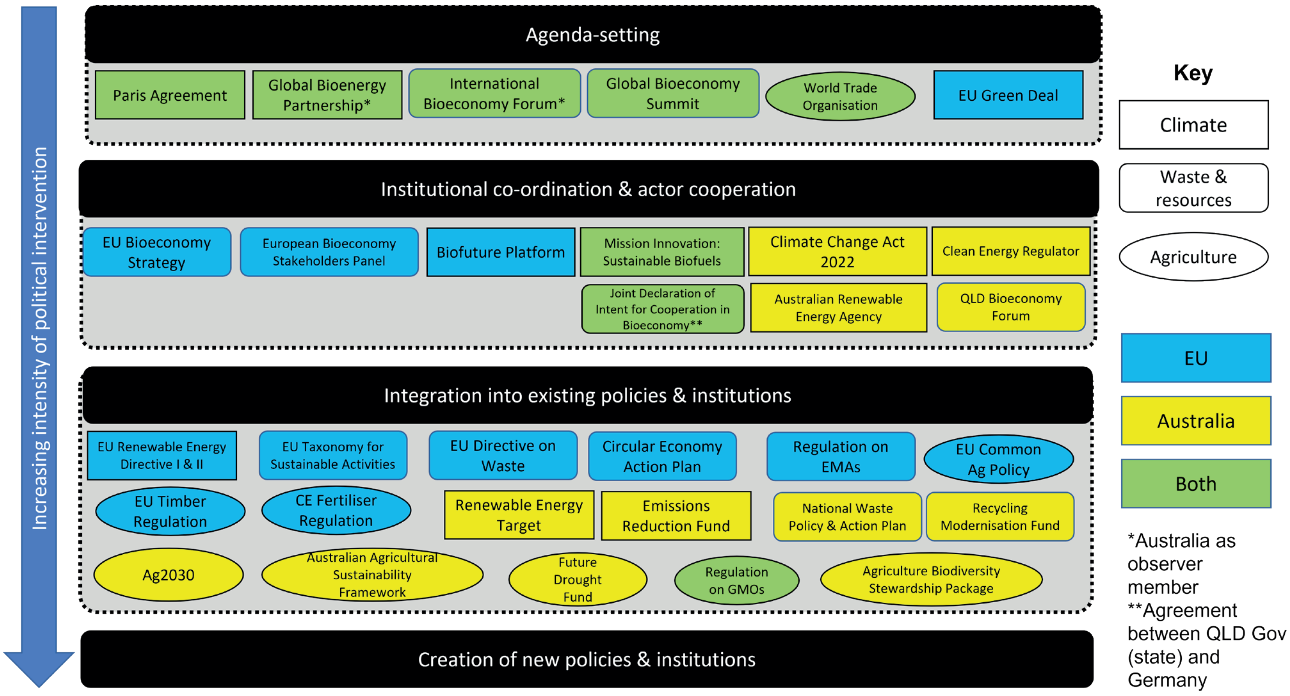

FIGURE 1: Governing a circular bioeconomy: A comparison between the European Union and Australia (modified from Iriarte et al. 2021).

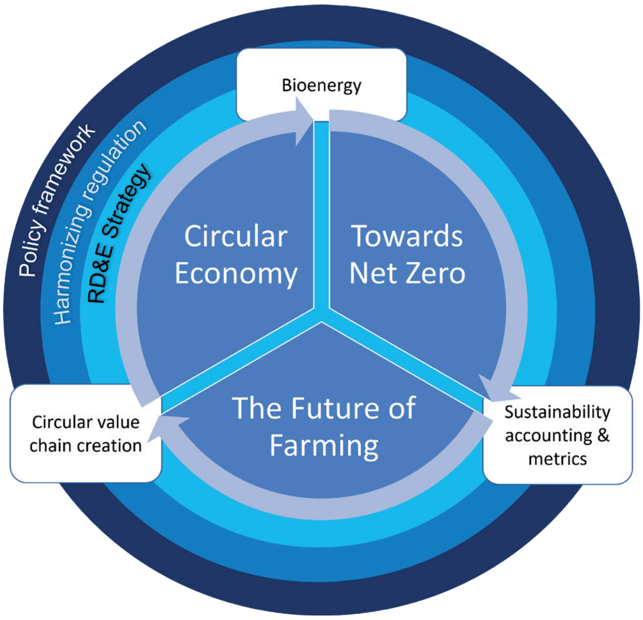

FIGURE 2: A conceptual model outlining the potential roles of bioenergy, emerging circular value chains, and the development of transparent and traceable sustainability accounting platforms and metrics to coordinate actions towards CE models, net zero pathways and sustainable agricultural systems.

rely on the successful integration of circular bioeconomy concepts across multiple systems and governance frameworks. The techno-economic, social and policy barriers limiting the use of these resources could be addressed by recognising the key role of agricultural stakeholders in emerging bioenergy technologies and supply chains, where bioenergy has the potential to generate multiple valuable bioresources to support sustainable agricultural production. Future actions to realise this potential include the development of a national circular bioeconomy framework and governance structure, integrating systems such as auditing mechanisms within new sustainability tracing and accounting platforms, and identifying critical research and technology, development, and extension priorities. Through this approach, bioresources in organic wastes could be used to sustainably establish energy and agri-food production, while reducing emissions and improving resource use efficiency.

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