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Upcycling fruit waste into microalgae biotechnology: Perspective views and way forward

Alicia Lee [a,b], John Chi-Wei Lan [b,*], Anet Režek Jambrak [c], Jo-Shu Chang [d,e,f], Jun Wei Lim [g,h], Kuan Shiong Khoo [a,i,*]

[a] Algae Bioseparation Research Laboratory, Department of Chemical Engineering and Materials Science, Yuan Ze University, Taoyuan, Taiwan
[b] Biorefinery and Bioprocess Engineering Laboratory, Department of Chemical Engineering and Materials Science, Yuan Ze University, Taoyuan, Taiwan
[c] Faculty of Food Technology and Biotechnology, University of Zagreb, Zagreb, Croatia
[d] Department of Chemical Engineering, National Cheng Kung University, Tainan 701, Taiwan
[e] Research Center for Smart Sustainable Circular Economy, Tunghai University, Taichung 407, Taiwan
[f] Department of Chemical and Materials Engineering, Tunghai University, Taichung 407, Taiwan
[g] HICoE-Centre for Biofuel and Biochemical Research, Institute of Self-Sustainable Building, Department of Fundamental and Applied Sciences, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia
[h] Department of Biotechnology, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India
[i] Centre for Herbal Pharmacology and Environmental Sustainability, Chettinad Hospital and Research Institute, Chettinad Academy of Research and Education, Kelambakkam, 603103, Tamil Nadu, India

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ABSTRACT

Fruit and vegetable wastes are linked to the depletion of natural resources and can pose serious health and environmental risks (e.g. eutrophication, water and soil pollution, and GHG emissions) if improperly managed. Current waste management practices often fail to recover high-value compounds from fruit wastes. Among emerging valorization methods, the utilization of fruit wastes as a feedstock for microalgal biorefineries is a promising approach for achieving net zero waste and sustainable development goals. This is due to the ability of microalgae to efficiently sequester carbon dioxide through photosynthesis, utilize nutrients in wastewater, grow in facilities located on non-arable land, and produce several commercially valuable compounds with applications in food, biofuels, bioplastics, cosmetics, nutraceuticals, pharmaceutics, and various other industries. However, the application of microalgal biotechnology towards upcycling fruit wastes has yet to be implemented on the industrial scale due to several economic, technical, operational, and regulatory challenges. Here, we identify sources of fruit waste along the food supply chain, evaluate current and emerging fruit waste management practices, describe value-added compounds in fruit wastes, and review current methods of microalgal cultivation using fruit wastes as a fermentation medium. We also propose some novel strategies for the practical implementation of industrial microalgal biorefineries for upcycling fruit waste in the future.

1. Introduction

Comprising 38 % of global food waste by mass, fruits and vegetables are the most highly wasted food categories, with a global average of 7.65 kg of edible fruit waste and 16 kg of edible vegetable waste per person annually. This corresponds to 1.358 kg CO_2 equivalent, 15.78 m^2

Abbreviations: AI, Artificial intelligence; BBM, Bold's Basal Medium; BG-11, Blue Green-11; BOD, Biochemical oxygen demand; CO_2, Carbon dioxide; COD, Chemical oxygen demand; EAE, Enzyme-assisted extraction; EU, European Union; FSC, Food supply chain; GHGs, Greenhouse gases; GM, Genetically modified; GMO, Genetically modified organism; IoT, Internet of Things; LCA, Life cycle assessment; MAE, Microwave-assisted extraction; MMT, Million metric tonnes; MSW, Municipal Solid Waste; PBR, Photobioreactor; PEF, Pulsed electric field; PLE, Pressurized liquid extraction; SFE, Supercritical fluid extraction; SmF, Submerged fermentation; SSF, Solid-state fermentation; TEA, Techno-economic analysis; TS, Total solids; UAE, Ultrasound-assisted extraction; US, United States; VOC, Volatile organic carbon; VS, Volatile solids.

[*] Corresponding authors at: Biorefinery and Bioprocess Engineering Laboratory, Department of Chemical Engineering and Materials Science, Yuan Ze University, Chung-Li 32003, Taiwan (J.C.-W. Lan). Algae Bioseparation Research Laboratory, Department of Chemical Engineering and Materials Science, Yuan Ze University, Taoyuan, Taiwan (K.S. Khoo).

E-mail addresses: lanchiwei@saturn.yzu.edu.tw (J.C.-W. Lan), kuanshiong.khoo@saturn.yzu.edu.tw (K.S. Khoo).

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of cropland usage, 3810.6 L of freshwater usage, 232.87 g of nitrogen usage, and 38.544 g of phosphorus usage per person per year for agricultural production (Chen et al., 2020). Due to their high fermentability and biodegradability, fruit wastes can cause considerable human health risks and environmental pollution issues if improperly managed, including eutrophication, water and soil pollution, and GHG emissions (de Medeiros et al., 2020; Leong & Chang, 2022), and this wastage also represents a loss of valuable nutrients and biomass.

Current waste management practices (particularly, incineration and landfilling) often fail to recover high-value compounds from fruit wastes, and they generate products with lower economic value than the original food product (Eriksson, 2015; Esparza et al., 2020). Among emerging waste management practices that treat fruit waste as a resource to generate value-added compounds, the usage of fruit waste as a cultivation medium for microalgae is of particular interest, as microalgae can produce several commercially valuable compounds (e.g. carbohydrates, proteins, lipids, unsaturated fatty acids, vitamins, pigments, coenzymes, and antioxidants) that have applications in food, biofuels, bioplastics, cosmetics, nutraceuticals, pharmaceutics, and various other industries (Cheng et al., 2022; Chew et al., 2017). Additionally, microalgae can sequester CO_2 through photosynthesis, grow rapidly (life cycles of up to 10 days), and have high photosynthetic efficiency (Cheng et al., 2022). However, the commercial utilization of microalgae is currently limited by its high production cost (up to 570 Euros per kg dry weight, depending on the production method) (Novoveská et al., 2023).

Rich in soluble sugars and dietary fibres, fruit wastes also contain protein, fat, phenolic compounds, antioxidants, and other compounds (Kosseva, 2011). As such, fruit wastes have great potential as a low-cost, alternative nutrient source for microalgal cultivation that can reduce or eliminate the usage of expensive synthetic medias (e.g. BG-11 and BBM) and other organic carbon sources (e.g. glucose, glycerol, and acetate) (Perez-Garcia et al., 2011). In addition to mitigating the GHG emissions and other negative environmental impacts associated with the disposal of fruit wastes through landfilling or incineration, the upcycling of fruit wastes as a microalgal fermentation medium supports the global transition towards a circular bioeconomy, where material loops are closed through product recycling and reuse and where biomaterials are increasingly leveraged while restoring natural ecosystems and resource health (Teigiserova et al., 2020). However, the valorization of fruit wastes using microalgal biotechnology is currently limited mostly to the laboratory scale due to several economic, technical, operational, and regulatory challenges. Previous reviews have focused on the valorization of fruit wastes using microalgal biotechnology on the laboratory scale and have neglected to discuss the practical challenges of implementing this waste management strategy on the industrial scale.

This review paper provides insights on the different sources of fruit waste along the global food supply chain (e.g. agricultural production and harvest, post-harvest operations and storage, processing, distribution, retail, and consumption). The environmental impacts associated with current fruit waste management practices (e.g. landfilling, composting, incineration, animal feed, and anaerobic digestion) and emerging fruit waste management practices (e.g. conversion into derivative edible and non-edible products, biorefinery approach, and microbial fermentation medium for biomanufacturing) are investigated. This review also evaluates the composition of various fruit wastes, the potential applications of several value-added compounds that can be derived from various fruit wastes, and microalgal cultivation strategies that have been applied in upcycling fruit wastes as an alternative fermentation medium. Most importantly, this review article makes several recommendations to address potential challenges in the practical implementation of microalgal biotechnology as an industrial solution for upcycling fruit wastes into value-added products.

1.1. Global scale of fruit waste and associated environmental impact

Over 492 million tonnes of fruit and vegetable are wasted annually throughout the entire FSC, which is comprised of several segments, including: (1) agricultural production and harvest; (2) post-harvest operations and storage; (3) processing; (4) distribution; (5) retail; and (6) consumption (Conway, 2018; FAO, 2013). “Food loss” is defined by the Food and Agriculture Organization (FAO) as the decrease in food quality/quantity from agricultural production through distribution, while “food waste” refers to the decrease in food quality/quantity from the retail stage onwards (FAO, 2019). The term “food wastage” encompasses both loss and waste. Wastage that occurs farther along the FSC has higher embedded environmental impacts that include the energy and resource usage and environmental footprint of previous steps in the supply chain (FAO, 2013). In developing regions, FSCs for the rural poor tend to be short and possess limited post-harvest infrastructure and technologies, while FSCs for urban populations involve many intermediate agents between growers and consumers. In contrast, transitional and industrialized regions have FSCs that more closely integrate producers, suppliers, processors, distribution systems and markets, with supermarkets serving as the main intermediary between producers and consumers (Parfitt et al., 2010). Fig. 1 evaluates various reasons for fruit and vegetable wastage along each step of the FSC.

1.1.1. Agricultural production and harvesting

An estimated 10–20 % of fruits and vegetables are lost during agricultural production and harvest (FAO, 2011). This is partly due to unpredictable factors such as harsh weather, disease, and pest infestation. In order to meet quotas while managing these potential risks, farmers may plan to produce larger quantities of crops than needed (FAO, 2011). If a crop surplus is indeed generated, this may drive down the market price such that it is too low to justify transporting goods to the market, prompting farmers to leave crops unharvested (FAO, 2019). Alternatively, farmers may choose to prematurely harvest crops to obtain urgently needed food or cash, especially in developing countries. Prematurely harvested fruits that fail to ripen may be unsuitable for consumption and are thus lost (FAO, 2011), though several organizations are now exploring the upcycling of these unripe fruits into edible products (Upcycled Food Association, 2023). During harvest, some ripened fruits may be left in the field due to inadequate harvesting techniques and machinery, while other fruits may be damaged, leading to spoilage (FAO, 2019).

1.1.2. Post-harvest operations and storage

About 4–10 % of fruits and vegetables that enter post-harvest operations and storage are lost (FAO, 2011). Post-harvest losses are mainly due to damage by labourers during the harvest and selection process (FAO, 2019). During the selection process, fruits that fail to meet rigorous aesthetic quality standards by supermarkets regarding their appearance, shape, weight, and size (colloquially referred to as “ugly produce” or “ugly fruits”) are rejected and discarded before leaving the farm gate (FAO, 2011, 2019). Accepted produce may then be stored for periods ranging from a few hours up to several months (FAO, 2019). Due to their high moisture, sugar, and crude protein content (80–90 %, 6–64 %, and 10–24 %, respectively) (Wadhwa & Bakshi, 2013), fruits are highly perishable and may spoil within a few hours if improperly disinfected or stored in facilities that lack adequate temperature and humidity control. In developing countries, which often lack refrigerated warehouse capacity and other storage facilities, a greater proportion of fruits and vegetables is lost due to poor storage infrastructure than in industrialized countries, which mostly have adequate and effective storage facilities throughout the supply chain. Instead, storage losses in industrialized countries are generally due to technical failures, overstocking, or poor temperature or humidity management (FAO, 2019).

