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Value-added Chemicals from Food Supply Chain Wastes: State-of-the-art Review and Future Prospects

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Abstract

Food wastes are generated massively across global food supply chains. Conventional treatments of food waste (e.g., landfilling and incineration) cause environmental, economic, and social problems. There is a more sustainable and profitable management option by valorization of food waste into value-added chemicals. Consumer chemicals, including acids, sugars, and their derivatized forms, can be synthesized from food waste. Refined specialty chemicals from food waste ranging from solvents to antioxidant materials can be important for nutraceutical and biomaterial applications. Meanwhile, commodity chemicals derived from food waste such as biofuel, biogas, and biochar help meet the global demand for large-scale reutilization of resources and energy. Niche chemicals (e.g., chitosan, glucose, and free amino nitrogen) converted from food waste also show great prospect in nutrient recycling and use for industrial applications. This paper reviews and discusses the latest technological advances in different physical, chemical, and biological treatments of food waste, such that the productivity of value-added chemicals and cost-effectiveness of these valorization methods can be improved for future scaled-up operations. This paper covers holistic comparison and in-depth discussion regarding the feasibility and sustainability of food waste derived chemicals, together with the market outlook of recycling and valorization of food wastes from state-of-the-art perspectives.

Keywords: biomass valorization; waste management/recycling; sustainable biorefinery; engineered biochar; platform chemicals; green solvents.

Graphical Abstract

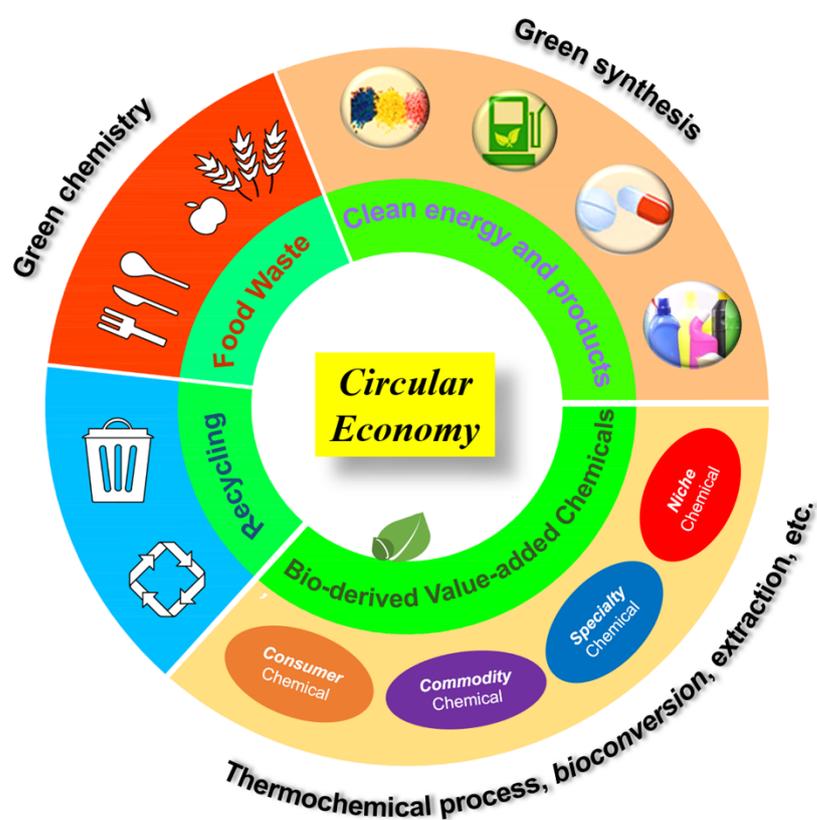


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1. Introduction

As there is a global shortage of energy and resources, which has aroused increasing public attention, research efforts are being made to develop innovative and practical technologies to recycle useful materials from waste streams. Food loss occurs from initial agricultural production to various later steps and procedures across the food supply chain (e.g., harvesting, transport, storage, processing, packing, distribution, marketing, and household consumption). Food waste is generated in the process of these retail and final consumption parts of the food supply chain, according to the Food and Agriculture Organization (FAO) of the United Nations [1, 2].

Food waste generation and disposal is an emerging and critical issue around the world. The per capita annual food loss in North America and Europe amounts to 280-300 kg, while that in sub-Saharan Africa and South/Southeast Asia is 120-170 kg [2]. In 2010, United States had 195 million tons the available food supply, of which 60 million tons were lost at the retail and consumer levels with an estimated total value of US\$161.6 billion [3]. As for Europe, a recent study revealed that an annual amount of food waste was approximately 88 million tons in the EU, with an estimated associated cost at 143 billion euros [4]. The costs are expected to rise to about 126 million tons by 2020 unless action is taken. With the increasing global food supply as indicated in the latest biannual report by FAO [5], food waste generation is expected to remain significant, and should be addressed from both technological and managerial perspectives.

Traditional options for food waste treatments such as landfilling, composting, and incineration cannot meet the demand in reducing the adverse impact to the environment while providing sufficient economic merits for resource and energy recovery. In fact, the applicability of these approaches varies with different locations. For example, landfill disposal is not suitable for populated cities while composting is not cost-effective in urbanized areas with limited agricultural activities. As for environmental impacts, disposal of every ton of food waste would emit > 4.2 tons of CO_2 to the atmosphere, not to mention secondary emissions to soil and water [6]. While each ton of food waste brought about US\$60-200 in economic value for electricity generation or cattle feed, US\$1000 could be obtained if food wastes were used for bulk chemical production (e.g., hydroxymethylfurfural and furfural [7]). In a life cycle assessment study, innovative alternatives such as bioconversion and thermochemical conversion were shown to give the best environmental performances, and could cause less energy consumption, secondary pollution, and recovery of more resources, compared with conventional methods such as landfilling and incineration [8-10]. Such technological innovations could diversify options for food waste treatments. Decision makers could design configuration of a recycling system with a mix of technologies, depending on the local environment and constraints (e.g., space, food culture, industrial activities).

