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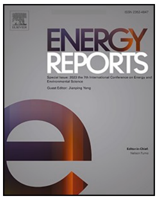

Waste biorefinery to produce renewable energy: Bioconversion process and circular bioeconomy

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ABSTRACT

Continual global energy scarcity and its future challenges, as well as environmental disasters, are causing global devastation. Additionally, a substantial quantity of food is being wasted regularly. Therefore, the adoption of circular bioeconomy principles and the bioconversion of wasted food appears to be both highly advantageous and urgently required. However, previous studies have placed limited emphasis on the technological progress and circular bioeconomy aspects associated with the bioconversion of wasted food. The present review thus investigates how mass-generated food waste can be used to produce valuable bioproducts through bioconversion techniques such as oleaginous metabolism, anaerobic fermentation, and solventogenesis. These techniques have attracted considerable interest due to their eco-friendly and resource-recycling capacities, as well as their efficiency and sustainability. The paper also discusses approaches to integrate biorefineries within existing economies to establish a circular bioeconomy and analyses the challenges as well as the techno-economic, environmental and life cycle scenarios of these approaches. Analysis of the techno-economic and environmental effects reveals that food waste biorefineries can be lucrative if certain pathways are maintained. The environmental impact of bioconversion methods that produce valuable bioproducts is also found to be substantially lower than that of conventional methods. Integrating bioconversion processes further improves the efficiency of the process and sustainably recovers resources. Developing a circular bioeconomy requires the adoption of a biorefinery strategy with an integrated approach.

1. Introduction

Over the next decade, worldwide food waste production is projected to rise by 33% (Pour and Makkawi, 2021). Humans waste almost 1.3B tons of food per annum (Kim et al., 2021) whose impact on the global economy is close to USD 750B (Boliko, 2019). Food waste affects the

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Abbreviations: **ABE**, Acetone-butanol-ethanol; **AD**, Anaerobic digestion; **AF**, Acidogenic fermentation; **ATJ**, Alcohol to jet; **BES**, Bioelectrochemical system; **BES**, Bioelectrochemical systems; **CBD**, Convention on Biological Diversity; **COD**, Chemical oxygen demand; **DF**, Dark fermentation; **EF**, Electro-fermentation; **FTS**, Fischer-Tropsch synthesis; **GBF**, Global Biodiversity Framework; **GHG**, Greenhouse gas; **HEFA**, Hydroprocessed esters and fatty acids; **HMF**, Hydroxymethylfurfural; **HRT**,, Hydraulic retention time; **LCA**, Life cycle assessment/approach; **LCFA**, Long-chain fatty acids; **MCFA**, Medium-chain fatty acids; **MDC**, Microbial desalination cells; **MEC**, Microbial electrolysis cells; **MES**, Microbial electrosynthesis; **MFC**, Microbial fuel cells; **MRC**, Microbial remediation cell; **MSW**,, Municipal solid waste; **OECD**, Organisation for Economic Co-operation and Development; **PCOP**, Photochemical oxidation potential; **PEI**, Potential environmental impact; **RJF**, Renewable jet fuel; **SBES**, Solid-state bio-electro-fermentation system; **SCFA**, Short-chain fatty acids; **TRL**, Technology readiness level; **VFA**, Volatile fatty acid; **VOC**, Volatile organic compounds; **WAR**, Waste reduction algorithm.

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environment negatively through its contributions to greenhouse gas emissions, exhaustion of natural resources, use of energy to produce food, and interruption of natural biological cycles (Bartek et al., 2021). Research to produce usable and valuable bioproducts and bioenergy from food waste is an ambitious proposal to reduce reliance on fossil fuels. Biorefining is understood as the process where different energy outputs such as fuel, heat and electricity are facilitated through various processes of biomass conversion (Nizami et al., 2017). Along with biorefinery processes, optimizing the circular bioeconomy can help us move towards a sustainable, environment-friendly, efficient future by integrating biowaste into refineries and adding value to this waste. Implementing a circular bioeconomy can allow us to recycle our current resources and maximize their value and efficiency (Awasthi et al., 2021; Ishangulyyev et al., 2019; Munesue et al., 2015; Vilariño et al., 2017). Food waste can originate during different food processing steps, such as production, moving, storing and circulation (Girotto et al., 2015). They are usually high in organic materials with trace inorganic materials. The range of sugar and protein contents in food waste falls between 35.5% and 69% and 3.9–21.9%(Uçkun Kiran et al., 2014). The presence of carbohydrates, amino acids, fats and fatty acids in solid and liquid waste allows it to be used as an ingredient in the production of usable and advantageous biochemicals and products (Bilal and Iqbal, 2019; Chen et al., 2017; Dahiya et al., 2015; Hegde et al., 2018; Yu et al., 2018). Its composition allows it to be transformed into a variety of bioproducts, energy and biochemicals through different biochemical processes (Dahiya et al., 2018a; Karmee, 2016; Lee et al., 2014).

Researchers extensively use food waste to produce biogas and fuel through anaerobic fermentation. Further, the use of oleaginous microbes as cell factories to produce biofuel and biochemicals has been heavily researched due to its effectiveness in the production and storage of oils using carbohydrate-rich food wastes (Caporusso et al., 2021). Electroactive bacteria that produce electricity using electrons from food waste has been another active area of research (Dahiya et al., 2018a). Many of the products of food waste biorefineries are fuels or energy-based products, which is mediated by the rising price of oil and the ability of specific biorefineries to create unique fuel types depending on the feedstock (Elmekawy et al., 2014; Krishna and Kalamdhad, 2014; Mohan and Sarkar, 2017; Venkata Mohan et al., 2016). Food waste to energy conversion technologies that function at a high technology readiness level (TRL) are usually implemented at an industrial scale since real-time prices have become more accessible for escalation and validation of the outcomes (Ren et al., 2018). But refineries that are specifically designed for value-added products and function at a low TRL face more difficulty in assessing the cost and benefit of their processes (Tsagkari et al., 2016).

The rapid exhaustion of natural resources and fossil fuels along with the accelerating demand for energy has encouraged the growth of sustainable and economically friendly waste bioconversion processes, particularly those used to convert food waste into valuable bioproducts (H. S. Ng et al., 2020). The circular bioeconomy concept further encourages these processes, making sustainable bioproducts and bioconversion methods more appealing to investors and producers. Yet, certain issues, such as the lack of a precise idea about the life cycles of food biowaste and techno-economic and robust environmental analyses, have delayed the outright commercial use of this approach (Awasthi et al., 2021; Venkata Mohan et al., 2019). Without accurately assessing the current and future challenges faced by waste biorefining, it is not possible to integrate it into a circular bioeconomy. Thus, this review extensively discusses the various food waste bioconversion processes, the potential to generate valuable bioproducts, and the integration of the biorefinery approach to the circular bioeconomy, while analysing the techno-economic, environmental and life cycles of food biowastes and the potential challenges that may be faced.

2. Waste generation and energy demands

Waste is generated by the disposal of the remnants from human activities in day-to-day life. In recent times, the volume of waste has increased compared to the pre-historic era due to rapid urbanization and population increase around the globe (Minelgaitė and Liobikienė, 2019). Therefore, there has been a huge influx of waste generated including a range of additional waste types(Vergara and Tchobanoglous, 2012). Thus, with increasing waste management demands, societies have learned how to manage waste safely for the environment and human health. Waste can be categorized according to its physical form, source, and environmental impact (Petar et al., 2022). It can be solid, liquid or gas and come from sources like households, industry, agriculture, commercial sites and so on (Amasuomo and Baird, 2016). Waste can also be classified as hazardous or non-hazardous to the environment. Most waste generated is municipal solid waste (MSW) produced by households on a daily basis.

Due to the development of society and industries around the world, there is considerably more MSW than in the past (Malinauskaite et al., 2017). The annual global production of municipal solid waste is 2.01B tons (Roy et al., 2022). It is predicted that by 2030, the annual rate of MSW generation will rise to 2.59B tons, and by 2050, to 3.40B tons (World Bank, 2018). It is estimated that 33% of that is not dealt with in an environmentally sound manner (Jerin et al., 2022). The reason for this is an increase in the consumption of products by customers, especially the use of disposable items. Moreover, population growth, improvement in living standards, and marketing through the internet are major contributing factors. As shown in Fig. 1, East Asia and the Pacific generate the most MSW, while the Middle East and North America generate the least. The MSW includes a wide range of materials, including yard waste, product labels, textiles, furniture, foodstuffs, plastic containers, electronics, papers, devices, and cells, among others. This percentage share of each source of the total waste can differ from one place to another depending on local practices and the level of financial investment in waste management (Abdel-Shafy and Mansour, 2018). As waste has a higher calorific count and combustible wood content, several researches have been conducted to find the feasibility of converting waste into fuel as an alternative to help the world meet its growing energy demand. However, only technologies that can ensure sustainable development should be implemented so that hazards are avoided.

As the population increases, the call for energy supply has become crucial, and thus various forms of energy are required at each stage. Demand for energy is not solely due to rising populations. Growth in the economy, technology, the standard of living, urbanization, industrialization, transportation, climate control, population behavior and culture, and so on all play significant roles in driving the need for more energy, which is growing as a result. Hence, energy consumption is rising gradually and is estimated to increase over 2007 rates by 14% in OECD countries and 84% in non-OECD countries by the year 2035 (Wolfram et al., 2012). As a result, the world's energy demand is growing daily due to population growth, global warming caused by carbon emissions, and an increase in waste (Kothari et al., 2010). However, scientists have designed the concept of waste-to-energy which is an economically viable option to generate renewable energy from unusable waste products. This is not only economically feasible but can also be environmentally beneficial to the world as it provides a means to manage waste. Therefore, through this management strategy, world energy demands can be fulfilled accordingly.

3. Food waste and their environmental impact

Food waste represents what is discarded at the end phase of the food chain. Mismanagement without effective treatment of food waste poses risks to the environment in the form of organic pollution and GHG emissions (El Gnaoui et al., 2020). The volume of food waste mainly

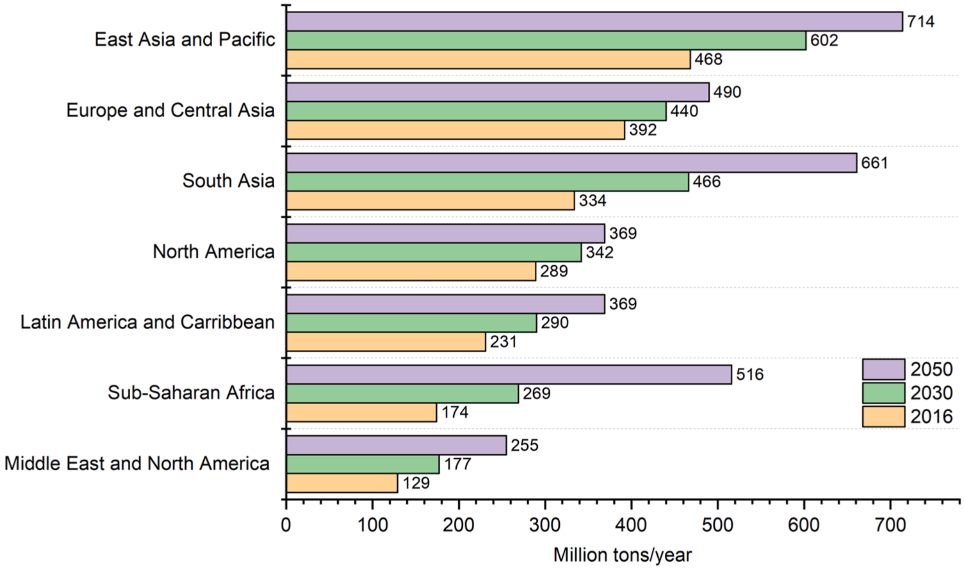

Fig. 1. Regional projections for waste generation (million tons/year) (Data Source: World Bank (2018)).

depends on consumers' awareness of their food habits and practices (Seberini, 2020). Moreover, food waste also originates from processing, distribution, and storage factors which adds to the problem. Food waste contributes to the largest share of biowaste produced internationally (Dahiya et al., 2018c). Around one-third of all food generated is wasted annually, resulting in 1.3B tons of food waste (Gustavsson et al., 2011). This is because the generation of food waste leads to the consumption of resources and energy. Land usage is one such resource which is needed in every stage of food production (Tonini et al., 2018). The production of food involves both farming and processing which requires labour as well as water for processing and irrigation purposes (Avgoustaki and Xydis, 2020). The manufactured food is then packaged which creates another huge expense. The food is then distributed which involves transportation costs and fuel. Food preparation is an area that involves refrigeration, requiring energy, and cooking, which needs fuel. Lastly, waste management of food, including treatment and disposal, requires significant investment (Tonini et al., 2018). Therefore, wasting food means wasting all the effort and energy that went into the manufacturing of that food, causing negative environmental impacts, and incurring significant unnecessary economic liability.