1.1.3. Processing

Fresh fruits are processed for direct consumption or into various products, such as juices, canned or dried fruits, and food ingredients. Large volumes of solid wastes (e.g. leaves, twigs, peels, rinds, pulp,

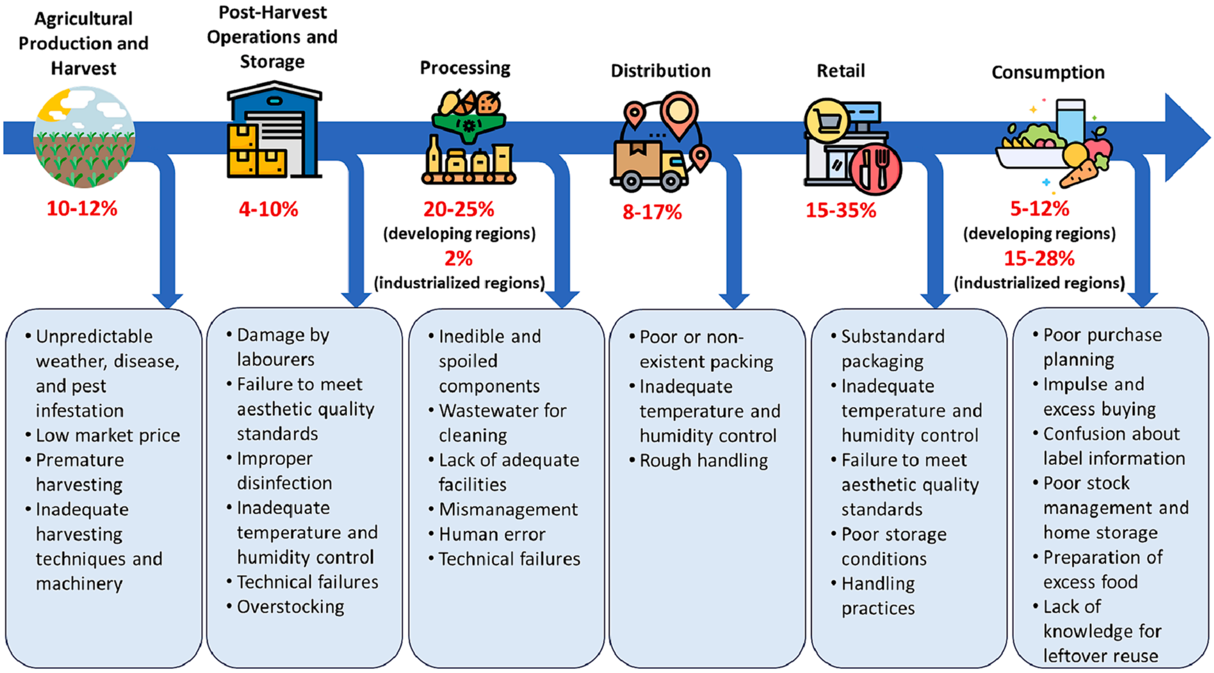

Fig. 1. Due to various environmental, technical, operational, and socioeconomic reasons, fruit and vegetable wastage occurs at each stage of the FSC: (1) Agricultural production and harvest; (2) Post-harvest operations and storage; (3) Processing; (4) Distribution; (5) Retail; and (6) Consumption. Numbers in red indicate the percentage of fruits and vegetables entering each FSC stage which are lost or wasted (FAO, 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pomace, pits, and spoiled fruits) are generated as the fruits are cleaned, processed, cooked, and packaged (Esparza et al., 2020). Fruit processing waste accounts for 16 % of global food processing waste and 6 % (over 20 million tonnes of CO_2 equivalent) of GHG emissions (Banerjee et al., 2017). Different types of fruits produce varying amounts of waste, with 20 % of bananas, 30–50 % of mangoes, 30–50 % of citrus fruits, 10 % of guavas, and 45–55 % of pineapples going to waste (Banerjee et al., 2018). Additionally, the fruit processing industry generates extremely large volumes of wastewater that contain low concentrations of macronutrients and micronutrients (Esparza et al., 2020), as well as dissolved pesticides, herbicides, and cleaning chemicals (Mirabella et al., 2014).

In industrialized regions, about 2 % of fruits and vegetables that enter processing and packaging operations are lost, while 20–25 % is lost in developing regions (FAO, 2011). High processing losses in developing regions are due to a shortage and/or lack of adequate processing facilities, especially for fruits and other seasonal and perishable products. Food losses in the processing stage may also be due to human error, mismanagement, or technical failures that result in final products that do not comply with buyer standards and are therefore rejected (FAO, 2019).

1.1.4. *Distribution*

The time spent in transport between different stages of the food supply chain is a key point of loss for fruits, given their highly fragile and perishable nature. Fruits are extremely vulnerable to deterioration caused by poor or non-existent packing, transport in open vehicles with inadequate temperature and humidity control, and mechanical damage from rough treatment during handling operations and transportation (FAO, 2019). About 8–17 % of fruits and vegetables in the distribution stage are ultimately lost (FAO, 2011), with significant variation in the transport capacity of different regional supply chains affecting losses in each region (FAO, 2019).

1.1.5. *Retail*

Limited shelf life of perishable goods, personal buyer criteria regarding food quality, and variable demand for fresh produce are key issues linked to food waste during retail. Shelf life, food quality, and consumer acceptability are greatly affected by packaging quality, food storage conditions, and handling practices by retailers and suppliers. Additionally, the demand for homogeneous and aesthetically pleasing produce items contributes significantly to food waste at the retail level, especially in high-income countries, where “ugly produce” that does not meet these high standards is discarded or downgraded to produce derivative food products (e.g. juices, vinegar, and chutney) (Eriksson & Spångberg, 2017; FAO, 2019; Plazzotta et al., 2017). At the retail level, up to 15 % of fruits and vegetables are wasted globally, except in sub-Saharan Africa, where fruit and vegetable wastage rates of up to 35 % are likely due to substandard packaging and poor control of temperature and humidity, particularly in open-air markets (FAO, 2019).

1.1.6. *Consumption*

In developing countries, 5–12 % of fruits and vegetables that reach end consumers are wasted and comprise about 60–70 % of household food wastes. 15–28 % of fruits and vegetables are wasted in industrialized areas, comprising the largest category of household food wastes in the EU (Esparza et al., 2020; FAO, 2011). Consumer food waste often occurs due to: (i) poor purchase planning; (ii) impulse and excess buying due to promotions, bulk discounts, and overly large package sizing; (iii) lack of understanding of label information; (iv) poor stock management and storage at home; (v) preparation of excess food; and (vi) inadequate knowledge about how to reuse leftovers (FAO, 2019). Socio-economic, demographic, and cultural factors influence the amount of food waste generated by households, with larger amounts of food wasted with increasing household income. This may be because high-income households can afford to buy more food than they can consume, and they may purchase larger quantities and greater varieties of foods, especially to demonstrate their wealth to others at social events. Food also has lower relative value for households with higher income. Additionally, the time constraints and complex, contradictory demands of everyday life have prompted consumers to modify their consumption habits to favour convenience and to buy greater quantities of food less often, resulting in increased waste (FAO, 2019). Finally, fruits generally have inedible components that are disposed of and therefore wasted (De Laurentiis et al., 2018).

1.2. Management of fruit waste

There are several strategies for the prevention and management of fruit waste within the waste management system, which is defined as "the whole set of activities related to handling, disposing, or recycling waste materials" (Plazzotta et al., 2017). Using the waste management hierarchy, which is a globally adopted framework by the European Waste Framework Directive (WFD) that seeks to deliver the best overall environmental outcome, these strategies can be classified and prioritized according to their overall environmental impact (Papargyropoulou et al., 2014). However, the WFD has not set criteria for determining the best overall environmental outcome, and the environmental impact of each waste management method can vary greatly depending on differences in local contexts, the specific type of food waste, and the criteria used to evaluate the different waste management practices (Eriksson, 2015).

1.2.1. Conventional management practices

Conventional methods of managing fruit waste are based on biological and chemical transformations of the waste's organic components into simple molecules (e.g. CO, CO_2, CH_4, H_2, H_2O, H_2S, and NH_3), a relatively inert solid (e.g. stabilized sludge, compost, ashes, and slag), and wastewater streams (primarily leachates) (Esparza et al., 2020). Considered to be of lower priority in the waste management hierarchy, these methods include landfilling, composting, incineration, animal feed, and anaerobic digestion. As these practices do not require food waste with high levels of product quality, hygiene, separation, or storage conditions, they are cheap and generally able to handle all types of food wastes (Eriksson, 2015). These management practices generate value-added products (e.g. bio-hydrogen, biogas, compost, power, and heat) that can replace energy and goods from fossil fuel-based production systems. However, these methods are unable to recover complex molecules from the fruit waste, as the fruit waste is destroyed, consumed, or simply left to degrade. The generated products generally have much lower economic value than the original food products (Eriksson, 2015; Esparza et al., 2020). Additionally, although these practices seek to minimize the health and environmental hazards of mis-managed fruit waste, they often pose considerable environmental impact themselves through the generation of atmospheric air pollution, GHG emissions, and wastewater and solid wastes (Esparza et al., 2020; Leong & Chang, 2022).

1.2.1.1. Landfilling. Used for the disposal of over 95 % of food wastes due to its low cost, relatively low technical and labor requirements, and suitability for all waste types, landfilling refers to the disposal of waste materials via burial in a designated terrestrial site (Melikoglu et al., 2013; Nanda & Berruti, 2021). As organic matter in the landfill is decomposed by bacteria, a mixture of gases (known as "landfill gas" or "biogas") is produced (Breeze, 2018; Esparza et al., 2020), with one tonne of landfilled food producing approximately 125,000 L of biogas (Melikoglu et al., 2013). When oxygen is initially present in the landfill, aerobic bacteria will break down complex organic materials and produce carbon dioxide. Once the oxygen has been completely consumed, these aerobic bacteria are replaced by anaerobic species that produce acids and alcohols which will acidify the landfill and release other elements from the soil. Over time, usually within 3 years of waste burial, conditions become less acidic, allowing methanogenic bacteria to produce a mixture of methane, carbon dioxide, and water. The landfill will then stabilize and continue to produce methane-rich biogas for up to 50 years, especially if the landfill contains a high percentage of organic waste (Breeze, 2018). Gases may also be produced through the volatilization of non-methane organic compounds (e.g. reduced sulfur gases and aromatic, fluorinated and chlorinated hydrocarbons), as well as through chemical reactions between different wastes (such as bleach) that create toxic gaseous products with adverse health risks (Bogner et al., 2008; Breeze, 2018; Nanda & Berruti, 2021). Biogas is often released directly into the atmosphere and is typically composed of up to 60 % methane and 40–60 % carbon dioxide by volume, with several other trace components (e.g. nitrogen, ammonia, sulfides, VOCs, and carbon monoxide) (Breeze, 2018; Nanda & Berruti, 2021).

Another environmental issue related to landfilling is the generation of highly toxic leachates due to the percolation of precipitation, as well as moisture contained in the waste, through the waste. Rich in organic matter, inorganic salts, ammonia, xenobiotic organic compounds, and heavy metals, these leachates accumulate at the bottom of landfills and may contaminate soil and groundwater if the landfill is not adequately engineered to prevent leakage (Esparza et al., 2020; Nanda & Berruti, 2021). Properly sequestered leachates must be treated in municipal wastewater treatment plants or other dedicated infrastructure prior to disposal into natural bodies of water (Esparza et al., 2020; Nanda & Berruti, 2021). Approximately 170–250 L of leachate are produced per tonne of MSW (Melikoglu et al., 2013). Due to its high moisture content, fruit waste is particularly prone to generating leachates (Ji et al., 2017).

Landfilling is widely considered as the lowest priority method in the waste management hierarchy as it primarily produces methane, which is a highly potent GHG that can remain in the atmosphere for 12 years and has a global warming potential 25 times that of carbon dioxide (Eriksson, 2015; Nanda & Berruti, 2021). This means that food waste in landfills generates a much higher carbon footprint than if it was simply left to degrade in aerobic conditions, where it would produce only carbon dioxide (Eriksson, 2015). Globally, landfills produced an estimated 1 billion tonnes of CO_2 equivalent in 2020 (about 8 % of global GHG emissions), making them one of the largest anthropogenic sources of methane (Bogner et al., 2008; Ganesh et al., 2022; Kaza et al., 2018). Due to its high methane content, biogas has an energy content about half that of natural gas (Breeze, 2018). It is commonly burned for heat or electricity generation, or it can be processed to obtain bio-methane (an alternative to natural gas) through the removal of carbon dioxide and other components (Bogner et al., 2008; Esparza et al., 2020; Kaza et al., 2018). Fossil fuel-associated GHG emissions are avoided by substituting biogas and bio-methane for fossil fuels (Bogner et al., 2008), but biogas combustion generates carcinogenic emissions and converts methane into carbon dioxide, which is then released into the atmosphere (Nanda & Berruti, 2021; Paolini et al., 2018).