Therefore, recent attention on food waste valorization has drawn great interest from the research community. In the process, food wastes undergo various thermochemical or biological treatments to produce abundant valorized products.

This can not only reduce waste disposal but regenerate resources from waste streams. However, existing reviews mainly focus on valorization of certain types of food waste, such as animal, fruit, vegetable, and cereals wastes [6, 11-14]. Other reviews emphasize specific products such as bio-fertilizers, hydroxymethylfurfural, and levulinic/succinic/lactic acids [15-18]; or examine particular approaches of food waste processing such as anaerobic digestion, thermal conversion, and fermentation [19-22]. Little information is available for comparing potential alternatives of food waste valorization. In view of this, an encyclopedic review is needed to cover all the possible synthesized chemicals from the perspective of industrial and commercial applications.

A wide range of value-added chemicals synthesized from food waste can be further categorized for clearer illustration [230]. Specialty chemicals are a group of materials used for achieving particular effects on products to enhance their specific properties or functions, such as solvents and antioxidant chemicals [68, 69]. Consumer chemicals refer to household products directly interacting with customers as the end-user, such as health supplements and detergents [231]. Commodity chemicals refer to chemicals of high global demand that are usually produced at large quantity, including biofuel, biogas and biochar [232]. Niche chemicals (e.g., chitosan, glucose, and free amino nitrogen) are chemical products targeting a particular section of profitable industry or market [233].

In regard to the shortage of global resources, this paper reviews the research advances and scientific knowledge in food waste treatments, with a focus on

integrated valorization technologies that convert food wastes into a diverse range of value-added chemicals. These chemicals are categorized into specialty chemicals, consumer chemicals, commodity chemicals, and niche chemicals, of which the formation mechanisms and conditions will be critically discussed. This review will provide a holistic comparison of the feasibility and sustainability of different approaches to food waste valorization. These practices are possible means to realize efficient closed-loop resource utilization and circular bio-economy.

2. Current status and need for innovative treatment processes

Nearly one-third of the edible food, i.e., 1.3 billion tons, is lost or wasted globally each year. It is suggested that one-fourth of the global food waste could feed 870 million hungry people [23]. For instance, Europe generates food waste of approximately 88 million tons [4] that could potentially feed 200 million people [23], while in the United States, 40 million tons of the municipal solid waste (262 million tons) was food waste in 2015 [24].

Food wastes result from various causes. For developing areas, food loss may take place when farmers harvest premature crops for economic need; inadequate processing facilities and market systems result in inefficient storage and sales conditions; and even some food is wasted due to safety issues and contamination [2]. In contrast, in developed countries, food tends to be lost when production exceeds demand. At the processing level, there are cases such as overproduction, defects in packaging, and tight food cosmetic standards. At the retail level, there are high “appearance quality

standards” for fresh products in supermarkets or retail stores. These standards apply to a large quantity and wide range of products on display or in supply, which make unsalable food products into a countless amount of food waste. At the household level, food waste is generated by excessive retail promotions, inadequate shopping and meal planning, and misunderstanding between the meaning of “best before” and “use by” date labels.

Food waste disposal at landfills remains one of the most popular options across the world. For example, in the United States, the majority of food waste (30 million out of 40 million tons) were landfilled, with only 2.1 and 7.4 million tons being treated by composting and combustion, respectively [24]. One of the major reasons for such a low recycling rate is the relatively low disposal costs compared to the costs of recycling/conversion. With growing public concerns about the current challenges of efficient food supply chains, the European Parliament and Council in 2018 agreed to launch a legislative procedure entitled the Circular Economy Package [23]. Such actions imply urgency for us to reflect on food waste management strategies and discuss behavioral, social, and technological solutions for improvement.

In regard to technological solutions, the valorization of food wastes for the synthesis of building block chemicals is emerging as a high-potential option. These molecules have an array of functional groups that can be subsequently used for the synthesis of various value-added bio-based chemicals or materials, including specialty chemicals, commodity chemicals, consumer chemicals, and niche chemicals. It has been demonstrated that sugars (e.g., glucose), organic acids (e.g., lactic acid), pectin,

polysaccharide, polyphenols, and fatty acids, can be synthesized from specific food wastes [16, 17, 25, 26]. Biodiesel and biogas which are major products produced on a commercial scale from food waste, are being used for transportation or industrial processes. For example, companies such as Veolia (France), Proper Oils (UK), Olleco (UK), Green Oil Recycling Limited (HK), and Champway Technology Limited (HK) provide commercial service of recycling waste cooking oil into biodiesel. Secondary chemicals are also generated from food wastes. For example, glycerol (~10% (w/w)) is a major by-product in biodiesel production that is usually combusted in a kiln. It provides great opportunities in the synthesis of secondary chemicals such as 1,3-propanediol, acrolein, citric acid, lipids, and hydrogen [27, 28]. Recently, the European Union has reached a provisional agreement on the renewable energy policy, with one of the aims to mandate the development of waste-derived biofuels [5]. Biochar, as the by-product of thermochemical treatments of biomass waste, has potentially important environmental and agricultural applications, including soil amendment, contaminant removal, solid catalyst synthesis, etc. [29, 30].