The impact of food waste is detrimental to our environment. The largest contributor to the carbon footprint caused by food waste comes from the food production stage, and mainly in the generation of meat and dairy products. This is because the farming of livestock requires nourishment, water, labour, land use, etc. Livestock produces methane through the digestion of their food and their manure as it decomposes. Methane is the largest contributor to greenhouse gases which cause global warming (Höglund-Isaksson et al., 2020). The use of fuel for cooking and the transportation of food waste also contributes to global warming via carbon emissions (Iqbal et al., 2022). In the packaging industry, a huge amount of plastic packaging is used which degrades the environment as plastic is non-biodegradable. In addition, worldwide water supplies are depleting rapidly as a result of food preparation and processing.

Food waste management systems have been set up in most developed countries. However, many developing and underdeveloped countries lag behind on this front, which is why their food waste decomposes in landfills. This decomposition happens through anaerobic respiration which leads to the release of methane (Tonini et al., 2018). The environmental impact of food waste can be evaluated using life cycle approaches. The life cycle assessment/approach (LCA) is a quantifying tool which finds the environmental impact originating from food waste and the resources and energy that have been wasted as a consequence (Cakar et al., 2020). The LCA includes evaluation of all relevant resources including the collection of raw materials, production, distribution, usage, and waste management, i.e., removal and recycling of the food (Finnveden et al., 2009). Moreover, this tool is also useful in the implementation of mitigation strategies in food waste management (Seberini, 2020). Avoidable food waste in many developing countries is comparatively higher due to people's disregard for the environment. Moreover, with more limited financial capability, the governments of these countries are much less able to implement proper waste management systems which can positively affect the environment (Abedin and Jahiruddin, 2015).

4. Bioconversion processes and potential bioproducts

By using biological agents or processes, such as certain microbes, the bioconversion process transforms organic materials, including food waste, into energy sources or useable products (Maurya et al., 2021). Due to its lower mineral- and higher fat content, food waste feedstock is comparatively more effective than others (Ho and Chu, 2019). For instance, food waste enables the production of more amount of biofuel per waste tonne compared to other available feedstocks. Easily transformed into a pumpable slurry, food waste lowers pre-processing expenses as well as streamlines production. Many current bioprocesses such as microbiological, enzymatic methods, bio-acidogenesis, electro-fermentation, anaerobic fermentation, oleaginous metabolism and solventogenesis have been successful and popular as sustainable and cost-effective methods for bioconversion of food waste into value-added bioproducts (Dahiya et al., 2015; Lin et al., 2013; Torres-León et al., 2021). The bioproducts may include butanol, biogas, methane, hydrogen, ethanol, biohythane, electricity, organic acids, biopolymers, proteins, enzymes, and bio-degradable plastics (Uçkun Kiran et al., 2014; AlMomani et al., 2022; Almomani et al., 2022).

The most crucial phase in enhancing the bioproducts' production from food waste is now the pretreatment phase. The pretreatment technique should be chosen based on food waste properties and subsequent bioprocessing methods (Singh et al., 2022; Carrere et al., 2016). Different pretreatment techniques are available for food wastes (Karthikeyan et al., 2018): (i) thermal pretreatments that are categorized as dry-type and wet-type. Food waste is often processed with a wet-type process prior to DF or AD; (ii) mechanical and physical pretreatments, which are required to enhance the physical properties of food waste, i.e. surface area; (iii) biological pretreatment techniques that are often a sluggish process that necessitates a prolonged retention period, and throughout the pretreatment step, microorganisms use easily accessible sugars as their primary carbon source; (iv) chemical pretreatments, which depend mostly on powerful to light chemical agents in order to alter the biological and physicochemical aspects of food waste.

4.1. *Solventogenesis*

Solventogenesis manufactures industrially suitable solvents (Millat and Winzer, 2017). Solventogenesis for the production of bioethanol and biobutanol from food waste has gained popularity due to the lower production cost and high protein and sugar content of food waste (Ibrahim et al., 2018). For instance, new genetic solventogenic *Clostridium* sp. strain HN4, which may secrete amylase indigenously for the subsequent acetone-butanol-ethanol (ABE) fermentation, was used to produce biobutanol from food waste, glucose and starch (Qin et al., 2018). Solventogenic *Clostridium* sp. strain HN4 demonstrated significant potential for increasing biobutanol generation from food waste. In cellular metabolic activity, the significant shift to solventogenesis from acidogenesis (which is the formation of acid) is a characteristic of the fermentation of clostridial ABE. *Clostridium* falls under the genus of gram-positive bacteria, and solventogenic clostridia can be utilized to generate many types of bulk chemicals by growing them in a range of low-cost substrates such as lignocellulosic materials, CO, CO_2, or H_2 (Yang et al., 2017). Consequently, for over ten decades, ABE fermentation using saccharolytic clostridia was regarded as relevant in academia and industry (Millat and Winzer, 2017).

Acidogenesis and solventogenesis are important processes or phases for ABE fermentation (Xin et al., 2019). When the required or proper operational conditions exist, the most frequently solventogenic *Clostridium* species carry out the ABE fermentation process (Niglio et al., 2019). *Clostridium* species have the unique ability to ferment various types of substrates including monosaccharides and disaccharides as well as hexoses and pentoses. Their ability to ferment such saccharides stems from the fact that they are saccharolytic butyric acid generating bacteria (Bharathiraja et al., 2017; Raganati et al., 2015). The process of ABE fermentation can be achieved by starting with either a first generation or second generation feedstock (Niglio et al., 2019). A first generation biomass is composed of organic materials such as cereal grains, corn, and sugarcane, whereas a second generation biomass is composed of lignocellulosic materials such as agricultural residues (Huzir et al., 2018). Each of these feedstock types comes with its own set of benefits and downsides.

Suitable feedstock/biomass selection for converting into various goods depends on several factors, such as the goods being produced, feedstock availability in the region, environmental considerations, and technological developments. However, lignocellulosic biomass has great potential for the production of a wide range of valuable products, including jet fuel and hydrogen (Blasi et al., 2023). This comprises feedstocks like wood, energy crops, and crop residues. By converting waste into useful resources, its use not only meets energy needs but also promotes the growth of a circular bioeconomy (Devi et al., 2022). First generation biomass has also several advantages, including the fact that it is easily available, fermentable, contains a high concentration of sugars, does not require pretreatment, and is simple to hydrolyse (Cherubini, 2010). It also has various drawbacks, such as competing with human or animal food, which results in a higher cost. The disadvantage of second generation biomass is the complexity of its composition, necessitating an additional stage of hydrolysis or pretreatment before it can be used for fermentation, resulting in a higher cost. However, such feedstock is readily available at all times of the year, and its price is substantially cheaper than that of first generation biomass (Niglio et al., 2019).

4.1.1. *Bioethanol*

Bioethanol is a well-known type of renewable biofuel that is an environmentally friendly alternative to fossil fuels. Bioethanol can be produced by hydrolysing cellulose from lignocellulosic biomass and fermenting sugars from various lignocellulosic sources (Vasić et al., 2021). Aside from the fact that bioethanol is biodegradable, it has the advantage of being less toxic, allowing biomass to be employed as a primary substrate (Balat, 2011; Saha et al., 2017). Lignocellulosic products are the main source for the production of bioethanol. They can be classified into three categories: marine algae, forest woody feedstocks, and agricultural residues and municipal solid wastes. The below Fig. 2 is a diagrammatic representation of the ethanol production process using lignocellulosic biomass.

Depending on the composition and structure, various types of raw materials can be utilized to produce bioethanol. Numerous research studies (Anu et al., 2020; Jugwanth et al., 2020; Keshwani and Cheng, 2009; Yao et al., 2015; Zhao et al., 2020) have reported the utilization of a variety of lignocellulosic wastes in the production of bioethanol, including grass, bagasse, rice straw, and so on. Marine algae exhibit significant potential as a viable third-generation feedstock for the production of bioethanol, owing to its notable properties such as rapid and sustainable growth (Sulfahri et al., 2017), as well as the absence of land competition (Ashokkumar et al., 2019; Sulfahri et al., 2020). However its pretreatment costs are fairly high (Vasić et al., 2021).

Bioethanol production comprises several steps, with the pretreatment process the primary step in the system (Devi et al., 2022). The purpose of this method is to modify the structural characteristics of the original material to facilitate enzyme access and generate a large number of sugar monomers. Following that, hemicellulose, cellulose, and starch are hydrolysed enzymatically. Hexoses and pentoses are released during this process and can be used later in the fermentation process (Mirfakhar et al., 2020). The newly available sugars are then digested by microorganisms during the fermentation process, producing ethanol that is then distilled (Vasić et al., 2021). The highest ethanol yields can be achieved with the help of advanced fermentation techniques and microbial strains. Ethanol can be made more efficiently from biomass with the help of genetically modified yeast and bacteria. The latest researches summarized in Table 1 indicated a maximum ethanol yield of 7.9 g/L. The optimal conditions for producing 7.9 g/L ethanol were bacterial biomass to fungal biomass ratio of 1:1, an initial pH of 5.5, and a solids loading of 5% (pretreated organic fraction of MSW) (Ebrahimian et al., 2022). The substrates and fermentation conditions used to produce bioethanol in numerous studies are summarized in Table 1.

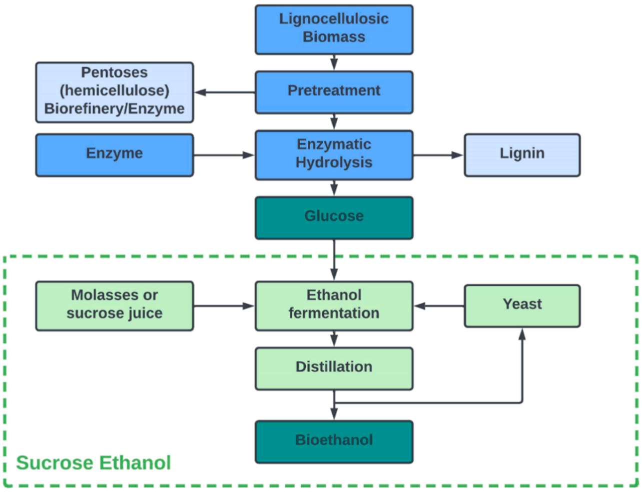

Fig. 2. Bioethanol production process using lignocellulosic biomass. Modified from Vasić et al. (2021).

Table 1
Substrates/feedstocks and microorganisms used in bioethanol production.

