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Review

Food waste biorefinery towards circular economy in Australia

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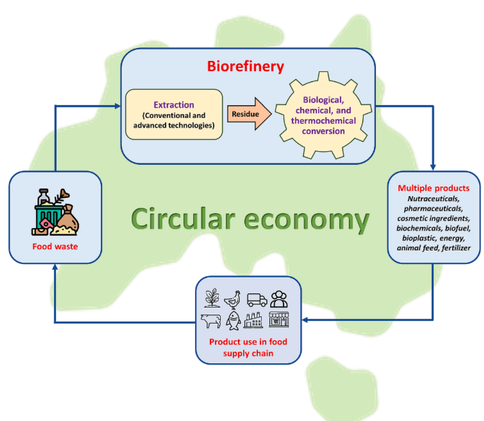
HIGHLIGHTS

- Food waste generation, management, and legislation in Australia is reviewed.
- Major Australian food waste streams and their biorefinery potential was evaluated.
- Biorefineries from major food waste streams for circular economy are discussed.
- Existing food waste conversion initiatives and future research areas are provided.

GRAPHICAL ABSTRACT



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ABSTRACT

Staggering amounts of food waste are produced in Australia, and this review provides food waste based biorefinery opportunities in moving towards a circular economy in Australia. The current food waste scenario in Australia including an overview of primary food waste sources, government regulation, and current management practices is presented. The major food waste streams include fruit and vegetable (waste from wine grapes, citrus, apple, potato, and tomato), nuts (almond processing waste), seafood (Fish waste), dairy whey, sugarcane bagasse, and household and businesses. The composition of these waste streams indicated their potential for use in biorefineries to produce value-added products via various pathways combining direct extraction and biological and thermochemical conversion. Finally, the efforts made in Australia to utilize food waste as a resource, as well as the challenges and future directions to promote the development of concrete and commercially viable technologies for food waste biorefinery, are described.

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1. Introduction

Food waste is a food that is discarded or lost at various stages of the food supply chain, including production, storage, processing, distribution, and uneaten food from households and businesses (retail, wholesale, restaurants, supermarkets, and catering services) (Teigiserova et al., 2020). A large amount of food is wasted worldwide as it moves from the producer to the consumer. Approximately 1.3 billion tonnes of food waste (one-third of total global food production) is generated each year, costing nearly $990 billion and leaving a high carbon footprint of 3.3 billion tonnes of CO_2 equivalent (Patel et al., 2019). With current generation rates, global food waste is expected to reach 3.40 billion tonnes by 2030. As a result, food waste has become a significant financial and environmental issue, necessitating an urgent intervention to reduce food waste generation and the development of more innovative food waste management. Food waste typically contains biopolymers and bio-actives such as proteins, carbohydrates, lipids, lignin, polyphenols, and natural colours that can be recovered and used in food, feed, pharmaceutical, and cosmetic products. Some of these constituents can also be transformed into various high-value chemicals, bioplastics, functional materials, and biofuel. Thus, food waste can be diverted from traditional elimination routes and used as a resource in an integrated biorefinery framework to produce multiple value-added materials that can be fed into the forward supply chain, thereby creating a circular economy (Narisetty et al., 2022).

Australia generated about 31.2 million tonnes of food waste in 2020–21 from across the production, supply, and consumption chain (Joe Pickin et al., 2022). This waste has a significant environmental cost, consuming 2600 GL of water and accounting for 3% of Australia's annual glasshouse gas emissions (17.5 million tonnes of CO_2 equivalent), as well as a $36.6 billion annual economic cost (Van Biene et al., 2021). Furthermore, traditional food waste disposal methods such as landfilling, composting, and incineration are used in Australia, which emit large amounts of greenhouse gases (CO_2 and methane) into the atmosphere, landfill leachates causing groundwater contamination, odours, unhealthy landforms, and pathogen growth, resulting in environmental and health problems while providing few economic benefits (Shadbahr et al., 2022). Although some of the methane produced in large landfills has been captured and used to generate electricity, current trends show a significant decline in landfill energy recovery, particularly in New South Wales, South Australia, Tasmania, and Victoria (Pickin et al., 2018). Furthermore, depending on the type of waste and landfill site location landfill charges ranging from $50 to $200 per tonne of waste must be paid to the state raising the landfill cost (Pickin et al., 2018). Thus, in November 2017, the Australian government released a National Food Waste Strategy to reduce the generation of food waste and its disposal to landfills. This strategy ensures sustainable food production and consumption while also helping Australia to minimize greenhouse gas emissions to meet the commitments of the UN Framework Convention on Climate Change (Arcadis, 2019). The Australian government encourages research and investment in food waste treatment through this strategy to return maximum waste to the product lifecycle and achieve a circular economy. An integrated bio-refinery approach can provide an opportunity to attain Australia's circular economy goal, where food waste can be used to generate significant economic benefits, while also minimizing its negative impact.

Therefore, this review provides an overview of the trend of food waste generation from various sources, as well as the current state of food waste disposal, management, and legislation development in Australia. The major food waste streams in Australia and their potential for utilization as a resource in integrated biorefinery concept is presented. This review also discusses potential biorefinery schemes for converting major food waste streams into high-value products based on recent research conducted in Australia and around the world, as well as initiatives and efforts undertaken by Australia in this regard. Finally, the current challenges and road maps for Australia's transition to a circular economy based on food waste biorefineries are discussed.

2. Overview of food waste generation and management

2.1. Food waste sources and production

Most of the food waste (more than 90%) generated in Australia comes from primary production sources, food processing facilities, and households and businesses (Arcadis, 2019). The food waste from primary sources is usually produced due to damage caused during harvesting and handling, fresh produce loss due to not meeting retail criteria, no harvest when market prices are low, loss through poor storage at the primary production site, and diseases or bad weather. Fruits, vegetables, and broadacre crops are the main food waste generating primary production sectors in Australia that generated about 2.5 million tonnes in 2020–21 (Joe Pickin et al., 2022). The food and beverage processing industry is Australia's largest manufacturing industry and a significant contributor to the Australian economy. Undoubtedly, the largest quantity of food waste (23.4 million tonnes in 2020–21) in Australia comes from food and beverage processing sector, with the key generators being the processing of fruits, vegetables, broadacre crops, nuts, and seafood, as well as the production of wine and dairy products. The majority of food waste generated by households and businesses in Australia constitute unconsumed, unsold, and damaged food, as well as inedible food scrap, accounting for approximately 4.6 million tonnes in 2020–21 (Joe Pickin et al., 2022).

2.2. Legislation and current management practices

Waste management is primarily the responsibility of state, territory, and local governments in Australia. Each Australian state and territory has its own set of legislation and policy frameworks, but they all share common themes and waste management goals. States and territories oversee imposing waste recycling licence requirements, landfill levies, recycling incentives, and environmental protection measures. On the other hand, local governments provide a variety of services including waste collection, recycling, processing, disposal, landfill management, gas capture, and power cogeneration (Environment Committee, 2018). Fig. 1a depicts the evolution of national level laws and policies in Australia that are relevant to the control of national food waste. The first comprehensive approach to waste management is National Waste Minimisation and Recycling Strategy which was established in 1992 by Council of Australian Governments to develop a common approach to waste management programmes across various jurisdictions in Australia, with the goal of reducing landfill waste by 50% by the year 2000 (Jones, 2020). This strategy, along with the National Environment Protection Council Act of 1994, laid the foundation for existing state and territory legislation and serves as a framework for developing National Environmental Protection Measures (NEPMs) to reduce waste impact and maximise reuse and recycling (Jones, 2020). As part of this framework, a National Waste Policy was established in 2009 to provide a clear direction for reducing waste disposal and using it as a resource through 2020. The Product Stewardship Act 2011, one of the outcomes of the National Waste Policy, was enacted to establish a national framework for reducing waste increasing recycling and recovering valuable materials from end-of-life products in an environmentally friendly manner (DCCEEW, 2011). However, the National Waste Report 2016 revealed a continuous increase in waste volumes due to a lack of effective collaboration among different jurisdictions (Randell, 2016). As a result of this, as well as China's waste import ban, the Australian government announced a new National Waste policy in 2018 that provides a foundation for stakeholder collaboration to address national waste issues, with a focus on avoiding waste generation, reducing waste for disposal, and utilising waste as a resource to deliver economic, environmental, and social benefits to achieve circular economy by 2030. The action plan of the new national waste policy includes supporting the development of

