Synergizing food waste management and microalgae biorefinery for bioenergy production: recent advance on direct and indirect conversion pathway

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Abbreviations

ABE	Acetone-butanol-ethanol
C/N	Carbon to nitrogen
CNT	Carbon nanotubes
COD	Chemical oxygen demand
DCW	Dry cell weight
FAME	Fatty acid methyl ester
GHG	Greenhouse gasses
HHV	Higher heating value
LHV	Lower heating value
MNP	Magnetic nanoparticle
PAC	Powdered activated carbon
SDGs	Sustainable development goals
VS	Volatile solid

Abstract

Food waste is a persistent global environmental issue that contributes to global warming and climate change by releasing significant amounts of greenhouse gases as it decomposes in landfills. Converting food waste into bioenergy could serve as a sustainable solution. Direct conversion of food waste through methods like anaerobic digestion, fermentation, and pyrolysis, produces diverse energy products. Besides, the indirect approach involving the cultivation of microalgae on food waste offers a sustainable approach, owing to the ability of microalgae to assimilate nutrient-rich components such as nitrogen, phosphorus, and carbon from food waste, converting them into valuable biomass. The microalgae biomass can be further transformed into biofuels, offering a dual benefit of waste management and energy production. This review work provides a holistic review of food waste-to-energy conversion methods, both direct and indirect, evaluating their feasibility and benefits. Specifically, a comprehensive analysis of using microalgae grown on food waste for biofuel production is provided, offering insights into how the method could effectively address both environmental and energy crises, and contribute to sustainable development goals. Future research should focus on enhancing conversion process efficiency, optimizing microalgae bioprocess, and scaling-up these technologies to industrial levels, while addressing challenges such as economic feasibility, supportive policies, and robust supply chains. Collaboration among industry, academia, and government is essential to boost the global implementation of these technologies.

Keywords: Bioenergy; food waste; sustainable development goals; biotransformation; third-generation biofuels; microalgae

1. Introduction

Food waste, one of the largest global waste streams at 1.05 billion ton in 2022 from retail, food service, and household sectors, poses significant environmental and economic challenges due to its unsustainable disposal practices [1]. The rapid growth of the world's population drives up the food demand, and at the same time, substantial amounts of food waste are being generated from farms, grocery stores, food service sectors, and households. It is estimated that one-third of all food produced globally is lost or wasted in the food supply chain [2]. By mass, food waste consists of 62% fruit and vegetables, 11% meat, 11% dairy, and 16% bakery products, with 39% classified as edible and 61% inedible [1]. Food waste contributes significantly to the municipal waste, with over 60% of the trash found in a restaurant's bin being food waste [3]. Most of the generated food waste ends up in landfill; however, in terms of net greenhouse gas (GHG) emission, it appears to be the worst disposal option [4]. The GHG released from landfilled food waste is remarkably high compared to those generated from other wastes such as paper, wood, and yard trimmings, releasing around 2708 kg carbon dioxide equivalent (CO_2e) ton^{-1} of dry food waste [5]. There are several alternatives to landfill disposal. Composting has been promoted with its advantages of converting food waste into fertilizer with the reduced GHG emissions as low as about 926 kg CO_2e ton^{-1} of dry food waste, which was 38 – 84% lower than landfilling [6]. However, composting requires maintenance, including regular watering and aeration, and large-scale implementation faces challenges such as limited land availability in urban areas and the need for odor control measures to mitigate unpleasant smells.

In this context, the transformation of food waste into bioenergy presents a promising alternative for effective waste management and energy recovery. Food waste sorting is currently practiced in many countries, facilitating its valorization into bioenergy. However, the least developed countries still lack sorting systems for waste streams and do not implement effective conversion pathways for its valuation. Several conversion methods are available. Anaerobic digestion, a method with its initial use on decomposing sewage sludge at wastewater treatment facilities, is increasingly popular and frequently used to dispose food waste and generate renewable energy (biogas, mostly methane) and nutrient rich-digestate. It was reported that the anaerobic digestion is favored among various food waste disposal options in view of its relatively lower GHG emissions compared to composting and landfills [4]. However, food waste from different sources, along with uncontrolled mixing with agricultural feedstocks, influence methane yield, since the biodegradability varies significantly. Higher levels of proteins and lipids in food waste lead to increased concentrations of ammonia and sulfide, which inhibit the metabolism of anaerobic consortia [7]. Apart from biomethane, another renewable energy source (biohydrogen), can be produced from anaerobic fermentation of food waste. In fact, biohydrogen is an intermediate product of anaerobic digestion, and lately there has been a gaining interest in optimizing its production [8]. Furthermore, pyrolysis represents an efficient thermochemical conversion option for converting food waste into bio-oil, biochar, and bio-syngas [9]. It can be used to treat food waste with large amounts of solid impurities and even the recalcitrant organic residues generated from anaerobic digestion of food waste [9].

Alternatively, processed solid food waste and/or liquid food waste such as waste cooling oil can be served as a low-cost nutrient source to grow microorganisms such as bacteria, fungi, yeast, and microalgae. Microalgae are an attractive choice due to their rapid growth rates, high biomass productivity, and ability to utilize a wide range of food waste substrates for nutrient uptake. Their ability to metabolize diverse waste-derived nutrients, including glucose, nitrogen, and phosphorous, enables the conversion of food waste into valuable biomass composition (i.e.

carbohydrates, proteins, and lipids) [10]. These food waste-derived substrates provide an important resource for reducing the costs associated with synthetic cultivation medium. Furthermore, microalgae also contribute significantly to the circular bioeconomy by transforming food waste nutrients into biofuels, thereby supporting sustainable development goals. Microalgae-based biofuels have been progressed over the past decade to replace petroleum-based energy source. The waste nutrients from food waste can be upcycled as an alternative culture medium for the production of microalgal biomass, and its whole biomass and isolated products can be further exploited to produce various types of biofuels (e.g. biodiesel, bioethanol, and biogas). For instance, food waste hydrolysate rich in glucose and fructose was served as the carbon source to support the heterotrophic growth of *Auxenochlorella protothecoides*, achieving a biomass yield of 0.346 g g^{-1} sugar and a lipid yield of 0.216 g g^{-1} sugar [11]. By applying the proposed integrated method, 1 kg of food waste produced 248 g of biodiesel [11]. Microalgae do not require arable land or fresh water and can be fully utilized for biofuel production, making them an ideal solution for food waste valorization. Furthermore, microalgae contribute to carbon sequestration, helping mitigate the effects of climate change. As research continues to optimize upstream processes and enhance downstream processing, microalgae could play a pivotal role in advancing sustainable, low-carbon energy solutions. Promising results have been frequently reported in the relevant studies, implying that microalgae cultivation using food waste nutrients holds potential to revolutionize biofuel industries [12]. Regardless of the different conversion methods used, process economics and profitability remain critical factors in determining the sustainability of these technologies. Cost competitiveness is crucial for biofuels, and their market viability is highly influenced by the price of fossil fuels. A recent study demonstrated that the total operational cost for cultivating *Chlorella vulgaris* FSP-E can be reduced to $\$2.15 \times 10^5$ by using industrial biscuit waste powder as the cultivation medium, compared to \$3.78 × 10^6 when using the BG-11 medium [13]. Despite that, the successful implementation of food waste valorization to energy requires careful examination of advancements in conversion technologies

The novelty of this review lies in its holistic approach, evaluating the advancements of both direct conversion (e.g., anaerobic digestion, fermentation, and pyrolysis) and indirect biotransformation (e.g., microbial biomass cultivation using food waste) methods for turning food waste into bioenergy. The potential for integrating various direct conversion methods and the interaction between direct and indirect approaches is examined. The integration could maximize resource utilization, reduce waste, and enhance the efficiency of biofuel production while contributing to environmental sustainability and circular bioeconomy. Additionally, pretreatment of food waste prior to conversion processes is essential to ensure process efficiency, since it enhances the availability of organic materials. This work aims to provide insights into the effective food waste management protocols that can be implemented on a large-scale to valorize food waste sustainably. Finally, the challenges and perspectives are outlined.

2. Food waste and their pretreatment for valorization

Different forms of food waste influence the choice of conversion technologies due to their varying composition, moisture content, and biodegradability. Solid food waste can be processed and converted into biogas rich in methane through anaerobic digestion, biohydrogen via fermentation, and bio-oil, biochar, and pyrolysis gas through pyrolysis (**Figure 1**). Besides, liquid food waste (e.g., waste cooking oil) and lipid holds within solid food waste can be converted into biodiesel though esterification and transesterification [14]. In another indirect approach, processed solid and liquid food waste can be used as feedstocks for microbial fermentation, supporting the growth of microbial cells that are then converted into various energy products, including biodiesel and bioethanol/biobutanol (**Figure 2**).