Feedstock/ Substrate	Fermentation condition	Microorganism	ABE (g/L)	Ethanol (EtOH) (g/L)	Ref.
Rotten potato	96 h fermentation	*Clostridium beijerinckii* DSMZ 6422	12.0	0.16	(Avcı et al., 2023)
Green coconut husk	96 h fermentation	*Clostridium beijerinckii* ATCC 10132	530	0.6	(de de de Brito Bezerra et al., 2023)
Rotten potato	96 h fermentation	*Clostridium acetobutylicum* DSMZ 1731	12.3	0.59	(Avcı et al., 2023)
Sotol bagasse	72 h fermentation at 37 °C	*Clostridium beijerinckii*	310 ± 20	1.90 ± 0.40	(Piñón-Muñiz et al., 2023)
Rotten potato	96 h fermentation	*Clostridium acetobutylicum* DSMZ 6228	17.6	1.24	(Avcı et al., 2023)
Switchgrass	72 h fermentation	*C. beijerinckii*_SDR	20.24	1.48	(Olorunsogbon et al., 2022)
Organic fraction of MSW	ABE fermentation	*M. indicus* and *C. acetobutylicum*	16.1	7.9	(Ebrahimian et al., 2022)
Microalgal biomass	48 h fermentation at 37 °C	*Clostridium acetobutylicum* DSM 792	15.47 ± 0.47	0.92 ± 0.05	(Figueroa-Torres et al., 2020)
Corn stover	72 h fermentation	*C. saccharobutylicum* DSM 13864	~ 7.13	0.39 ± 0.01	(Hijosa-Valsero et al., 2020)

4.1.2. *Biobutanol*

Biobutanol is considered to be superior to other biofuels, namely bioethanol, biodiesel, and biohydrogen since it is the most gasoline-like biofuel in terms of chemical composition. As a result, it has generated considerable interest during the last few years (Ibrahim et al., 2018). Biobutanol may be obtained using similar sources to bioethanol (Obergruber et al., 2021). It is comparatively less polluting and more renewable than gasoline. Li et al. (Li et al., 2020) shed light on several recent discoveries, including how biobutanol's mixture exhibits superior vapor pressure behaviour in the absence of an azeotrope, and a higher energy density, lacks a separate phase at low temperatures, and has a high viscosity and a slightly lower octane number. Additionally, noteworthy advantages of employing biobutanol as a biofuel include its less corrosive character, lower volatility, increased energy input, and ability to be used in modern pipeline distribution without modification. Therefore, biobutanol has the potential to completely replace the gasoline that is currently used for transportation (Ibrahim et al., 2018). There are two methods for producing biobutanol: (i) through ABE fermentation, which is a traditional approach, and (ii) using microbial fermentation with industrial, residential, and agricultural wastes (Rathour et al., 2018). Table 2 summarizes the feasible substrates and fermentation conditions employed in numerous studies to produce biobutanol.

4.2. *Anaerobic fermentation*

When compared to alternative bio-platforms for biofuels and biocommodity chemical production employing organic waste such as food waste, anaerobic fermentation has received great attention in recent years (Dahiya et al., 2018b; Kim and Gadd, 2019). This is the most useful technique for turning food waste into methane (CH_4), hydrogen (H_2), and fatty acids (Dahiya et al., 2018b). The process of anaerobic fermentation is divided into five stages as shown in Fig. 3: (a) hydrolysis, (b) acidogenesis, (c) acetogenesis, (d) dehydrogenation, and (e) methanogenesis Different kinds of bacteria, such as hydrolytic, acidogenic, acetogenic, hydrogen-producing, acetoclastic methanogens and others, actively perform in these stages to convert the food waste into useful bioproducts such as CH_4, H_2, various kinds of fatty acids, and so on. Different kinds of redox reactions occur in the presence of these bacteria. Through this process, it is also possible to generate animal foods which are much cheaper than regular foods.

Bioelectricity can be generated by combining traditional anaerobic fermentation with electrodes in bioelectrochemical systems (BES) (Dahiya et al., 2018b). This process can also prevent contamination throughout the whole fermentation process. According to (Dahiya et al., 2018b; Kim and Gadd, 2019) anaerobic fermentation not only becomes a solution for controlling waste but also helps to reuse the biogenic waste material by producing animal food, bioelectricity and valuable chemicals. For instance, silage is a type of animal feed made from biogenic

Table 2
Feasible substrates/feedstocks and microorganisms used during the production of biobutanol.

Feedstock/ Substrate	Fermentation condition	Microorganism	ABE (g/L)	BuOH (g/L)	Ref.
Rotten potato	96 h fermentation	*Clostridium beijerinckii* DSMZ 6422	12.0	7.9	(Avcı et al., 2023)
Green coconut husk	96 h fermentation	*Clostridium beijerinckii* ATCC 10132	530	3.4	(de de de Brito Bezerra et al., 2023)
Rotten potato	96 h fermentation	*Clostridium acetobutylicum* DSMZ 1731	12.3	8.2	(Avcı et al., 2023)
Sotol bagasse	72 h fermentation at 37 °C	*Clostridium beijerinckii*	310 ± 20	1.97 ± 0.52	(Piñón-Muñiz et al., 2023)
Rotten potato	96 h fermentation	*Clostridium acetobutylicum* DSMZ 6228	17.6	11.4	(Avcı et al., 2023)
Switchgrass	72 h fermentation	*C. beijerinckii*_SDR	20.24	11.21	(Olorunsogbon et al., 2022)
Municipal solid waste	ABE fermentation	*M. indicus* and *C. acetobutylicum*	16.1	5.9	(Ebrahimian et al., 2022)
Glucose	Co-culture fermentation of ABE	*Weissella cibari*	7.21	3	(Ijoma et al., 2021)
Microalgal biomass	48 h fermentation at 37 °C	*Clostridium acetobutylicum* DSM 792	15.47 ± 0.47	12.67 ± 0.30	(Figueroa-Torres et al., 2020)
Corn stover	72 h fermentation	*C. saccharobutylicum* DSM 13864	~ 7.13	9.02 ± 0.11	(Hijosa-Valsero et al., 2020)
Cauliflower waste	Batch fermentation, 80 °C, 96 h	*C. acetobutylicum* NRRL B-527	5.29	2.99	(Khedkar et al., 2017)
Corn stover hydrosylate	68 h batch fermentation at 37 ℃	*C. saccharobutylicum* DSM 13864	11.7	7.4	(Ding et al., 2016)
Barley straw hydrolysate	ABE fermentation with gas stripping	*C. beijerinckii* P260	47.2	30.86	(Qureshi et al., 2014)
Rice bran (RB), de-oiled rice bran (DRB)	128 h batch fermentation	*C. saccharoperbutyl-acetonicum* N1–4	RB: 8.9 DRB: 10.5	RB: 6.8 DRB: 7.10	(Al-Shorgani et al., 2012)
Spoilage date palm	Batch fermentation, 72 h at 30 °C	*Bacillus subtilis* DSM 4451 and *Clostridium acetobutylicum* ATCC 824	21.56	14.9	(Abd-Alla and Elsadek El-Enany, 2012)

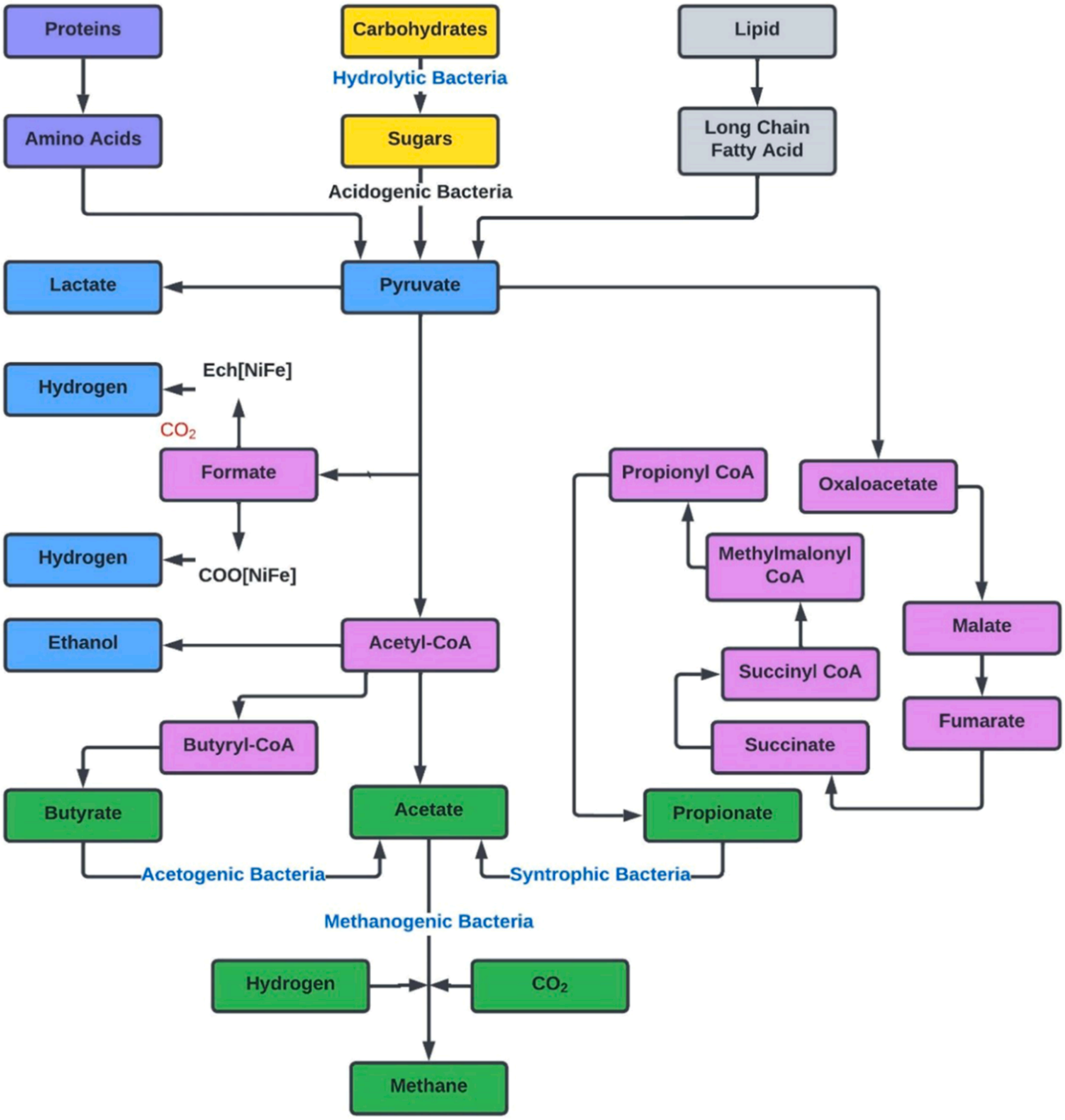

Fig. 3. Production of biobased products using anaerobic fermentation process. Modified from Dahiya et al. (2018b).

waste through anaerobic fermentation. It refers to a form of animal feed derived from green foliage crops that have undergone fermentation to the extent of acidification in order to preserve them (Tomar et al., 2021). This process can play a significant role in a sustainable economy in the future if people are able to fully embrace current technologies.

4.2.1. Biohydrogen

Biohydrogen (H_2) is a renewable fuel that can be produced from waste and has captured the interest of experts throughout the world. According to recent articles, more research on the production of H_2 from organic waste products is needed (Osman et al., 2020; Yun et al., 2018). The approach of utilizing waste materials from various biological sources to make sustainable biohydrogen could be useful in solving current environmental issues and promoting a net zero carbon economy (Osman et al., 2020). Food waste has potential as a source material since it comprises a high concentration of easily biodegradable organic material with net positive energy and economic balance (Dahiya et al., 2018b).