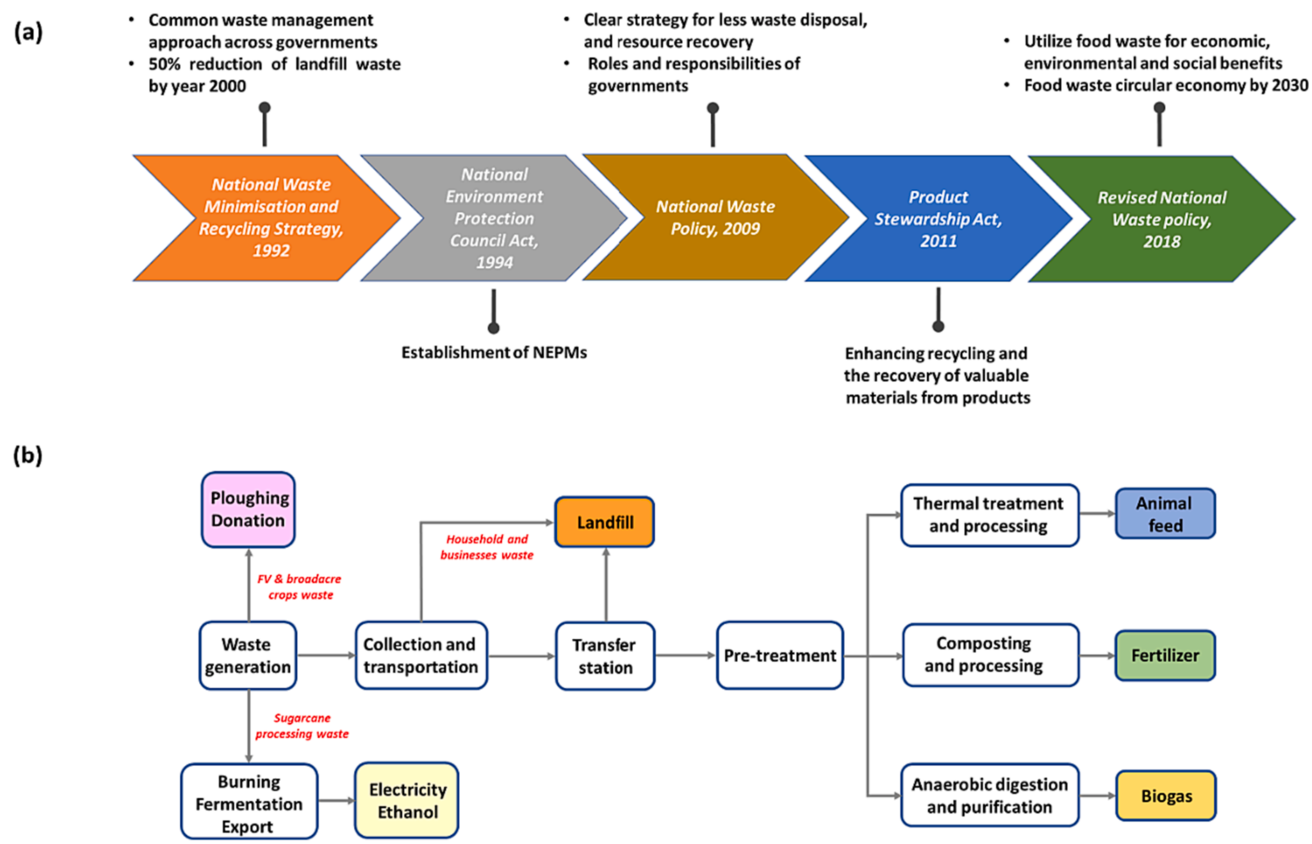

Fig. 1. (a) Australian national level legislation and policy framework for food waste management (b) Food waste management routes in Australia.

infrastructure for organic waste processing by 2022, halving organic waste going into landfills, achieving 80% resource recovery, and lowering per capita waste production by 10% by 2030 (DCCEEW, 2019).

Australia employs a variety of first-generation waste management strategies, including landfilling, composting, animal feed, anaerobic digestion (AD), and incineration. The majority of food waste (approximately 85%) generated by primary production sources (fruits, vegetables, and broadacre crops) is not collected and ploughed into the ground for soil benefit, and only a small portion is reused for donation and animal feed (11%) and composting (4%) (Joe Pickin et al., 2022). Sugarcane bagasse and molasses account for approximately 55% of food waste generated by food processing facilities, with sugarcane bagasse being incinerated inefficiently to generate energy in sugar mills, resulting in a loss of 52–67% of its energy content while emitting a significant amount of CO_2. Half of the molasses produced is exported, while the other half is used to produce domestic ethanol (Hamawand et al., 2021). The remainder of food waste generated by food processing facilities is used for animal feed (27%), composted (16%), and anerobic digested (2%) (Joe Pickin et al., 2022). The majority of food waste (83%) generated by households and businesses is directly disposed of in landfills, with the remainder recycled through composting or AD (Arcadis, 2019). The major food waste management routes in Australia are depicted in Fig. 1b. Food waste is collected at its source and transported either directly to a landfill (mostly in the case of food waste generated by households and businesses) or to a transport station for transport to a remote processing or disposal site. Landfills dominate waste management infrastructure in Australia, with 1172 (licenced and unlicensed) landfills in operation. However, landfills emit approximately 8.7 million tonnes of CO_2 equivalent greenhouse gas in Australia (Joe Pickin et al., 2022). The most common methods for processing food waste at processing sites are conversion to animal feed, composting, and AD. Prior to such processing, food waste is typically pre-treated through alternative waste treatment facilities to ensure that it is free of non-organic components (plastics and metals) that are unacceptable for animal feed and impede biodegradation in composting and AD. In the case of animal feed, a specific type of food waste is usually chosen based on its nutritional (protein and oil) and energy content, and then thermal treatment is used to dehydrate and sterilise the food waste. The variability in composition and the presence of pathogens, heavy metals, and organic pollutants in food waste can limit its use as animal feed (Li et al., 2019). Around 150 composting facilities in Australia convert food waste into products such as fertilisers for soil application (Solutions, 2020). It is important to consider the issues of reduced microbial activity caused by food waste specific characteristics such as acidity, high oil content, and high salinity, as well as the possibility of heavy metal contamination of soil (Li et al., 2019). Over 100 sewage AD facilities in Australia have spare capacity, which is sometimes used for co-digestion of food waste to produce biogas (Elieta and Mendo, 2019).

3. Major food waste streams and their potential for biorefinery

3.1. Major food waste streams

The major sectors in Australian food supply and consumption chain include production and processing of fruits and vegetables, crops, nuts, eggs, seafood, livestock, wine, dairy, businesses (wholesale, retail, and institutions), and households. The main food waste streams from the production and processing sectors were determined by adding the amount of food commodity lost at the production site (food commodity produced that never made it to the next stage of the food supply chain) and the amount of food waste generated by processing food commodity. The amount of food commodity produced, lost at the production site, and entering the processing stage was calculated using the Australia's horticulture statistics handbook (2021–22), Fisheries and aquaculture statistics database (2021–22), Australian bureau of statistics database (2021–22), and Dairy Australia report (2022), as well as the CSIRO's

Table 1
Major food waste streams in Australia.

Food commodity	Production (Kt/year)	Processing (Kt/year)	Production loss[a] (Kt/year)	Processing waste[b] (Kt/year)	Total waste (Kt/year)
Fruits and vegetables					
Wine grapes	1750	1750	14	437.5 (Grape marc)	451.5
Citrus	760.1	222	48	133.2 (Peels)	181.2
Apple	307.6	89.5	32	26.8 (Pomace)	58.8
Potato	1462.0	979.5	110.0	365.5 (Peels)	475.5
Tomato	436.9	222.8	127.0	15.6 (Pomace)	225.6
Broadacre crops					
Sugarcane	31,500	31,500	475	12,900 (Bagasse and molasses)	13,375
Nuts					
Almond	177.7	177.7	–	151 (Shell and hull)	151
Seafood					
Fish	164.2	106.6	–	58 *(Muscles skin fins bones heads viscera scales)*	58
Dairy					
Milk	8,554,000	5,303,000	–	1600 (Whey)	1600
Household and businesses					
Mixed food	4600	–	–	–	4600

[a] Production loss (loss at production site) is not considered in the measurement of food commodity production. [b] amount of processing waste was calculated using the percentage of waste generated by processing of each food commodity given in section 3.1.