Solid food waste needs to undergo multi-step pretreatments such as mechanical, physical, chemical, and biological methods. Mechanical pretreatment (e.g., blending, shredding, grinding, and pulverizing) is indispensable to reduce the size of food waste solids, making them more accessible to the subsequent treatment. Size reduction and sieving pretreatment are needed to ensure the efficiency of anaerobic digestion and prevent clogging of the digestion system. The selection of pretreatment is dependent on the nature of food waste and the requirements of the waste-to-energy conversion techniques. For wet anaerobic digestion, water was added into blended food waste and the feedstock was processed in the form of dilute organic slurry with typically a low total solid of $< 15\%$ [15]. In contrast, the feedstock for dry anaerobic digestion with $> 15\%$ of total solids was prepared by drying blended food waste at 105 °C in hot air oven for 24 h [16]. In dry fermentation, the colonization of biomass by anaerobic consortia is slow due to the absence of additional liquid in the chambers, which limits their metabolism and subsequently reduces biogas production. The disintegration of biowaste (e.g., shockwave pretreatment) enhances the fermentation process, and can be implemented either before the biowaste enters dry anaerobic fermentation or during later stages when the anaerobic consortia have exhausted the easily biodegradable sources of organic matter [17]. Similar to anaerobic digestion, pretreatment is indispensable to increase pyrolysis product yields, e.g., solid food waste requires extensive drying to remove its water content prior to pyrolysis [18]. It was also reported that the food waste pretreated by torrefaction before pyrolysis yielded high-quality bio-oils with the increased heating values ranging from 31.51 – 34.34 MJ kg^{-1} compared to that of obtained from unpretreated feedstocks (27.69 – 31.58 MJ kg^{-1}) [19]. High-quality bio-oil is typically characterized by its low moisture content, low oxygen content, and high energy density, making it more suitable for use as a fuel.

Additionally, complex compounds within food waste are broken down into simple molecules using physical, chemical, and biological pretreatment, allowing an effective nutrient assimilation by microorganisms. Physical method like thermal treatment is effective for certain types of food waste but often come with high cost and moderate environmental impacts due to its high energy consumption. On the other hand, chemical pretreatment, though highly efficient in breaking down complex compounds, is also costly and can lead to potential environmental issues due to chemical residues. Another milder pretreatment, which involves microorganisms or enzymes, is more environmentally friendly but may require longer processing time and specific conditions for optimal efficiency. Generally, pretreatment steps increase overall production cost and energy consumption considering the buildup and operational costs of infrastructure and facility, and the resources required. Therefore, it is important to carefully evaluate the benefits and drawbacks of pretreatment processing before implementing it on an industrial scale. Alternatively, by-products like liquid digestate discharged from anerobic digestion, which is rich in nitrogen and phosphorus, can be also utilized for microorganism cultivation to optimize cost-effectiveness and sustainability in the waste-to-energy conversion platform [20]. Apart from that, hydrothermal technologies present promising alternatives for valorizing food waste with high moisture content, since it eliminates the need for pre-drying wet materials, which in turn reducing energy costs and lowering operational expenses.

3. Direct conversion of food waste to biofuels

Conversion of wasted food to biofuels is one of the best options to divert from landfills. Landfilling of food waste is illegal in most developed countries, and this ban advocates for the use of more effective methods to reduce residual waste and advance toward a circular economy. Anaerobic digesters and pyrolysis facilities can be located in highly populated urban areas, whereby the energy content of food waste is recovered, and the volume is significantly reduced, without the need for a long-distance transportation. Recent studies are summarized in **Table 1**, showcasing various conversion technologies used to obtain different biofuel products. Each method has its own pros and cons. For example, fermentation offers high energy efficiency and low environmental impact but requires additional processing steps for biofuel production. Meanwhile, pyrolysis has advantages in energy recovery and waste volume reduction but it is energy-intensive [21].

3.1 Production of biomethane

Anaerobic digestion involves the use of bacteria to break down organic matters in the absence of oxygen and produces biogas rich in biomethane, which can be served as an energy source. The digestate, the residual material left after the digestion process, can be used as fertilizer or further processed using other techniques such as pyrolysis. Anaerobic digestion encompasses several main phases, including hydrolysis, acidification, acetogenesis, and methanogenesis, which play critical roles in affecting the efficiency of biogas production. Previously conducted research have validated the need of pretreatment step to improve the hydrolysis of organic matters in food waste. Food waste is usually complex and constituted of high amounts of fats (i.e., 3 – 6% on wet basis) that impede the effective hydrolysis of other substrates, and thus pretreatment is applied to improve hydrolytic rate and efficiency. Chen et al. [22] showed that the food waste pretreated with alkali enhanced the solubilization of its organic matters and achieved a high yield of biogas at 829 mL g^{-1} volatile solid (VS) with 65.5% of methane. Another recent study also showed that food waste, which has been pretreated using the subcritical water hydrolysis method, was mixed with pulp wastewater at a volatile solids (VS) ratio of 3:1 for anaerobic digestion, resulting in an increased biogas yield of 807 mL g^{-1} VS [23].

It is a common practice to mix food waste with other co-digested materials, such as manure and agricultural residues, to enhance the overall efficiency of anaerobic digestion while balancing the economic performance of the process. Anaerobic digestion of food waste often incorporates cow dung, since cow dung contains many types of bacteria that can act as decomposers in the process. It was reported that the mixed liquid tofu waste and cow dung at a percentage composition of 75:25, in the presence of 5% of EM-4 biocatalyst, produced biogas containing > 90% of methane and with a higher heating value (HHV) and a lower heating value (LHV) of 50,149 and 46,909 kJ kg^{-1}, respectively [24]. Besides, anaerobic co-digestion of canteen food waste and sewage treatment plant sludge, at its optimum ratio of 3:1, yielded high biogas production at 280 – 860 mL g^{-1} VS [25]. Another work demonstrated the use of catering waste mixed with the pretreated parthenium weed for biogas production [26]. These reports implied that food waste is a potential feedstock for enhanced biogas production. Recently, the use of additives such as biochar [27] and conductive materials like magnetite nanoparticle (MNP), carbon nanotubes (CNT), and powdered activated carbon (PAC) [28] have shown to improve the process efficiency of anaerobic digestion. The addition of biochar was proven to promote the acetogenesis and hydrogenotrophic methanogenesis processes in a continuous two-stage anaerobic digestion system, and improved the energy recovery efficiency by 25 – 71% [27]. On the other hand, conductive materials displayed their abilities to improve production of biohydrogen and biomethane in a two-stage anaerobic fermentation. Particularly, PAC facilitated high removal efficiency of chemical oxygen demand (COD) and increased yield of biomethane in the second stage of anaerobic fermentation [28].

3.2 Production of biohydrogen

Food waste has a high content of carbohydrates, making it a suitable feedstock for hydrogen production. Typically, the hydrogen-producing potential of carbohydrate is relatively greater than lipid and protein, and thus hydrogen yield is frequently reported on a hexose basis. The theoretical maximum yield of hydrogen generated from hexose is 4 mol of H_2 mol^{-1} hexose, but the actual yield is usually < 50% of theoretical value due to thermodynamic constraints [29]. The hydrogen yields reported in literature are generally below 3 mol of H_2 mol^{-1} hexose [30]. Various techniques are available for producing biohydrogen from food waste, which can be broadly categorized into light fermentation and dark fermentation. Light fermentation utilizes photosynthetic bacteria that converts sunlight into energy to produce biohydrogen, while dark fermentation involves the adoption of anaerobic bacteria like *Clostridium* species for producing biohydrogen in the absence of light [31]. The latter technique is considered more superior owing to its rapid hydrogen production and low operation cost without the need for a light source. The selection of pretreatment technique is dependent on the composition of food waste. Common pretreatment techniques used include physical (e.g., thermal and sonication), chemical (e.g., acids and alkalis), and biological (e.g., use of enzymes and microorganisms) [32]. Kim et al. [33] found that the fermentative hydrogen production from food waste without the addition of inoculum was possible given that the food waste has undergone appropriate pretreatment. Amongst the pretreatment methods including acid, alkali, and thermal treatments, food waste that was thermally treated at 90 °C for 20 min obtained the highest yield (i.e., 1.65 mol H_2 mol^{-1} hexose) [33]. On the other hand, Lee et al. [34] demonstrated an alternative method of using a glucose-adapted species, *Thermococcus onnurineus* NA1, which has undergone adaptive evolution process, to produce hydrogen using potato peel waste through simultaneous saccharification and fermentation.

Apart from that, there are several key parameters influencing the efficiency of hydrogen generation through fermentation, including feedstock composition, operating pH, temperature, and agitation speed [35]. The variations in composition and quality of food waste increase the complexity level of pretreatment, demanding a careful process optimization to ensure consistent and efficient product conversion. Xue et al. [36] found that a highly concentrated food waste contributed to the strong substrate acidification at the beginning of fermentation, inactivating non-hydrogen producing bacteria and consequently enhanced the yield up to 120.78 mL H_2 g^{-1} VS. Another report highlighted that the pH and total solid content in food waste were also two important factors in lactate-driven dark fermentation that allowed a concomitant production of hydrogen and medium-chain carboxylic acids such as caproate [37]. The study showed that a more neutral pH (at 6.5) and an increment of solid concentration (at 8% total solids) favored to hydrogen production using dark fermentation, yielding about 103.4 NmL H_2 g^{-1} VS and a simultaneous production of 8.7 g L^{-1} of caproate [37]. Overall, hydrogen production from waste seems viable, with the recent advancements in waste refining making it more cost-effective at €5.4 $(100\ km)^{-1}$ compared to fossil fuels at €15.6 $(100\ km)^{-1}$ [38]. Nonetheless, its infrastructure for everyday mobility is still in the early stage globally.