To exploit value-added products and biofuel precursors from food waste, it is imperative to advance conversion and extraction technologies on basis of green chemistry. The diversity of components in food wastes reflects the potential impact on broad chemical industries, which can partially replace conventional petroleum-based feedstocks with renewable feedstocks. Increasing food waste utilization in chemical synthesis will change the public perception about food waste and help create renewable supply chains for achieving a closed-loop economy [31]. A food waste-based

biorefinery is expected to play a vital role in the future, contributing to a greener and more sustainable society [32].

3. Consumer chemicals

3.1 Applications and current market

Consumer chemicals refer to daily life products directly interacting with customers as the end-user, including cosmetics, vitamins and health supplements, soaps, detergents, and household chemicals, as well as perfumes and flavors. They can be produced via biochemical and thermochemical processes as the two major pathways (Figure 1). Important consumer chemicals include volatile fatty acids (VFAs), lactic acid, citric acid, succinic acid, and ellagic acid.

As for VFAs, they have two to six carbon atoms (e.g., formic acid, acetic acid, propionic acid, butyric acid, and valeric acid), which can be distilled at atmospheric pressure. They play diverse roles in physiological body functions, nutrient removal from wastewater, and production of bioplastics and bioenergy [33]. The chiral lactic acid consists of two optical isomers, i.e., L- and D-lactic acid. With the structure of a hydroxyl group adjacent to the carboxyl group, lactic acid has gained importance in pharmaceutical and cosmetic applications, detergent industry, and as a food additive. In particular, D-lactate (DLA) is an essential precursor to various chiral chemicals and polylactic acid. The latter is potentially biodegradable plastic for producing packaging materials, fibers, and films. Citric acid, a weak organic acid with three carboxyl groups and naturally occurring in citrus fruits, widely serves as an acidifier,

flavoring, and chelating agent. Succinic acid can act as a signaling molecule reflecting the cellular metabolic state in living organisms, and a precursor to polymers, resins, solvents, foods, and dietary supplements. Ellagic acid, a natural phenol with antiproliferative and antioxidant properties, can be applied in nutraceutical fields. The global market of organic acids, including the abovementioned chemicals, is significantly expanding from US\$16,837 million in 2016 to a forecasted value of US\$29,197 million by 2023 [34].

3.2 Biochemical conversion

The aforementioned consumer chemicals can be converted from food wastes, ranging from fruits and vegetables to animal wastes and dairy products, through fermentation as a metabolic process that consumes sugar in the absence of oxygen (Table 1). Food wastes contain cellulose, hemi-cellulose, and starch, which are high-potential carbon sources for microbial fermentation, while nitrogen-rich food wastes can serve as alternatives for nitrogen supplementation. Soybean meal has proved to be an inexpensive but efficient nitrogen source for lactic acid production [35]. By adding amylolytic and proteolytic enzymes (e.g., glucoamylase, amylase, and protease) to a bread waste suspension, a hydrolysate containing over 100 g/L glucose and 490 mg/L free amino nitrogen (FAN) could be generated [36]. D-Lactic acid could be produced from the fermentation of corncob residue hydrolysates as a carbon source and cottonseed meal as a nitrogen source, using *Sporolactobacillus. inulinus* YBS1-5 [25]. This reduced the cost by 95%, in comparison to the use of refined sugars and yeast

extract in conventional practice.

In biochemical conversion of food waste, soluble sugars and nutrients as food waste hydrolysates are firstly obtained via enzymatic or catalytic hydrolysis, followed by microbial fermentation to produce target chemicals. Separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF) are the commonly adopted systems. The latter can achieve continuous use of produced sugars and protect the enzyme complex from end-product inhibition, resulting in a higher product yield within shorter retention time, compared to that in SHF. In a case where ethanol was produced, SSF (0.57 USD/L) cost less than SHF (0.63 USD/L) [37]. The energy consumption by both SSF and SHF can be reduced by increasing the substrate concentration and recycling the process streams [37]. However, it is difficult to separate the yeast from the slurry for yeast recirculation in SSF.

When using wheat bran waste as a substrate, the SHF and SSF processes produced 99.5 g/L D-lactate with 0.89 g/g glucose yield and 87.3 g/L D-lactate with 0.65 g/g glucose yield, respectively, in the presence of *S. inulinus* [38]. Compared with SHF, the SSF system reduced the cost of pretreatment and facilitated the rapid conversion of glucose to DLA, which reduced excessive accumulation of glucose [38]. The high content of protein (19.7%) and starch (14.9%) in wheat bran provided both sugars and nutrients for DLA production. In another study, 77.7 g L⁻¹ of L-lactic acid and 76.8 g L⁻¹ of D-lactic acid were obtained from an SSF system using waste corn stover as a carbon source and commercial peptone as a nitrogen source [39]. Peanut meal gave 207 g/L D-lactate in an SSF system, with commercial glucose as a carbon

source maintained at ~50 g/L in fed batch fermentation [40].

Pretreatments using acid, alkali, steam explosion, or ozonolysis can be performed to improve the conversion efficiency [41]. It was found that kitchen wastes treated by 1.12–1.17% HCl for 86–94 min at 100 °C could increase the concentration of soluble sugars by 120% compared to untreated kitchen wastes [42]. In contrast, NaOH pretreatment did not improve mono-sugar production possibly due to Maillard reaction between amino acids and sugars as a side reaction. Therefore, investigations on chemical pretreatment of food waste are important to enhance the fermentable fraction in form of degradable carbohydrates for saving energy and cost.