grower's food loss survey (2019). The amount of by-products produced by food commodity processing was calculated using previous literature from Australian and international studies. Table 1 shows the major food waste streams in Australia. Sugarcane is the food commodity that generates the most waste. Australia is a major producer of sugarcane and the world's second largest exporter of raw sugar. Whole of its sugarcane produce (31.5 million tonnes) is processed into raw and refined sugar (Joe Pickin et al., 2022), generating a large amount of sugarcane bagasse (30% of total sugarcane) and molasses and mud (7% of total sugarcane) (Meghana & Shastri, 2020). Australia ranks fifth wine producer in the world (1.48 billion litres produced in 2021) and generates a large amount of grape marc (25% of the grape mass) as a waste, the majority of which is pomace (50–60%) and seeds (40–50%) (Kwiatkowski et al., 2020; Sirohi et al., 2020). Fruits and vegetables are perishable food commodities with a higher percentage of inedible parts. Among the fruits and vegetables, potato and tomato are major commoditise contributing to food waste in Australia due to large amount of loss at farms and significant processing (50% for potato and 70% for tomato) to chips (from potato) and sauce/ketchup and puri (from tomato) (Horticulture, 2022; Pickin et al., 2018) which generates potato peels (25% of the potato mass) and tomato pomace (3–5% of the tomato mass) as waste (Ebrahimian et al., 2022; Lu et al., 2019). Furthermore, citrus and apples are the major fruits produced and processed to juice in Australia and thus contributes to food waste generation, particularly through the production of citrus peels (up to 60% of the citrus fruit mass) (Jeong et al., 2021) and apple pomace (30% of the apple mass) (Zhang et al., 2021). Australia processes a large quantity of its milk (62% of total milk production) and is the world's third largest exporter of milk products (such as cheese, butter, and milk powders). Consequently, a large amount (1.6 million tonnes) of whey is produced through milk processing plants in Australia (Das & Ghosh, 2016). Australia is the world's second largest almond producer and processor with almond shells and hulls (85% of almond mass) constituting major nut waste streams (Almond Board, 2020). In terms of seafood, fish accounts for the lion's share (approximately 70%) in Australia the vast majority of which is processed (Howieson & Choo, 2017). Fish processing typically generates more than 50% of the processed mass as waste (fish head, internal organs, bone, fin, and scales), making it Australia's most significant

Table 2
Composition of major food waste streams.

Waste components	Composition (%)[a]	Reference
Wine grapes pomace	Phenolics: 2–6.5, Cellulose: 27–37%, Hemicellulose: 26, Lignin: 16.8–24.2%	(Ahmad et al., 2020; Madadian et al., 2022; Martinez et al., 2016)
Wine grapes seeds	Phenolics: 4–6, Oil: 13–20, Protein: 25–40, Cellulose: 7, Hemicellulose: 24, Lignin: 49	(Ahmad et al., 2020; Madadian et al., 2022)
Citrus peels	Phenolics: 5–8, limonene: 0.5–4, Pectin: 13–42.5, Cellulose: 9.2–37, Hemicellulose: 4.2–31.1, Lignin: 0.54–8.6	(Jeong et al., 2021; Singh et al., 2020)
Apple pomace	Phenolics: 0.001–0.29, Protein: 3–7, Cellulose: 14–39, Hemicellulose:10–29, Lignin:14–25, Pectin: 8–19	(Costa et al., 2022b; Zhang et al., 2021)
Potato peels	Starch: 16–35, Protein: 10–25, Phenolics: 0.25–1.2, Cellulose: 7–40, Hemicellulose: 4–14, Lignin: 12–32	(Ebrahimian et al., 2022)
Tomato skin	Phenolics: 4–15, Lycopene: 0.12–0.29, Cellulose: 20, Hemicellulose: 50, Lignin: 15–25	(Kehili et al., 2016; Lu et al., 2019)
Tomato seeds	Oil: 18–25, Protein: 24–40, Cellulose: 16, Hemicellulose:11, Lignin: 38	
Sugarcane Bagasse	Cellulose: 35–45, Hemicellulose: 26–35, Lignin: 11–25	(Chourasia et al., 2021)
Sugarcane Molasses	Total sugars: 63–65, Sucrose: 43–45	(Hamawand et al., 2021)
Almond shell	Cellulose: 16–41.5, Hemicellulose: 31–36, Lignin: 29–31	(Kaur et al., 2020; Morales et al., 2020)
Almond hull	Phenolics: 2.5–5, Pectin: 26, Cellulose: 9–35, Hemicellulose: 7–15, Lignin: 8–16	(Najari et al., 2022; Salgado-Ramos et al., 2022a; Salgado-Ramos et al., 2022b)
Fish muscles skin fins bones heads viscera scales	Protein: 49–58, Oil:7–19, Ash: 21–30, Collagen from skin and scales: 5–51	(Coppola et al., 2021)
Milk whey	Protein: 0.6–0.8, Lactose: 4–5	(Das & Ghosh, 2016)
Mixed food[b]	Phenolics: 3–10, Protein: 5–18, Lipids: 14–30, Fibers: 35–55	–

[a] the composition is based on both Australian and international research. [b]the composition of mixed food waste collected from various locations (apartments, hospitals, restaurants, and supermarkets) in Australia at various times was determined in our laboratory.

seafood waste stream. Australia has one of the highest per capita food waste production rates (180–190 kg) at the consumption stage (Joe Pickin et al., 2022), making mixed food waste from households and businesses a major food waste stream.

3.2. Biorefinery potential of major waste streams

Aside from availability, the composition of food waste is an important factor in determining the conversion potential to produce value-added products. Table 2 shows the composition of the major food waste streams in Australia. Fruits and vegetable (wine grape, citrus, apple, potato, and tomato) waste consists of peels/skin, pulp, and seeds. Seeds are majorly present in wine grapes and tomato waste. These fruits and vegetables waste mainly contain polyphenols, carotenoids, oil, pectin, starch, and lignocellulose. Polyphenols are bio-actives with a range of biological activities such as antioxidant, anti-inflammatory, antiaging, antimicrobial, anticancer, cardioprotective, antidiarrheal, antidiabetic, and anti-obesity (Singh et al., 2020; Sirohi et al., 2020). Tomato waste contains lycopene, the most powerful antioxidant carotenoid (Lu et al., 2019). Oil present in grape and tomato seeds is rich in bioactives such as tocopherols, phytosterols, and phenols as well as polyunsaturated fatty acids due to which it provides antioxidant, anti-inflammatory, antidiabetic, and antihyperlipidemic activities and has a high demand in the cosmetic, food, and pharma industries (Ahmad et al., 2020; Lu et al., 2019). Oil from fish waste is rich in omega-3 fatty acids while that from mixed food waste can be *trans*-esterified to produce biodiesel. Protein is another important component of grape and tomato seeds, potato peels, dairy whey, fish waste, and mixed food waste, and it can be used as an ingredient in the food and feed industries to compensate for a lack of certain amino acids like lysine and sulphur amino acids, or it can be hydrolysed to bioactive peptides (del Mar et al., 2019). The structural protein collagen, which is found in fish waste (skin and scales), is used as a biomaterial and food additive (Coppola et al., 2021). Citrus peels and apple pomace contain pectin, a commercial hydrocolloid widely used as a gelling and thickening agent in the food, cosmetic, and pharmaceutical industries (Talekar et al., 2020). Starch from potato peels is commercial polysaccharide widely used in the food, pharmaceutical, cosmetic, textile, chemical, paper industries, as well as the making of bioplastic and bioethanol (Ebrahimian et al., 2022). Sugarcane bagasse contains up to 85% of lignocellulose (mainly cellulose and hemicellulose) and molasses contains up to 65% of sugars (mainly sucrose) on a dry weight basis (Chourasia et al., 2021; Hamawand et al., 2021). Almond waste is another rich source of lignocellulose (up to 80%) along with the presence of other valuable products such as phenolics and pectin (Salgado-Ramos et al., 2022a). Lactose is abundant in dairy whey, whereas mixed food waste contains a mix of sugars, polysaccharides, and lignocellulose. The sugars and lignocellulose from these waste can be used as a substrate to produce biofuels, organic acids, pigments, biodiesel, oil, feed protein, bioplastic, functional polysaccharides via microbial fermentation, biochar and platform chemicals via thermochemical conversion, cellulose nanocrystals and prebiotic oligosaccharides via chemical and enzymatic hydrolysis (Kumar Awasthi et al., 2022; Morales et al., 2020; Reena et al., 2022).

4. Biorefinery for converting major food waste streams into products

Considering their quantity generated, availability at single point source (such as production and processing site), and potential as a resource for production of multiple products as described above, this section presents various biorefinery approaches for converting these major food waste streams into multiple high-value products.