1.2.1.2. Composting. Composting refers to the aerobic degradation of solid and semi-solid organic wastes by microbes, producing carbon dioxide, water, and compost (a stable, soil-like mixture of carbon and nitrogen-rich compounds that can improve soil microbial diversity, aggregate stability, tillage, and water holding capacity) (Ganesh et al., 2022; Lou & Nair, 2009; Melikoglu et al., 2013). Methane gas may also be produced in anaerobic pockets within the compost pile, with some studies claiming that methane emissions are negligible due to the oxidation of most of the methane into carbon dioxide near the surface and within aerobic portions of compost piles. Other studies have found significant methane emissions from well-managed compost piles. This variability is likely due to differences in key properties that influence the composting process (e.g. moisture content, temperature, pH, aeration, particle size, porosity, and carbon/nitrogen ratio) (Esparza et al., 2020; Ganesh et al., 2022; Lou & Nair, 2009).

Compost production can reduce both chemical fertilizer and pesticide usage, thereby mitigating the negative environmental impacts (e.g. groundwater contamination, eutrophication, soil degradation, ammonia emissions, and adverse effects on non-target organisms) and GHG emissions associated with their manufacturing and application (Baweja et al., 2020; Ganesh et al., 2022; Savci, 2012). Additionally, compost usage facilitates carbon sequestration in soil and increases the rate of plant biomass growth, which enhances carbon uptake and storage by plants (Ganesh et al., 2022). However, compost production is a time, labour, and energy-intensive process, requiring the sorting and grinding of waste organic materials, mixing and aeration of compost piles, and management of moisture level and other key parameters (Esparza et al., 2020; Ganesh et al., 2022; Suthar, 2009). In centralized composting facilities, these steps often involve heavy machinery that are expensive and produce GHG emissions through energy usage (Lou & Nair, 2009). Low-cost manual composting practices are more feasible in decentralized waste management systems (Nanda & Berruti, 2021). Poor management of the composting process often results in odour generation, GHG emissions, and the production of low-quality compost (Esparza et al., 2020; Lou & Nair, 2009). Although composting is generally considered to be the second least favourable practice on the waste management hierarchy, it has been found to be preferable over incineration for organic matter with high moisture content (e.g. fruit and vegetable wastes) due to the extremely large amounts of energy needed to heat up and vaporize the water during combustion (Eriksson, 2015).

Fruit and vegetable wastes may also be converted into compost through vermicomposting, which is defined as the degradation of organic compounds by synergistic interactions between earthworms and microorganisms. By ingesting organic materials, digesting them with various enzymes (e.g. proteases, amylases, lipases, and cellulases), and aerating the substrate through physical movement, the earthworms facilitate microbial activity and aerobic decomposition of the organic matter (Huang et al., 2014; Rorat & Vandenbulcke, 2019). The produced vermicompost has better nutrient availability, reduced pathogenic load, and lower concentrations of heavy metals and other harmful compounds compared to conventional compost (Rorat & Vandenbulcke, 2019; Suthar, 2009). However, earthworms may accumulate heavy metals in their bodies, which will then be incorporated into trophic chains if the earthworms are consumed. The success of vermicomposting is heavily influenced by factors such as pH, temperature, moisture content, oxygen content, carbon/nitrogen ratio, the absence of light, and earthworm stocking density (Rorat & Vandenbulcke, 2019). Vermicomposting is relatively simple and can be conducted using very low-cost equipment (Huang et al., 2014; Rorat & Vandenbulcke, 2019).

1.2.1.3. Incineration. Incineration can significantly reduce the weight and volume of MSW (80–85 % and 95–96 % reduction, respectively) (Nanda & Berruti, 2021), generating inert ash and slag residues that are disposed of in landfills while also extending the landfills' lifespans by reducing the volume of landfilled wastes (Esparza et al., 2020; Melikoglu et al., 2013). The co-disposal of incineration slag with other MSW in landfills has been found to greatly accelerate the production of methane gas (Wang et al., 2023). Modern waste-to-energy incineration systems also produce thermal and electrical energy, thereby offsetting the use of fossil fuels, but these systems are expensive to build and require high technical and management capabilities to operate (Bogner et al., 2008; Kaza et al., 2018). Thus, modern incineration systems are used primarily in high-income countries that have limited land capacity (Kaza et al., 2018). Uncontrolled burning of waste remains common in developing regions (Bogner et al., 2008), where lack of proper preventative measures allows the release of particulate matter and fly ash containing heavy metals, VOCs, furans, dioxins, and other harmful GHGs (including carbon dioxide, sulphur dioxide, and nitrogen oxides) into the environment (Bogner et al., 2008; Melikoglu et al., 2013).

Incineration is generally considered to be the third least favourable practice in the waste management hierarchy (Eriksson, 2015). However, due to the high moisture and low calorific content in fruit waste, incineration of fruit waste is energetically less favourable than composting, as more energy is often required to heat up and evaporate the water content than is produced through combustion of the fruit waste (Eriksson, 2015; Esparza et al., 2020). Therefore, fuel and high-energy wastes must be added to the combustion process to sufficiently sustain the required high operating temperatures. Because of its high energy requirements, incineration of fruit waste produces the highest amount of GHG emissions when compared to anaerobic digestion, donation, and conversion of fruit wastes into alternative food products (Eriksson & Spångberg, 2017; Esparza et al., 2020).

1.2.1.4. Animal feed. Fruit and vegetable wastes are used globally to feed various livestock species (e.g. ruminants, pigs, poultry, and fish) (Wadhwa et al., 2015), which offsets some of the resources and energy required to produce crops for conventional animal feed, along with associated emissions and environmental impacts (Esparza et al., 2020). This practice also upcycles the low-quality fruit wastes into high-quality food products that will re-enter the human food supply chain (Kasapidou et al., 2015; Wadhwa et al., 2015), so it is ranked quite favourably on the waste management hierarchy (Papargyropoulou et al., 2014). Additionally, with the world's population projected to increase from 7.7 billion people in 2019 to 10 billion people by 2050 (Facchini et al., 2023), demand for meat, dairy, and other animal products is expected to surge by 60–70 %, especially with increasing income and urbanization in developing countries (Wadhwa et al., 2015). This will exacerbate current shortages of animal feed in many developing countries (Wadhwa & Bakshi, 2013). As a promising source of antioxidants, phytochemicals, vitamins, antimicrobials, dietary fats, fibre, and other nutrients (Kasapidou et al., 2015; Plazzotta et al., 2017), fruit and vegetable wastes may help address this deficit of good quality feed while also reducing the cost of feeding, thereby allowing farmers to reap higher profits (Wadhwa & Bakshi, 2013).

However, not all fruit wastes are suitable for animals to consume (Esparza et al., 2020), especially with their low protein content and high amounts of indigestible compounds (such as insoluble fibre) (Plazzotta et al., 2017). Negative effects on animal health and final food product quality have been observed in various livestock species due to the feeding of certain fruit-derived compounds (Kasapidou et al., 2015). For example, broiler chickens fed on diets supplemented with grape seed extracts have been found to exhibit slowed growth rates and reduced feed conversion (Chamorro et al., 2013). Fruit residues may negatively impact feed palatability, and their nutritional compositions will naturally vary depending on seasonality, origin, and processing conditions, which may force manufacturers to regularly adjust feed formulations (Kasapidou et al., 2015; Plazzotta et al., 2017). Fruit wastes must also be monitored for the presence of pesticide residues, heavy metals, furans, mycotoxins, dioxins, and other contaminants that pose health risks if incorporated into animal products meant for human consumption (Wadhwa et al., 2015). Additionally, due to its high moisture content, fruit waste is susceptible to microbial contamination and must be heat-treated (i.e. thermal treatment), processed, transported, and stored with appropriate precautions to prevent the spread of disease, which increases costs and energy usage (Esparza et al., 2020; Kasapidou et al., 2015; Plazzotta et al., 2017; Salemdeeb et al., 2017). In some regions, particularly the EU, strict regulations inhibit the usage of fruit and vegetable wastes as animal feed (Salemdeeb et al., 2017).

1.2.1.5. Anaerobic digestion. Similar to landfilling, anaerobic digestion produces biogas through the degradation of organic wastes by anaerobic bacteria. However, the process of anaerobic digestion is carried out in specially designed bioreactors (known as "digesters") that allow the control of various key parameters, such as temperature, pH, carbon/nitrogen content, moisture content, organic acid profile, and nutrient feeding strategy (Esparza et al., 2020; Ji et al., 2017). These parameters affect the composition and activity of the microbial consortia, which in turn affect the composition of the produced biogas. Therefore, control of these parameters enables optimized methane yields compared to landfill biogas. Additionally, anaerobic digestion produces solid digestate that may be used as livestock bedding, fertilizer, or an ingredient in soil treatments after further processing (Esparza et al., 2020).

Due to its high moisture content, fruit waste is well-suited for anaerobic digestion (Eriksson & Spångberg, 2017). Different types of fruit waste have varying potential for methane generation through anaerobic digestion, with banana skins, pineapple peels, pomegranate pomace, mandarin peels, and mango peels yielding 277, 357, 420, 486, and 370–520 normalized litres of methane per kg of VS of substrate, respectively (Esparza et al., 2020; Ji et al., 2017). One of the main challenges in anaerobic digestion is that fruit wastes are quickly hydrolyzed due to their high VS and low TS content, resulting in rapid acidification that inhibits methane production. Potential solutions include co-digestion of fruit wastes with other materials (e.g. activated sludge, landfill waste, MSW, wastewater, and other food waste), pretreatment of wastes before anaerobic digestion, and the use of two-stage anaerobic digesters that are designed to separate methane production from acid production (Ji et al., 2017; Leong & Chang, 2022).

Out of the aforementioned practices, anaerobic digestion is generally considered as the most favourable option in the waste management hierarchy. This is because it produces biogas and has the lowest carbon footprint for processing several types of food wastes as compared to other conventional waste management practices (Eriksson, 2015). Anaerobic digestion systems prevent the release of biogas into the atmosphere and instead retain the biogas to be used as an alternative to conventional energy, heat, and fuel sources (Eriksson, 2015; Kaza et al., 2018), thereby indirectly reducing GHG emissions that would be produced through fossil fuel consumption (Bogner et al., 2008). The use of the solid digestate as a fertilizer can reduce the usage of chemical fertilizers and their associated environmental impacts. However, if improperly managed, digestates can cause nitrate leaching from soil, as well as significant methane, ammonia, and nitrous oxide emissions (Paolini et al., 2018). Additionally, anaerobic digestion systems are expensive to construct and operate, requiring high technical and management competency, so anaerobic digestion is rarely used outside of high-income countries (Kaza et al., 2018). Generated effluents must be treated before they can be discharged into the environment (Bouallagui et al., 2005), and biogas combustion produces carbon dioxide and various gaseous pollutants (e.g. CO, SO_2, nitrogen oxides, non-methane VOCs, and formaldehyde) (Paolini et al., 2018).

1.2.2. *Emerging valorization methods*

Emerging methods of fruit waste valorization preserve nutrients and valuable compounds inside the waste, allowing for their extraction for either direct use or transformation into other value-added, complex compounds. By recovering valuable components from fruit waste and reincorporating these compounds into various product supply chains (e.g. food, cosmetics, and pharmaceuticals), these practices create products of higher value than the waste while also reducing the amount of fruit waste that is ultimately disposed of, unlike conventional waste management methods (Eriksson, 2015; Esparza et al., 2020). These methods of valorization are thus considered to be highly favourable in the waste management hierarchy (Eriksson & Spångberg, 2017). However, waste valorization has not yet been widely implemented due to high costs associated with transportation of waste residues to processing plants, preservation of residues to prevent decomposition, and scaling up of the processing technologies (Esparza et al., 2020). In order to ensure their cost-effectiveness and sustainability, waste valorization processes should be designed to not only recover high-value components from biomass feedstocks, but also effectively utilize the remaining byproducts. This will reduce the overall economic and environmental impacts of emerging valorization methods, as well as their consumption of natural resources (Esparza et al., 2020).

In addition, the variability in fruit waste supply and composition due to geographic origin, seasonality, processing conditions, and perishability complicates the conversion of fruit wastes into stable quantities of consistently high-quality products (Kasapidou et al., 2015; Leong & Chang, 2022). Potential solutions include storing large quantities of dried and ensiled fruit wastes during harvest season, using alternative fruit wastes as feedstock during non-harvest seasons, and designing integrated biorefinery processes that can flexibly use multiple feedstocks throughout the year (Banerjee et al., 2018; Leong & Chang, 2022).