Nitrogen sources, enzyme compositions, nitrogen concentrations, and composition and concentrations of raw materials are important parameters for achieving cost-effective fermentation. Cottonseed meal and corncob residue could be simultaneously utilized as nitrogen and carbon sources to produce D-lactic acid, with an average productivity of 1.19 g/L/h and a yield of 0.85 g/g glucose [25]. In simultaneous saccharification and co-fermentation of *Curcuma longa* waste, the waste conversion and lactic acid yield increased with increasing feedstock loading, which was the optimal at 140 g/L [35]. Further increase in the feedstock loading lowered the performance because free lactic acid and calcium lactate in excess inhibited enzymatic activity or viscosity increased. The substrate-to-inoculum (S/I) ratio and the pH are also important. For example, increasing S/I ratio from 2 to 6 led to the maximum yields of metabolites (21.4 g/L acetate and 34.5 g/L butyrate), whereas increasing pH from 5 to 9 achieved the maximum lactate production (15.7 g/L) from cheese whey

fermentation [43]. Trace elements also can have an influence on the yield of chemicals, e.g., copper and zinc favored citric acid production, while iron and manganese resulted in a deleterious effect [219].

There is a wide variety of succinic acid-producing bacteria such as *Actinobacillus succinogenes*, *Anaerobiospirillum succiniciproducens*, *Mannheimia succiniciproducens*, and *Bacteroides fragilis* [15]. Fermentation of bakery waste (cakes and pastries) by *Actinobacillus succinogenes* resulted in a 28-35% yield of succinic acid [44]. Compared to bacteria, yeast is regarded to be more tolerant to low pH and safer for industrial application. Immobilization of an engineered yeast strain (*Yarrowia lipolytica*) on support material was achieved for efficient glucose metabolism, resulting in robotic production of succinic acid (76% yield) from food waste hydrolysate [45]. Pomegranate wastes after yeast fermentation (*Saccharomyces*) in winery contained methanol-extractable ellagic acid of 40% (w/w) with antioxidant activity [46].

In recent studies, electro-fermentation has been applied as a novel approach to produce value-added chemicals from food waste [26, 47], in which microbial fermentation is controlled with electrodes as electron sinks (anode) and sources (cathode) for overcoming the thermodynamic limitations. VFAs of 53-58% were achieved by the fed batch mode with a bench-scale suspended growth configuration [26]. The electrogenic microenvironment presented a 25% improvement in VFA and in particular, an increase in acetic acid production due to significantly enhanced electron transfer when comparing with conventional fermentation system [26]. High

productivity of lactic acid ($0.658 \text{ g L}^{-1} \text{ h}^{-1}$) from food waste was achieved using a mixed microbial consortium with the stimulation of 100 mV through the cathode [47]. More research is needed to identify the relationship between electrochemical and microbiological actions and to explore the mechanisms of substrate transformation during electro-fermentation.

3.3 Thermochemical conversion

The carbohydrates in food wastes can be thermochemically converted to various value-added products. Glucans such as cellulose and starch are polymers comprising glucose units linked by glycosidic bonds. The latter are subjected to proton attack followed by hydrolysis when Brønsted acidity is present, leading to the release of glucose. Subsequently, glucose as an aldose can undergo isomerization to form fructose (a ketose) in the presence of Lewis acid catalysts, via an intramolecular 1,2-hydride shift from the C2 to C1 position. Alternatively, glucose-fructose isomerization can be catalyzed by a Brønsted base through hydrogen transfer from O2 to O1. Fructose can be transformed to hydroxymethylfurfural (HMF) via the elimination of three water molecules [17].

HMF can result from the Brønsted acid-catalyzed dehydration of the food waste-derived fructose, for which the activation energy is lower than that for the pathway with direct glucose dehydration to HMF, bypassing the formation of fructose as an intermediate [16]. HMF is one of the top building blocks, and it acts as a precursor for useful derivatives such as ethoxymethylfurfural, 2,5-furandicarboxylic acid, furfuryl alcohol, dimethylfuran, and 2,5-diformylfuran [17, 30]. As such, HMF plays

an important role in the manufacture of pharmaceuticals, polymers, resins, solvents, fungicides, and biofuels. Levulinic acid (LA) can be produced by the rehydration of HMF or direct dehydration of glucose derived from food waste [48, 49]. It is also platform chemical for the production of chemicals, polymers, and biofuels. For example, LA could be hydrogenated over metal-based catalysts to form γ -valerolactone (GVL), a renewable platform chemical serving as a food or fuel additive as well as a green solvent [50].

Homogeneous catalysts such as low-cost inorganic acids (HCl, H₃PO₄, and H₂SO₄) generally result in 20-50% HMF yield (mostly with respect to cellulose content) from maple wood, pinewood, and wheat straw [51-53]. Metal chlorides (e.g., AlCl₃ and SnCl₄) were proven to convert starch-rich food waste such as rice and bread waste into HMF of ~30-35% at maximum under microwave heating at 140-160 °C for 20-60 min [54-57]. As the metal ions provide both Lewis acid sites and derived Brønsted acidity from its partial hydrolysis in aqueous media, the Brønsted acidity-catalyzed hydrolysis and dehydration, as well as the Lewis acidity-catalyzed rate-determining isomerization, could be promoted simultaneously [58]. It has been suggested that adjusting the Lewis-to-Brønsted acid (L: B) ratio may tune the selectivity of reaction systems toward different chemical products [17].

The use of heterogeneous catalysts may overcome the disadvantages of homogeneous catalysts such as corrosion, reusability, and disposal problems [16]. Amberlyst 36, an ion-exchange resin with Brønsted acid sites, could achieve up to 17 C mol% (yield calculated by carbon content) LA and 17 C mol% HMF from

vegetable waste under aqueous and dimethyl sulfoxide (DMSO)/H₂O media, respectively [48]. Biochar-supported acid catalysts present an innovative and sustainable option. Using wood waste-derived biochar treated with concentrated sulfuric acid, a HMF yield of 30.4% was obtained from bread waste under microwave heating at 180 °C for 20 min [59]. In the absence of catalysts, the formation of products was limited under these mild heating conditions [56]. Nevertheless, the recyclability of the biochar-based catalysts remains as a challenge in view of significant active site leaching, insufficient hydrothermal stability, and possible by-product deposition on surface, which should be subjected to more evaluations.