4.1. Biorefining strategies for production of value-added products

Some marketable products such as polyphenols, oils, protein, and polysaccharides can be extracted directly from food waste in the first step, while others can be produced in the following steps through chemical, thermochemical, or biological conversion of leftover residue, whole food waste, or extracted component. The conventional methods for recovering products directly from food waste are maceration or hydro-distillation using mechanical agitation and Soxhlet extraction with solvent, acid, and alkali. The conventional extraction methods are lengthy, typically require pre-drying of food waste and produce lower product yield with reduced quality and toxic/corrosive waste (Sirohi et al., 2020). Ultrasonic-assisted extraction (UAE), microwave-assisted extraction (MAE), enzyme-assisted extraction (EAE), hydrodynamic cavitation (HC), and pulsed electric field extraction (PEF) are examples of advanced technologies. They avoid energy intensive drying of food waste, promote cell lysis via the high energy released by bubble collapse in UAE and HC, rise in internal water temperature and pressure in MAE, cell wall degradation in EAE, and electroporation of cell membrane in PEF, thereby accelerating extraction with minimal solvent (Sirohi et al., 2020). Furthermore, advanced methods like subcritical water extraction (SWE) and supercritical fluid extraction (SFE) use water and high-pressure CO_2 as solvents, making them safer and more environmentally friendly (Sirohi et al., 2020). However, these advanced methods necessitate precise optimisation of operating conditions particularly in the case of UAE, MAE, HC, and SWE to avoid product breakdown, high capital costs in the case of PEF and SFE, and high enzyme cost due to limited enzyme stability and reusability in EAE (Caldeira et al., 2020). Thermochemical conversion encompasses thermal breakdown through incineration, pyrolysis, gasification, hydrothermal processing, as well as thermocatalytic conversion of food waste components into products. Incineration involves burning of food waste to generate heat for electricity production. However, it generates toxic dioxins due to high moisture content of food waste, toxic gasses, and ash, requiring pre-treatment to reduce moisture and the installation of pollution control equipment, which reduces its overall cost-efficiency (Shah et al., 2022). Pyrolysis operates above 400 °C in absence of oxygen and produces solid biochar, liquid bio-oil, and gaseous product, whereas gasification involves partial burning (700–1000 °C) to produce syngas and biochar. The high moisture content of food waste necessitates pre-drying, which limits the techno-economics of both techniques (Shah et al., 2022). Hydrothermal processing, on the other hand, deals with high moisture content and involves thermal treatment (120–550 °C) under pressure (20–150 bar) to keep water in liquid state, resulting in carbonization to energy rich biochar and breakdown of complex components into simple form (liquid biocrude product) (Son Le et al., 2022). In thermocatalytic conversion, acid, metal, or ionic liquid-based catalysts at 100–200 °C facilitate the hydrolysis of polysaccharides into monomeric sugars and conversion into platform chemicals by dehydration, rehydration, isomerization, and redox reactions (Amesho et al., 2022). Thermocatalytic conversion is both fast and high yielding, but it necessitates harsh conditions as well as costly equipment and catalyst (Shah et al., 2022). Biological conversion includes microbial transformation of food waste sugars or leftover residues after direct product extraction into biofuel, bioelectricity, biochemicals, bioplastic, and fertilizer via aerobic/anaerobic fermentation, composting, and AD (Sharma et al., 2020). Fermentation is ecofriendly, but it has long reaction times and requires pretreatment of food waste to release sugars (Narisetty et al., 2022). Composting converts food waste to compost for soil application via an aerobic process while AD produces methane via sequential hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Shah et al., 2022). Although composting is ecofriendly, it requires a very long time, high operational cost, and large area. Methane yield in AD is limited by the biodegradability and bioavailability of the food waste, which can be enhanced by the additives, enabling co-digestion, and pre-treatment (Narisetty et al., 2022). As both composting and AD do not harness full value of food waste, it is recommended to employ them following direct extraction or fermentation to increase revenue.

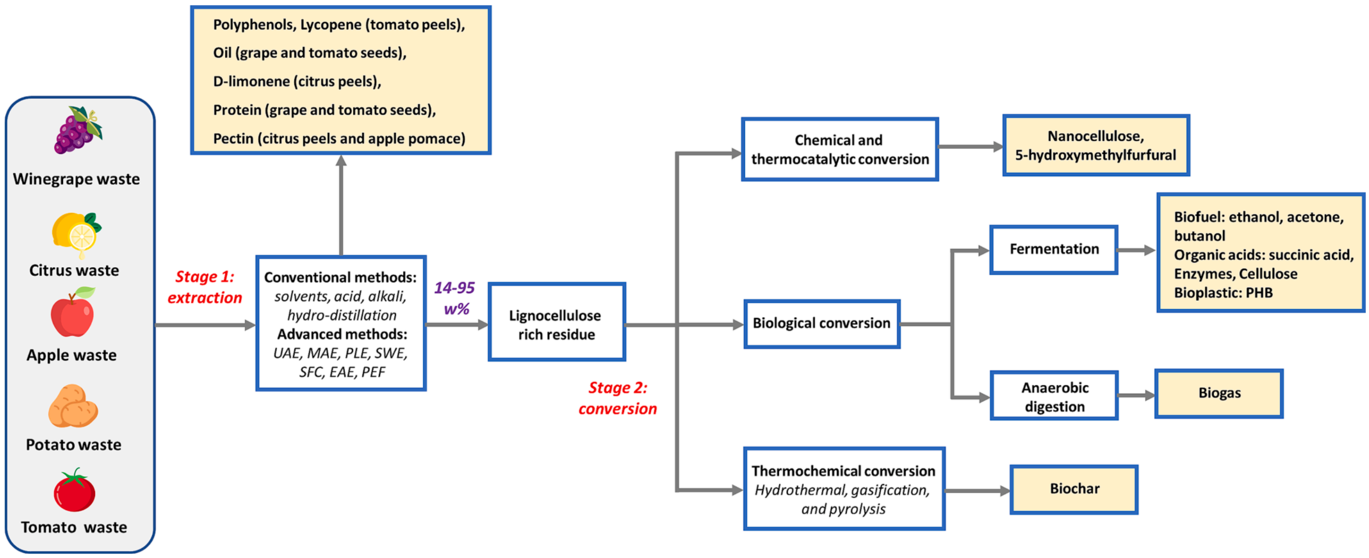

Fig. 2. Biorefinery routes for major fruits and vegetable waste. The weight percentage (w%) is used to express the leftover waste going to conversion stage after the extraction stage. Icons from flaticon.

4.1.1. Fruit and vegetable waste biorefinery

Fig. 2 demonstrates biorefinery schemes for the conversion of major fruit and vegetable wastes into value added products. The products such as phenolics, carotenoids, oil, starch, and pectin can be directly extracted from this waste. Phenolics can be extracted using both conventional solvent extraction and with advanced technologies with improved extraction rate. For instance, fast extraction of total phenolics (1.64–1.74 and 1.82–2.12 kg per tonne) was performed from Australian white and red grape pomace using microwave assisted thermal extraction over conventional thermal shaking with 60% ethanol as solvent (Kwiatkowski et al., 2020). Similarly, faster extraction of phenolics (2%) was obtained from Australian citrus pomace by aqueous ultrasound treatment (Papoutsis et al., 2018) compared to conventional organic solvent extraction without affecting the extraction yield. The phenolics yields in conventional solvent extraction can be improved by further treatments that release the bound phenolics. For instance, the higher phenolics yield (1.23–1.37%) was obtained with conventional extraction by aqueous-methanol extraction followed by sequential base and acid hydrolysis of the Australian apple pomace (Li et al., 2020b). Conventional solvent extraction with water, ethanol, and methanol yielded similar amount of phenolics (0.94–1.07%) from peels derived from waste potatoes collected from the Australian local market (Kuppusamy et al., 2020). Lycopene can be recovered from tomato waste using both conventional solvent extraction and advanced extraction technologies, with higher lycopene yield obtained by advanced techniques such as ultrasonication of tomato waste residue obtained from an Australian tomato juice producer with hexane:acetone:methanol:toluene 10:7:6:7 v/v/v/v as solvent (Wei, 2020). Up to 7–24% and 15–25% oil can be extracted from grape and tomato seeds, respectively using conventional nonpolar solvents and advanced methods such as supercritical CO_2, ultrasound, microwave, and enzymatic treatments (Sangeetha et al., 2023; Yang et al., 2021). After oil extraction, leftover tomato and grape seeds can be used for the extraction of proteins (39–55%) via alkaline extraction (Baca-Bocanegra et al., 2021; Kehili et al., 2016). Pectin is typically extracted from citrus peels, apple pomace, and sweet potato using both traditional hot acidic water treatment and advanced technologies (Mao et al., 2019). For instance, the microwave treatment (120–150 °C and pH 1.5–2 for 15 min) of dried Australian orange peels and conventional hot acidic water treatment (90 °C and pH 1–2 for 1 h) of Australian sweet potato residues yielded 5.3% and 9–10% pectin, respectively (Nurdjanah, 2008; Yeoh et al., 2008). Citrus peel also contains d-limonene, an essential oil used as a flavoring agent and solvent that can be extracted using hydro-distillation and microwave treatment up to a yield of 3–5% (Siddiqui et al., 2022). Starch from potato waste can be recovered using physical methods (stirring or blending in water), which successfully recovered 50–70% starch from discarded/whole potatoes and 20% starch from potato peels (Torres & Domínguez, 2020).