1.2.2.1. Conversion into derivative edible and non-edible products. Several types of fruit residues can be transformed into derivative edible products for human consumption, such as food additives (e.g. flour), vinegar, cider, beer, brandy, and jam (Eriksson & Spångberg, 2017; Wadhwa & Bakshi, 2013). For example, wastes from pineapple juice and orange juice production have been used to produce vinegar via acetic acid fermentation by *Acetobacter* bacteria (Wadhwa & Bakshi, 2013), surplus fruit and vegetables from supermarkets can be cooked with sugar and vinegar to produce chutney (Eriksson & Spångberg, 2017), and pineapple pomace and unripe bananas have been used to produce dietary fibre supplements (Ooi et al., 2023). These derivative food products, which are commonly referred to as “upcycled foods” or “upcycled ingredients”, divert food wastes destined for disposal and instead bring them back into the human food supply chain. Upcycled foods thereby create additional value, avoid wastage, and return the food to its original intended use of human consumption (Aschemann-Witzel et al., 2023).

Upcycling food wastes significantly mitigates the resource wastage, primary energy usage, and GHG emissions associated with food wastage while also increasing the efficiency of the food production system and addressing global food insecurity (Eriksson & Spångberg, 2017; The Upcycled Foods Definition Task Force, 2020). However, upcycled food products do not avoid the resource and energy usage required for production of the original food product, and the upcycling process requires additional energy input (Aschemann-Witzel et al., 2023). Furthermore, there are several food safety, quality, and traceability concerns associated with the manufacturing and sale of upcycled food products, and the adoption of upcycled food products is often limited by consumer acceptance since upcycled foods contain ingredients that would not otherwise be used for human consumption (Moshtaghian et al., 2021).

Fruit wastes may also be upcycled into non-edible products, such as biochar and biosorbents for pollutant removal, nanocellulose for biomedical applications, bioplastics, biodegradable coatings and films, metallic nanoparticles for medical and electrocatalytic applications, and photoluminescent carbon dots (Ding et al., 2023; Kumar et al., 2020; Leong & Chang, 2022). Fruit waste is a cheap and renewable source of several compounds that can replace conventionally sourced raw materials, catalysts, and stabilizing agents which are expensive and have limited re-generability (e.g. fossil fuels and activated carbon) (Kumar et al., 2020; Leong & Chang, 2022). Additionally, the manufacturing of certain products (such as carbon dots) from fruit wastes may utilize milder conditions and be significantly less complex than conventional synthesis methods (Kumar et al., 2020). However, these novel manufacturing approaches may be expensive and difficult to scale up (Ganesh et al., 2022), and the fruit wastes are often pre-treated and processed using high energy methods (e.g. steam explosion and pyrolysis), concentrated acids and bases, organic solvents, and toxic sulfides (Banerjee et al., 2018; Ding et al., 2023; Kumar et al., 2020). Moreover, inherent variability in the fruit waste’s chemical composition may affect the quality and performance of the final upcycled products (Ding et al., 2023).

1.2.2.2. Biorefinery approach. Fruit wastes are rich in several compounds (such as lignin, phenolic compounds, enzymes, and antioxidants) that can be extracted and converted into alternative products for applications across numerous industries (Ding et al., 2023; Leong & Chang, 2022). A biorefinery approach uses an integrated combination of various processes (e.g. thermochemical, physical, biological, and chemical) to synergistically convert biomass feedstocks into multiple value-added products (Moreno et al., 2020). A fruit waste biorefinery can significantly increase the proportion of fruit waste biomass that is valorized into marketable products and therefore maximize the derived value from fruit waste (Leong & Chang, 2022; Slegers et al., 2020). Although the total production costs of the biorefinery approach are significantly greater than that of producing a single product from the biomass feedstock, this is compensated by the increased overall revenue from multiple product streams, which improves the economic viability of the overall biorefinery platform (Slegers et al., 2020).

By using fruit wastes as a renewable feedstock to produce compounds that are conventionally made using non-renewable petroleum-based feedstocks (e.g. plastics and H_2), the biorefinery approach can mitigate the GHG emissions associated with such product supply chains (Esparza et al., 2020). However, conventional high-efficiency extraction methods generally rely on the use of an organic solvent, which often creates a toxic waste stream and requires a subsequent high-energy evaporation step. Novel extraction methods such as MAE, EAE, UAE, SFE, PLE, and PEF reduce the need for organic solvents but require high initial investment and further optimization and verification, especially at the industrial operating scale (Kandemir et al., 2022; Plazzotta et al., 2017). Additionally, the extraction process often generates relatively high amounts of residual waste which will still need to be disposed of (Plazzotta et al., 2017).

1.2.2.3. Microbial fermentation medium for biomanufacturing. Due to their high sugar and nutrient content, fruit wastes are a promising growth medium for the production of biomass and several commercially valuable metabolites through bacterial, fungal, and microalgal fermentation (Kumar et al., 2020; Leong & Chang, 2022). Examples of such microbially produced compounds include citric acid, single cell protein, exopolysaccharides, biodiesel, and various enzymes (e.g. pectinase, laccase, and cellulase) (Esparza et al., 2020; Kumar et al., 2020; Wadhwa & Bakshi, 2013). With the advent of precision fermentation processes, which use genetically modified microbial hosts to produce high-value compounds that are often not native to the host organism, microbial biomanufacturing processes can also be used to produce compounds that have significant negative environmental impacts when produced using conventional industrial methods (e.g. agriculture, husbandry, organic synthesis, bulk extraction, and foraging) (Chai et al., 2022). Additionally, the microbial biomanufacturing approach can be integrated into a biorefinery process, where the microbial biomass serves as the biorefinery feedstock (Slegers et al., 2020).

The use of fruit waste as a low-cost alternative to conventional fermentation media may substantially improve the economic viability of biomanufacturing various goods, as the cost of the fermentation substrate is a key cost driver for microbial fermentation (Leong & Chang, 2022). However, natural variability in the composition of fruit wastes will likely result in variable yield of desired end products as compared to the usage of standardized, commercially available fermentation media. The usage of fruit wastes as a fermentation media will thus require further optimization of processing and fermentation conditions in order to improve the efficiency and economic viability of the overall biomanufacturing process. The economic viability of fermentation processes is also driven by product yield, titre, and purity, which are in turn affected by operational variables such as pH, temperature, bioreactor design, microbial strain type, aeration, moisture level, and nutrient feeding strategy (Kosseva, 2011). Additionally, a typical biomanufacturing process utilizes several unit operations for the production and purification of desired compounds. Each unit operation often requires the use of complex and expensive equipment (e.g. bioreactor, centrifuge, and filtration system), each with inputs (e.g. electric power supply, water, fermentation substrate, and oxygen gas) and outputs (e.g. production intermediaries and wastewater) (Nikolov et al., 2023; Petrides et al., 2014). The overall biomanufacturing process generates side-streams that are widely considered as wastes and which require further energy for processing and disposal (e.g. spent fermentation media, leftover microbial biomass, and exhaust gas).

Fruit wastes with high solids and insoluble fibre content are well-suited to SSF, which involves the cultivation of micro-organisms on solid, moist substrates without a free liquid phase. However, due to the complexities in scaling-up and maintaining process control of SSF at the commercial level, SmF processes are generally preferred in industry as they offer better control of reaction conditions, but they have higher energy requirements compared to SSF. SmF involves the cultivation of microorganisms in liquid media with excess free-flowing water, where soluble compounds are dissolved in the liquid phase while insoluble compounds are suspended or submerged (Esparza et al., 2020). Thus, fruit wastes may need to be processed using physical (e.g. grinding and heat), chemical (e.g. acid or alkaline hydrolysis), enzymatic (e.g. fungal fermentation or direct enzymatic degradation), or other treatments prior to SmF in order to solubilize and enhance the bioconversion of contained compounds (Ding et al., 2023). These pre-treatments will require additional resource and energy consumption, may generate wastes (e.g. used solvents), and may require extensive optimization (especially in the case of enzymatic degradation). Fig. 2 highlights various value-added products that can be derived from fruit wastes using conventional and emerging waste management practices.

2. Characteristics of fruit waste composition

Given the different types of fruits and fruit wastes (e.g. twigs, peels, seeds, and whole fruits), the composition of fruit waste can vary greatly. Wasted fruits in wholesale markets consist of 7.5–23 % TS and 5–12 % VS on a wet weight basis, and they possess a carbon/nitrogen ratio of 19–53 % (Esparza et al., 2020). Fruit processing wastes generally contain large quantities of suspended solids and high COD and BOD (Mirabella et al., 2014). The organic composition of fruit wastes typically consists of 75 % soluble sugars (e.g. glucose, sucrose, and fructose) and insoluble hemicellulose, 9 % cellulose, and 5 % lignin (Kosseva, 2011). These dietary fibres are a source of prebiotic oligosaccharides, exhibit probiotic effects, and have been found to lower the risk of several chronic conditions (e.g. diabetes, hypertension, gastrointestinal disorders, coronary heart disease, and obesity) (Banerjee et al., 2018; Kumar et al., 2020). Fruit wastes also contain 80–90 % moisture content, small amounts of protein and fat, and several commercially valuable bioactive compounds that may function as alternative commodities (e.g. pigments, antioxidants, phenolic compounds, and essential oils) in the food, cosmetics, and pharmaceutical industries (Leong & Chang, 2022; Mirabella et al., 2014). Table 1 evaluates the specific composition of various types of fruit waste.

2.1. Banana (Musa acuminata)

Bananas are the most highly produced fruit, with 124.98 MMT produced globally in 2021 (Shahbandeh, 2023). About 30 to 40 % of bananas are rejected for failing to meet quality standards (i.e. damaged or too small), and other wastes from banana production include the peels, leaves, pseudo stems, and young stalks (Wadhwa & Bakshi, 2013). Fully mature bananas contain about 12 % sugar, which is mostly fructose and glucose (40 % and 48 %, respectively) (Ende & Noke, 2019). Comprising 30–40 % of the fruit by weight, banana peel consists of 6–9 % protein, 3 % starch, 43.2–49.7 % dietary fibre, and 6–12 % lignin (Murakonda & Dwivedi, 2021). Unripe (green) bananas are a good source of starch, which comprises 61.3–76.5 % of the whole fruit (pulp and peel) on a dry weight basis (Juarez-Garcia et al., 2006). 20–30 % of the total starch is amylose (da Mota et al., 2000), while about 23.84 % is resistant starch (i.e. the starch and products of starch degradation that are not digested in the healthy human small intestine and are instead fermented by microflora in the large intestine). Resistant starch has been found to provide similar health benefits as dietary fibre, such as protection against colorectal cancer and regulation of glycemic and insulin responses to food (Juarez-Garcia et al., 2006).