Conventional thermochemical reactions are conducted using autoclaves, oil baths, and aluminum heating blocks yet their heating performance is limited by substantial heat loss and inefficient heat transfer via conduction and convection [17]. Recent studies have focused on the green conversion of food waste using unconventional heating systems such as microwave irradiation. Microwave is absorbed by polar molecules in a reaction matrix to generate heat, which is considered as volumetric and selective dielectric heating with a lower energy demand [60, 61]. The efficient energy transfer process results in less mass-transport limitation than other heating processes. The alternating electric field in electromagnetic waves may distort the substrate structure [62]. It has been suggested that the CH₂OH group of cellulose rotated under microwave irradiation lowering the cellulose activation temperature [63]. Robust microwave-assisted extraction has also been demonstrated, in which D-limonene, pectin, α -terpineol, and cellulose can be obtained from waste

orange peel at 180-200 °C [64]. However, there is limited direct evidence of the microwave-specific effects on food waste (or biomass) conversions, in particular, with regard to the interplay between microwave and other system components (substrate, catalyst, solvent). This is critical information for tailoring high-performance and synergistic microwave systems.

Ultrasound irradiation allows for efficient heating and provides strong mechanical effects, as it transmits through pressure waves a direct link to the physical effect of acoustic cavitation [60]. Different from electromagnetic waves, energy in acoustic waves cannot be directly absorbed by molecules but initiates cavitation for further energy transfer. Sonochemical heating for carbohydrate conversion offers a mechanical effect similar to acoustic waves, which can avoid expensive solvents and promote the formation of transient reactive radicals. It was reported that starch could be fully hydrolyzed to glucose with ultrasonic assistance using a sulfuric acid catalyst at 23 °C [65].

Temperature is a crucial factor in determining the kinetics of catalytic conversions, which ranges from 80 to 300 °C [17]. While high temperatures generally increase reaction rates, they may not alter the product selectivity, according to a previous finding that the maximum yield of HMF did not vary markedly (27.4 -29.5 C mol%) as temperature increased from 140 °C to 160 °C [55]. High temperature could have enhanced the rates of both desirable pathways (hydrolysis, isomerization, dehydration) and side reactions (polymerization, rehydration) to a similar extent, inducing marginal change in the kinetics balance [55].

The composition of food wastes may also play a role in determining the catalytic efficiency. Sugary food waste (e.g., fruit) could be favorable due to the naturally occurring di/monosaccharides, which may eliminate the need for a hydrolysis step. Starch-rich food waste (e.g., bread, rice, pasta) can be easily hydrolyzed to glucose while the subsequent glucose isomerization may emerge as the rate-limiting step. In comparison, it is more difficult to hydrolyze crystalline fibers in food wastes (e.g., vegetables) due to the strong hydrogen bonding network [66]. For example, bread waste derived up to 30 C mol% HMF under microwave heating at 160 °C for 20 min [55], while vegetable waste only yielded up to 17 C mol% HMF [48]. While crystalline-to-amorphous transformation occurred at a moderate temperature (60-70 °C) for the semi-crystalline structure in starch, cellulose required a much higher energy input (up to 320 °C) to undergo a similar process [66]. Therefore, for the use of cellulosic food waste, pretreatment such as ball milling may be needed to increase surface reaction and mass transfer [60].

Solvents interact with catalysts as well as substrates and products. Green solvents such as propylene carbonate (PC) and γ -valerolactone (GVL) have been shown to play an important role in suppressing the hydrolysis of Sn^{4+} (Lewis acid sites) to the inactive SnO_2 , which was significant in aqueous and acetone-water media [67]. Solvent with a high dipole moment may tend to coordinate with Sn^{4+} , preventing it from SnO_2 formation. In addition, dielectric constant of solvents (e.g., acetone (20.7) < GVL (36.4) < PC (64)) may represent their ability in microwave absorption and hence the heating efficiency. In particular, PC can liberate free CO_2 to

increase the in-vessel pressure, which possibly accounted for the enhanced catalytic conversion [67]. As for comparison among conventional polar aprotic solvent-water mixtures as the reaction media, the rate of HMF formation (from bread waste) decreased in the sequence of acetonitrile (ACN)/H₂O, acetone/H₂O, DMSO/H₂O, tetrahydrofuran (THF)/H₂O, in relation to their efficiency in glucose isomerization [54]. Solvents were also suggested to determine the system selectivity toward specific products [48]. Therefore, it is intriguing to explore the diverse roles of solvents in catalytic food waste conversion, in addition to serving as a reaction medium.

4. Specialty chemicals

4.1. Applications and current market

Specialty chemicals are also referred to as performance chemicals, which exert various effects on different products (e.g., cosmetics, coatings, adhesives, and foods) to enhance their performance in terms of specific properties or functions [68, 69]. The specialty chemical market has shown massive development due to a wide range of industrial applications. North America has the highest market share in specialty chemical production, followed by China, other Asian countries, Western Europe, and Japan [70]. One of the main reasons for the huge demand for the various specialty chemicals is their unique ability to enhance human health via various food types and food packages [71].