The leftover waste residue after direct extraction of the above products is lignocellulose rich and therefore can be used to produce chemicals, biofuel, organic acids, energy, bioplastic, and biochar through microbial fermentation and thermochemical conversion (Ding et al., 2023). In the case of microbial fermentation, the waste residue is pretreated to improve access to polysaccharides for enzymatic hydrolysis (saccharification) to monomeric sugars, which are subsequently used as substrate in microbial fermentation (Kim et al., 2022). In this case, the pretreatment required could be mild due to the residues already had undergone different treatments used for direct extraction of products (Talekar et al., 2018). Ebikade et al produced 167 kg 5-hydroxymethylfurfural (by saccharification and dehydration of glucose) and 62 kg biochar (by pyrolysis of lignin) from the 1 tonne of waste potato peel residue remained after the extraction of phenolics (Ebikade et al., 2020). Similarly, after phenolics extraction, apple pomace was transformed to biochar (47.5% yield) via gasification (Sette et al., 2020), and grape marc was transformed to biochar (62% yield) via hydrothermal carbonization (Farru et al., 2022), biofuel (acetone-butanol-ethanol: 5.4% yield) (Jin et al., 2018), succinic acid (15% yield) (Filippi et al., 2022), polyhydroxybutyrate (PHB) via fermentation of lignocellulosic sugars, and biogas (160 mL/g VS) via AD (Martinez et al., 2016). In case of citrus, de-oiled and de-pectinized citrus peel residues were converted to biogas (89 mL/g of VS) via AD (Ortiz-Sanchez et al., 2021), bacterial cellulose (39.5% yield) (Tsouko et al., 2020) and succinic acid (5.15% yield) (Patsalou et al., 2020) via fermentation, and biochar (56% yield) (Tovar et al., 2019). Nanocellulose (>70% yield) for packaging was also isolated from citrus peels by alkali treatment after phenolic extraction (Espinosa et al., 2022). Recently, de-pectinized apple pomace was converted to ethanol (17.3% yield) via fermentation (Borujeni et al., 2023).

4.1.2. Almond and sugarcane waste biorefinery

Biorefinery routes from almond and sugarcane waste are presented in Fig. 3. Almond waste and sugarcane bagasse (SB) are high in lignocellulose and require pre-treatment before being converted into value-added products. However, a few value-added products such as polyphenols and pectin can be directly obtained from almond hulls (AH)

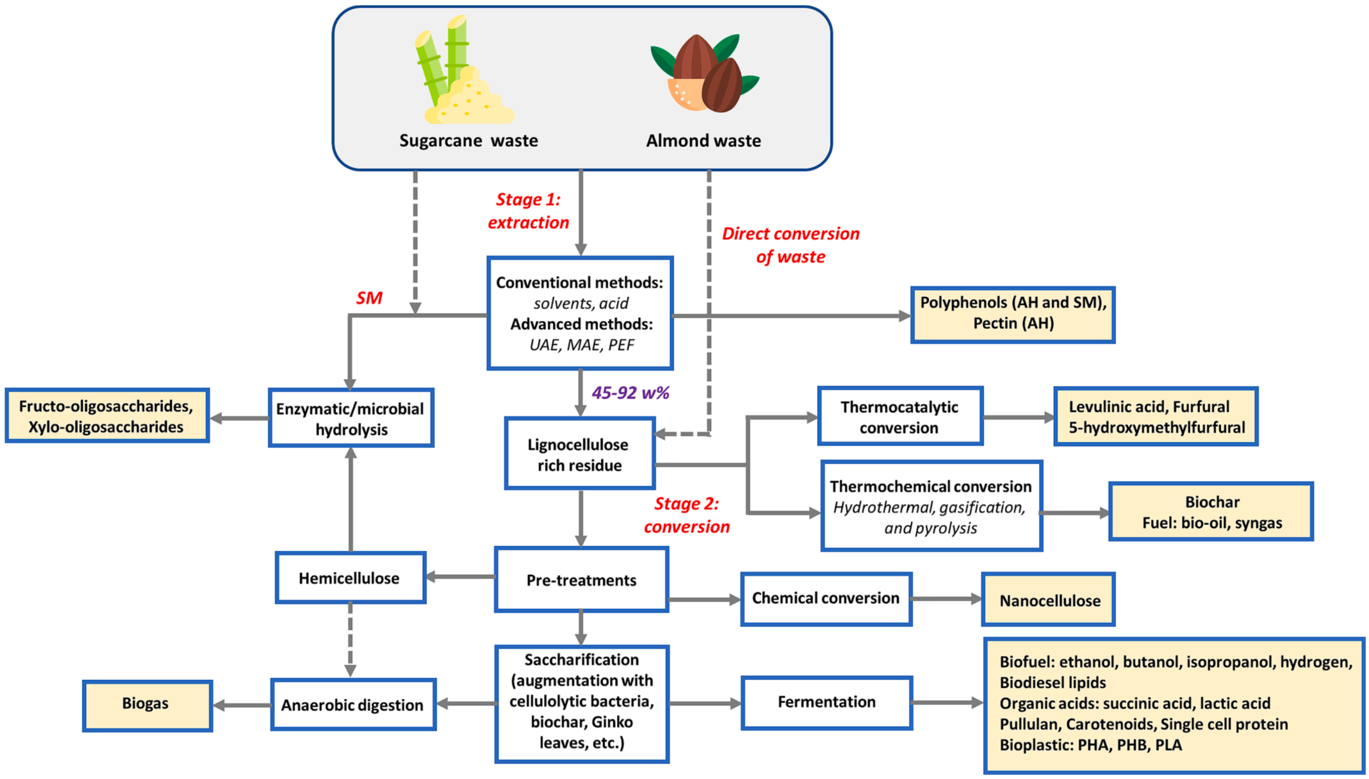

Fig. 3. Biorefinery routes for major lignocellulose food waste streams (sugarcane and almond waste). The weight percentage (w%) is used to express the lignocellulose mass going to conversion stage after the extraction stage. AH: almond hulls and SM: sugarcane molasses. Icons from flaticon.

prior to the pre-treatment and sugarcane molasses (SM). For example, polyphenols (3–8%) were extracted from AH by UAE, MAE, and PEF using 50% ethanol as a solvent (Salgado-Ramos et al., 2022a; Salgado-Ramos et al., 2022b), while they were recovered from Australian SM by conventional ethanol extraction followed by sugar removal from ethanol extract with amberlite resins to obtain 1.7% polyphenols (Deseo et al., 2020). In addition to polyphenols, pectin (26.3%) was also extracted via hot acid treatment of AH powder (Najari et al., 2022). A recent Australian study used transfructosylase producing *Aureobasidium pullulans* to convert sucrose from SM to prebiotics such as fructo-oligosaccharides (Khatun et al., 2020). Furthermore, SM sugars can also be fermented by yeast to produce bioethanol that is being done in Australia.

Lignocellulosic portion of almond and sugar cane waste can be pre-treated with chemical treatments (acid, alkali, ozone solvent-based treatments, deep eutectic solvent treatment) and physical treatments (comminution, hydro-thermolysis, HC) to release hemicellulose sugars and expose the cellulose for enzymatic or microbial saccharification to release cellulosic sugars for subsequent biological conversion to biofuel and chemicals or to produce prebiotic oligosaccharides (Nagarajan & Ranade, 2022; Reena et al., 2022). The fermentation of almond shell (AS) and sugarcane bagasse (SB) hydrolysates with *Saccharomyces cerevisiae* yielded 84% and 94% ethanol conversion, respectively (Kacem et al., 2016; Wang et al., 2018). In addition to ethanol, hemicellulose sugars generated during pre-treatment and saccharification were converted to succinic acid (8.7 g) via co-fermentation with *Actinobacillus succinogenes* (Xu et al., 2021), methane (27.46 $NLCH_4$/Kg) via AD (Bittencourt et al., 2019) from SB, and a mixture of hydrogen and methane via two stage fermentation and AD from AS (Kaur et al., 2020). Butanol (16.51 g/L) and isopropanol-butanol-ethanol mixture (2.75–7.9–0.75 g/L) was produced by *Clostridium* fermentation of SB hydrolysates in combination with vegetable extract (Mondal et al., 2022) and molasses (dos Santos Vieira et al., 2021), respectively. Co-fermentation with cellulolytic bacteria for enhanced cellulose hydrolysis and augmentation with biochar for enhanced electron transfer produced high biohydrogen 103–391 mL/g of SB (Bu et al., 2021; Huang et al., 2022) while Ginkgo leaves addition improved acetate pathway to enhance hydrogen production (1.58 mol/mol-hexose) from SM (Li et al., 2020a). Methane yields of 440 mL CH_4/g VS, 243 NmL CH_4/g CODr, and 224.7 mL CH4 /g VS were obtained with AD of cellulolytic bacteria augmented SB (Arelli et al., 2021), SB hemicellulose hydrolysate combined with vinasse, yeast extract, and SB fly ashes (Fernando Herrera Adarme et al., 2022), and press mud added with CuO/Cu_2O based nanocatalyst, respectively (Srivastava et al., 2022). Sugars from SB and AH hydrolysates can also be fermented with lactic acid bacteria to produce lactic acid (57 g/L), a bioplastic monomer (Qiu et al., 2023), with succinic acid bacteria to succinic acid (28% from SB) (Xu et al., 2023) with *Klebsiella pneumoniae G1* to PHB (9 g/L) (Siripurapu et al., 2022), and with *Bacillus megaterium Ti3* to polyhydroxyalkanoate (PHA) (0.58 g/L) (de Souza et al., 2022). Sugars from AH residue after phenolics extraction were converted to pullulan (34.2 g/L) an exopolysaccharide used in the food, pharmaceutical, and biomedical industries and single cell protein biomass (food ingredient and dietary supplement) with a protein content of 19.3 % (Najari et al., 2022).