Approximately 10–12 % of the banana peel consists of pectin

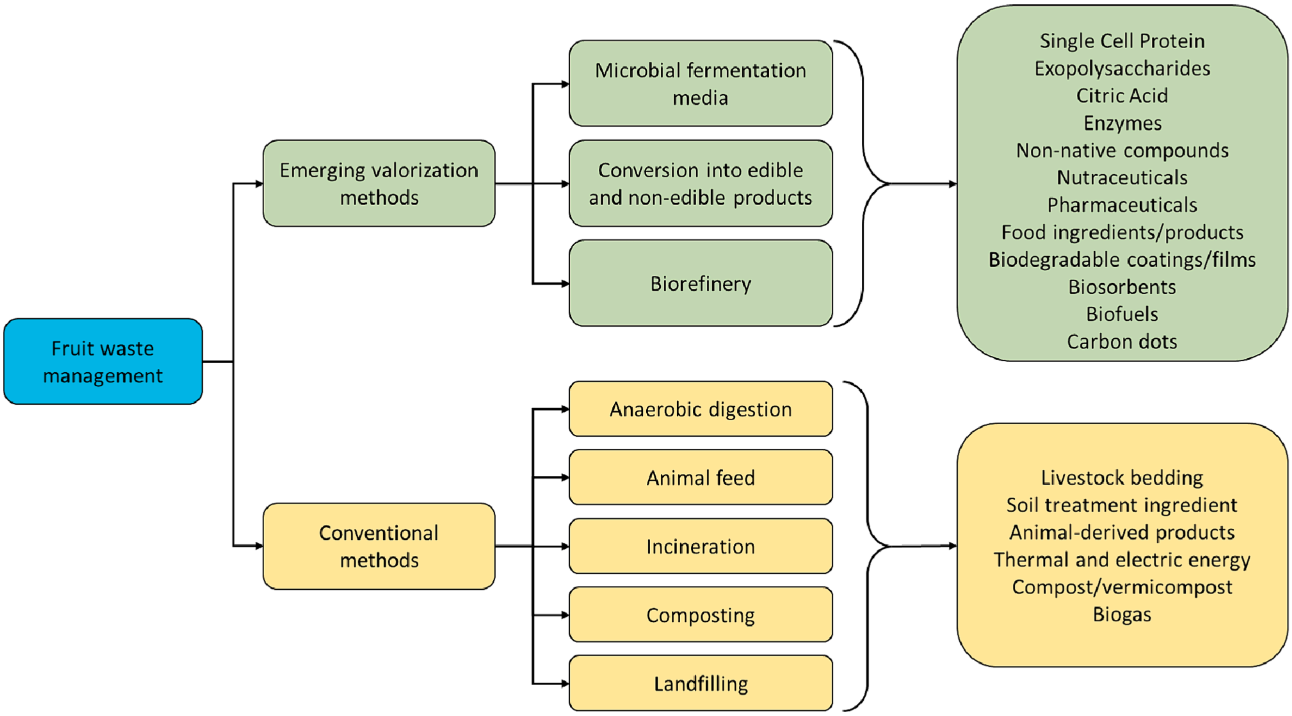

Fig. 2. Conventional and emerging methods of fruit waste management can generate various value-added products. The products generated from conventional methods are mostly of lower economic value than those generated from emerging valorization methods.

Table 1
Composition of various types of fruit waste (%w/w, dry basis). "—" indicates that a value was not stated.

Fruit waste type	Moisture content	Carbohydrates	Lipids	Proteins	Ash	Dietary fiber	Reference(s)
Banana (peel and pulp)	7.1	73.4	2.7	3.3	4.7	14.5	(Juarez-Garcia et al., 2006)
Watermelon (peel)	8.19	–	1.8	7.9	7.9	83	(Solangi et al., 2021; Wadhwa & Bakshi, 2013)
Watermelon (seed)	4.3	4.5	52.60	34.10	3.70	0.8	(Solangi et al., 2021)
Apple (pomace)	17.35	–	5.0	7.7	2.6	52.5	(Joshi, 2020; Wadhwa & Bakshi, 2013)
Orange (peel)	–	20.65	1.95	6.50	3.50	63.05	(Ángel Siles López et al., 2010)
Orange (pomace)	7.46	–	1.44	8.45	2.65	30.74	(Nagarajaiah & Prakash, 2016)
Orange (seed)	4.00	–	36.90	15.80	4.00	14.00	(Joshi, 2020)
Grape (pomace)	7.67	–	5.0–7.1	8.9–12.2	7.9	51.5–58.0	(Nagarajaiah & Prakash, 2016; Wadhwa & Bakshi, 2013)
Grape (stalk)	–	–	–	6.1	7.0	68.7	(Prozil et al., 2012)
Pineapple (peel and pulp)	3.77	43.46	0.61	4.71	2.24	45.22	(Selani et al., 2014)
Mango (peel)	10.5	80.7	2.2	3.6	3.0	51.2	(Ajila et al., 2008)
Mango (seed)	8.2	74.49	8.85	8.50	3.66	–	(Joshi, 2020)
Mango (kernel)	–	77	11	6.0	2.0	2.0	(Abdalla et al., 2007)
Sweet lemon (pulp)	7.02	–	2.16	7.27	4.15	43.86	(Nagarajaiah & Prakash, 2016)

(Murakonda & Dwivedi, 2021), which is a dietary fibre that is conventionally used as a stabilizer for fruit juices, as well as a thickening and gelling agent in several foods (Mirabella et al., 2014). Recently, several novel applications for pectin in the food (e.g. encapsulation agent for bioactive compounds, antimicrobial edible food packaging, and fat alternative), pharmaceutical (e.g. wound healing, tissue engineering, and drug delivery), and environmental (e.g. pollution absorption) industries have been explored (Leong & Chang, 2022). Banana peels also contain essential amino acids, catecholamines, procyanidins, prodelphinidins, and polyphenols (secondary metabolites that have antioxidant, anti-microbial, anti-inflammatory, anti-thrombotic, and anti-allergenic effects) (Banerjee et al., 2018; Ding et al., 2023), with higher flavonoid and total phenolic content than the banana pulp (Murakonda & Dwivedi, 2021).

2.2. *Watermelon (Citrullus lanatus)*

Watermelons are the second most produced fruit, with 101.63 MMT produced worldwide in 2021 (Shahbandeh, 2023). They may be consumed fresh or processed into juice and desserts. Only about 50 % of the fruit mass is consumed, while the other half (seeds, 15 % peel, and 35 % rind) is usually discarded, despite the rind and seeds being edible (Liu et al., 2012; Petchsomrit et al., 2020). Fresh watermelon rind is comprised of 2.44 % fat, 11.17 % protein, 17.28 % crude fibre, and 56.02 % carbohydrates by weight (Al-Sayed & Ahmed, 2013). With its high carbohydrate content, watermelon rind can be used as a source of pectin (Petkowicz et al., 2017), and it is naturally rich in the non-essential amino acid citrulline, which has antioxidant effects and can be converted into arginine (Al-Sayed & Ahmed, 2013). Consisting of 58 % cellulose, 14 % hemicellulose, and 11 % lignin on a dry weight basis (Solangi et al., 2021), watermelon peel contains the highest amount of phenols (mainly catechin, gallic acid, kaempferol, and ellagic acid) compared to several other types of fruit peels (Kandemir et al., 2022). The peel wax contains several fatty acids with 14–20 carbon atoms, such as arachidic acid, palmitic acid, stearic acid, oleic acid, linoleic acid, and myristic acid (Petkowicz et al., 2017). Watermelon seeds are also rich in phenolics and are comprised of about 10–35 % oil, of which linoleic acid (an essential omega-6 fatty acid that may decrease body fat deposition, improve impaired glucose tolerance, and reduce the risk of atherosclerosis) is the most abundant fatty acid (Kandemir et al., 2022; Petchsomrit et al., 2020; Skinner et al., 2018; Wadhwa & Bakshi, 2013). Additionally, watermelon seeds contain other essential fatty acids, tocopherols, thiamine, carotenoids, riboflavin, and flavonoids (Petchsomrit et al., 2020).

2.3. *Apple (Malus domestica)*

With 93.14 MMT produced worldwide in 2021, apples are the third most highly produced fruit (Shahbandeh, 2023). 30–40 % of apples are not marketed due to damage, and 20–40 % are processed into juice (Wadhwa & Bakshi, 2013). Apples may also be eaten fresh or processed into canned or dried fruits, cider, vinegar, jam, and desserts (Esparza et al., 2020; Wadhwa et al., 2015), leaving behind a residue known as apple pomace. Comprising approximately 25 % of the fruit by mass, apple pomace consists of the crushed skin, stalks, seeds, and pulp. Apple pomace is low in protein and fat (1.1–3.6 % and 2.7–5.3 % of the fresh weight, respectively), with fatty acids found mostly in the seeds, which contain oleic acid and linoleic acid (Skinner et al., 2018). A large portion of carbohydrates are in the form of fructose and glucose, with sucrose content varying greatly between different apple cultivars. Dietary fibre content (4.4–47.3 % by weight) also varies depending on the apple cultivar and the quantification method, with insoluble fibre comprising 33.8–60 % and soluble fibre comprising 13.5–14.6 % of the total fibre content. Of the insoluble fibre, 6.7–40.4 % is cellulose and 14.1–18.9 % is lignin (Skinner et al., 2018).

Apple pomace is a key source of pectin, which comprises 20 % of the pomace's fresh weight (Joshi, 2020). Apple pomace also contains phloretin and phlorizin, which are potential therapeutic agents for diabetes (Esparza et al., 2020). Apple peel is rich in calcium, magnesium, phosphorous, vitamins C and E, polyphenols (such as flavonols, flavanols, dihydrochalcones, and hydryoxycinnamates), and polyphenolic compounds (such as ferulic acid, caffeic acid, p-coumaric acid, and catechin). Additionally, apple peel contains ursolic acid, which is a wax on the apple cuticle that has been found to exhibit anti-inflammatory, anti-cancer, antioxidant, and anti-hepatotoxic activity (Skinner et al., 2018).

2.4. *Orange (Citrus sinensis)*

In 2021, 75.57 MMT of oranges were produced globally (Shahbandeh, 2023). About 70 % of oranges are used to produce juices, marmalades, desserts, and other products (Martín et al., 2010). During this process, around only half of the fruit's fresh weight is used, and the remaining 50–60 % of the fruit (i.e. peel, pulp, seeds, leaves, and fruits that do not meet quality standards) are discarded (Martín et al., 2010; Rezzadori et al., 2012). Additionally, the production of orange juice generates highly polluted wastewater (also known as "yellow water") which contains fibre, other organic matter, and binders that were added during the pressing stage (Martín et al., 2010; Mirabella et al., 2014; Rezzadori et al., 2012).

Orange waste contains 42.5 % (w/w) pectin, 10.5 % hemicelluloses, 9.21 % cellulose, and 16.9 % soluble sugars (i.e. fructose, glucose, and sucrose). The hemicelluloses and pectin are rich in galactose, arabinose, and galacturonic acid, along with small amounts of glucose, rhamnose, and xylose (Rezzadori et al., 2012). Citrus peel, pomace, and seeds have been found to contain more than twice as much polyphenols as the edible tissue (Wadhwa & Bakshi, 2013). Orange pomace exhibits excellent antioxidant activity and contains high amounts of phenolic acids (e.g. ferulic acid, chlorogenic acid, and gallic acid), flavonoids (e.g. hesperidin), and tannins (which can be used as food additives, tanning agents, polymers, adhesives, and more) (Kandemir et al., 2022; Nagarajaiah & Prakash, 2016; Prozil et al., 2012). Rich in saturated, unsaturated, and omega fatty acids, citrus seeds are a good source of limonoids (e.g. limonin, ubacunone, and nomilin), which are highly oxidized triterpenoids that exhibit anticarcinogenic, anti-tumour, anti-fungal, and anti-bacterial activity (Kandemir et al., 2022).

Orange peel contains antimicrobial essential oils (0.544 % by weight), of which approximately 90 % is D-limonene (Martín et al., 2010). The main aromatic compound in citrus fruits, D-limonene is used as a flavouring agent for medicines and food, and it has several applications in the cosmetics, household products, healthcare, and chemical industries (Martín et al., 2010; Wadhwa & Bakshi, 2013). Orange peel also contains flavonoids (e.g. hesperidin, rutin, and naringin), carotenoids, vitamins (especially vitamin C), and small amounts of organic acids (e.g. citric acid, malonic acid, malic acid, and oxalic acid) (Ángel Siles López et al., 2010; Kandemir et al., 2022).

2.5. *Grape (Vitis vinifera L)*

About 73.52 MMT of grapes were produced worldwide in 2021 (Shahbandeh, 2023). Grapes are mostly used to produce wine and juice (Kandemir et al., 2022), though they may also be eaten fresh or processed into jam and dried raisins. Wastes from grape processing include pomace (which consists of the skin and seeds) and stalks, with approximately 25 kg of byproducts (including 4 kg of stalks and 13.2 kg of skins) generated from the production of 100L of red wine and about 31.2 kg of byproducts (including 4 kg of stalks and 17 kg of skins) generated from the production of 100L of white wine (Prozil et al., 2012).