Moreover, the substantial development in pharmaceuticals, animal foods, and

paper production industries has increased the specialty chemical demand [72]. For instance, the world essential oil market in 2016 was 6.63 billion USD, and it is projected to increase at a rate of 9.7% per year until 2025. Such market growth is directly related to the high demand for aromatherapy, fragrance, and food flavors [73]. The pharmaceutical industry also exhibits an exponential growth due to prevalent chronic diseases, aging population, and new innovations [74]. To prevent human diseases, functional foods that incorporate specialty chemicals (e.g., antioxidants) have drawn significant attentions [75, 76]. Hence, a sustainable supply of specialty chemicals is essential to maintain these industries, such as using selected food wastes as a renewable feedstock.

4.2. Extraction

Physical and thermal extraction is a major approach for obtaining specialty chemicals when the chemicals are naturally present in food wastes (Figure 2), where most of the processes are based on energy-intensive separation via temperature or pressure. In other cases, biochemical fermentation is adopted to utilize the substrates of food wastes via microbial metabolisms. Essential oil (e.g., limonene) is one of the main products that can be extracted from waste materials of citrus fruits such as sweet orange and lemon. It can be used as a food flavoring ingredient, anti-inflammatory and antibacterial compound in pharmaceuticals, cosmetics, and homecare products [77, 78]. Sweet orange (*Citrus sinensis*) is one of the most demanding commercial citrus fruits around the world [79]. The estimated world orange production is more than 50 million tons, of which a large portion is utilized to

produce orange juice and result in waste materials of about 50 wt% (i.e., peel, pulp, and seeds) [80, 81]. Chemical compositions in orange peels vary with the climatic conditions and plant factors, such as growth stage and harvesting time [82].

Conventionally, limonene in citrus peels is extracted by cold pressing or hydro-distillation. To avoid high energy and solvent usage, new technologies have been developed such as supercritical CO₂ extraction, subcritical water, and microwave assisted extraction [83, 84]. Gök et al. [85] compared both traditional and modern methods of essential oil extraction (e.g., limonene) from lemon peels, and found no significant difference among the tested methods. Ferhat et al. [86] reported that microwave accelerated distillation was superior to hydro-distillation for essential oil extraction because the former shortened the extraction time to 30 min (from 3 h in the latter) (Table 2).

Antioxidant compounds are another vital group of specialty chemicals that can be extracted from food wastes, especially in fruits and vegetables. Considerably high amounts of antioxidants can be found in seeds, peels, and kernels, which are disposed as waste materials [72]. Solid-liquid and liquid-liquid extractions are conventional practices, in which the selection of extraction solvent is dependent on the polarity of target antioxidant. For instance, extractability of phenolic compounds was high when an organic solvent was mixed with water, while that of methoxylated compounds was high when extracted with a less polar solvent such as acetone [87, 88].

Identification and quantification of the extracted antioxidants from food wastes have been performed with high-pressure liquid chromatography and

spectrophotometric methods [72]. The diverse extracted antioxidant compounds include phenolics, flavonoids, proanthocyanidins, ferulic acid, chlorogenic acid, carotenoids, glucosinolate from food wastes of onion waste, apple pomace, macadamia skin, potato peels, pomegranate peels, passion fruit rinds, acerola peels, and mango peels [87, 89-92]. As naturally occurring bioactive ingredients, they can be utilized in the production of healthy food in place of synthetic additives [93]. They can be also applied in biomedical devices as biocompatible materials and in polymers for stabilization and functionalization [71]. Antioxidant biomaterials aid to stabilize polymers without undesirable degradation preventing the release of toxic compounds [94]. Such functionalized polymers delay the oxidative deterioration of packaged food [95]. While spent coffee grounds threatened the environment due to high levels of caffeine, tannins, and polyphenols, hydrolyzed spent coffee grounds rich in antioxidants were used successfully in polymers [71].

Food wastes have also been used to produce enzymes such as cellulases, amylases, proteases, lipases, and pectinases by solid state fermentation; although large scale production is difficult due to poor control of pH, aeration, temperature, and moisture [96, 97]. Amylase production by both solid-state fermentation and submerged fermentation from food wastes including potato peels, coffee wastes, tomato pomace, and bread wastes has been reported [98-101]. Moreover, lignocellulosic enzymes (i.e., xylanase, cellulase, β -glucosidase, cellulase, laccase), pectinolytic enzymes (i.e., pectinase, laccase, endopectinase, exopectinase), proteases, and lipase have been produced from different types of food wastes, including fruit

residues (e.g., banana wastes, citrus wastes, apple pomace, orange, pineapple), potato peels, wheat bran, and seafood processing wastes [100, 102, 103]. Peroxidase production from potato pulp has been recently reported [104]. Enzymes are widely used in many industries (e.g., production of leather, pulp and paper, textile, detergent, food and beverage, and pharmaceutical). Hence, continuous production is vital to sustain various industrial needs [97, 105].

In addition, different biochemicals have been extracted from food wastes. Pectin can be obtained from citrus peels, apple pomace, watermelon rind, and passion fruit peel [106-109]. Pectin is a highly essential functional ingredient for industrial production of various products, such as cosmetics, edible packaging films, personal care products, animal feeds, pharmaceuticals, and human foods [110]. Both conventional (i.e., mineral and organic acid extraction) and modern technologies (i.e., ultrasound-assisted, microwave-assisted, and enzyme-assisted extraction) are adopted to extract pectin from food wastes; but selection of a suitable method is necessary to maximize the pectin yield [111-114]. Microwave-assisted extraction has gained attention as a suitable technique for pectin extraction from food waste due to its short duration, cost effectiveness, high yield, and reduced usage of solvents [110]. For example, Balu et al. [64] extracted mesoporous cellulose, d-limonene, and pectin from waste orange peels in a single step, low temperature (i.e., 200 °C), hydrothermal microwave-assisted extraction.