Thermo-catalytic conversion involving acid catalysed hydrolysis and dehydration of sugars from lignocellulose portion or molasses can be used to produce platform chemicals. Lignocellulose portion of AH and SB was converted to levulinic acid (90% molar yield from AH and 35.6% from SB), 5-hydroxymethylfurfural (5-HMF) and furfural (28–31% from SB), and ethyl levulinate (82% from SM), a building block chemicals for many high-end products, via microwave assisted acid catalysed hydrolysis and dehydration (Amesho et al., 2022; Rodrigues et al., 2021; Salgado-Ramos et al., 2022b). Thermochemical routes such as pyrolysis, gasification, and hydrothermal treatment can also be used to convert lignocellulose portion of SB, AS, and AH into biochar (13–89%) and fuel material such as bio-oil (3–85%) and syngas (2–65%) (Aryal et al., 2023; Toscano Miranda et al., 2021; Ortiz et al., 2020; Remón et al., 2021).

The hemicellulose component of almond waste and SB can be used to make prebiotic xylo-oligosaccharides. AS hemicellulose was converted to xylo-oligosaccharides (17–54%) via aqueous autohydrolysis alone or in combination with enzymatic treatment (Morales et al., 2020; Singh et al., 2019) while SB hemicellulose recovered by ionic liquid treatment was enzymatically converted to xylo-oligosaccharide (5.6%) (Valladares-Diestra et al., 2022). The leftover cellulose-lignin rich residue from AS was delignified to produce nanocellulose or cellulosic fibres for reinforced composites (Malayil et al., 2022; Morales et al., 2020) and from SB was hydrolysed and supplemented with SM to use as a substrate for cultivation of oleaginous yeast to produce carotene (180.3 mg), biodiesel lipids (10.11 g), and animal feed protein (8.91 g) (Deeba et al., 2022). Nanocellulose and hydrogen can also be produced from SB by hemicellulose fermentation along with lignin recovery (Katakojwala and Venkata Mohan, 2022).

4.1.3. Fish waste biorefinery

Multiple products including enzymes omega-3 oil, proteins, gelatin, and collagen can be extracted directly from fish waste (Fig. 4). Extraction of naturally occurring enzymes such as lipases, proteases, chitinase, and collagenase from fish processing waste is a more cost-effective and efficient alternative for industrial applications (food, cosmetics, and textiles). In fact, the use of fish enzymes resulted in higher collagen yields than conventional techniques. These enzymes are extracted by aqueous buffer at low temperature followed by precipitation and purification by ultrafiltration and chromatography (Caldeira et al., 2020). After enzymes, oil can be directly recovered via cooking and pressing, as well as organic solvent, enzymatic, and supercritical fluid extraction of fish waste (Ozogul et al., 2021). The yield and omega-3 content of fish oil are affected by both the extraction method and the type of fish waste. In one example, oil with the yield of 25% (containing 25% omega 3 fatty acids) and 12.5% (containing 8.2% omega 3 fatty acids) was obtained by solvent extraction of Australian sardine viscera and salmon head respectively (Ahmad et al., 2019). Over 3% oil yield (containing 11.8% omega 3 fatty acids) was obtained by cooking of Australian Salmon discards (Nurdiani et al., 2015). Proteins can be extracted directly from fish waste or the de-oiled residues by solubilization with pH adjustment which yielded up to 70% of proteins from Australian Salmon discards (Nurdiani et al., 2015). Both oil and protein from fish waste can be used as a potential replacement of forage fish, lowering the risk of overfishing and improving fisheries sustainability (Caldeira et al., 2020). Proteins can also be obtained through hydrolysis with proteases, microorganisms, chemical or physical processes, resulting in bioactive peptides with antioxidant, antihypertensive, and emulsifying properties (Ozogul et al., 2021). The fish type, part of the fish, operational conditions (pH, temperature, and extraction time), and enzyme used can all have a significant impact on the bioactivity of the peptide obtained (Caldeira et al., 2020). For instance, peptides with high antioxidant and antihypertensive activities were produced from Australian Flathead and Barramundi by-products, as were peptides with high emulsifying activity from Salmon by-products (Nurdiani et al., 2016). Collagen can be effectively extracted using organic acids and enzyme (pepsin, papain, or collagenase) treatments (Ozogul et al., 2021). About 8% of collagen was extracted from de-oiled Australian fish skin with acetic acid treatment (Anand et al., 2013). The fish bones largely contain calcium phosphate and proteins (mainly collagen). They can be directly calcined in air to produce 30–60% of calcium phosphate-based biofertilizer/bio stimulant (Carella et al., 2021). Alternatively, the proteins (collagen) can be first extracted with alkaline extraction of bone powder followed by calcination of solid residue produce a calcium phosphate-based material for cosmetic and biomedical applications (Adamiano et al., 2023).

4.1.4. Dairy and household and business waste biorefinery

Biorefinery routes from dairy and household and business waste are given in Fig. 5a. Dairy whey constitutes proteins and lactose from which proteins can be separated by ultrafiltration and used in food and feed. These proteins can also be hydrolysed into bioactive peptides by the proteolytic activity of microorganisms and digestive enzymes (pancreatin and papain) (Monari et al., 2019). Currently, a few Australian milk processors are drying whey to produce whey powder for feed and food (Das & Ghosh, 2016); however, lactose is still underutilized. Lactic acid is another product found in whey, particularly acid whey (a by-product of cream cheese and yoghurt), and it can be recovered before spray drying of whole whey by membrane filtration and electrodialysis which reduces lactate:lactose ratio, reducing stickiness and increasing spray dried whey powder yield. In the case of sequential recovery, protein should be first recovered to avoid fouling the electrodialysis membrane. A few studies have successfully demonstrated the pilot scale recovery of lactic acid up to 90% from Australian whey (Chandrapala et al., 2017; Talebi et al., 2020). The mixed food waste from households and businesses is reservoir of proteins, oil, and carbohydrates. Similar to whey proteins from mixed food waste can be recovered by alkaline, enzymatic, UE, ME, HC, and PEF for feed ingredient (Kamal et al., 2021). The oil can be recovered with organic solvent extraction and heating in water and used for the production of biodiesel via transesterification (Barik & Paul, 2017; Kamal et al., 2021), which also enhances the food waste enzymatic hydrolysis for further utilization. The leftover lactose from dairy waste and carbohydrates from food waste can be converted to a spectrum of bio-commodity chemicals and bioenergy via biochemical

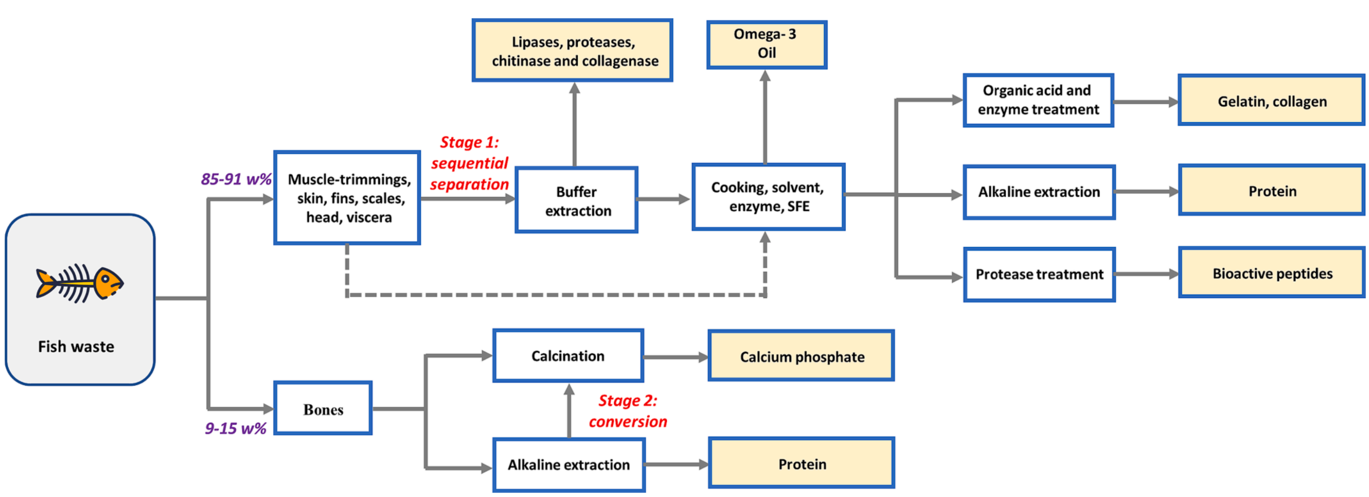

Fig. 4. Biorefinery pathway for fish waste. The weight percentage (w%) is used to express the percentage of different parts of fish waste going for sequential separation and conversion. Icons from flaticon.