Biofermentation (photofermentation and dark fermentation), direct and indirect biophotolysis, and bioelectrochemical systems (Ahmed et al., 2022a), for instance gasification and microbial electrolysis cells (MEC), are probably the most popular, extensively covered, and advanced techniques for producing biohydrogen from organic waste. Dark fermentation is claimed to be the most useful procedure due to its efficiency in breaking down organic wastes and a high H_2 production rate (Osman et al., 2020; Yun et al., 2018). Integrating anaerobic fermentation with photofermentation is an approach to increase biological production by making use of the compounds generated during anaerobic fermentation. Combining dark fermentation and photofermentation was proven to be the most efficient way to achieve the largest potential H_2 production (Dahiya et al., 2018b; Osman et al., 2020). Recently, biophotolysis, bioelectrochemical systems and gasification processes are also used to produce hydrogen (Ahmed et al., 2021). However, biophotolysis and bioelectrochemical processes have shown a lower yield than dark fermentation and photofermentation. Further, while the gasification process shows a high yield in H_2 production, its production rate is low.

Biohydrogen can be generated from microalgae via fermentative and photobiological techniques, but microalgae require pretreatment for efficient biohydrogen production (Ahmed et al., 2022a). Producing biohydrogen from microalgae via anaerobic fermentation is an eco-friendly strategy for generating renewable energy (Zhang et al., 2023). Using the metabolic flexibility of certain microalgal species, this method takes advantage of the microbes' ability to produce hydrogen gas even in oxygen-depleted environments. These microbes are cultivated and harvested in a controlled environment, and then their hydrogen-producing potential becomes available through a pretreatment process. The biomass can be converted into hydrogen gas and useful byproducts through anaerobic fermentation with the help of specialized bioreactors (Sarangi and Nanda, 2020), which serve as a dual benefit for the removal of organic waste and the production of clean fuel. Even though biohydrogen production from microalgae faces some obstacles—such as enzyme sensitivity to oxygen and competition for substrates—it has the potential to contribute to a sustainable energy landscape if further research and development are conducted.

Different process parameters, such as inoculum type, pretreatment of the substrate, inflow pH, reactor configuration, co-substrate addition, feed composition, and temperature, all have a significant impact on H_2 production in anaerobic fermentation. However, there are challenges with photofermentation and dark fermentation processes (Ahmed et al., 2022b). While the dark fermentation H_2 production rate is high, lignocellulosic waste requires pretreatment (Osman et al., 2020). However, photofermentation is a more efficient method of producing biohydrogen than dark fermentation (Ahmed et al., 2021). In a study conducted by (Zhang et al., 2020), the highest H_2 content (up to 58.90%) was found in photofermentation, making it the most efficient method. While dark fermentation produced the lowest H_2 yield (36.08 mL(g TS)$^{-1}$), light fermentation produced the highest (141.42 mL(g TS)$^{-1}$). It is assumed that achieving better yields using gasification and biofermentation for H_2 production will be a promising solution for domestic energy production which can lead to great success in promoting a net zero carbon economy in the future (Hoang et al., 2022a).

Food waste is a viable substrate for hydrogen fermentation due to its high carbohydrate content. Hydrogen can be produced through fermentation, and the carbohydrate percentage of food waste is a key component in this process (Jarunglumlert et al., 2018). An innovative hydrogen generation technology for food waste gasification was proposed in a research (Xu et al., 2022), which transforms food waste into hydrogen. Temperature increase enhanced hydrogen capacity, although the geographical effect was insignificant. With a hydrogen production capacity of 1.2 t/h H_2, the food waste-to-hydrogen process produced a significant amount of hydrogen (Xu et al., 2022). To some extent, this method can expedite the execution of the carbon neutrality goal.

4.2.2. *Biohythane*

The formation of biohythane, a particular combination of H_2 (5–25%) and CH_4 (75–95%) with improved fuel characteristics, is developing as a promising fuel that is both eco-friendly and sustainable (Ghimire et al., 2021). Both CH_4 and H_2 have their own set of constraints. For example, H_2 is reactive and combustible, leading to storage concerns, whereas CH_4 has a minimal flammability issue (Dahiya et al., 2018b). By eliminating CO_2, biohythane could be converted into hythane(O-Thong et al., 2018). The formation of biohythane (hydrogen + methane) from food waste can be done in two stages: dark fermentation (DF) and anaerobic digestion (AD) (Ghimire et al., 2021). The food waste is fermented into H_2, VFA, CO_2, lactic acid, alcohols, and other compounds in the initial stage. In the second stage, non-gas compounds are converted into CO_2 and CH_4 in the presence of alcohols (O-Thong et al., 2018). Two-stage AD has many benefits over one-stage AD, including a shorter hydraulic retention time (HRT), higher energy recovery, higher COD removal, higher H_2 and CH_4 yields, and a lower CO_2 in biogas concentration (Ta et al., 2020). For instance, using a two-stage process, the methane concentration can be increased from 61.2% to 70.1% (Baldi et al., 2019).

Various biochemical and physical parameters have a huge impact on biohythane formation (Ghimire et al., 2021; O-Thong et al., 2018). The biohythane process is affected by some control factors like temperature, inoculum characteristics, substrate complexity, nutrition, pH and alkalinity, HRT, H_2 concentration, trace elements, and hazardous chemicals (O-Thong et al., 2018). The two-stage anaerobic fermentation might improve COD (coxygen demand) degradation rate, net energy equilibrium, CH_4 production levels, and product yield and quality (O-Thong et al., 2018). However, it has been demonstrated that the combined thermophilic dark fermentation and anaerobic digesting process has a slightly higher total energy restoration capability (Ghimire et al., 2021). Depending on the organic pollutants of food waste, total biohythane production ranged from 128.7 L (60 g COD/l) to 163 L (100 g COD/l) (Dahiya et al., 2018b). These findings indicate that food waste has the potential to be a good substrate for biohythane production in the future. By combining dark fermentation and anaerobic digestion processes, food waste can be successfully transformed into effective energy in the form of biohythane which can be used as an alternative to methane in the transportation sector as well as being a positive example of a circular economy.

Biohythane (biohydrogen and biomethane) was produced on an industrial scale through two-step fermentation of microalgae and food waste, and a life-cycle assessment was conducted to assess its environmental impacts and energy conversion properties (Sun et al., 2019). In total, the system had a net energy input/output ratio of 0.24. Approximately 53.8% of the total energy input was used in the biomass pretreatment process, while 16.6% was used in the microalgae cultivation process. Overall, the system resulted in 124 g $CO_{2\text{-eq}}$ MJ^{-1} of net GHG emissions per unit of upgraded biohythane, while 49 g $CO_{2\text{-eq}}$ MJ^{-1} was the equivalent of the carbon sources absorbed by microalgae during photosynthesis (Sun et al., 2019). GHG emissions and energy conversion are found to be the most sensitive to changes in growth rate and overall biohythane production.

4.2.3. *Biodiesel*

Biodiesel can be produced from various lipid sources such as microalgae, oil crops, animal fats, and waste oils. Notably, microalgae have emerged as a sustainable feedstock for biodiesel, thriving in environments like saltwater, wastewater, and even non-arable lands (Sani et al., 2013). This makes them an ideal choice as they don't compete with food production or freshwater resources (Chen et al., 2012). Utilizing anaerobic fermentation techniques, microalgae can be cultivated and then subjected to anaerobic conditions. This leads to the fermentation process that generates biodiesel precursors like fatty acids, along with other valuable by-products (Zhang et al., 2022). Such a method showcases promise for eco-friendly biodiesel production, leveraging the ability of microalgae to transform light energy into biofuels. However, scaling this to a commercial level would require further research and process optimization.

Optimal biodiesel quality calls for reduced levels of long-chain saturated and polyunsaturated fatty acid methyl esters (FAME) for better low-temperature performance and oxidative stability (Selvarajan et al., 2015). The suitability of microalgae as a biodiesel feedstock is closely tied to the properties of its fatty acids, measured by key indicators like iodine value, cold filter plugging point, cetane number, and oxidation stability (Schlagermann et al., 2012). Additionally, to minimize the environmental footprint of biodiesel derived from microalgae, it is critical to improve the efficiency of drying the microalgae and extracting lipids from them, as these processes contribute to over 70% of the global warming potential in current production methods (Dasan et al., 2019).

4.2.4. *Sugars*

One of the major topics to address when considering multiple energy recovery options is the production of sugars from food waste. Sugars like monosaccharides and oligosaccharides can be processed from food waste (Mohd Thani et al., 2020). These sugars can be separated from the waste and used to make other food products as a real value-add ingredient. Subcritical water treatment is a relatively new alternative technology that is regarded as environmentally friendly. The sugars can be hydrolysed and extracted using high-temperature, high-pressure water. A synthetic consecutive acid-enzymatic hydrolysis process can be used to create high concentrations of sugars that can ferment, such as glucose, sucrose, fructose, and maltose (Hafid et al., 2017). Fig. 4 shows the production process for fermentable sugar.

This approach begins with a hydrothermal and dilute acid pretreatment utilizing sulphuric acid (H_2SO_4) and hydrochloric acid (HCl), with the goal of eliminating bigger polysaccharide molecules before glucoamylase can proceed with the enzymatic hydrolysis phases. The pretreatment technique is defined to meet minimum targets which are increased sugar yields, reduced sugar degraded compound production or losses, removal of inhibitory by-product formation, and lastly, increased process cost-benefit. Physical, biological, chemical, physicochemical, and enzymatic procedures can all be performed separately or in combination in pretreatment.

A combination of amylase and glucoamylase enzymes is used to convert starch to monomeric sugars. The expense of existing hydrolytic enzymes, e.g. amylase, and the extended incubation time (Hafid et al., 2017) are obstacles to the manufacture of fermentable sugar and bioethanol from food waste. The use of an efficient pretreatment approach to replace the use of enzymes in the processing of food wastes with fermentable sugars and bioethanol remains a concern. Dilute acid pretreatment shows effective performance among the different pretreatment procedures and appears to be more financially efficient at a greater scale. The use of dilute acid to hydrolyse carbohydrate polymers has several benefits, including a faster reaction time and easier pretreatment. The formation of breakdown products due to the harsh conditions employed during the hydrolysis process, for example, high temperature and low pH, is one of the main disadvantages of hydrothermal and dilute acid pretreatment (Hafid et al., 2017).

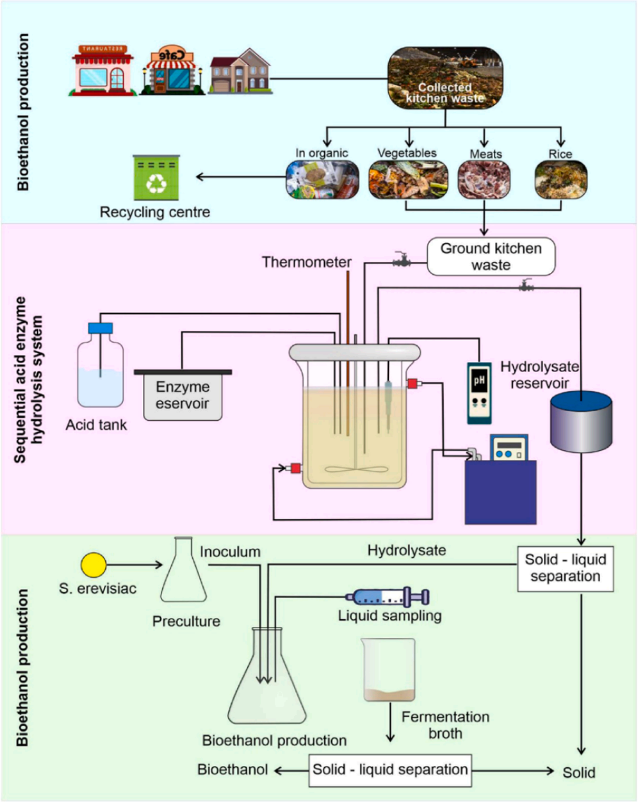

Fig. 4. Pretreatment with acid-enzymatic hydrolysis in the production of fermentable sugars and bioethanol.
Modified from Hafid et al. (2017).