Bioactive compounds obtained from food wastes, such as proteins, polysaccharides, fibers, flavor compounds, and phytochemicals, can be utilized as a

valuable source of nutraceuticals [115, 116]. Nutraceuticals are medicinal food additives improving immunity and treating specific diseases such as cancer [69]. Apple peel and pomace, grapes seeds and skin, citrus peel, banana peel, and mango kernel have been successfully used to extract phenolic compounds as nutraceuticals [117].

5. Commodity chemicals

5.1 Applications and current market

Commodity chemicals are chemicals of high global demand that are usually produced at large quantity from petroleum. Due to the global climate and energy crisis, a transition of energy structure from fossil fuels to renewable biofuel is of urgent need. Biodiesel is an efficient and sustainable alternative fuel, which comprises monoalkyl esters of long-chain fatty acids produced from the catalytic reaction of vegetable oils or animal fats and a low molecular weight alcohol [16]. Biodiesels are biomass-derived, non-toxic, biodegradable, and carbon-neutral. With similar properties to commercial diesels, biodiesels can be used directly in a combustion engine without major modification.

Biogas is another sustainable energy alternative, which mainly consists of methane and carbon dioxide, providing a high thermal efficiency with limited emission of volatile organic compounds (VOCs). It is increasingly produced from food wastes through anaerobic digestion (AD) [118, 119]. In the past two decades, significant transition from landfill disposal to AD treatment has been observed, and the latter

emerges as a promising treatment option in view of low gas emission and renewable energy production [120]. Currently in the UK, there exist 473 operational AD plants and on-going projects on 327 more AD systems [121].

Biochar is a commodity derived from thermal conversion of organic biomass, which can be applied as a soil conditioner to improve soil environment and crop growth [122, 123]. Recent studies extended to using biochar as renewable carbon materials in various high-value industries (e.g., gas sorbent, solid catalyst, energy) [30, 124]. The biochar market is growing rapidly and expected to be doubled in 2020 (US\$585 million) compared to 2014 (US\$260 million) [125]. To sustain the future market, turning food wastes of significant global amount into biochar is one of the possible solutions [126, 127].

5.2 Biodiesel/bio-oil production

Biodiesels can be made from edible and non-edible oils, animal fat, and algae through direct blending, micro-emulsions, catalytic cracking, and transesterification [128]. Among them, transesterification of food waste, such as waste cooking oil and animal fat, might be the most feasible and cost-efficient approach to achieve both biodiesel production and food waste recycling (Table 3). Fatty acid methyl esters (FAME) are the primary component of biodiesels derived from raw feedstocks containing triglycerides (TGs) and free fatty acids (FFAs) [16, 129]. During the synthesis of FAME, TGs and FFAs react with alcohol and a base catalyst (e.g., KOH) or with an acid catalyst (such as H_2SO_4 , HNO_3) through transesterification and

esterification, respectively, as illustrated in Figure 3. In transesterification, the electron and proton acceptors from the catalyst provide adsorptive sites for alcohol (i.e., methanol), where the OH bonds readily break into methoxide anions and hydrogen cations. Then the methoxide anion reacts with triglyceride molecules to yield FAME [133, 138, 223]. In esterification, the catalytic H^+ firstly activates FFA and the intermediate combines with methanol to form a tetrahedral structure. Subsequent elimination of water and deprotonation result in FAME as the product [129, 223, 229].

FFAs in oils sometimes exert adverse effects on biodiesel production, as it can induce saponification under alkaline aqueous conditions, consume catalysts, and cause formation of emulsions. In a study of biodiesel production from waste cooking oil, there was incomplete conversion of TGs and FFAs due to the adsorption of FFA onto the alkaline-based catalyst surface [129]. Oil feedstock containing less than 0.5% FFA was recommended for a base-catalyzed transesterification reaction, otherwise, an acid-catalyzed process for pretreatment of waste oils should be conducted [130]. Hence, biodiesel production can be accomplished through a two-step reaction: the FFA content is decreased by using an acid catalyst for esterification; followed by TG transesterification using a base catalyst with a high selectivity [129, 131]. Excessive FFA can also be removed through pretreatment by adding activated carbon to waste cooking oil and shaking for 30 min under a certain temperature, followed by filtration to obtain suitable feedstock for transesterification [132]. Feedstocks with a high FFA content are exemplified by waste cooking oil, jatropha,

polanga, rice bran oil, and chicken fat [128].

The presence of highly unsaturated acids in oil feedstocks decreases the stability of biodiesel due to rapid oxidation, whereas the presence of exceedingly saturated fatty acids leads to poor cold flow properties of biodiesel limiting its use in cold climates. Oils from soybean, mustard, waste cooking, sunflower, and rapeseed have more unsaturated fatty acids, whereas palm oil and *Spirulina platensis* algae have more saturated fatty acids [128]. Water content in waste cooking oil has a negative effect on biodiesel yield, which, for example, was reduced by 15% due to the occurrence of saponification when water content increased from 0.64% to 2.48% [133].

For waste cooking oil, a series of pretreatments, such as visual separation, homogenization, and lyophilization before oil extraction, may help preserve the organic material from microbial contamination and enhance lipids extraction and further processing during biodiesel production [131]. In a study by Karmee et al. [134], lipids were obtained from fungal hydrolysis of bakery waste, which served as a feedstock producing FAME of ~100%. Other comparable properties of feedstocks with petroleum diesel (e.g., kinematic viscosity, calorific value, flash point) can make them desirable for conversion into biodiesel [128]. Properties of feedstock oils within the range specified by biodiesel standards (American Society for Testing and Materials/EN 14214) may be suitable for blending and use as an alternative to diesel without any modification [135]. It has been suggested mixing oils from different restaurant food wastes to produce biodiesel, which can be blended with diesel fuel or with additives to improve biodiesel quality [131].