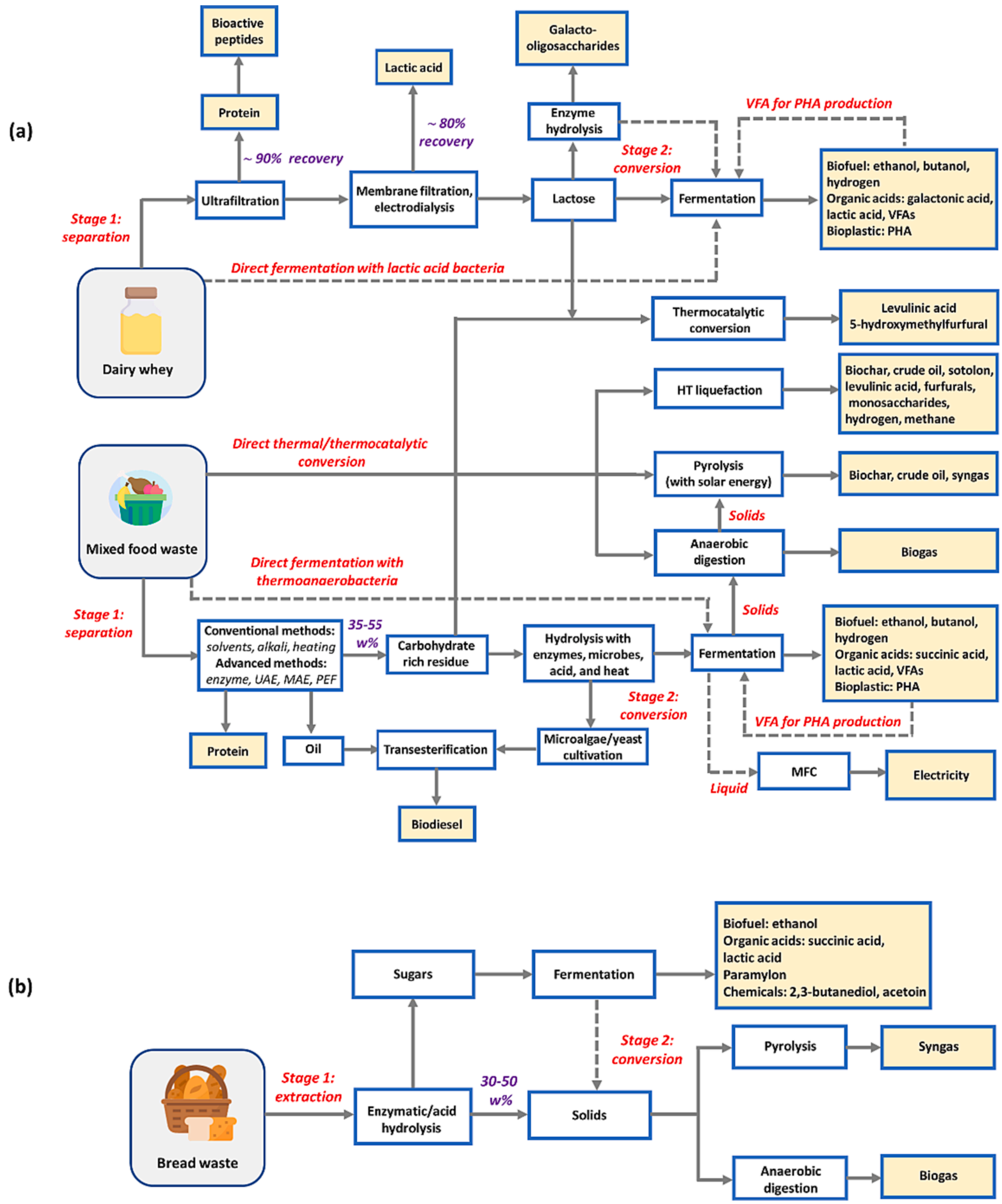

Fig. 5. Biorefinery routes for (a) dairy whey and mixed food waste streams (b) bread waste. The weight percentage (w%) is used to express the percentage of recovered products stream (dairy whey) and leftover residue going for conversion stage after extraction stage (mixed food and bread waste). Icons from flaticon.

and thermochemical conversions. Lactose was hydrolysed with β-D-galactosidase to galacto-oligosaccharides (up to 74% yield) which is a prebiotic (Orrego & Klotz-Ceberio, 2022). It was also sequentially converted to low calorie sweeteners such as D-tagatose (68.35 g/L), D-arabitol (60.12 g/L), and galactitol (28.26 g/L) via whole cell biocatalysis and fermentation (Zhang et al., 2022). Lactose and mixed food waste carbohydrates can be utilized as a carbon source to produce bioethanol, biodiesel, hydrogen, methane, organic acid, and bioplastic. For example, lactose was hydrolysed to glucose and galactose with subsequent *S. cerevisiae* fermentation of glucose to ethanol (110 g) and *G. oxydans*-mediated bio-oxidation of galactose to galactonic acid (350 g) a sugar acid with variety of applications in food and pharmaceutical industries (Zhou et al., 2019). The yeast *K. marxianus* which can directly ferment lactose was used to produce ethanol (79.33 g/L) (Saini et al., 2017) and *Clostridium* sp. to produce butanol (4.9 g/L) in continuous packed bed reactor (Raganati et al., 2013). Recently, whey lactose was also directly fermented to resveratrol, an antioxidant, using engineered *S. cerevisiae* strain via two stage fermentation, with the first stage favouring ethanol production and the second stage converting ethanol and lactose to resveratrol (210 mg/L) (Costa et al., 2022a). Due to their diversity, mixed food waste carbohydrates are generally hydrolysed with a mixture of carbohydrases or enzyme producing microbes to release a mixture of sugars (glucose, fructose, xylose, arabinose, lactose, and sucrose) which are then used as a carbon source. For instance, bioethanol (58 g/L) was produced by *S. cerevisiae* fermentation of cafeteria and households mixed food waste hydrolysed with fungal enzyme cocktail (Kiran & Liu, 2015), butanol (16.3 g/L) with *Clostridium* fermentation of kitchen garbage hydrolysates obtained with commercial cell wall degrading enzyme cocktail (Chen et al., 2017a), and succinic acid (30 g/L) with recombinant *E. coli* fermentation of mixed food waste hydrolysates obtained with mixed fungal hydrolysis (Sun et al., 2014). Biodiesel (135.8 g/kg food waste) was also produced from lipids obtained by cultivating microalgae on food waste hydrolysates produced with cellulase and amylase hydrolysis with reuse of crude glycerol as carbon source (Patel et al., 2019). In Australia, chemical hydrolysis with acid and thermal treatment was used to hydrolyse mixed food waste, with subsequent yeast fermentation of hydrolysates to obtain lipids for biodiesel production (Nguyen Hao et al., 2015). These hydrolysates can also be converted to volatile fatty acids through acidogenic fermentation and leftover residue to methane through AD, increasing economic profitability by 180% (Gianico et al., 2021). Another cost-effective option is thermophilic fermentation with *Thermoanaerobacter* sp., which can convert a wide range of sugars to ethanol without the need for prehydrolysis of food waste carbohydrates (Dhiman et al., 2017). Following the production of ethanol, the liquid fraction was used in a microbial fuel cell (MFC) to generate electricity, while the solid fraction was subjected to thermophilic AD to produce methane 95 L/kg VS, which was then oxidised by methanotrophs to methanol (0.042 mM) (Dhiman et al., 2018).