Comprising about 25–45 % of the fruit's wet weight, grape pomace consists of 3.1–5.4 % hemicellulose, 54 % cellulose, 4–5 % phenolic compounds, and large quantities of polyphenols (e.g. catechins, glycosylated flavonols, and proanthocyanidins) (Kandemir et al., 2022; Wadhwa & Bakshi, 2013). Also known as condensed tannins, proanthocyanidins are highly efficient antioxidants with strong *in vivo* activity (Qi et al., 2023). They can be heated to form the water-soluble pigment anthocyanin, which also has antioxidant properties and is mainly responsible for the red, purple, and blue colours of grapes and red wine. Anthocyanins are mostly found in the grape skin, while grape seeds are the source of most proanthocyan products currently available on the market (Dwyer et al., 2014; Qi et al., 2023). Grape seeds, which comprise 3–6 % of the fruit, also contain 12–17 % oil that is rich in linoleic acid (Wadhwa & Bakshi, 2013). Grape stalks comprise 2.5–7.5 % of the fruit and are rich in cellulose, hemicellulose, and lignin (30.3 %, 21.0 %, and 17.4 % by weight, respectively) (Prozil et al., 2012; Wadhwa & Bakshi, 2013). Grape stalks contain large amounts of tannins (15.9 %) (Prozil et al., 2012), and, depending on the grape cultivar, geographic origin, and extraction method, grape stalks may contain almost twice as much phenolics as compared to the pomace (Qi et al., 2023).

2.6. *Mango (Mangifera indica L.)*

More than 50 million tonnes of mangoes were produced globally in 2019 (Kandemir et al., 2022). The mango fruit consists of the peel (7–24 % on a fresh weight basis), kernel (9–40 %), and edible pulp (33–85 %) (Wadhwa & Bakshi, 2013). As mangoes are processed into juices, desserts, and fresh or dried fruits, several types of wastes are generated (e.g. peels, kernel meal, and fruits that do not meet quality standards) (Wadhwa & Bakshi, 2013). Mango peel consists of 51.2 % dietary fibre on a dry weight basis (19.0 % soluble fibre and 32.1 % insoluble fibre) and is rich in pectin (Ajila et al., 2008). The peel also has a high sugar content (13.2 %) and contains several molecules with antioxidant properties (e.g. vitamins C and E, carotenoids, phytochemicals, and polyphenols) (Kandemir et al., 2022; Wadhwa & Bakshi, 2013). Out of the polyphenols in mango peel, mangiferin has been found to be the most prominent (Kandemir et al., 2022). Comprising 45–75 % of the mango seed, the kernel is rich in edible oil (11.6 % on a dry weight basis), with a composition of 52–56 % unsaturated fatty acids (primarily oleic) and 44–48 % saturated fatty acids (primarily stearic) (Abdalla et al., 2007). Additionally, the kernel contains several phenolic compounds (e.g. gallotannins, tocopherols, and phytosterols) that exhibit high tyrosinase inhibitory activity and antioxidant activity, with a higher total phenolic content than the mango skin (Abdalla et al., 2007; Kandemir et al., 2022). The kernel also contains carotenoids, vitamin C, and several essential amino acids (notably valine, leucine, and lysine) (Kandemir et al., 2022; Mirabella et al., 2014).

2.7. Pineapple (*Ananas comosus*)

About 28.65 MMT of pineapples were produced worldwide in 2021 (Shahbandeh, 2023), and they are widely consumed as fresh or canned fruit, juices, jams, and concentrates (Banerjee et al., 2018; Selani et al., 2014). Pineapple production may result in two types of wastes: (1) Pineapple on farm waste (POFW), which includes the leaves, stem, and roots remaining in the fields after harvest; and (2) Pineapple peel waste (PPW), which includes the pineapple crown, peel, core, and leftover pomace from processing. For each kilogram of pineapples that is produced, an estimated 6 to 8 kg of fresh POFW and 0.75 kg of fresh PPW is generated, with PPW accounting for about 30–35 % of the fresh fruit weight (Banerjee et al., 2018; Wadhwa et al., 2015). POFW and PPW have high polysaccharide contents, with pineapple leaves comprised of 75–85 % cellulose (Banerjee et al., 2018), while the pineapple peel and core consist of 76 % fibre (of which 99.2 % is insoluble and 0.8 % is soluble) (Selani et al., 2014).

Pineapples are a key source of bromelain (a mixture of proteolytic enzymes, peroxidases, cellulases, and glucosidases), which can be extracted from the juice, POFW, and PPW. Bromelain has applications across the food, pharmaceutical, cosmetics, and textile industries. Bromelain may be used as a food additive to tenderize meats and prevent fruit browning, an anti-tumour and anti-inflammatory therapeutic agent to treat burns and other dermatological disorders, and an ingredient that increases bioavailability of amino acids in infant formula (S. Banerjee et al., 2018; Hikal et al., 2021). PPW also contains several polyphenols, mainly gallic acid, epicatechin, and ferulic acid (Banerjee et al., 2018). Additionally, pineapple peel is a source of vitamin C, carotenoids, flavonoids, saponins, and tannins (Hikal et al., 2021).

3. Upcycling fruit waste with microalgae biotechnology: A practical strategy towards achieving net zero waste and sustainable production

Global waste generation and consumption of natural resources have reached unsustainable levels, and their associated adverse environmental effects (e.g. pollution, GHG emissions, and natural resource depletion) will continue to worsen with the increasing global population unless sustainable consumption and production patterns are adopted. According to the United Nations' Sustainable Development Goal 12: "Responsible Consumption and Production", this involves the "production and use of goods and services that respond to basic needs and bring a better quality of life, while minimizing the use of natural resources, toxic materials and emissions of waste and pollutants over the life cycle, so as not to jeopardize the needs of future generations". In order to achieve this goal, economic growth must be decoupled from environmental degradation while continuing to meet basic human needs, and the negative environmental impacts of both the production and consumption of goods and services must be reduced (Papargyropoulou et al., 2014).

Microalgae are of particular interest as a renewable source of several commercially valuable compounds because microalgae can utilize nutrients in wastewater, and microalgae cultivation ponds and fermenters can be built on degraded land. Microalgal cultivation can thus avoid competition for arable land and other resources needed for food crops (Cheng et al., 2022; Chew et al., 2017). To address the high production costs that currently limit the commercial viability of microalgal-based biomanufacturing while simultaneously mitigating GHG emissions and valorizing waste streams, a zero waste microalgal biorefinery concept can be applied, where various components of microalgal biomass (including extracted crude biomass waste) are sequentially extracted and converted into several different high-to-low value-added products with no wastes (Cheirsilp & Maneechote, 2022). In addition, the reduction of food wastage is expected to positively impact water management, marine resources, climate change, terrestrial ecosystems, forestry, biodiversity, and other environmental sectors. This is because food wastage has an estimated carbon footprint of 3.3 gigatons of CO_2 equivalent and accounts for the usage of 250 trillion litres of surface and groundwater resources and almost 1.4 billion hectares of land during production (Socas-Rodríguez et al., 2021). Therefore, by utilizing food waste as a resource to generate multiple renewable products that can potentially replace conventionally manufactured goods and mitigate their negative environmental impacts (Esparza et al., 2020), microalgal biorefineries offer a promising strategy to achieve SDG 12 through more sustainable and efficient resource management and waste reduction.

3.1. Cultivation of microalgae using alternative fermentation medium derived from fruit wastes

Microalgae are photosynthetic microorganisms that can utilize autotrophic growth, where light energy from the sun is used to fix inorganic atmospheric CO_2 into simple carbohydrates (e.g. glucose and starch) and to synthesize biomolecules for growth through the Calvin cycle, producing oxygen as a by-product (Cheng et al., 2022; Yang et al., 2000). Autotrophic cultivation may be conducted either in open ponds or closed PBRs. However, biomass productivity is limited by inefficient light penetration due to biofilm fouling and mutual shading of cells at high cellular concentrations, as well as uneven light dispersal in large culture volumes (above 50 to 100L in PBRs). This may result in low biomass density, which increases biomass harvesting costs and lowers the biomass productivity of value-added compounds (Liang et al., 2009; Perez-Garcia et al., 2011).

Instead, some microalgal species can be cultivated through heterotrophic, photoheterotrophic, and mixotrophic cultivation modes, where nutrients from fermentation media are used as energy and/or carbon sources for growth and biosynthesis through aerobic respiration, which consumes oxygen and produces CO_2 (Perez-Garcia et al., 2011). By reducing or eliminating the microalgae's requirement for light, these three cultivation modes can potentially achieve much higher cell densities and productivity compared to autotrophic cultivation, thereby improving the economic feasibility of large-scale microalgal production. However, non-autotrophic cultivation requires the addition of an organic carbon source (e.g. glucose or acetate) to the fermentation medium, which is often expensive (about 80 % of the fermentation costs) and increases energy expenditures (Mitra et al., 2012; Perez-Garcia et al., 2011). The use of low-cost, nutrient-rich fruit wastes as a fermentation medium can help improve the cost effectiveness of microalgal biomanufacturing processes while simultaneously reducing fruit wastage along the food supply chain.

Heterotrophic, photoheterotrophic, and mixotrophic cultivation methods have been applied in several studies to utilize fruit wastes as nutrient sources for microalgal fermentation in order to produce various value-added compounds. However, not all microalgal species can utilize non-autotrophic growth strategies, and excessively high concentrations of organic substrates may inhibit microalgal growth. Additionally, the addition of an organic substrate to fermentation media increases the likelihood of contamination by undesired microorganisms, which will compete with the microalgae for nutrients and potentially hinder microalgal growth (Perez-Garcia et al., 2011). Table 2 evaluates the cultivation modes of microalgae using different fruit waste to produce various value-added compounds.

3.1.1. Heterotrophism

In the absence of light, certain microalgal species (e.g. *Chlorella* sp.,

Table 2
Cultivation of microalgae using fruit wastes to produce value-added compounds.

Microalgal strain	Fruit waste type(s)	Cultivation mode	Targeted product(s)	Reference(s)
Arthrospira platensis and *Chlorella vulgaris* co-culture	Winery wastewater	Heterotrophic and mixotrophic	Functional food compounds (protein)	(Spennati et al., 2022)
Aurantiochytrium sp. KRS101	Orange peel	Heterotrophic	Nutraceutical (docosahexanoic acid)	(Park et al., 2018)
Aurantiochytrium SW1	Peeled whole fruits (banana and pineapple)	Heterotrophic	Nutraceutical (docosahexanoic acid)	(Nazir et al., 2020)
Chlorella minutissima	Banana peel, orange peel	Heterotrophic	Biofuel	(Kumari et al., 2023)
Chlorella protothecoides	Papaya pulp	Heterotrophic	Biofuel	(Heller et al., 2015)
Chlorella sorokiniana KMBM_I and KMBM_K	Banana peel, sweet lime peel	Mixotrophic or photoheterotrophic	Biofuel	(Malakar et al., 2022, 2023)
Chlorella sp.	Whole fruits (Apple, banana, cherimoya, cucumber, grape, mango, melon, orange, peach, pear, pineapple, plum, strawberry, tangerine, tomato)	Autotrophic/ mixotrophic cycle	Algal biomass and lipids	(Condori et al., 2023)
Chlorella sp.	Sweet lime pulp and peel	Mixotrophic	Biofuel	(Katiyar et al., 2019)
Chlorella vulgaris	Various peels and pomace (apple, banana, mango, musk melon, orange, papaya, pomegranate, sapota, sweet lime, watermelon)	Autotrophic/ mixotrophic cycle	Biofuel	(Limbu & G, 2017)
Chlorella vulgaris	Apple, banana peel, mango, musk melon, orange, papaya, pomegranate, sapota, sweet lime, watermelon	Heterotrophic	Functional food compounds (protein, carbohydrates), biofuel, pigments (chlorophyll and carotenoids)	(Pratap et al., 2017)
Chlorella vulgaris	Plantain peel	Mixotrophic	Biofuel	(Agwa et al., 2017)
Chlorella vulgaris	Sweet lime peel, sweet lemon peel, and pomelo peel	Mixotrophic	Functional food compounds (protein, fatty acids)	(Nateghpour et al., 2021)
Chlorella vulgaris and *Haematococcus pluvialis*	Whole fruits (Mango, papaya, pineapple)	Autotrophic/ heterotrophic cycle	Microalgal biomass	(Tan et al., 2021)
Chlorella vulgaris OW-01	Orange peel	Mixotrophic	Biodiesel	(Park et al., 2014)
Euglena gracilis	Tomato pomace and peels	Mixotrophic	Nutraceutical (paramylon)	(Kim et al., 2021)
Euglena gracilis	Waste wine	Heterotrophic	Nutraceutical (paramylon)	(Rubiyatno et al., 2021)
Euglena gracilis LIMS-1351	Orange peel, apple pomace	Heterotrophic	Nutraceutical (beta-glucan)	(Yu et al., 2024)
Lagerheimia longiseta D133WC, *Monoraphidium contortum* D173WC, and *Scenedesmus quadricauda* D125WC	Composted whole fruits (apple, banana, mango, melon, papaya, passion fruit, pineapple, tomato, and watermelon)	Mixotrophic or photoheterotrophic	Functional food compounds (e.g. protein, lipid, phenolic compounds)	(de Medeiros et al., 2020)
Oscillatoria sancta PCC 7515	Fruit peels (banana, papaya, and pineapple)	Heterotrophic	Functional food compounds (polyphenols, protein, lipid, carbohydrates)	(Bala et al., 2023)
Scenedesmus acutus PPNK1	Pineapple peel	Mixotrophic	Biofuel	(Rattanapoltee & Kaewkannetra, 2014)
Tetraselmis indica	Kinnow peel	Autotrophic/ heterotrophic cycle	Biofuel	(Amit & Kumar Ghosh, 2019)

Nitzschia sp., and *Tetraselmis* sp.) can utilize heterotrophic growth, where dissolved organic compounds in the fermentation media are used as the carbon and energy source instead of atmospheric CO_2. Heterotrophism is also known as “dark fermentation” and “dark respiration”. Heterotrophic growth relies exclusively on aerobic respiration for energy and biosynthesis, so oxygenation is a limiting factor for biomass productivity and the specific growth rate (Perez-Garcia et al., 2011). The produced CO_2, which is not sequestered due to lack of photosynthetic activity, lowers the pH of the culture and can negatively impact microalgal growth and biomass productivity (Yun et al., 2021).