3.3 Production of bio-oil, biochar and bio-syngas

Conversion of food waste into liquid (bio-oil), non-condensable gaseous (bio-syngas), and solid residue (biochar) products involves a thermal decomposition process that occurs in the absence of oxygen. In the process, solid food waste is heated at the elevated temperature to break down into its constituent parts. The resulting biochar can be used as a soil amendment, while bio-oil can be further processed into liquid fuels, and bio-syngas can be used for power generation. Solid food waste is pretreated before pyrolysis process to remove its water content. Pyrolysis of food waste with the assistance of microwave irradiation have been examined. Kadlimatti et al. [39] demonstrated that the production of bio-oil from microwave-assisted pyrolysis of food waste with a yield of 30.24% under the optimized conditions, and the bio-oil has a heating value of 23.94 MJ kg^{-1}. Nonetheless, the bio-oil obtained is unsuitable for use as biofuel owing to its high contents of water and nitrogenated compounds [39]. Likewise, the bio-oil produced from the pyrolysis of waste cooking oil reported in another work also required further processing because of its high acidity index of 126.8 mg KOH g^{-1} oil and high viscosity of 8.95 cSt, though it has a high HHV at 8843 kg Kcal^{-1} [40]. Besides, the work showed the bio-oil yield can be optimized to reach 80wt% with the use of final pyrolysis temperature of 800 °C with a heating rate of 15 °C min^{-1} [40].

In addition to food waste, pyrolysis can be used to treat solid digestate produced from anaerobic digestion of food waste. A recent study by Zhao and co-workers [41] compared the quality of the products yielded from the pyrolysis of food waste and food waste solid digestate, respectively, and found that the pyrolytic gas derived from food waste has an increased LHV by 8% compared to that of acquired from food waste solid digestate. Nonetheless, the biochar obtained from food waste solid digestate possessed a specific surface area of about 10-fold greater than that of attained from food waste, suggesting its potential use as an adsorption material. Moreover, the pyrolytic oil from food waste solid digestate displayed the characteristics that are suitable for use as fuel. This work highlighted the benefits of combining pyrolysis and anaerobic digestion [41]. Furthermore, pyrolysis can be coupled with gasification for enhanced hydrogen fraction in the syngas produced. It was reported that the hydrogen content increased to 66.7% in syngas using *in-situ* gasification after pyrolysis [42]. In contrast to pyrolysis, advanced methods such as HTL process wet biomass at elevated pressures and temperatures to produce energy-dense biocrude oil and a nutrient-rich aqueous phase product. It was reported that HTL of simulated food waste yielded approximately

30wt% of bio-oil with HHV of 35 MJ kg^{-1} [43]. The optimal conditions for achieving high yield of biocrude oil was at temperatures close to the critical point (i.e., 374 °C) and pressures sufficient to keep water in a liquid or dense (> 0.4 g cm^{-3}) supercritical phase [43].

4. Indirect transformation of food waste to biofuels through microorganism cultivation

Indirect transformation involves the use of microorganisms that are cultivated on nutrient-rich food waste hydrolysate to produce bioenergy (**Figure 2**). Various microorganism species, including bacteria, fungi, yeast, and microalgae, have displayed wide adaptability to grow on food waste hydrolysate. They can accumulate lipids or carbohydrates within the cells which can be processed into biofuels. Alternatively, the whole and spent microbial biomass can be served as feedstock in conversion processes for turning it into energy products. Integrating microbial technology with food waste management for biofuel production presents a sustainable alternative to traditional energy systems (e.g., fossil fuels and direct food waste conversion to bioenergy). This approach enhances the economic feasibility of microbial-based biofuels, since relying on synthetic growth media is unsustainable for large-scale microalgae biorefineries due to the high costs associated with the chemicals.

4.1 Bacteria, fungi, and yeast grown on food waste

Oil-producing microorganisms or known as oleaginous microorganisms for those accumulate > 20% of lipids on a dry cell weight (DCW) basis, are the alternative lipid sources for biodiesel production. Bacteria (e.g., *Bacillus subtilis*, *Rhodococcus opacus*, *and Gordonia* sp.), fungi (e.g., *Aspergillus oryzae*, *Mortierella isabellina*, and *Humicola lanuginose*) and yeast (e.g., *Yarrowia lipolytica*, *Cryptococcus curvatus*, and *Lipomyces starkeyi*) species have been recognized for their high lipid contents. For instance, *Rhodosporidium toruloides* grown on catering food waste hydrolysate achieved a high biomass productivity of 32.9 g L^{-1}, with 36.4% lipid content [44]. The biodiesel produced from the lipids extracted met the satisfactory performance according to the European standard EN 14214 [44]. Similarly, food waste saccharified liquid can be used to support cultivation of *R. toruloides* without any additional nutrient supplementation, resulting in a biomass production of 12.09 g L^{-1} with 52.7% lipids [45]. The promising results evidently suggested that biodiesel production through culturing oleaginous microorganisms on food waste is feasible and holds industrial application prospects.

4.2 Microalgae grown on food waste

In addition, microalgae, key feedstocks for third- and fourth-generation biofuels, display wide adaptability to thrive on food waste hydrolysate. The macro- and micro-nutrients within food waste can be upcycled through nutrient assimilation by microalgae cells and transformed into useful compounds such as lipid, carbohydrate, and protein, which can be converted to value-added energy products (**Figure 3**). Microalgae are classified into prokaryotic (e.g., *Cyanophyta* and *Prochlorophyta*) and eukaryotic (e.g., *Glaucophyta, Rhodophyta, Heterokontophyta, Haptophyta, Cryptophyta, Dinophyta, Euglenophyta, Chlorarachniophyta*, and *Chlorophyta*) microorganisms. The high lipid content of microalgae, ranging from 20 − 70%, makes them potential feedstocks for the production of biodiesel [46]. For examples, *Chlorella sorokiniana* HS1, *Tetraselmis* sp., and *Chlorella protothecoides* have been reported to yield lipid contents of 37.5, 51.7, and 35.3%, respectively [47-49]. Triglycerides are used in the biodiesel production because of their higher fatty acid content (>50%) and the absence of impurities (e.g., phosphate, sulfur, and nitrogen) that interfere with the final product [50]. It was reported that *Schizochytrium mangrovei* can grow well on food waste hydrolysate in heterotrophic cultivation, achieving a growth rate that was twice than that of growth on conventional medium [51]. Under controlled nutrient-deficient conditions, *S. mangrovei* grown on food waste hydrolysate accumulated 32% lipids, 39% carbohydrates, and

13% proteins, with the majority of fatty acids present in the lipids are suitable for biodiesel production. In the study, the canteen food waste was hydrolyzed using fungal *Aspergillus awamori* and *Aspergillus oryzae* for 24 h to produce hydrolysate rich in glucose (31.9 g (100 g)$^{-1}$ dry food waste), free amino nitrogen (0.28 g (100 g)$^{-1}$ dry food waste), and phosphate (0.38 g (100 g)$^{-1}$ dry food waste) [51]. Besides, enzymatically hydrolyzed food waste was reported to support growth of *C. sorokiniana*, with the biomass produced containing 26.4% lipids and 37.8% proteins [52]. Another recent report also demonstrated that the food waste hydrolysate with an initial glucose concentration of 10 g L^{-1} was successfully used as culture medium in the mixotrophic cultivation of *Chlorella* sp. GY-H4 [53]. The resultant microalgal lipid had a high triglyceride content (28.8%), and the biodiesel produced exhibited improved quality, e.g., with an iodine value of 70 g I_2 (100 g)$^{-1}$, which was much lower than the maximum limit of 120 g I_2 (100 g)$^{-1}$ [53].

Alongside with lipid synthesis, microalgae accumulate carbohydrate inside their chloroplasts (for eukaryotes) and cytosols (for prokaryotes), which are mainly composed of monosaccharide and polysaccharide for structural and metabolic purposes [54]. Carbohydrate can be converted to bioenergy (e.g., bioethanol, biobutanol, and biogas) through microbial fermentation [55]. Like lipids, carbohydrate content in microalgal cell and its sugar profile can be enhanced by shifting its cell metabolism towards carbohydrate accumulation through upstream cultivation strategies. For example, carbohydrate content of *C. vulgaris* increased by 72% when cultured in modified BG-11 medium compared to standard medium, reaching 58% [56]. Ajala and Alexander [57] reported that high carbohydrate contents of 29, 38, and 33% were found in *C. vulgaris*, *Scenedesmus obliquus*, and *Oocystis minuta*, respectively. *Chlamydomonas* sp. also achieved 50.5 and 19.0% of carbohydrate and lipid, which can be used to produce bioethanol and biodiesel, respectively [58]. *S. mangrovei* and *C. pyrenoidosa* cultivated on food waste hydrolysate accumulated up to 38.9 and

31.0% carbohydrates, respectively, under nutrient-restricted culture conditions [51]. Additionally, it was suggested that the depleted food waste hydrolysate used for microalgae cultivation, which was still rich in sugars and organic acids (e.g., lactic acid) and not metabolized by *C. sorokiniana*, can be used as the feedstock for anaerobic digestion for producing biogas [52].