Sugars, for example monosaccharides and oligosaccharides, can also be hydrolysed from food waste. There is increasing research interest in subcritical water treatment due to its benefits as a green extraction approach, in providing better quality extracted outputs, and also in being cost-effective with a short recovery time relative to traditional techniques (Mohd Thani et al., 2020). Although this technology has been used to extract sugars from bakery waste, it is expected that it could be applied to other carbohydrate-rich substrates. Considering the advantages of dilute acid pretreatment and subcritical water treatment, it can be said that sugar manufactured from food waste, which utilizes cleaner energy, has the potential to be a huge success in the future when it comes to producing green products.

4.2.5. *Biomethane*

Biomethane is a type of biogas that has been improved by removing CO_2 and purifying it of impurities (Chan Gutiérrez et al., 2018). The correlation between energy consumption, environmental impact and the economy can be addressed by biogas production via anaerobic digestion of biowaste because it provides a single-line solution to numerous concerns such as fossil fuel depletion, increased energy demands, inefficient waste management, and greenhouse gas (GHG) emissions (Batool et al., 2020). The generation of biomethane (CH_4) from food waste as a feedstock using anaerobic fermentation is undoubtedly the most developed approach for the manufacture of bioenergy. Biogas refineries remove CO_2 from biogas and produce renewable fuel biomethane. This process can be influenced by several parameters: reactor design, temperature, pH, inoculum type, nitrogen/carbon ratio, organic loading rate, volatile fatty acid, co-digestion, and so on. By reusing food waste in CH_4 formation, 42.32 PJ of CH_4 can be produced per year, which is equivalent to 6.5% of the total diesel energy used in vehicles in 2015 (Chan Gutiérrez et al., 2018).

Biomethane has the capability to reduce greenhouse gas (GHG) emissions from urban transportation. A decrease of 17.91 $MtCO_2e$, or 6.06% of the 2050 GHG emissions goal can be achieved by replacing diesel with biomethane (Batool et al., 2020; Chan Gutiérrez et al., 2018). Due to the work of numerous companies in designing and deploying comprehensive plants, biomethane generation in biogas from food waste has reached commercial levels all around the world and become a sustainable and renewable biofuel (Batool et al., 2020; Dahiya et al., 2018b). In comparison to the separate anaerobic digestion of food waste and dairy manure, findings demonstrate that co-digestion of food waste and dairy manure generated higher biogas yields (Batool et al., 2020; Chan Gutiérrez et al., 2018). As there will always be an endless supply of food waste which can be easily and economically converted into biomethane easily, demand for fossil fuels can be minimised and environmental sustainability ensured for the present and into the future.

4.2.6. *Fatty acids*

4.2.6.1. Short-chain fatty acids. Food waste is plentiful and high in organic compounds, making it an excellent raw material for conversion into short-chain carboxylic acids, also referred to as volatile fatty acids (VFAs), by acidogenic fermentation (AF) (Sukphun et al., 2021). Anaerobic digestion, which converts organic compounds into useful resources like methane or VFAs, is one of the most extensively used waste treatment procedures (Carvalheira and Duque, 2021). Short-chain carboxylic acids or VFAs, for example, HAc, HBu, HPr, HVa, HIBu, and HIVa, are important co-products of H_2 in AF (Dahiya et al., 2018b). VFAs can be isolated chemically from petroleum-derived molecules, but this method requires excessive energy consumption and has an adverse environmental impact. Therefore, biological synthesis methods, such as acidogenic fermentation, could receive a lot of attention (Dahiya et al., 2018b). However, according to recent studies, VFAs synthesized during the acidogenic step appear to be most effective when utilised in the anaerobic digestion process (Sukphun et al., 2021). Significant attempts have been made in recent years to improve the VFA yield and production rate from food waste by analysing various types of food waste and improving production conditions (Carvalheira and Duque, 2021). For instance, VFA in the form of HAc is usually produced when a specific amino acid is degraded or when long-chain fatty acids (LCFA) are acidified (Dahiya et al., 2018b). Again, anaerobic bacteria create HAc, HPr, and HBu from monosaccharides where HAc is more energetically stable than HBu and HVa (Dahiya et al., 2018b). As a result, acetate is assumed to represent the maximum amount of VFA in food waste containing primarily carbohydrates (Dahiya et al., 2018b; Sukphun et al., 2021).

Various parameters, including carbon supply, pH, temperature, HRT (hydraulic retention time), inoculum, and OLR (the daily amount of organic matter given per reactor working volume) influence the formation, composition, and yield of VFAs (Carvalheira and Duque, 2021; Dahiya et al., 2018b; Sukphun et al., 2021). However, the key properties of acidogenic output make VFA recovery complicated, costly, and challenging (Sukphun et al., 2021). In this case, membrane-based VFA recovery is considered to be the most advanced and effective of the VFA recovery solutions since it can minimize the number of functional areas, improve the stability of the acidogenic fermentation process, and result in better VFA yields (Sukphun et al., 2021). Fig. 5 illustrates the step-by-step process of VFA formation. VFAs can be used in producing numerous sustainable items, Such as biodegradable plastics, biodiesel, bioelectricity, and biofertilizers (Dahiya et al., 2018b). Therefore, producing VFAs using food waste can help prevent future environmental deterioration and encourage the transition to a more sustainable society and the development of a bioeconomy.

4.2.6.2. Medium-chain fatty acids. The most extensively used method for treating food waste is anaerobic fermentation, in which high amounts of organic compounds in waste are microbially transformed into useful compounds, for example, methane or short-chain fatty acids (SCFAs), providing for energy efficiency and formation (Wu et al., 2021). The process of converting ethanol and SCFAs into medium-chain fatty acids (MCFAs) is known as microbial chain elongation (Reddy et al., 2018). Several MCFAs can be produced by food waste, including caproic acid, caprylic acid, capric acid, and lauric acid (Jadhav and Annapure, 2022). There are two steps in the formation of MCFAs from food waste. The presence of anaerobic bacteria converts food waste into leachate (which contains SCFAs) in the first step. Then the chain elongation bioprocess transforms leachate into MCFAs in the second step (Reddy et al., 2018). The four experimental approaches used to synthesise MCFAs are: control (no bacteria), non-augmentation (only enriched mixed culture), pure culture (*Clostridium kluyveri*), and bio-augmentation. These steps are illustrated chronologically in Fig. 6. Again, rather than converting VFAs into methane (CH_4), the MCFA synthesis route allows them to be extended by two carbons in each cycle to produce MCFAs (C_6-C_{10}) (Dahiya et al., 2018b; Wu et al., 2021).

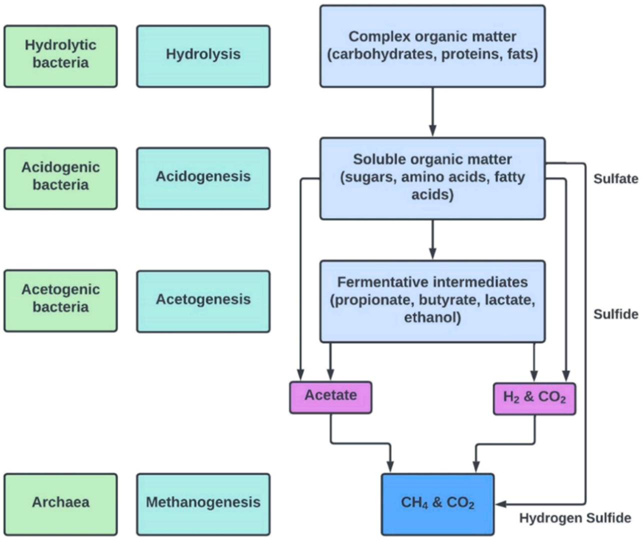

Fig. 5. The production process of VFAs from food waste.
Modified from Hafid et al. (2017).

In the MCFA production process via the chain elongation pathway, reverse oxidation needs a carbon source and energy from particular electron donors such as ethanol, hydrogen, and lactate to reduce carbon flow (Dahiya et al., 2018b; Wu et al., 2021). During the manufacture of n-caprylate, it was discovered that ethanol can function as an electron donor. The anaerobic fermentation system's ethanol levels increase MCFA production and waste selectivity. Besides, in comparison to ethanol, MCFAs have a longer hydrocarbon tail, which means they have higher energy density and poorer solubility. MCFAs can be used in several ways. One type of MCFA, saturated monocarboxylic acids, can be employed as aviation fuels, antimicrobials, corrosion inhibitors, scent and flavoring intermediates, and biodiesel and biodegradable plastic precursors (Dahiya et al., 2018b; Reddy et al., 2018). This MCFA can replace fossil fuel-based products in the future, helping develop a sustainable environment and economy for the next generations.

4.2.7. Electro-fermentation

Along with the need to control energy intake and ionic usage during the fermentation process, product formation requires neutralization of the system's energy while limiting inefficiencies (Bhagchandanii et al., 2020). Electro-fermentation (EF) is characterized by electrodes in a bioreactor that work as an electron source. EF was utilized to solve the thermodynamic boundaries of traditional microbial fermentation and to modulate metabolism to produce specific bio-based ingredients (Shanthi Sravan et al., 2018). In the EF process, external activation of the electrodes with applied energy (positive or negative) results in a combination of interactions between the electrode and the microorganisms at the solid-liquid interface, regulating their electro metabolic processes (Dahiya et al., 2018b). By combining a microbiological habitat with electrochemistry, which is what the EF method is known for, all electrochemical redox reactions can be catalysed (Bhagchandanii et al., 2020).

In microbial fermentation, electro-fermentation is the technique of effectively collecting electrons by employing particular electrodes (Hadiyanto et al., 2022). It works by oxidizing organic and inorganic acids found in waste materials using a minimal cost platform containing self-sustaining anodifilic microorganisms (Kumar et al., 2018). This concept is demonstrated in Fig. 7. The EF process can be divided into four stages. Microbial fuel cells (MFC) can utilize organic compounds to generate electricity. When an MFC is given external voltage to lower the cathode potential, it transforms into a microbial electrosynthesis cell (MEC), generating H_2 and other compounds in the cathode compartment (Hoang et al., 2022b). A microbial remediation cell (MRC) is an MEC-type method that extracts pollutants from a medium, while an MEC creates value-added molecules by microbial catalysis at the cathode (MES).