Heterotrophic cultivation has been found to yield significantly higher algal biomass densities (50–100 g of dry cell weight per litre) and higher intracellular lipid levels than autotrophic cultivation (30 g of dry cell weight per litre), with biomass synthesis occurring at near maximum theoretical efficiency (Liang et al., 2009; Perez-Garcia et al., 2011). For example, lipid content in *C. protothecoides* was found to increase 4.2 times in heterotrophic cultivation on corn powder hydrolysate compared to autotrophic cultivation (Li et al., 2007), and the biomass productivity of *C. ellipsoidea* in heterotrophic cultivation using glucose was 26.9 times higher than that of autotrophic cultivation (Abreu et al., 2022). Heterotrophic cultivation is generally simpler to operate and more cost-effective than autotrophic cultivation, as heterotrophic cultivation does not require the use of an expensive illuminated PBR and can be performed using practically any fermentor (Perez-Garcia et al., 2011). However, heterotrophic cultivation has been reported to be unable or have limited ability to produce certain light-induced metabolites (e.g. photosynthetic pigments) (Chojnacka & Marquez-Rocha, 2004; Perez-Garcia et al., 2011). Additionally, heterotrophic cultivation generally results in lower protein content than autotrophic and mixotrophic cultivation, with *C. vulgaris* producing only 400 mg protein per gram dry mass during heterotrophic culture as compared to 600 mg protein per gram dry mass during mixotrophic culture on molasses (Ende & Noke, 2019).

3.1.2. *Mixotrophism*

During mixotrophic growth, microalgae use both organic (simple sugars or fatty acids) and inorganic (CO_2) carbon sources (Cheng et al., 2022). The photosynthetic and respiratory metabolic pathways both operate simultaneously (Perez-Garcia et al., 2011), so the CO_2 produced during aerobic respiration is thus able to be reused and sequestered through photosynthesis (Yun et al., 2021). Mixotrophic growth requires minimal CO_2 and reduced light intensity compared to autotrophic cultivation (Cheng et al., 2022). Mixotrophic cultivation has also been shown to achieve greater biomass productivity and higher intracellular lipid content compared to autotrophic and heterotrophic cultivation, alongside the production of photosynthetic metabolites (Park et al., 2014; Perez-Garcia et al., 2011; Yun et al., 2021). For example, *C. vulgaris* was found to produce 137.43 mg of biomass per litre per day with 39 % (w/w) lipid content during mixotrophic cultivation, compared to 91.7 mg of biomass per litre per day with 19 % (w/w) lipid content during autotrophic cultivation (Laraib et al., 2021). Additionally, in media supplemented with 15 g/L glucose, *C. vulgaris* was found to yield 2.05 g/L of lipids in mixotrophic cultivation, compared to 0.61 g/L lipids in heterotrophic cultivation (Yun et al., 2021). Other microalgal species with mixotrophic capabilities include *Chlamydomonas* sp., *Graesiella* sp., *Monoraphidium* sp., *Nannochloropsis* sp., and *Haematococcus pluvialis* (Laraib et al., 2021). Some microalgal species such as *Galdieria sulphuraria* are able to switch between autotrophic and heterotrophic growth depending on environmental conditions (e.g. light intensity and organic carbon source concentration) in a metabolic mechanism known as amphitrophy. This is different from true mixotrophism, where autotrophic and heterotrophic metabolisms operate in parallel (Abreu et al., 2022).

3.1.3. Photoheterotrophism

In photoheterotrophic cultivation, energy (NADPH and ATP) from light-induced photophosphorylation is used to metabolize organic carbon into biomass. Photoheterotrophic growth has reduced dependency on photosynthesis compared to mixotrophic growth and primarily uses organic carbon as the carbon source (Cheng et al., 2022). Additionally, unlike mixotrophic growth, photoheterotrophic growth generates little or no CO_2, and some oxygen is produced through glucose photolysis rather than purely through photosynthesis (Chojnacka & Marquez-Rocha, 2004). Photoheterotrophic cultivation has been found to significantly increase biomass productivity and cell density compared to autotrophic cultivation. For example, photoheterotrophic cultivation of *C. vulgaris* on glucose produced 1.43 g of dry biomass per litre, while autotrophic cultivation produced only 0.69 g of dry biomass per litre. Other microalgal species with photoheterotrophic capabilities include *Dactylococcus dissociatus*, *Platymonas convolutae*, *Micractinium inermum*, and *Tetraselmis gracilis*. Photoheterotrophism is often considered to be synonymous with mixotrophism, with no standardized distinction between the two cultivation modes. Therefore, many photoheterotrophic studies are reported in literature as mixotrophic, and vice versa (Abreu et al., 2022).

3.2. Potential challenges and future prospects

Although the use of microalgal biorefineries to upcycle fruit wastes into value-added products is a promising waste management strategy, it is not yet widely implemented on the industrial scale. This is due to several concerns regarding economic, technical, operational, and regulatory challenges related to the management and usage of fruit wastes as a feedstock and the scaling up of microalgal fermentation processes.

3.2.1. Variability in feedstocks

Intrinsic variability in the nutritional composition, quality, and quantity of fruit wastes that are used as microalgal fermentation media will likely result in inconsistent production of microalgal-derived compounds. It is thus ideal to utilize standardized waste streams as a feedstock (Kumar et al., 2022). Therefore, fruit wastes from industrial sources (e.g. processing plants and supermarkets) may be preferable over post-consumer fruit wastes as a fermentation substrate because food wastes from the food production sector tend to be segregated and more stable in volume and chemical composition than household food wastes (Kim et al., 2022; Moreno et al., 2020). Consequently, industrial fruit wastes will require less heavy processing in order to extract higher value products. In addition, because the composition of fruit waste varies depending on geographic origin and processing conditions (Kasapidou et al., 2015; Leong & Chang, 2022), large volumes of fruit waste feedstock with consistent quality and composition may be sourced from large industrial stakeholders in the fruit supply chain. Alternatively, different types of fruit wastes from several small sources could be blended together to potentially maintain consistent product yield while managing seasonal variation in feedstock availability, as the blending of different lignocellulosic biomass feedstocks for biofuel production has been found to result in similar sugar yields and production costs as the weighted average of those from the individual feedstocks (Li et al., 2022). However, the effect of using mixed waste feedstocks on microalgal biomass yield needs further investigation (Kumar et al., 2022). Fluctuations in fruit waste supply can also be managed by storing surplus dried or ensiled fruit wastes for later utilization during periods of low availability (Leong & Chang, 2022). Effective valorization of fruit wastes as a microalgal biorefinery feedstock will require identification, quantification, and characterization of the fruit wastes, followed by the classification of fruit waste sources and associated high-value compounds, as well as the exploration of conventional and emerging processing and recovery technologies (Mirabella et al., 2014). This will ultimately facilitate the selection of appropriate fruit waste feedstocks, processing technologies, and desired end-products to design effective microalgal biorefinery processes.

3.2.2. Transport and storage of feedstocks

Fruit wastes are extremely susceptible to decay and microbiological contamination due to their high perishability and fermentability, which makes it challenging to maintain fruit waste quality during transport and storage prior to the cultivation of microalgae (Plazzotta et al., 2017). Compared to various methods of preserving fruit wastes (such as refrigeration and the addition of preservatives), oven drying may be the most cost-effective approach as it removes the water content in fruit wastes. This reduces both the perishability and weight of fruit wastes, which will subsequently reduce transportation and handling costs. In addition, oven drying does not introduce compounds that may hinder the fermentation process or affect downstream usages (e.g. preservatives) (Esparza et al., 2020), and oven drying can reach sufficiently high temperatures to kill pathogens, viruses, fungi, and other biological contaminants in the fruit waste. However, overly high temperatures may damage any heat-sensitive compounds in the fruit wastes, and oven drying is an energy-intensive method that, similar to other pre-treatment methods, will increase overall processing costs compared to the lack of any pre-treatments (Esparza et al., 2020; Nwakuba et al., 2016). To reduce the capital investment required for drying ovens and other infrastructure needed for fruit waste pre-treatment, these technologies can potentially be integrated into existing processing plants and other industrial sites where fruit wastes are generated (Koutinas et al., 2014), though this will depend on safety regulations and space availability.

Although open-air (solar) drying and lyophilization (freeze drying) may be used to remove moisture from fruit wastes on the laboratory scale, these methods are economically and logistically impractical on the industrial scale. Commercially available large scale freeze dryers currently have a maximum condensation capacity of only about 120 kg per batch (Laboquest, n.d.). Additionally, the high costs of lyophilization limit its commercial application primarily to the stabilization of products where maintenance of extremely high product quality is the overriding criteria (e.g. pharmaceuticals, biological materials, and certain high-quality foods) (Nowak & Jakubczyk, 2020). Lyophilization is thus generally not economically feasible for the industrial production of commodity food compounds, nutraceuticals, and other lower-value products. Although open-air drying is a much cheaper and less energy-intensive method of moisture removal, fruit wastes would be exposed to uncontrollable weather and pests, and open-air drying is unable to reach sufficiently high temperatures to destroy pathogens, fungal spores, and other biological contaminants. Relatively low drying temperatures would also result in long drying times, which would increase the likelihood of fruit waste decay. Furthermore, open-air drying does not offer precise control of the moisture removal process, so the final moisture content in fruit wastes may vary from batch to batch, introducing another source of variability into the valorization process. Open-air drying of industrial quantities of fruit wastes would also require large areas of open land, which may not necessarily be available.

To reduce feedstock transportation time and costs, microalgal biorefinery plants should ideally be located in a centralized area with a high density of agri-food industries, rather than obtaining fruit wastes from several decentralized sources (Esparza et al., 2020). IoT technologies and other digital tools can be used to improve the traceability of fruit wastes during transport and storage and guarantee a high level of food safety, which can improve consumer acceptance of products derived from food waste valorization (Facchini et al., 2023). Governmental support to offset the investment costs required for these innovations and other infrastructure required to safely transport and store fruit wastes can encourage private investment and further research and development efforts in upcycling fruit waste through microalgal biorefineries (Kandemir et al., 2022). In developing regions, governmental investment should supplement market-led private investments with reach into developed world markets, and local level support for governmental policies will be key (Parfitt et al., 2010). Ultimately, the development of specialized infrastructure to coordinate the transport and shipping of fruit wastes from the sites of generation to microalgal valorization plants will require the active collaboration of the food and related industries on multiple action levels (Esparza et al., 2020; Kosseva, 2011).