5. Biorefinery of microalgae for biofuel production

Given the significant potential of microalgae for biofuel production, advancing their conversion technologies is essential to improve process efficiency, enabling better utilization of microalgae as a sustainable energy source. **Figure 4** explicitly details different biorefinery routes for microalgal biomass to produce various biofuel products, and the related studies are summarized in **Table 2**.

5.1 Production of biodiesel

Microalgal lipid can be converted to biodiesel via ex-situ transesterification, which is a two-step approach involving cell pretreatment and lipid extraction prior to the transesterification process. Conventional lipid extraction strategies such as Bligh and Dyer, Folch, and Soxhlet methods are available and the advanced techniques using ionic liquid, deep eutectic solvent, and switchable solvent have also been explored [59]. Besides, direct transesterification (in-situ) allows lipid extraction and transesterification to occur in a single step within the same reaction vessel. Karimi et al. [60] reported that the *in-situ* transesterification achieved 99% conversion of bio-oil from *Nannochloropsis* to biodiesel, and the biodiesel yield was about 8% of DCW. The remarkable conversion efficiency obtained using in-situ transesterification method indicates its potential for streamlining biodiesel production process by reducing the number of processing steps involved. Likewise, Yasin et al. [61] demonstrated that direct transesterification achieved a higher fatty acid methyl ester (FAME) yield than two-step method. However dry biomass is preferred because of the presence of water in wet biomass led to losses of FAME composition in direct transesterification process. Therefore, more research works are needed to improve the application of direct transesterification method on wet biomass, to reduce the need for the energy-intensive drying.

5.2 Production of bioethanol and biobutanol

Carbohydrate-rich biomass appears as an alternative renewable feedstock for acetone–butanol–ethanol (ABE) fermentation to produce alcohol-based biofuels such as butanol and ethanol. The processes involve acidogenesis and solventogenesis [61]. During acidogenesis, microalgal biomass is fermented to produce organic acids, such as acetic acid and butyric acid, and the process is accompanied with a drop of pH levels [62]. These organic acids are then converted into biobutanol through solventogenesis, in which the solvent (e.g., acetone, butane and ethanol) and bacteria (e.g., *Clostridium acetobutylicum*) are added to ferment the acids produced [62]. Al-Shorgani et al. [63] reported that the ABE fermentation using *C. acetobutylicum* YM1 increased the yield of biobutanol from 13.82 to 21.71 g L^{-1}. Apart from that, Condor et al. [64] showed that the bioethanol of 0.18, 0.17 and 0.2 g g^{-1} biomass were obtained from *C. vulgaris* FSP-E with the use of *Saccharomyces cerevisiae* FAY-1, *S. cerevisiae* FAY-2, and *Zymomonas mobilis*, respectively. The findings highlight the importance of selecting suitable strains for maximizing bioethanol production, indicating that the choice of fermentation microorganism is critical for optimizing yield. Besides, advanced pretreatment methods can significantly enhance the accessibility of carbohydrates in microalgae biomass, achieving improved fermentation efficiency and overall yield. For instance, Yirgu et al. [65] reported that the bioethanol yield of 0.08 g g^{-1} biomass was achieved in a 24-h fermentation process after the microwave-assisted acid hydrolysis pretreatment.

5.3 Production of biogas

Anaerobic digestion can be used to produce biogas from dry and wet microalgal biomass, and even microalgal biomass residues after lipid and pigment extraction [66]. Microalgal biomass is converted into gaseous methane and carbon dioxide in the methanogenic process after the acetogenic stage. The multi-step approach maximizes the efficiency of biogas production from microalgal biomass. Vargas-Estrada et al. [66] identified the factors influencing the yield, including pH and pretreatment used (e.g., thermal, thermochemical, and enzymatic methods). The findings of Xiao et al. [67] ascertained the need of pretreatment to break down organic compounds and increase the availability of substrate for methanogenic bacteria. The biogas produced from microalgal biomass pretreated with solar-driven hydrothermal process displayed a relatively high exergy efficiency (40.85%) compared to that of obtained from the biomass without any pretreatment (26.2%) [67]. It was also found that the organic loading rate and temperature during anaerobic digestion affected the yield of biogas [68]. These findings highlight the need for a robust process design to maximize energy recovery from the anaerobic digestion of microalgal biomass.

5.4 Production of biohydrogen

The approaches for the production of biohydrogen from microalgae include bio-photolysis and fermentation [69]. Direct bio-photolysis involves the conversion of water molecules into hydrogen and oxygen with the use of sunlight and photosynthetic microorganisms, whereas indirect bio-photolysis utilizes synthetic catalysts or enzymes to increase process efficiency. By combining the natural abilities of microorganism and catalyst, indirect bio-photolysis is capable to optimize hydrogen production and overcomes the limitations of natural system. Bio-photolysis can be facilitated by harnessing the capabilities of microalgae and cyanobacteria since these organisms are capable of carrying out the reaction efficiently. A recent study showed that a multispecies algae-bacteria consortium formed by *Chlamydomonas reinhardtii* and *Microbacterium forte* sp. yielded sustainable production of up to 313 mL H_2 L^{-1} for 17 days [70].

On the other hand, fermentation can be grouped into photo- and dark-fermentation. Photo-fermentation uses light energy to convert organic matters into hydrogen using photosynthetic bacteria (e.g., purple non-sulfur bacteria, purple sulfur bacteria, and green sulfur bacteria). In contrast, dark fermentation relies on the use of anaerobic bacteria, particularly thermophile and mesophile microorganisms, to break down organic matters and produces hydrogen alongside with byproducts such as lactic, acetic, propionic, butyric, and ethanol. Sharma et al. [71] reviewed the approaches of hydrogen generation from organic waste and concluded that there are still technological challenges such as the pretreatment method, operational cost, and gaseous hydrogen storage. Besides, high carbohydrate-accumulating microalgal strains are sought after considering the inevitable loss of carbohydrate during pretreatment [72].

5.5 Production of bio-oil, biochar, and bio-syngas

Unlike some other biomass types, microalgal biomass does not require extensive pretreatment before pyrolysis. This is due to the unique composition of microalgae, which typically contains higher amounts of lipid, protein, and carbohydrate, but lower amounts of lignin compared to lignocellulosic biomass. Bio-oil, biochar, and bio-syngas can be produced from microalgal biomass via conventional and advanced pyrolysis. Conventional pyrolysis can be grouped into slow, intermediate, and fast, which are mainly characterized by the operating temperature range, which are 400 – 500, 400 – 650, and 850 – 1250 ºC, respectively [73]. The classification of pyrolysis methods underscores the significance of temperature in determining the yield and quality of bio-products. For instance, the yield of bio-oil obtained from *C. vulgaris* increased from 30.9 to 48.1% when the temperature was raised from 300 to 700°C [74].

Recently, advanced pyrolysis technologies such as catalytic pyrolysis (i.e., with the use of catalyst), co-pyrolysis (i.e., mixture of two or more biomass), hydro-pyrolysis (i.e., with the use of pressurized hydrogen and hydrogen-based technologies) and microwave-assisted pyrolysis have been investigated [75]. Ferreira and Soares Dias [76] reported that the different catalysts were added in the pyrolysis of *C. vulgaris*, such as Na_2CO_3 and $MgCO_3$, yielding bio-oils of 30.6 and 42.8%, respectively. The addition of catalyst in the pyrolysis process significantly affects the process efficiency. Further research is needed to optimize the selection of appropriate catalyst for maximum bio-oil yield.

6. Research needs and way forward

With the growing awareness of sustainability, there has been a significant increase in the number of developed countries recognizing the importance of waste-to-energy conversion technologies. Cost is one of the most critical considerations for implementing food waste-to-energy systems. The large capital investment in infrastructure and technology, along with the ongoing costs for operation and maintenance, must be balanced against the environmental and economic benefits of food waste-to-energy conversion system to ensure long-term feasibility and promote large-scale adoption. The realization of food waste-to-energy plants on both national and international scales needs a careful techno-economic assessment, along with the environmental evaluation. Huiru et al. [77] analyzed the economic viability of an anerobic digestion plant fed with food waste collected from 29 canteens in a China university, and a simple payback period of 7.8 years was obtained. The results showed that the project's economic feasibility was highly dependent on the electricity price and initial plant investment, with a 10% change of these two parameters potentially extending the equity payback to a maximum of 12.4 years [77]. Another recent techno-economic analysis by Chen et al. [78] supported the use of anaerobic digestion to treat city-scale food waste for biogas production, with most of the studied pathways showed positive net present values in the baseline scenario. In addition, the proposed approaches were found to be advantageous in reducing carbon footprints over the landfills. Other direct conversion method for biohydrogen and bio-oil production also showed potential for economic gain [79, 80] and should be further explored. It is noteworthy to highlight that the concurrent production of additional valuable products alongside biofuels from food waste can significantly improve economic viability of the process by diversifying revenue streams and reducing reliance on a single product. This has been validated in the techno-economic analysis of Rajendran and Han [81] that the plant has a short project payback period of 7.31 years for the integrated production of polyhydroxyalkanoates and biofuels such as biohydrogen, bioethanol, and 2,3-butanediol from food waste.