There are a few commercial anaerobic digesters in Australia that use biogas from food waste to generate electricity or heat energy. According to a recent study, mixed food waste in Australia has the potential to generate up to 1.54 million m^3 biogas, which can be used to generate up to 52.36 GW of electricity and 554.4 TJ of heat per year (Mahmudul et al., 2022). The profitability of AD of mixed food waste can be increased by fermentative lactic acid production prior to AD (Demichelis et al., 2017), which can be integrated directly in existing digestion facility. At a commercial AD plant in Australia, an average of 21.7 g/L of lactic acid was produced from mixed food waste under non-optimized uncontrolled conditions (Bühlmann et al., 2021). Another Australian study demonstrated high energy recovery from food waste by AD followed by pyrolysis which produced energy rich products such as gas (5.3%), char (42.4%), and bio-oil (52.2%) (Opatokun et al., 2015). Similarly, Australian cheese whey was fermented with lactic acid bacteria via acidogenic fermentation to simultaneously produce biohydrogen (1 mol/mole of hexose) and a mixture of lactic acid (bioplastic precursor) and volatile fatty acids (0.08–4.9 mol/mole of hexose) (Pandey et al., 2019). Volatile fatty acids can be further used as a carbon source for aerobic production of PHA, as demonstrated for mixed food waste (Amulya et al., 2015). Furthermore, an Australian study demonstrated methane production in the second step, after hydrogen and volatile acid production in the first step and the addition of biochar increased hydrogen and methane yields due to its ability to promote biofilm formation and mitigate ammonia and acid inhibition (Sunyoto et al., 2016).

Hydrothermal liquefaction is a cost-effective thermochemical processing for high moisture food waste that leads to formation of biochar along with the liquid phase enriched with different products depending on the mixed food waste composition. For instance, hydrothermal liquefaction of mixed food waste at 200°C; 100 bar produced 30–35% biochar, 25–30% aqueous fraction containing sotolon (flavouring agent) levulinic acid, furfurals, monosaccharides, 10–15% crude oil for fuel, and 15–20% gasses containing hydrogen and methane (Katakojwala et al., 2020). Given Australia's abundance of solar resources, solar-powered pyrolysis of food waste to produce bio-oil, bio-char, and syngas has enormous potential (Hamilton et al., 2020). Platform chemicals such as 5-hydroxymethylfurfural and levulinic acid were also synthesized from mixed food waste carbohydrates (4–17%) and lactose (25–45%) via hydrolysis and dehydration/rehydration process in thermos-catalytic conversion with Brønsted/Lewis acid based catalyst (Chen et al., 2017b; Jeong, 2022; Parshetti et al., 2015).

Food waste from households and retail businesses is a major source of bakery waste (0.34 million tonnes) in Australia (DCCEEW, 2022). Bakery waste mostly include bread, which is rich in clean inhibiter-free sugars (50–70% starch) that are easier to recover than lignocellulose, which requires harsh pretreatments (Kumar et al., 2022). Thus, if collected economically, it is an attractive sugar source to produce fuel, organic acid, and chemicals (Fig. 5b). For example, titres of ethanol (35–128 g/L), succinic acid (43.3 g/L), lactic acid (62–155 g/L), 2,3-butanediol (138.8 g/L), and paramylon (1.93 g/L d, medical and cosmetic ingredient), even higher than 2G or 3G feedstocks were produced by *S. cerevisiae, Actinobacillus succinogenes, Bacillus coagulans, Enterobacter ludwigii* fermentation and *Euglena gracilis* cultivation, respectively from bread hydrolysates obtained by acid/enzymatic hydrolysis (Jung et al., 2022; Kumar et al., 2022). Furthermore, the butanediol fermentation can be diverted to acetoin by increasing the volumetric oxygen transfer coefficient during fermentation (Maina et al., 2021). Finally, the leftover residues generated after enzymatic hydrolysis and fermentation can be combined and subjected to AD to produce methane or pyrolysis to produce syngas (Kumar et al., 2022).

4.2. Food waste to value-added products initiatives and industrial development in Australia

In Australia, significant collaborative efforts between government, universities, and industries are underway to convert food waste into value-added products. The Fight Food Waste Cooperative Research Centre (FFWCRC) was established in 2018 with the Australian government's support (A$30 million), and it includes 43 industry partners, 8 universities, and 8 state agencies. Its mission is to build knowledge and capacity for the transformation of food waste streams into value-added products (FFWCRC, 2018). Similarly, the Victorian government recently funded the Circular Economy Accelerator-Organics (CEA-O) project (A $16.4 million) to establish a 'BioFactory' in Geelong in collaboration with three universities and twenty industry partners to test processes for food waste conversion at pilot scale (Andrews 2021). The Australian Government has established 'The Food Waste for Healthy Soil Fund' by allocating A$67 million in the federal budget for 2021–22 for the use of household and commercial organic waste as fertiliser for soil improvement (DCCEEW 2023). Growing industry-university research collaborations have resulted in the development of pilot and commercial scale technologies for converting food waste into products. Great Wrap, an Australian materials science company, makes home compostable stretch wrap out of potato waste. Viridi Innovations, a start-up, has developed an efficient process for extracting polyphenols from Australian winery waste and has established a pilot plant in Victoria. BioMar Australia has recently commissioned a facility in Tasmania to produce algal omega-3 oil for aquafeed from sugarcane waste. Mercurius Australia has set up a new pilot biorefinery plant in Queensland for the thermo-catalytic conversion of SB into renewable diesel and aviation fuel. Australia has begun efforts to convert fish waste into high-value products with Tassal and Huon Aquaculture, two Tasmanian salmon farming companies, constructing fish waste collection and fish waste oil and protein extraction plants. Gottera, a Canberra-based startup, has created a

Modular Infrastructure for Biological Services (MIBs) that uses Black soldier fly larvae to convert mixed food waste into high-value protein and fertiliser. As the food waste is difficult to handle and immediately spoils due to its high moisture content, a few Australian companies, such as Green Eco Technologies and Eco Guardians, have developed innovative technologies such as WasteMaster and GAIA Rotary Food Waste Dehydrator, respectively, for dehydrating food waste into dry and pathogen-free residue that can be converted into value-added products or fertiliser depending on the type of food waste. Similarly, Jet Technology Corporation, a well-known international firm that has developed an environmental recycling system (a high-speed aerobic fermentation and drying technology) to produce animal feed, fertiliser, or biomass fuel from organic waste has begun operations in Australia.

5. Challenges and future directions for food waste biorefinery in Australia

The biorefinery has been recognised worldwide as an efficient method of managing food waste while also producing marketable products and creating new businesses and jobs. The review highlights several potential biorefinery pathways from Australia's major food waste streams to produce multiple products, demonstrating their high potential to contribute to the country's circular economy goal. However commercialization of food waste biorefinery is fraught with difficulties. Australia has initiated quantifying the volume and type of food waste through its national food waste baseline. However, the chemical composition of food waste, as well as its variability with respect to time, location, and food species is critical in determining its biorefinery potential. Therefore, having access to such information is essential for supporting biorefinery investment decisions, which could be done in collaboration with local universities. High moisture content of food waste makes it difficult to handle store and avoid spoilage. The innovative dehydration and sterilization technologies developed by a few Australian companies may be useful to overcome this challenge. However, it is important to determine whether these technologies reduce the valuable properties of the products present in food waste. Although food waste biorefinery is expected to bring environmental and economic benefits, the cost and environmental impact of the food waste conversion technology determines these outcomes. Most Australian studies and reported potential biorefinery pathways are currently at a low technology readiness level, with little information on their viability and performance on a large scale. As a result, a comprehensive techno-economic and life cycle assessment of the biorefinery pathway should be conducted. Public awareness of food waste biorefinery should be increased to increase market acceptance of biorefinery products, which will also assist companies in planning their biorefinery set ups. Government policies such as subsidising transportation and utilities, launching training programmes to develop skilled workforce for food waste biorefineries, and instituting procurement quotas for products derived from food waste could all contribute to creating a favourable environment for investment in food waste biorefineries. Given Australia's diversity, it is also critical for the government to promote small-scale regional biorefineries where regional food waste can be converted into products for local consumption, thereby empowering local businesses, lowering transportation costs, and creating local jobs.

6. Conclusions

Food waste in Australia has the potential to establish a circular economy using a biorefinery approach, diverting them from existing practises such as landfilling, composting, and incineration. This review provided biorefinery pathways for converting major food waste streams in Australia into a variety of high-value products other than the low-value animal feed and fertilisers that are currently produced from some of them. Food waste biorefinery development in Australia is still in its early stages, necessitating additional efforts to improve technological maturity and techno-economic feasibility for industrial implementation. A current collaboration between government, industry, and academia aligns with this goal.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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