Electrode voltage is important in determining whether a bioelectrochemical system (BES) operates perfectly in EF to minimize electrochemical losses and increase energy generation. As bacteria are usually negatively charged, applying a positive voltage to the anode might hasten the production of biofilm microorganisms due to electrostatic interactions. A negative voltage should be applied to the cathode to accelerate the reductive reaction. Moreover, in the BES, syntrophic interactions and optimal circumstances influence the quick and increased transformation of food waste into green bioproducts. The production of electrofuels like bioelectricity, biohydrogen, biomethane, and bioethanol, and chemical compounds in a solid-state bio-electro-fermentation system (SBES), such as SCFAs, MCFAs, and bio alcohols, demonstrates the effectiveness of electro-fermentation for food waste

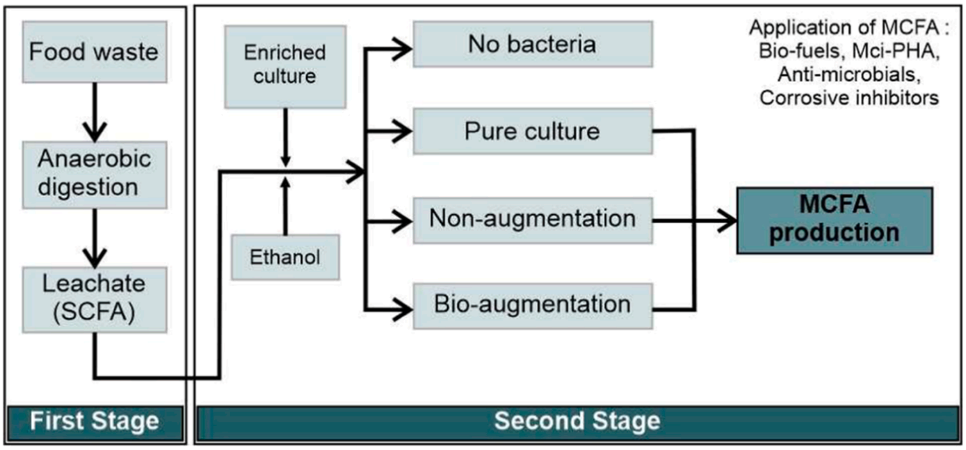

Fig. 6.. The production process of MCFA from food waste.
Modified from Reddy et al. (2018).

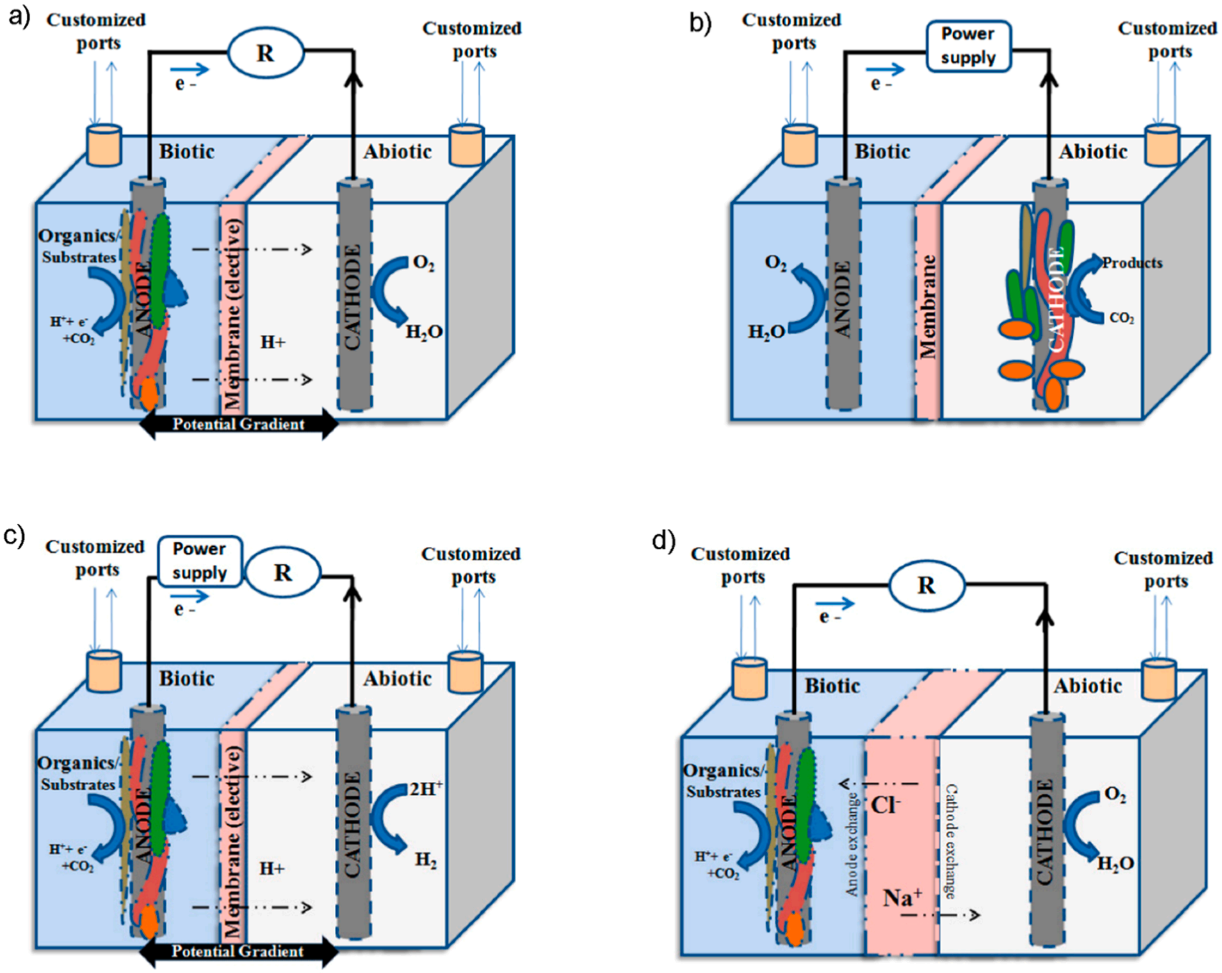

Fig. 7. Electro-fermentation process steps: a) microbial fuel cells (MFC); b) microbial electrolysis cell (MECs); c) microbial electrosynthesis (MES); and d) microbial desalination cells (MDCs*)* (Kumar et al., 2018).

recovery and reuse (Bhagchandanii et al., 2020; Dahiya et al., 2018b). The bioproducts produced from food waste in numerous studies are summarized in Table 3.

Although EF systems are already being used, the transfer route over the membrane and the microbial surface is still to be understood (Kumar et al., 2018). Limited power efficiencies, ohmic voltage loss, low transport across membranes, high conductivity, proton flux, and oxidant towards the bio-cathode are other key concerns. Otherwise, the integrative strategy of merging microbiological environments with electrochemistry is a promising technique that promotes EF as a modern, environmentally friendly, and long-term solution.

Table 3
Bioproducts from anaerobic fermentation of food waste.

Product	Inoculum	Substrate	Yield	Ref.
Biohydrogen	Biofermentation	Food waste wastewater, co-supplemented domestic sewage, vegetable waste, supplementation and so on	9.67 l/h	(Dahiya et al., 2018b)
	Biofermentation, biophotolysis, bioelectrochemical, and gasification	Organic feedstocks	219.9 mL/g V (39.1 mL/g food waste)	(Osman et al., 2020)
Biohythane	Anaerobic fermentation	Food waste	163 L	(Dahiya et al., 2018b)
	Dark fermentation (DF) and anaerobic digestion (AD)	Food waste	3.79 MJ/kg VS	(Ghimire et al., 2021)
Sugars	Dilute acid pretreatment, pretreatment using hydrochloric acid and sulphuric acid	Food waste	-	(Dahiya et al., 2018b)
	Subcritical water treatment	Carbohydrate-rich bakery waste (food waste)	80% Temp: 280–380 °C Time: 0–60 min	(Mohd Thani et al., 2020)
	Acid-enzymatic hydrolysis pretreatment	Carbohydrate polymers, e.g., cellulose, starch, and sugars (food waste)	150.5 ± 0.11 g/L	(Hafid et al., 2017)
Biomethane	Anaerobic fermentation	Food waste	-	(Dahiya et al., 2018b)
	Co-digestion of food waste and sewage sludge	Food waste and dairy manure	3.24 Mm^3 CH$_4$/year	(Chan Gutiérrez et al., 2018)
Volatile fatty acids	Anaerobic fermentation	Food waste	6.3 g/L	(Dahiya et al., 2018b)
	Acidogenic fermentation and membrane based VFA recovery techniques	Organic waste	0.54 g-VFAs/g-VS; 0.65 g-COD/g-VS	(Sukphun et al., 2021)
	Anaerobic fermentation with mixed or pure microbial cultures	Food waste as a carbon source	36.99 ± 1.68 g/L; 0.46 g/VS added	(Carvalheira and Duque, 2021)
Medium chain fatty acids	Anaerobic fermentation	Food waste	-	(Dahiya et al., 2018b)
	Anaerobic fermentation	Waste activated sludge	5.37 mg COD/L	(Wu et al., 2021)
	Bioaugmentation process	Food waste	8.1 g/l of caproic acid	(Reddy et al., 2018)
Electro-fermentation	Electrode based electron acceptors and bioelectrochemical systems (BES)	Food waste	-	(Dahiya et al., 2018b)
	Electrochemical fuel cell technology and fermentation	Food waste	4595 mg/L d	(Bhagchandanii et al., 2020)
	Electrical stimulation on fermentation	Biobased products (food waste)	-	(Shanthi Sravan et al., 2018)
	Anaerobic digestion (electro-fermentation)	Organic materials	MEC= 4.5 L m− 2d− 1; BES= 0.8 mM L^{-1}h^{-1}	(Kumar et al., 2018)

4.3. Oleaginous metabolism

Oleaginous microorganisms are those that have an oil content greater than 20% of their biomass (Meng et al., 2009). Microbial oils, commonly referred to as single-celled oils, are generated by oleaginous microorganisms (Ali et al., 2022), namely microalgae, fungus, bacteria, and yeasts. To understand oleaginous metabolism, it is first necessary to understand the concept of metabolism (Liang and Jiang, 2013). Metabolism, broadly defined, can be described as the process through which living organisms use or produce energy (DeBerardinis and Thompson, 2012). Although the composition and quality of biomass feedstocks vary, microbial systems efficiently utilize different biomass feedstocks (Spagnuolo et al., 2019). Oleaginous yeast is the most favourable of all bacteria because it can collect fatty acids in the triglyceride form, which makes them advantageous precursors for the generation of jet fuel, green diesel, and biodiesel (Kruger et al., 2018; Sànchez i Nogué et al., 2018). The high flux pathways for the natural precursors used in the biosynthesis of fatty acids may encourage oleaginous yeasts to produce non-native molecules with improved fuel properties and an effective biofuel. Efforts have been made to include *Saccharomyces cerevisiae* in order to generate substantial fatty acids (Ferreira et al., 2018). However, oleaginous yeasts outperform non-oleaginous yeasts in terms of yield (Spagnuolo et al., 2019). In order to produce biodiesel, transesterification of triglyceride (TAG) is a vital component as it is found in numerous oleaginous microorganisms that can contain oils (Liang and Jiang, 2013). Glycerol and fatty acid methyl ester (biodiesel) are produced as a by-product when alcohol combines with TAGs using an alkali or acid catalyst during the transesterification process (Li et al., 2008). The oil content discovered in various investigations using numerous microalgal species is summarized in Table 4.

Yarrowia lipolytica (*Y. lipolytica*) is a commonly known oleaginous yeast (Yu et al., 2020). It has the capacity to store substantial amounts of lipids, grow efficiently on a variety of inexpensive hydrophobic substrates, and produce a variety of compounds and enzymes for industrial purposes, all of which have the potential to be advantageous for a variety of industrial applications. Many genetic tools have been developed to genetically manipulate *Y. lipolytica* so that it can be successfully used as an ideal host to engineer biochemicals as well as generate biofuels from high level fatty acid production processes(Yu et al., 2020). Table 5 tabulates bioproducts of the *Y. lipolytica* platform derived from fatty acid synthesis.

Table 4
Oil content found using different microalgal species.

Species of Microalgae	Lipid content (dry weight percentage)	Lipid production (mg/L/day)	Biomass production (g/L/day)	Ref.
Chlorella vulgaris	20–42	44–147	0.21–0.35	(Y.Feng et al., 2011)
Scenedesmus obliquus	21–58	19.0–43.3	0.07–0.09	(Abou-Shanab et al., 2011)
Chlorella protothecoides	49	586.8	1.2	(Gao et al., 2010)
Haematococcus pluvialis	15.61	-	-	(Damiani et al., 2010)
Tetraselmis tetrathele	17.25–23.5	240–440	1.0–2.6	(Araujo et al., 2011)
Isochrysis zhangjiangensis	29.8–40.9	66.2–140.9	0.667–3.1	(D.Feng et al., 2011)
Chaetoceros gracilis	15.5–60.28	530–2210	3.4–3.7	(Araujo et al., 2011)

Table 5
Bioproducts derived from fatty acid synthesis using the *Y. lipolytica* platform.