On the other hand, microalgae-based bioenergy from food waste has been initiated since 2000 and continue to develop in recent years (**Figure 5**). The approach seems promising but significant challenges to commercialization remain. Although microalgae cultivation on food waste greatly reduces the chemical expenses associated with synthetic media, the overall production costs remain high due to the expenses of waste pretreatment processes, the setup and operation of photobioreactors, and the biorefinery process. Open pond systems offer the benefits of reduced construction and maintenance costs particularly for large-scale cultivation, but they face challenges such as contamination and difficulty to maintain optimal productivity due to uncontrollable environmental conditions. It was reported that the cultivation method affects the production cost substantially, with the FAME from *Spirulina* produced from an open pond system costs around \$4 kg^{-1}, while those cultivated using a solar-lit photobioreactor costs approximately \$25 kg^{-1} [82]. Similar to direct conversion methods, the generation of co-products is particularly beneficial in microalgae-based bioenergy production, creating extra revenue that can be used to improve the final selling price of the fuel, as highlighted by Dutta et al. [83] in their techno-economic analysis. The calculated minimum fuel selling price was improved from \$10.55 to \$4.35 gasoline gallon equivalent $(GGE)^{-1}$ by incorporating additional processes, including fermentation and anaerobic digestion, to generate co-products such as bioethanol, biogas, and digestate along with biodiesel, maximizing the valorization of microalgal biomass.

The integrated zero-waste microalgal biorefinery concept aims to maximize the utilization of all components of microalgal biomass, thereby minimizing waste and creating a circular, sustainable production process. The economic and environmental benefits of the integrated microalgal biorefinery are substantial. By fully utilizing all components of the biomass, the process becomes more economically viable. The extraction of microalgal lipids for biodiesel leaves behind a protein-rich residue, which can be used to produce animal feed or as an ingredient in aquaculture feed, reducing reliance on conventional feedstocks that contribute to deforestation and greenhouse gas emissions [84]. Bioactive compounds (e.g., carotenoids, chlorophylls, and phycobiliproteins) can also be extracted for use in food and pharmaceutical industries, since these products display numerous health benefits. The integrated biorefinery also focuses on the production of bioethanol or biobutanol from carbohydrates from microalgae through fermentation processes. Lastly, the biomass residue can be used as the feedstock for anaerobic digestion to generate biogas, ensuring that no biomass goes to waste. Additionally, in order to create a circular bioeconomy concept in microalgae-based biofuels, by-products and waste generated should be continuously repurposed to maximize resource efficiency. For instance, carbon emissions from industrial processes can be fed directly into microalgal cultivation units, providing CO_2 for photosynthesis. This approach contributes to reducing carbon emissions, supporting the transition to a low-carbon economy.

Future works should prioritize reducing microalgae production costs to address current challenges and accelerate the progress of microalgae-based bioenergy. Advancements in food waste pretreatment method and robust cultivation strategy to address the inconsistent nutrient contents of food waste are essential to improve the efficiency and reliability of the cultivation of microalgae on food waste. Additionally, developing an integrated biorefinery approach allows for the simultaneous production of multiple products, which can improve overall efficiency and profitability. The lipid extraction techniques for microalgae require improvement, since the use of hexane is extremely problematic due to its large contribution to GHG emissions [83]. Continued improvement in conversion technology is essential to enhance the effectiveness of transforming microalgal biomass into bioenergy products. Integrating data-driven technologies such as machine learning and artificial intelligence into food waste management for process optimization and scale-up could offer promising opportunities.

It must be emphasized that energy is inherently a political issue, with significant social consequences. Therefore, the shift to sustainable energy sources, such as microalgae-based biofuels, has the potential to reshape not only environmental outcomes but also socio-political dynamics by reducing dependence on fossil fuels and promoting energy security. Government policies play a crucial role in supporting the scaling up of microalgae cultivation using food waste for biofuel production. Subsidies for initial investments help mitigate the high costs associated with infrastructure and technology, making projects more financially viable. Government regulations that mandate or incentivize the use of biofuels in transportation and energy sectors create market demand and ensure a stable market for biofuel producer. For example, the attempts made to achieve affordable and clean energy (SGD 7) also aid in reducing GHGs and combat climate change (SDG 13), while also promoting sustainable economic development (SDG 8) and protecting ecosystems and biodiversity (SDGs 14 and 15). Furthermore, the establishment of partnerships fosters knowledge sharing, technology transfer, and capacity building, ultimately accelerating progress towards all the SDGs [85]. Baldassarre et. al [86] highlighted that the research institutions need to work together with industry partners to validate the proposed solutions on an industrial-scale. With these efforts, research institutions provide evidence-based solutions to realize the integrated zero-waste microalgal biorefinery concept [87]. Continued development efforts are crucial to overcoming existing challenges and maximizing the potential benefits of sustainable biofuel production from food waste on a global scale.

7. Conclusions

Both direct and indirect conversion approaches contribute to food waste management and biofuel production. Direct conversion methods efficiently convert food waste into biofuels but may generate byproduct like sludge that requires further treatment or disposal. On the other hand, the microalgae-based bioenergy platform offers dual benefits, including the recovery of food waste nutrients and the generation of biomass that can be transformed into multiple bioenergy products, effectively closing the loop in the food waste-to-energy cycle. However, this approach requires a complex infrastructure that encompasses both upstream to downstream processes, resulting in higher capital investments. An optimal technology for producing biofuels from food waste should leverage both direct and indirect conversion methods by integrating them to harness their complementary strengths. Continued research, technological advancements, and supportive policies are crucial for realizing the full potential of these bioenergy production methods, ultimately contributing to a more sustainable and resilient energy future.

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Table Titles

Table 1. Recent studies on the direct conversion of food waste into biofuels.

Table 2. Recent studies on the conversion methods of microalgal biomass into different forms of bioenergy. These include biodiesel (transesterification), alcohol-based biofuel (fermentation), biomethane (anaerobic digestion), biohydrogen (fermentation), bio-oil, biochar and bio-syngas (pyrolysis).

Figure Captions

Figure 1. Direct conversion approaches of food waste to biofuels.

Figure 2. Indirect transformation methods through the cultivation of microorganism grown on food waste for the generation of biofuels.

Figure 3. Photosynthesis process of microalgae cell assimilating light, water, and organic substrates from food waste for the synthesis of intracellular products. Adapted and modified from [88].

Figure 4. Biorefinery of microalgae for biofuel production using different processes. The techniques include esterification/transesterification, fermentation, anaerobic digestion, fermentation, and pyrolysis.

Figure 5. Historical events and prediction for microalgae cultivation since its initiation in 2000 − 2050 for the production of biofuel product and the correlation with SDGs.

Table 1. Recent studies on the direct conversion of food waste into biofuels.

Technology	**Food waste (co-substrate)**	**Food waste pretreatment**	**Inoculum**	**Process conditions**	**Biofuel**	**Production level**	**Reference**
Anaerobic digestion	Restaurant food waste	Drying, milling, subcritical water hydrolysis	Seed sludge from a pulp wastewater treatment plant	Batch, 37 °C, 120 rpm	Biogas	807 mL g^{-1} VS (329.5 mL CH_4 g^{-1} VS)	[23]
Anaerobic digestion	Food waste prepared by mixing 20% meat, 15% tofu, 30% vegetables, 20% rice, 15% steamed bread	Blending	Seed sludge from an anaerobic digester	Continuous two-stage anaerobic digestion, 37 °C, addition of biochar	Biogas	Specific energy yields up to 1.23 kJ g^{-1} VS d^{-1} g^{-1} biochar	[27]
Anaerobic digestion	Cafeteria food waste	Blending, heat shock at 90 °C for 20 min, cooling at 4 °C for 1 h	Seed sludge from a brewery wastewater treatment plant	Batch, 38 °C, pH 5.5, 270 rpm, absence of light, addition of PAC catalyst	Biogas	277 mL CH_4 g^{-1} COD (1446 mL in total)	[28]
Anaerobic digestion	Canteen food waste	Blending, alkaline treatment using 1 % CaO	Inoculum from a municipal wastewater treatment plant	Fed-batch, 37 °C, 30 d solid retention time	Biogas	829 mL g^{-1} VS (65.5% CH_4)	[22]
Anaerobic digestion	Catering food waste (*Parthenium hysterophorus*)	Grinding (drying, microwave irradiation, steam sterilization	Cattle manure	Batch, 30 °C	Biogas	559 ml L^{-1} d^{-1} (5532 ml L^{-1} in total)	[26]