3.2.3. Regulations regarding the use of fruit wastes as a feedstock

The handling, storage, transport, and processing of fruit wastes are strictly regulated in order to minimize health and environmental safety risks associated with their high perishability and the potential presence of pathogens and other contaminants (Moreno et al., 2020; Socas-Rodríguez et al., 2021). Legislation varies between different regions, and current legislative frameworks provide limited support for the valorization of fruit wastes as a microalgal biorefinery feedstock. Lack of regulations regarding the safety and suitability of goods derived specifically from food by-products for consumer usage also limit the practical feasibility of emerging valorization methods (Socas-Rodríguez et al., 2021). In Taiwan, for example, food wastes are separately collected from other types of wastes by local municipal collection teams or legal waste clearance facilities and then sold to private recyclers. According to the Environmental Protection Administration, food wastes may be valorized only into organic fertilizers, animal feed, and bioenergy (either through incineration or anaerobic digestion), and products derived from such valorization methods must comply with national and international standards and regulations (Tsai, 2020). Fig. 3 outlines the collection and processing of food wastes in the Taiwanese waste management system.

Although the US Environmental Protection Agency aims to halve national food wastage by 2030, the US lacks relevant federal regulations and instead relies primarily on voluntary initiatives and standards led by non-profit organizations, communities, and firms. Emerging solutions from the private sector are hampered by uneven implementation of local, state, and federal food waste regulations that lead to variable costs and profits (Ryen & Babbitt, 2022). The EU has recently developed several frameworks and regulations (e.g. Circular Economy Policy Package and the Bioeconomy Strategy) to support the usage of food wastes in a circular bioeconomy model (Teigiserova et al., 2020). Under the waste management hierarchy established by Directive 2008/98/EC and an amendment published under Directive 2018/851, food waste is collected with other biowastes and preferentially managed with composting, anaerobic digestion, and/or biorefineries, and household biowastes are separately collected for better sorting (Moreno et al., 2020). The production and marketing of new chemicals are regulated by Regulation (EC) no. 1907/2006 (also known as REACH), which requires manufacturers and importers in the EU to register any chemicals with an annual production/import volume of at least one tonne. The considerable testing and administrative costs associated with the registration process may be economically unfeasible for small scale producers/importers of novel substances, which may in turn limit the commercial viability of microalgal biorefineries for fruit waste valorization. Additionally, with the US, China, and other major economies demonstrating interest in adopting legislation similar to REACH, the global manufacturing and distribution of compounds derived from microalgal biorefineries may become increasingly challenging (Lin et al., 2013).

3.2.4. Microalgal fermentation scale-up

Most microalgae are unable to directly assimilate complex molecules (e.g. polysaccharides, long fatty acids, and proteins) through their metabolic processes. Therefore, fruit wastes must often be processed and/or pre-treated prior to microalgal fermentation to produce hydrolysates with simpler micronutrients (e.g. sugar monomers, short fatty acids, phosphates, and free amino nitrogen) that can be metabolized by

Fig. 3. In the Taiwanese waste management system, food waste is collected separately from other types of waste by local municipal teams. Food wastes are then sold to private recyclers for valorization into organic fertilizers, animal feed, or bioenergy (Tsai, 2020).

microalgae (Chong et al., 2021; Gélinas et al., 2015). These pretreatments typically involve solvent extraction, thermal treatments, enzymatic degradation, and/or novel energy-intensive treatments (e.g. UAE, MAE, and SFE), which will add to the overall processing costs and may require extensive optimization prior to usage on the commercial scale (Chong et al., 2021; Kandemir et al., 2022). Fruit wastes may contain toxic compounds (e.g. pathogens, xenobiotics, and heavy metals) that can be transferred to the microalgae, so fruit wastes must be treated (i.e. disinfection to kill harmful bacteria, viruses, fungi, and spores) prior to the cultivation of microalgae (Kim et al., 2022). In order to justify the economic investment required for such pretreatments, high-value products must be manufactured from the microalgae (Mirabella et al., 2014).

In an effort to improve the microalgal bioconversion of nutrients in food wastes, various microalgae strains have been co-cultured with other algae, fungi, bacteria, and yeast, where symbiotic exchanges of nutrients and metabolites enhance productivity of microalgal biomass and value-added compounds. However, the co-culture approach may require further optimization of culture conditions, careful selection of consortia members to avoid potential competition that could inhibit microalgal growth, and more detailed studies to better understand the biochemical pathways that underlie their symbiotic interactions (Ray et al., 2022).

Large scale microalgal cultivation using mixotrophic and photoheterotrophic methods is generally conducted in open ponds or PBRs. Open ponds are simpler and cheaper to construct and operate than PBRs and have been found to exhibit lower global warming potential compared to PBRs for microalgal biofuel production. However, open pond cultivation is exposed to uncontrollable weather conditions and has a much larger land footprint, which may conflict with other types of land usage. On the other hand, PBRs offer better control of culture conditions, lower risk of contamination, and higher productivity and nutrient uptake efficiency (Chew et al., 2017), so they are likely more suitable for fruit waste valorization via microalgal fermentation. In order to address the problem of limited light dispersal in PBRs with operational volumes above 100 L, as well as to achieve high mass transfer rates with lower space requirements, various large scale PBR configurations have been explored throughout the years (e.g. stirred tank, bubble column, airlift, horizontal tubular, and flat panel) (Gupta et al., 2015). Commonly used in wastewater treatment, biofilm reactors (where microbes are immobilized onto submerged material surfaces that can be arranged in multiple layers to increase productivity and land use efficiency) are also of interest for microalgal valorization of organic wastes. This is because biofilm reactors have been found to minimize light diffusion limitations, achieve high cell densities, reduce biomass harvesting and concentration costs, and increase microbial resistance to growth stresses (Novoveská et al., 2023). Advances in the fields of bioreactor engineering, mathematical modelling, and AI can also be applied towards creating commercial scale PBR designs that can minimize the high energy costs associated with fermenter operation and maintenance (e.g. media agitation, lighting, aeration, temperature control, and cleaning) while enhancing product yield and quality (Esparza et al., 2020; Leong & Chang, 2022; Novoveská et al., 2023).

Another approach to improve the cost effectiveness of microalgal-based biomanufacturing utilizes various genome-editing tools (e.g. traditional recombinant nucleic acid technologies, CRISPR-Cas9, TAL effector endonucleases, and zinc-finger nucleases) to create GM (genetically modified) microalgal strains with more favourable cultivation characteristics and increased productivity of value-added compounds (Beacham et al., 2017). For example, RNA interference technology has been applied to downregulate the expression of light-harvesting antenna complex proteins in *Chlamydomonas reinhardtii*, resulting in increased light penetration throughout the liquid culture and higher resistance to photodamage (Mussgnug et al., 2007). However, the use of GM microalgae mostly remains at the laboratory scale, with very few projects having reached pilot or commercial scale (Beacham et al., 2017). This is partly due to a shortage of appropriate fermentation facilities for pilot scale evaluation of strain robustness and scalability, as well as limited information and assessment tools to address the technical challenges of industrial scale GM microalgal cultivation (such as genetic drift) (Beacham et al., 2017; Cheirsilp & Maneechote, 2022).

Additionally, public concern about the potentially negative effects of GMOs on human health and the environment has given rise to consumer resistance against GM technologies and derived products, particularly in the food and pharmaceutical industries. Commercialization of GMO-derived products is further complicated by differing regulations between regions regarding the labelling and usage of GMOs. For example, the US has deemed plants that have been modified with CRISPR-Cas9 to be non-GMOs, while the European Commission has yet to decide how to classify organisms modified using CRISPR-Cas9, and several members of the EU have banned or restricted the cultivation and sale of GMOs (Beacham et al., 2017). This ambivalence limits the total accessible market for GMO-derived products and may discourage further research and development in the usage of GM microalgal strains for biomanufacturing (Chai et al., 2022).

Moving forward, the technical challenges of industrial scale GM microalgal cultivation can be addressed by learning from existing best practices in the industrial scale cultivation of recombinant bacteria, yeast, and fungi (Beacham et al., 2017), as well as by applying tools such as mathematical modelling, process simulation, big data analytics, and AI-assisted technologies (Ganesh et al., 2022; Leong & Chang, 2022). LCA, TEA, and pilot-scale feasibility studies should be used to evaluate and optimize the profitability and environmental impact of proposed processes, determine medium and long-term research objectives, and bridge the gap between laboratory scale and commercial scale application of non-GM and GM microalgal biorefineries to valorize fruit wastes (Koutinas et al., 2014; Leong & Chang, 2022). LCA is an approach which has been used to compare the GHG generation and natural resource consumption of docosahexaenoic acid (DHA) produced from fish oil against that of DHA produced from microalgae cultivated heterotrophically using food waste. LCA should also be applied towards comparing the environmental impacts of GM microalgal-derived products with similar, conventionally sourced products. This will facilitate the creation of relevant benchmarks for products from industrial microalgal biorefineries (Bartek et al., 2021). As the fields of genetic and metabolic engineering rapidly advance while the regulatory landscape continuously evolves, a rigorous and dynamic Environmental Risk Assessment (ERA) process must be developed to ensure that GM microalgae can be successfully commercialized while meeting health and environmental safety concerns. Open communication and early engagement between scientists and the general public can facilitate consumer acceptance of GMO-derived products (Beacham et al., 2017). Furthermore, with the recent commercialization of several products that contain substances manufactured using precision fermentation (e.g. textiles, honey, dairy products, egg protein, animal fats, and sweet proteins), as well as increasing consumer demand for more sustainably manufactured goods, public acceptance of products derived from GM microalgal biorefineries will likely increase over time (A Corporate Guide to Alternative Protein Precision Fermentation, 2023; Carter et al., 2023). In order to create truly zero-waste microalgal biorefineries to achieve SDG 12, by-products from the microalgal fermentation process (such as spent media) should also be valorized (e.g. used as bacterial cultivation media or reused for further microalgal cultivation) (Cheirsilp et al., 2023; Mishra et al., 2019).

4. Concluding remarks

Fruit wastage occurs throughout the entire FSC due to complex interactions between environmental, technical, operational, and socio-economic factors that differ between regions. In order to effectively address natural resource depletion and other negative environmental impacts of fruit wastage, it would be ideal to prevent the initial generation of fruit wastes rather than to simply focus on the valorization of fruit wastes after they have already been generated. Valorization methods should seek to complement, rather than replace, the prevention of fruit waste generation. The identification of specific measures to prevent fruit waste generation is out of the scope of this review paper, though the authors believe that effective measures will require collaboration between governmental agencies, the private sector, end consumers, and other stakeholders. Additionally, effective fruit waste prevention measures will need to consider the specific constraints of local contexts, and practices that work well in one region may not necessarily translate well to other regions.

In order to effectively recover valuable compounds from fruit wastes while meeting sustainable development goals, more environmentally friendly extraction and processing technologies need to be optimized for industrial usage. Valorization processes should be designed such that they do not inadvertently generate additional waste streams (e.g. used solvents and residual biomass) or pose further negative environmental impacts (e.g. high energy usage). As with the prevention of fruit waste generation, effective solutions for fruit waste valorization will be highly context specific. Additionally, product end-of-life management should consider the circularity of products derived from emerging valorization methods in order to avoid the generation of non-recyclable and non-biodegradable products that will ultimately be disposed of in landfills or incinerators.

With regards to the valorization of fruit wastes into microalgal fermentation medium, mixotrophic and photoheterotrophic cultivation modes may be preferred over heterotrophic cultivation due to reduced CO_2 generation; however, this will depend on the specific type of microalgae strain, fruit waste, and desired end products. Further optimization of culture conditions will be required for each specific process, which can be supported by the usage of mathematical modelling, AI-assisted technologies, and other process simulation tools. To mitigate the high energy usage required for fruit waste pretreatment and the overall fermentation process, the use of renewable energy sources should be explored, as well as the potential recovery of waste heat streams as a power source. Although the usage of GM technologies requires higher initial investment and faces several regulatory and technical challenges, it may significantly improve the yield and diversity of high-value products from microalgal biorefineries. The additional revenue generated from a wide variety of high-value products can better compensate for the extremely high monetary investment and the long research and development timelines required for establishing commercial scale microalgal biorefinery processes for fruit waste valorization.

CRediT authorship contribution statement

Alicia Lee: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **John Chi-Wei Lan:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition. **Anet Režek Jambrak:** Writing – review & editing, Validation, Investigation. **Jo-Shu Chang:** Writing – review & editing, Validation, Investigation. **Jun Wei Lim:** Writing – review & editing, Validation, Investigation. **Kuan Shiong Khoo:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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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