Target	Genetic manipulation	Strain	Production level	Ref.
Fatty alcohols	FAR overexpression in *Arabidopsis thaliana* and FAT overexpression in *C. palustris*. Pex10, the primary peroxisome assembly factor, was deleted	*Y. lipolytica* Δ*pex10*: *FATcpa/FAR*	> 500 mg/L	(Rutter and Rao, 2016)
	Maqu2220, a fatty acyl-CoA reductase from *Marinobacter aquaeolei*, and *fadD*, an *E. coli* fatty acyl-CoA reductase, were expressed	*Y. lipolytica* Maqu2220-EcfadD	2.15 g/L (in a 3-L bioreactor)	(Xu et al., 2016)
	FAR gene expression in *Barn owl*	*Y. lipolytica Tafar1*-5copy-Δ*dga1 fao1* strain	53.32 mg/L (extracellular), 636.89 mg/L (intracellular)	(Wang et al., 2016)
FAEE	*Acinetobacter baylyi* ADP1 wax-ester synthase *Ab*AtfA expression Overexpression of a mitochondrial/ peroxisomal carnitine acyltransferase, perCat2. Mixtures of canola oil and dextrose	*Y. lipolytica* AD strain	142.5 mg/L	(Xu et al., 2016)
	adhB and *pdc* expression from maqu_0168 *Z.* and *mobilis* from *Marinobacter* sp. *mfe1*, *gut2*, and *pex10* deletion	*Y. lipolytica* YL6	82 mg/L	(T.-K.Ng et al., 2020)
	WS gene expression from *Marinobacter* sp., *PEX10* gene deletion	*Y. lipolytica* GQY20	1.18 g/L (containing 5 vol% ethanol)	(Gao et al., 2018)

5. Biorefining and bioeconomy

The importance of biorefineries as environmentally friendly replacements for fossil fuels is growing (Macias Aragonés et al., 2022; Atabani et al., 2022). The ever-increasing need for energy and resources is putting pressure on humanity to make the transition from a fossil fuel based linear economy to a circular bioeconomy that is more sustainable. The circular economy concept, in which useable materials that were once viewed as waste are recycled into the supply chain to generate new products, benefits from the valorization of food waste (Mhatre et al., 2021). Valorization of food waste presents an economic and environmental potential that can alleviate the issues associated with its usual disposal (O'Connor et al., 2021). Due to growing public awareness of the negative environmental effects of food waste disposal, the sector of food waste valorisation is growing. To provide financial incentives for the widespread valorisation of food waste to generate value-added goods, more thorough data collecting on food waste is required.

Waste biorefineries could be a source to shift the linear economy to a circular bioeconomy. Biorefineries refer to industrial scale facilities which ensure optimized and sustainable use of biomass that can be converted into energy, fuels, materials, and chemicals (de Albuquerque et al., 2019). The prime motivation behind biorefineries is their cost-effectiveness, climate change mitigation impact, economic development potential, and encouragement of technological and rural development. The biorefinery concept is emerging as an important element of the circular economy as biomass offers a window of opportunity to provide a broad spectrum of sustainable products (Lago et al., 2018). There are different kinds of biomass available and some of the main categories are shown in Fig. 8 which describes the biorefinery concept. After going through the process of biomass degradation and conversion, the biomass is altered into fuel and highly valued outputs such as proteins and amino acids.

Currently, there is no standard classification of biorefineries in the literature. However, biorefineries can be classified based on the categories of raw materials used or how the biomass is converted and how the biorefineries are used. Biorefineries are categorized based on the type of feedstocks, such as primary and secondary feedstocks (Gundekari et al., 2020). In this way, biorefineries can be categorised as follows: agriculture-based biorefineries, forestry biorefineries, organic waste biorefineries, and biorefineries using aquatic biomass (Holm-Nielsen and Ehimen, 2014). Primary feedstock biorefineries use biomass that can be harvested, and which do not have to go through any pre-processing, such as forestry and agriculture biorefineries, as shown in Fig. 9.

Secondary feedstock biorefineries use biomass that needs to undergo technological processing, and this kind of biorefinery uses feedstocks that include industrial and household residues. Moreover, this type of technological processing biorefinery converts feedstocks into biofuels like ethanol, biodiesel, green diesel, and biogas. Other kinds of biorefineries are available based on the methods of transformation, including biochemical, thermodynamic, and two platform biorefinery concept. The third and fourth generations of biorefineries are also available which are based on the basic materials and feedstocks (Dahman et al., 2019).

The bioeconomy has been defined as a development that facilitates the conversion of renewable natural resources into valuable resources,

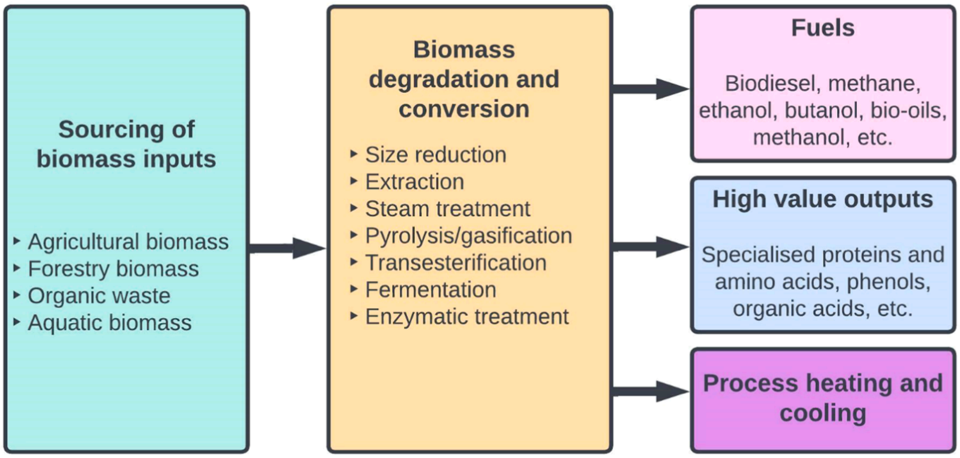

Fig. 8. Biorefinery concept.
Modified from Holm-Nielsen and Ehimen (2014).

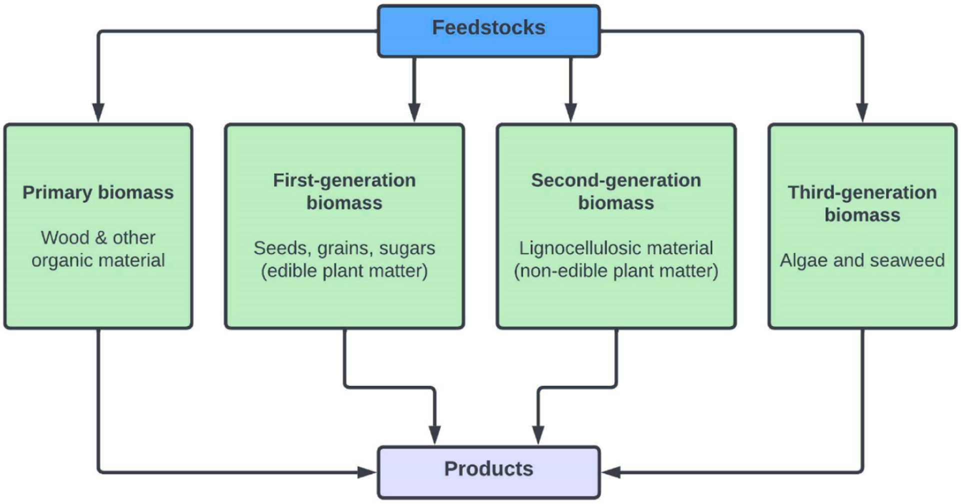

Fig. 9. Biorefinery classification.
Modified from Dahman et al. (2019).

including bioenergy, biochemicals, and food (European Commission, 2018)(Atabani et al., 2021). Moreover, the bioeconomy can reduce the pollution that is affecting climate change and offer regenerative carbon resources that can generate power and energy. Also, a sustainable circular bioeconomy can help the population by providing business and employment opportunities. Food wastes can be crucial to the development of biorefineries in the circular economy. Biorefineries serve as the strategic framework for implementing the circular bioeconomy as the circular economy gives prominence to tackling the environmental, economic, and social aspects of industrial sectors (Venkata Mohan et al., 2016). Biofuel and biochemicals manufactured from lignocellulosic food waste biorefineries can play a vital role in making the transition to a fossil-free society (Sirohi et al., 2022). The shift to a circular economy can be achieved if food waste goes through the 5 Rs of the waste management process, as illustrated in Fig. 10: Refuse, Reflect, Reduce, Reuse, and Recycle. With the right biorefinery implementation and socio-political intervention, a green bioeconomy and sustainable environment could be established in the near future.

6. Challenges and future perspectives of waste biorefineries

Each year one-third of the world's food ends up as food waste, which comprises the highest proportion of biowaste globally (Despoudi et al., 2021). This number is increasing as the human population increases. Therefore, biorefinery technology is the only solution to develop and maintain a sustainable circular bioeconomy. However, even though waste biorefineries have significant potential to produce valuable bioproducts, there are also challenges and barriers with their production processes which hinder the creation of bioproducts (Alazaiza et al., 2022). There are some sustainable and well-known valorisation methods that are used in converting biomass into bioproducts. Nevertheless, their potency in handling food waste in biorefineries is arguable due to the significant volumes of food waste produced, high operating and transportation costs, as well as tough environmental restrictions. There are some environmental, social, and economic impacts, and thus these valorisation techniques need to be improved to increase their effectiveness (Kaur et al., 2020). Composting of food waste is included in the production process when waste is converted into useful bioproducts. This is an essential process as it helps retain moisture and promotes the production of an equilibrated organic matrix (Cerda et al., 2018).

Despite its benefit, composting has certain challenges with its smell, heterogeneous composition mixtures, the different kinds of parameters included in the process (such as the microbial process, temperature, the ratio of carbon to nitrogen, oxygen, and water supply), and gas exchanges (Nasini et al., 2016). Moreover, greenhouse gases such as methane (CH_4) and nitrous oxide (NO_2) are produced during the process

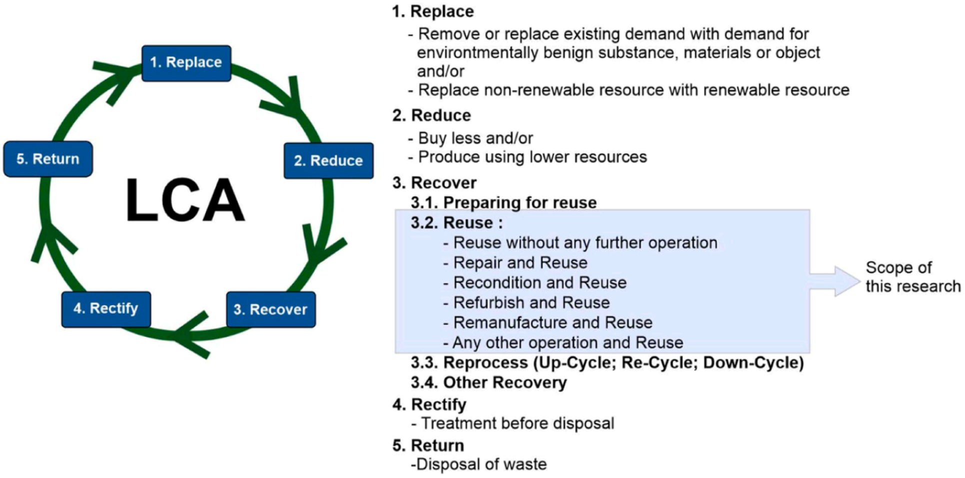

Fig. 10. The 5 Rs of waste management.
Modified from Gharfalkar et al. (2016).

of composting because of their anoxic state. Apart from methane and nitrous oxide, gases like carbon monoxide, ammonia, and volatile organic compounds (VOC) are also emitted during composting (Cerda et al., 2018). Despite the challenges involved in food waste biorefinery processes, there are prospects for biorefineries to tackle these challenges. If food waste biorefineries can be rigorously evaluated and valued, they can benefit society, the economy, and the environment. The calorie content of food waste is 5.35 Mj/kg under STP conditions which indicate its potential as a good source of bioenergy (Dahiya et al., 2018b). Biorefineries, as the producers of bioenergy and bioproducts, will be a significant part of the world in the future and will continue to underscore the great value in maintaining a circular bioeconomy (Venkata Mohan et al., 2016). The development of biorefineries began to minimize GHG emissions, and it is crucial to note that biorefinery production processes are not excluded from this rationale.