		for co-substrate)					
Anaerobic fermentation	Food waste from food waste treatment plant	Sorting, shredding	Inoculum from a lake in a China park	37 °C	Hydrogen	120.78 mL g^{-1} VS	[36]
Anaerobic fermentation	Food waste prepared by mixing 78 % potato, 14 % chicken, 4 % lard, 4 % cabbage	Grinding, storage at -20 °C	Digestate from an anaerobic digester	35 °C	Hydrogen	9.7 NL $(L\ d)^{-1}$	[89]
Anaerobic fermentation	Food waste prepared by mixing 78% potato flakes, 14% chicken breast, 4% cabbage, 4% pork lard	Storage at -20 °C	Digestate from an anaerobic digester	37 °C, 200 rpm	Hydrogen	103.4 NmL g^{-1} VS	[37]
Anaerobic fermentation	Potato peel waste from a local restaurant	Drying, grinding, freeze storage	*T. onnurineus* NA1	80 °C, 60 min, pH 6.1 – 6.2	Hydrogen	1.29 mmol L^{-1} h^{-1}	[34]
Anaerobic fermentation	Kitchen food waste (palm oil mill effluent (POME))	Blending, sterilization	Immobilized *Bacillus anthracis* PUNAJAN1	35 °C, pH 5.0	Hydrogen	67 mL h^{-1}	[90]
Pyrolysis	Food waste prepared by mixing 30% vegetables, 70% cereals (trash plastic bag)	Not stated	–[a]	Microwave at 800W, 550 °C, 7 s	Bio-oil, biochar, bio-syngas	40 – 52% bio-oil, 30 – 46% biochar, 10 – 30% bio-syngas	[91]
Pyrolysis	Food waste digestate (corn husk)	Drying, grinding	–[a]	600 °C, ratio of food waste digestate to corn husk at 4:1	Bio-oil, biochar, bio-syngas	15.25% bio-oil, 52.75% biochar, 30.5 % bio-syngas	[92]

				(w/w), addition of CaO catalyst			
Pyrolysis	Household food waste (13% trash plastic bag)	Drying, grinding	–[a]	Microwave at 1000 W, 550 °C, 7 s, addition of 6 wt% of granular activated carbon	Bio-oil, biochar, bio-syngas	42% bio-oil, 42% biochar, 16% bio-syngas	[93]
Pyrolysis	Food waste from hostels and hotels	Drying, pulverization, sieving	–[a]	Microwave at 450W, 400 °C, 30 min, 50 mL min^{-1} N_2 purging	Bio-oil	30.2% bio-oil	[39]
Pyrolysis	Waste cooking oil	None	–[a]	800 °C with a heating rate of 15 °C min^{-1}	Bio-oil, biochar	80% bio-oil, 20% biochar	[40]
Transesterification	Lipid from bakery waste	Fungal hydrolysis, heating for water removal	–[a]	60 °C, 2h, addition of CH_3OH and KOH	Biodiesel	100% yield	[14]
Transesterification	Used mixture of olive oil and sunflower oil (1:1) from catering service	Filtration, heating for water removal	–[a]	60 °C, 30 min., 0.67 Hz oscillatory frequency, addition of CH_3OH and NaOH	Biodiesel	72% yield	[94]

–[a] indicates not applicable.

Table 2. Recent studies on the conversion methods of microalgal biomass into different forms of bioenergy. These include biodiesel (transesterification), alcohol-based biofuel (fermentation), biomethane (anaerobic digestion), biohydrogen (fermentation), bio-oil, biochar and bio-syngas (pyrolysis).

Microalgae species	**Conversion method**	**Process conditions**	**Biofuel**	**Conversion yield**	**Reference**
Nannochloropsis	*In-situ* transesterification using H_2SO_4 (0.13wt% in methanol)	69 °C, 30 min, ratio of methanol to biomass of 15:1 (v/w)	Biodiesel	99%	[60]
C. vulgaris	*In-situ* transesterification using H_2SO_4	85 °C, 2 h, 860 rpm, 12 mL methanol, 0.02 g dry biomass	Biodiesel	243.48 mg FAME g^{-1} biomass	[61]
C. pyrenoidosa	*In-situ* transesterification using H_2SO_4 (5% in methanol)	90 °C, 60 min, ratio of hexane to wet biomass of 2:1 (v/w)	Biodiesel	46.5%	[95]
Scenedesmus	Transesterification using CaO nano-catalyst prepared from goat bone after microwave-assisted lipid extraction	60 °C, 3 h, ratio of methanol to microalgal oil of 11:1	Biodiesel	92%	[96]
C. pyrenoidosa	*In-situ* transesterification using H_2SO_4	40 − 80 °C, 150 min, methyl ether as solvent	Biodiesel	71 – 92%	[97]
C. vulgaris sp. ESP-31	Fermentation using *S. cerevisiae* FAY-1 after acid hydrolysis pretreatment	Batch, 30 °C, 8 h, 200 rpm, 10 g L^{-1} biomass	Bioethanol	84.2%	[98]
Chlamydomonas reinhardtii CCAP 11/32C	Fermentation using *C. acetobutylicum* DSM 792 after autoclave pretreatment	Batch, 37 °C, 20 h, pH 6.5, 10 g L^{-1} biomass	Biobutanol	0.10 g butanol g^{-1} DCW	[99]
Synechococcus elongates PCC7942 (pigment extracted residue)	Fermentation using *C. acetobutylicum*	Batch, 37 °C, 30 − 40 h, 180 g L^{-1} biomass	Biobutanol	0.09 g butanol g^{-1} biomass	[100]

Chlorococcum humicola	Fermentation using *C. acetobutylicum* 11274 after acid hydrolysis pretreatment	Batch, 30 °C, 72 h, pH 6.5	Biobutanol	- [a]	[101]
Chlorella sp.	Two-stage anaerobic fermentation	1st stage: 37 °C, pH 6 2nd stage: pH 7	Biomethane, biohydrogen	434 mLCH$_4$ g^{-1} VS, 5.15 mL H$_2$ g^{-1} VS	[102]
Chlorella sp. TISTR 8411	Two-stage anaerobic fermentation	1st stage: 55 °C, 7 d 2nd stage: 55 °C, 30 d	Biomethane, biohydrogen	164 – 177 mL g^{-1} VS, 23 – 35 mL H$_2$ g^{-1} VS	[103]
C. sorokiniana 1412 (lipid-extracted biomass)	Anaerobic digestion	30 °C, 42 d	Biomethane	220 – 280 mL CH$_4$ g^{-1} VS	[104]
C. vulgaris and mixed culture of native algae species dominating by *Scenedesmus* sp.	Anaerobic digestion	35 °C, 46 d	Biomethane	154 – 252 mL CH$_4$ g^{-1} VS	[105]
Chlorella sp. *and Scenedesmus* sp. (food waste)	Anaerobic digestion	35 °C, 40 d	Biomethane	640 mL CH$_4$ g^{-1} VS	[106]
C. pyrenoidosa, S. obliquus, C. sorokiniana	Dark fermentation	4 d	Biohydrogen	45.5 mL H$_2$ g^{-1} VS (*C. pyrenoidosa*) 38.4 mL H$_2$ g^{-1} VS (*S. obliquus*) 34.8 mL H$_2$ g^{-1} VS (*C. sorokiniana*)	[107]
Mixed microalgal biomass *Gelidium amansii*	Co-digestion	35 °C, 6 d, pH 7.0	Biohydrogen	45 mL H$_2$ g^{-1} DCW	[108]
Mixed microalgae consortia	Fermentation	37 °C, 835 h	Biohydrogen	38 mL H$_2$ g^{-1} VS	[109]
C. pyrenoidosa	*In-situ* pyrolysis	500 °C	Bio-oil, biochar, pyrolysis gas	35.33wt% bio-oil, 51.23wt% biochar,	[110]

				13.44wt% pyrolysis gas	
Pavlova sp. (catalyst Ni/TiO_2)	*In-situ* pyrolysis	500 °C, 60 min, 545 mL min^{-1} N_2 purging	Bio-oil	22.55wt%	[111]

[a]– indicates not available

Figure 1

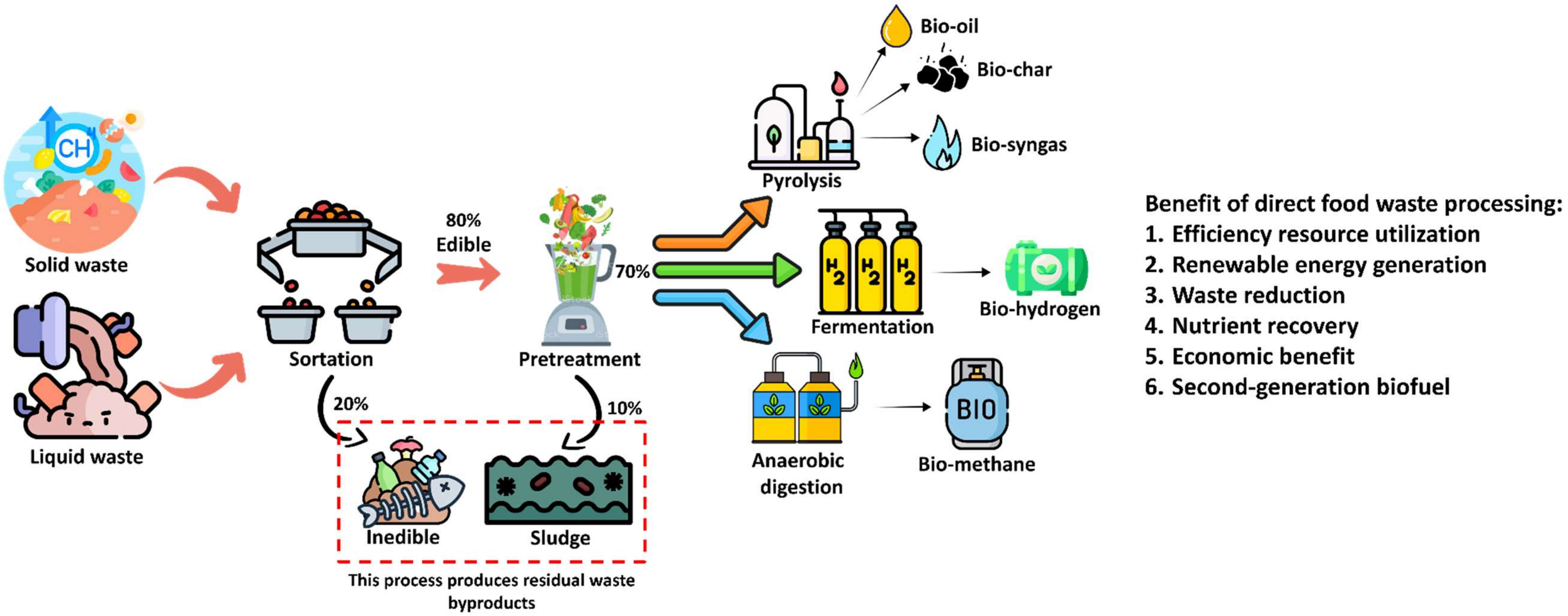

Solid waste
Liquid waste
CH
Sortation
80%
Edible
Pretreatment
70%
20%
10%
Inedible
Sludge
This process produces residual waste byproducts
Pyrolysis
Bio-oil
Bio-char
Bio-syngas
Fermentation
H2
Bio-hydrogen
Anaerobic digestion
BIO
Bio-methane
Benefit of direct food waste processing:
1. Efficiency resource utilization
2. Renewable energy generation
3. Waste reduction
4. Nutrient recovery
5. Economic benefit
6. Second-generation biofuel

Figure 2

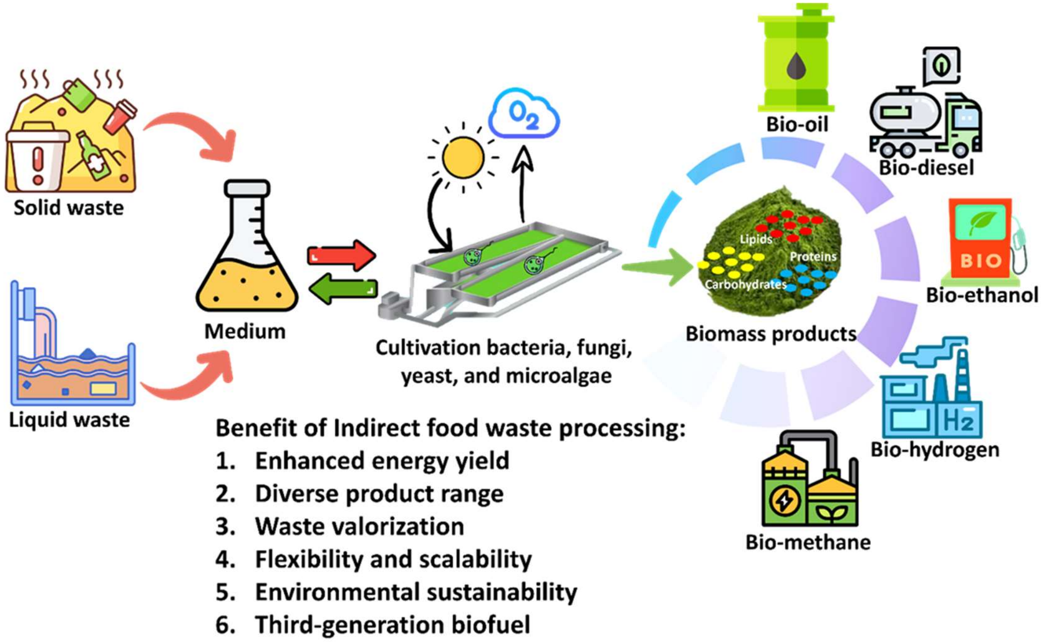

Solid waste
Liquid waste
Medium
O_2
Cultivation bacteria, fungi, yeast, and microalgae
Lipids
Proteins
Carbohydrates
Biomass products
Bio-oil
Bio-diesel
BIO
Bio-ethanol
H_2
Bio-hydrogen
Bio-methane
Benefit of Indirect food waste processing:
1. Enhanced energy yield
2. Diverse product range
3. Waste valorization
4. Flexibility and scalability
5. Environmental sustainability
6. Third-generation biofuel

Figure 3

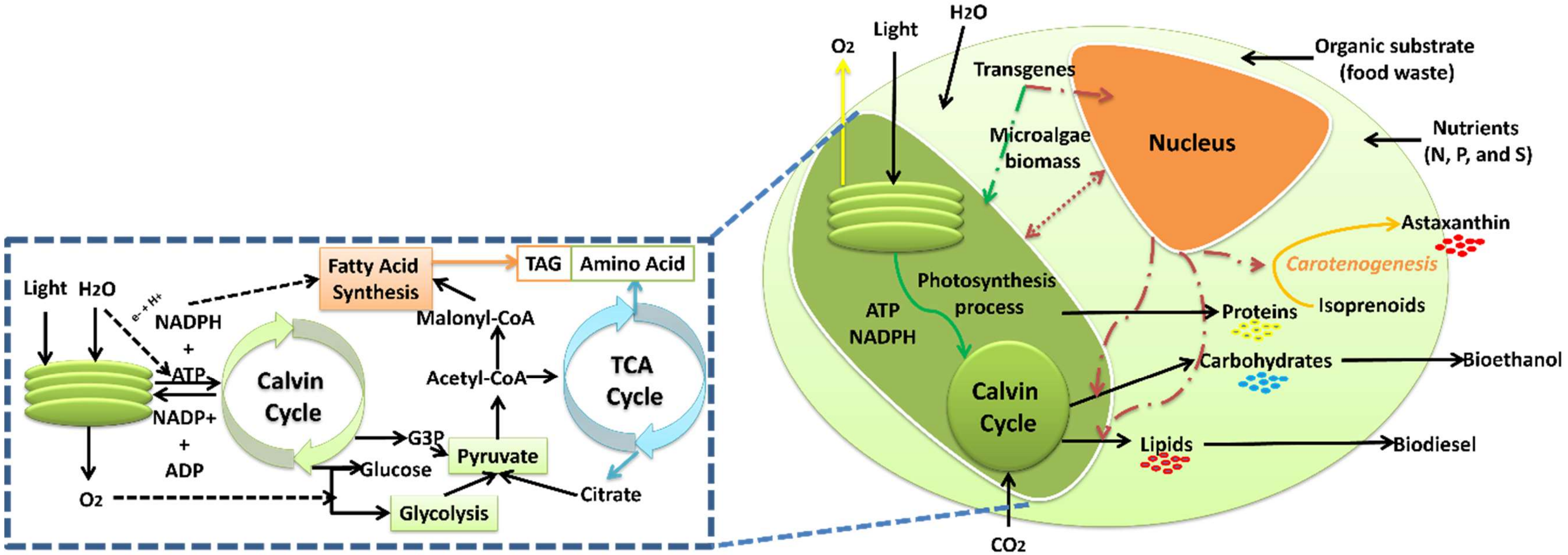

Light
H2O
e⁻ + H+
NADPH
+
ATP
NADP+
+
ADP
O2
Calvin Cycle
Fatty Acid Synthesis
TAG
Amino Acid
Malonyl-CoA
Acetyl-CoA
TCA Cycle
G3P
Glucose
Pyruvate
Citrate
Glycolysis
O2
Light
H2O
Transgenes
Microalgae biomass
Nucleus
Organic substrate (food waste)
Nutrients (N, P, and S)
Astaxanthin
Carotenogenesis
Isoprenoids
Photosynthesis process
ATP NADPH
Proteins
Carbohydrates
Bioethanol
Calvin Cycle
Lipids
Biodiesel
CO2