Biorefineries should always have the environment as the prime focus so technological advances need to concentrate on both the generation of bioproducts and effective waste management processes. A bio-design refinery must be environmentally friendly, taking into consideration all negative consequences such as competitiveness with biomass and other raw materials, water consumption, quality of products, land use, carbon footprint, and biodiversity impacts. In the forthcoming sections, the impact of food waste biorefineries will be evaluated using techno-economic and environmental analyses and a life cycle assessment.

6.1. Techno-economic analysis

Techno-economic analysis of food waste biorefineries is required to evaluate the performance of the production and supply system (Dragone et al., 2020). Food waste biorefineries need to be assessed for their feasibility in terms of the physical infrastructure, food waste valorisation economics, and supply-chain aspects to determine their overall impact. A biorefinery usually deals with waste handling and pretreatment technologies first and then moves to the main processing methods, which may include biochemical or thermochemical procedures (Zetterholm et al., 2020). In this process, unwanted residues are discarded, and the remaining products are combined to create the final output. The performance of a biorefinery is determined by the appliances and operational parameters which decide the plant's energy and mass balances and biomass-to-product yield.

The techno-economic analysis determines biomass-to-product yield, energy effectiveness, and production value. Few studies have been conducted which analyse food waste biorefineries specifically. However, according to available literature, some valorisation methods are difficult to implement on a broad scale and were not successfully operationalised at a pilot plant scale in the process of manufacturing food waste (Caldeira et al., 2020). Some of the valorisation methods tested in pilot plants showed potential for industrial scale implementation. Some valorisation techniques, such as ultrasonic solvent extraction, are commonly implemented in industry, while other valorisation methods, such as microwave steam diffusion or steam diffusion, are still challenging to put into practice on a large scale with satisfactory results (Caldeira et al., 2020). There are only a few papers that have analysed the food waste valorisation techniques based on investment return and duration of payback.

One study looked at the revenues of different kinds of valorisation pathways and demonstrated that the economic success of these pathways could only be seen with some distinctive pathways, and that market value and economic scale have a significant impact on the profitableness of these biorefineries (Cristóbal et al., 2018). Methods used in food waste biorefineries have a significant impact on profits. In another study (Bastidas-Oyanedel and Schmidt, 2018), it was found that the combination of organic waste anaerobic digestion and mixed culture anaerobic fermentation methods, such as lactic acid and dark fermentation, increases the economic profitability of food waste biorefineries. Furthermore, when an economic assessment of food waste biorefineries is carried out, it is important to include the geographical location and quantity of food waste produced in that location as it is vital that the waste biorefineries require is produced in sufficient quantities in a location at or close to the biorefinery. Thus, the location of origin and the quantity of food waste are crucial to the economic assessment as it is important to calculate the annual quantity of final products and the expense of transporting the food wastes to the biorefinery.

The location of the plant is also important from a supply chain perspective. Logistics issues related to food waste are also important factors in the profitability of a biorefinery. One study demonstrated how predicting losses based on the shelf life and potential wastage of food might help to increase the efficiency of the supply chain for food waste collection and recovery (Muriana, 2017). Another logistic issue is about how to collect food wastes in time for their most effective use. Storing food waste in distribution centres for a longer period of time can solve these issues as more foods can be taken to specialization centres, which will reduce cost and environmental consequences (Bottani et al., 2019).

6.2. Environmental analysis

Environmental analysis is a method of analysing the environmental effect of a final product produced from certain biomass or feedstock. The prime goal of environmental assessment is to offer a framework for determining if there should be a change in any process parameter (Rao and Rubin, 2002) that would enhance the product's environmental performance and ensure compliance with current environmental legislation. Environmental analysis is one of the important assessments, and it is intricately related to technical and economic assessment factors such as raw materials, land, and fuels used in the process, and the product flow system. Following data collection and comparison of specific process results, there should be some areas where environmental goals can be raised further. The potential environmental impact (PEI) method can be used when doing the environmental analysis of a biorefinery (Romero-García et al., 2018). The PEI method can be described as the indices of how the energy or mass to be generated from the final product will affect the environment. The PEI method is calculated using the following equation based on the material's input and output (Romero-García et al., 2018):

$dI_{sys}/dt = \text{In - Iout} + \text{Igen}.$

In this equation, Isys is the environmental impact inside the system, Iin and Iout are impact input and output, and Igen is the generation rate impact. Using the PEI method, WAR (waste reduction algorithm) can be assessed. The WAR consists of eight environmental factors which are used when undertaking environmental analysis (Young et al., 2000). Several case studies have used the WAR algorithm. Photochemical oxidation potential (PCOP) is one of the impact factors of the WAR and it has turned out to be one of the most significant factors for food waste biorefineries. A case study (Martínez-Ruano et al., 2018) into the production of biogas from banana peel showed that the biorefinery process is environmentally friendly compared to the conventional biogas production method. When comparing the biorefinery biogas concept with the stand-alone process, it was found that the environmental parameters for the biorefinery concept were lower than the stand-alone process. Also, the individual impact of PCOP and the potential of human toxicity by exposure to dermal exposure and inhalation (HTPE) is less than the traditional method (Martínez-Ruano et al., 2018). Another study (Ocampo Batlle et al., 2020) demonstrated that residues from the palm oil industry can be used to make biochar and bio-oil using the fast pyrolysis technique and with an extra step, it can make biodiesel and glycerine. This study showed that the production of bio-oil using the fast pyrolysis technique has a lower economic impact than other biorefineries. A comparison study was undertaken on sugarcane-based jet fuel where three renewable jet fuel (RJF) production technologies were compared: alcohol to jet (ATJ), hydroprocessed esters and fatty acids (HEFA), and Fischer-Tropsch synthesis (FTS). These technologies were proven to offer a 70% reduction in economic impact and are also economically compatible with other jet fuel technologies (Klein et al., 2018). To conclude, these studies have shown that there are significantly fewer negative environmental effects from food waste biorefineries than from the traditional process.

6.3. Life cycle assessment

Life cycle assessment (LCA) or also known as cradle-to-grave analysis, is a method to assess a product's environmental impact by analysing its life cycle, which includes extraction of raw materials, manufacturing, disposal, and consumption (Lago et al., 2018) as shown in Fig. 11. The GHG footprint of food waste is large, contributing to the global warming issue (Cakar et al., 2020). Large amounts of CO_2 are released during food production, transit, and processing, and when food is dumped in landfills it produces methane, a more potent GHG (Mandal et al., 2021). Global warming demands a shift to a circular economy where products from sustainable food waste biorefineries will replace traditional products which negatively affects the environment more. The use of food waste biorefinery is constantly increasing because of its environmental friendliness. The goal of developing biorefineries is to reduce GHG emissions and ensure a steady supply of renewable energy. Some 8–10% of global GHG emissions come from wasted food, and growing demands on the world's limited supply of land and water also pose a threat to biodiversity (Daszkiewicz, 2022). Therefore, it is important to assess how food waste biorefineries will benefit the environment as well as compete in the market by performing an LCA of their products.

There has been little research about LCAs on food waste biorefineries. However, a comparative study of a life cycle assessment of an ethanol biorefinery system versus a traditional waste management method has been undertaken. It has been shown that 238 kg CO_2eq/ton more is emitted in the traditional waste management method than the biorefinery method, and the biorefinery demonstrates good economic performance (Papadaskalopoulou et al., 2019). In another study, LCA was performed on hydroxymethylfurfural (HMF), a value-added chemical produced from food waste via biorefining. Eight kinds of biorefinery methods have been implemented to produce HMF, and it has been found that the method using bread waste as substrate and aluminium chloride ($AlCl_3$) as a catalyst is the most environmentally favourable option compared to the other methods. However, the study only considered the environmental aspect, and could not assess economic factors due to the lack of information (Lam et al., 2018).

Currently, little data is available in the literature with good comparisons between food waste biorefinery methods and traditional methods using LCA. Because the boundaries of a system and its functional parts are not well defined, it is difficult to compare the results. Moreover, in most of the literature, LCAs are focused on environmental aspects and only a few papers are available where an LCA was performed on socio-cultural and economic aspects. Primary data and background and foreground data sources are scarce (Liu et al., 2021). Therefore, the LCA of food waste biorefineries should be constructed where the function of functional and systemic regions is clear. LCA should be focused on various aspects, including social, cultural, economic, and operational aspects. More research is needed on the primary data to refine life cycle assessment techniques.

7. Conclusion

Food waste can originate during all stages of food processing, such as production, transportation, storing, and circulation. Several bioconversion processes, including anaerobic fermentation, solventogenesis and oleaginous metabolism, were reviewed in this paper along with potential bioproducts including biofuels and biochemicals that have been shown to be effective, sustainable and resource efficient. The integration of biorefinery processes into the circular economy giving rise to a circular bioeconomy will help us create a sustainable and environmentally friendly economy. Implementing proper pathways, economic scale, and the right methods along with an assessment of the location, quantity and collection of food waste has an enormous impact on sustainability and profit. Through this review, it has been found that the negative environmental effect of the food waste biorefinery is significantly lower than conventional methods. Biorefineries must always prioritize the environment, therefore technological developments must concentrate on both the production of bioproducts and efficient waste management techniques. This review has not found any satisfying life cycle assessment studies into food waste biorefineries and conventional methods in terms of socio-economic perspectives. However, addressing current challenges, implementing proper ecological management and use of waste, and building a strong biorefinery infrastructure can make a circular bioeconomy profitable and climate friendly. The strategy for food waste biorefineries requires optimizing the cascade of various bioprocesses to transform from a linear into a circular bioeconomy.

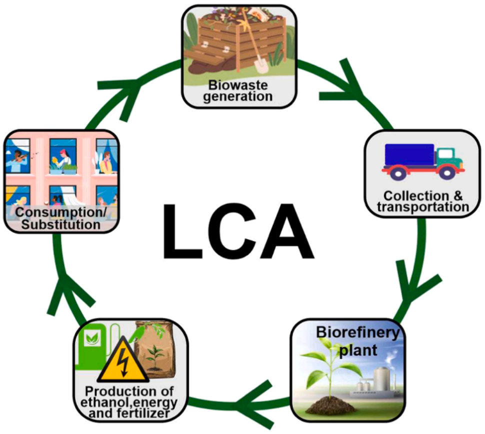

Fig. 11. Life cycle assessment.
Modified from Papadaskalopoulou et al. (2019).

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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

Data will be made available on request.

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