Figure 4

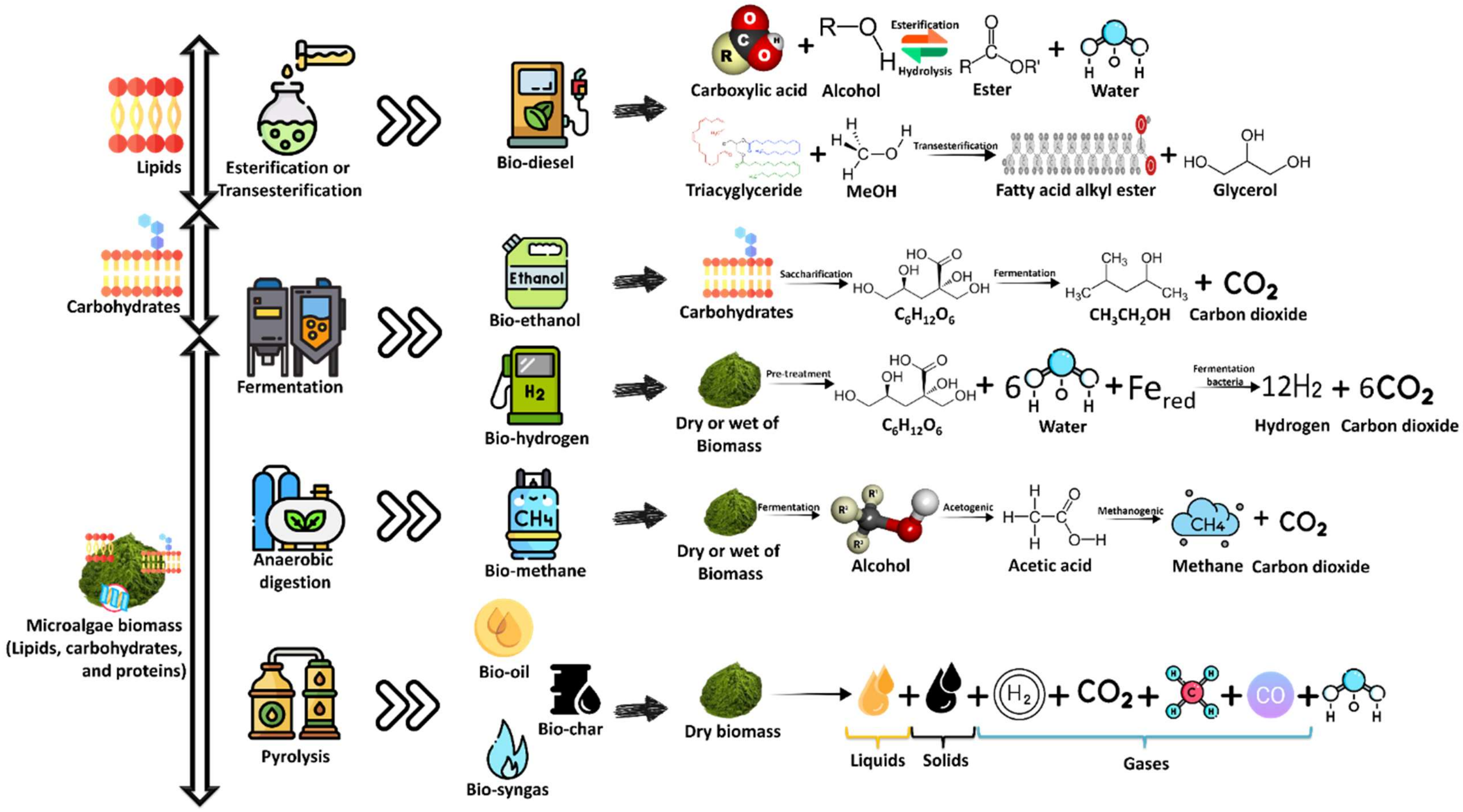
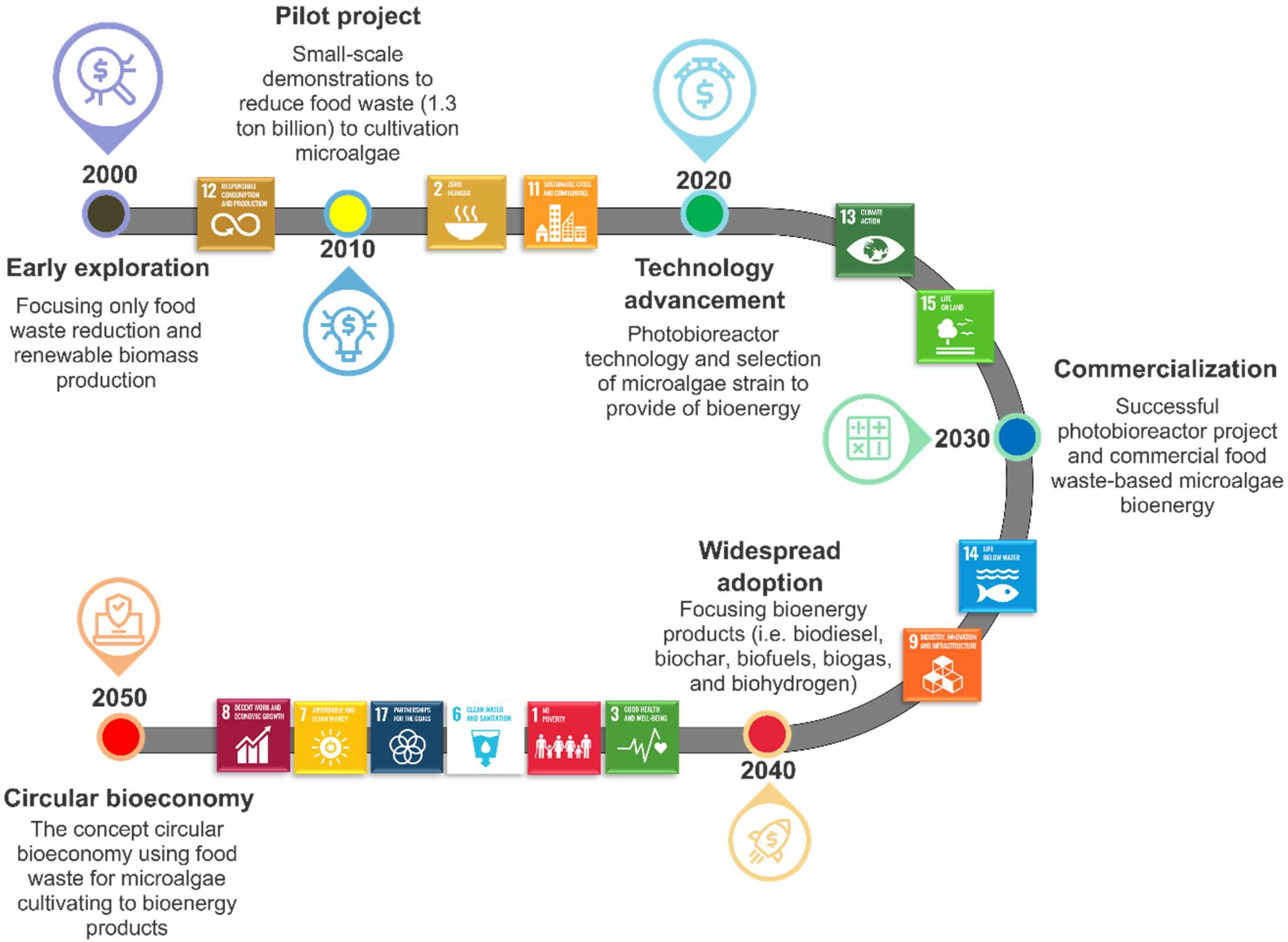

Lipids
Esterification or Transesterification
Bio-diesel
Carboxylic acid
Alcohol
Esterification
Hydrolysis
Ester
Water
Triacyglyceride
MeOH
Transesterification
Fatty acid alkyl ester
Glycerol
Carbohydrates
Fermentation
Ethanol
Bio-ethanol
Saccharification
$C_6H_{12}O_6$
CH_3CH_2OH
$+ CO_2$
Carbon dioxide
H_2
Bio-hydrogen
Dry or wet of Biomass
Pre-treatment
$+ 6$
Water
$+ Fe_{red}$
Fermentation bacteria
$12H_2 + 6CO_2$
Hydrogen
Carbon dioxide
Anaerobic digestion
CH_4
Bio-methane
Dry or wet of Biomass
Fermentation
Alcohol
Acetogenic
Acetic acid
Methanogenic
Methane
Carbon dioxide
Microalgae biomass (Lipids, carbohydrates, and proteins)
Pyrolysis
Bio-oil
Bio-char
Bio-syngas
Dry biomass
H_2
CO_2
CO
Liquids
Solids
Gases

Figure 5


2000
Early exploration
Focusing only food waste reduction and renewable biomass production
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
Pilot project
Small-scale demonstrations to reduce food waste (1.3 ton billion) to cultivation microalgae
2010
2 ZERO HUNGER
11 SUSTAINABLE CITIES AND COMMUNITIES
2020
Technology advancement
Photobioreactor technology and selection of microalgae strain to provide of bioenergy
13 CLIMATE ACTION
15 LIFE ON LAND
2030
Commercialization
Successful photobioreactor project and commercial food waste-based microalgae bioenergy
14 LIFE BELOW WATER
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
Widespread adoption
Focusing bioenergy products (i.e. biodiesel, biochar, biofuels, biogas, and biohydrogen)
2040
3 GOOD HEALTH AND WELL-BEING
1 NO POVERTY
6 CLEAN WATER AND SANITATION
17 PARTNERSHIPS FOR THE GOALS
7 AFFORDABLE AND CLEAN ENERGY
8 DECENT WORK AND ECONOMIC GROWTH
2050
Circular bioeconomy
The concept circular bioeconomy using food waste for microalgae cultivating to bioenergy products