Apart from feedstock quality, the biodiesel yield also depends on the use of catalysts and alcohols [128, 135]. Homogenous acid catalysts for esterification have various limitations, including removal, reuse, erosion, and secondary pollution. Biodiesel production over heterogeneous catalysts and their reusability have been investigated, including metal oxides, ion-exchange resins, zeolites and clays, acidic polymers and resins, miscellaneous solid acids, and carbon-/biochar-based catalysts [16, 30, 136, 137]. In transesterification reaction, methanol reacts with CaO and transforms into a nucleophile, which can attack a carbonyl carbon in glycerides, thus forming FAME as well as glycerol [138]. Sulfonated carbon derived from coconut meal residue served as a catalyst for biodiesel production from waste palm oil for four cycles, in which both FFA and TGs were simultaneously transformed into their esters by esterification and transesterification reactions [139]. Similarly, calcined scallop shell was used in catalytic transesterification, which produced 66-86% biodiesel from waste cooking oil for four cycles [133]. This food waste-derived catalyst showed higher catalytic activity than commercial CaO because of its high surface area and co-existing Mg and Sr that promoted catalytic activity.

Biodiesel yield is generally promoted by increasing catalyst loading [132]. For example, FAME yield increased from approximately 10% to 60% as catalyst loading increased from 1% to 2%, after 60 min of reaction at 65 °C [133]. However, high catalyst loading may cause mass transfer limitation due to high viscosity. Excessive alkali catalyst can react with triglycerides to form soap and reduce biodiesel yield, especially for long reaction time. Future research on heterogeneous catalysis for

biodiesel production may focus on advanced materials and greener synthesis routes, with the goal of producing solid catalysts with high catalytic activity and reusability while achieving simplicity and cost-effectiveness in conversion process [137].

Another important factor is the oil-to-methanol (O:M) ratio. The minimum stoichiometric O:M ratio is 1:3 (v:v) for fatty acid ester synthesis. Transesterification, a reversible reaction, requires excessive methanol to shift the reaction to the product side (i.e., esters) according to Le Chatelier's principle. Biodiesel yield increased from 43 to 96% when the O:M ratio was increased from 1:3 to 1:8 at 55 °C for 60 min [138], and FAME yield significantly increased with increasing O:M ratio from 1:3 to 1:6 at 65 °C for 120 min [133]. Nevertheless, methanol in extreme excess may lower the activity of catalyst and may interfere with the separation of glycerol due to increase in solubility [132, 139]. A decrease in product yield has been reported at a high O:M ratio of 1:9 or 1:12 [133, 138]. Therefore, the O:M ratio should be optimized (ranging from 1:6 to 1:12 in most studies) and the cost of removal of excessive methanol from final product should be considered. Similarly, the biodiesel yield increased with increasing temperature from 35 to 55 °C or with increasing reaction time from 10 to 50 min. Further increase in temperature caused the vaporization of methanol, while prolonged reaction time resulted in the accumulation of water and the deactivation of catalyst due to leaching or binding of active sites [138, 139].

5.3 Biogas production

Biogas is produced via anaerobic digestion (AD), in which the pathway begins with reactions similar to those of producing biologically converted consumer chemicals

discussed in Section 3.2, followed by transformation of fatty acids to biogas (known as methanogenesis). Electro-fermentation of food wastes produced VFAs through acidogenesis with 23-30% biogas co-generated simultaneously [26]. As illustrated in Figure 4, the process of AD comprises hydrolysis, acidogenesis, and methanogenesis [140]. First, the insoluble complex molecules in food wastes are converted into smaller and soluble organic substrates, i.e., hydrolysis or liquefaction. The second step can be divided into: (a) acidogenesis in the narrow sense, where the products from the previous stage are converted into VFAs; and (b) acetogenesis process, which further digests VFAs into CH_3COOH , H_2 , and CO_2 with acetogenic bacteria. During methanogenesis as the final stage, methanogens facilitate the cleavage of the produced acetic acid and the reduction of carbon dioxide with hydrogen, producing methane and carbon dioxide. In comparison to composting where fertilizer/conditioner is the final product, AD aims to produce energy in form of biogas.

Recent advancements of AD systems for food waste digestion are summarized in Table 4. Instead of applying fermentative bacteria, hydrolysis can be conducted in chemical and/or physical ways. In terms of the methane production from food wastes, pre-treatment with HCl and mechanical maceration could not completely hydrolyze food waste for bioconversion, thus obtaining lower methane yield than thermal or thermo-chemical hydrolysis [141]. Another study suggested that pressurization–depressurization pretreatment of kitchen food waste resulted in the highest cumulative biogas production (60%) and the highest anaerobic biodegradability, while thermo-acid pretreatment achieved the highest solubilization [142]. In addition, when food waste

leachate collected from a fertilizer-producing center was used for anaerobic digestion, a methane yield of 478 mL/g volatile solids was achieved after 28 d because of its high biodegradability (82.6%) [143].

In contrast to employing inoculum of certain bacteria in fermentation, food waste AD can be assisted by microbes from the anaerobic digester sludge in sewage treatment plants [43, 141, 144]. Co-digestion of food waste with other wastes, such as manure waste and sewage sludge, could blend wastes of different sources, obtain better balance of nutrients, increase the biodegradation of long chain fatty acids, enhance the methane yield, and assure the long-term stability of AD system [118]. For instance, anaerobic co-digestion of food waste and cattle manure at the optimum ratio of 2 enhanced the methane production by 41.1% with the yield of 388 mL/g volatile solids [145]. By comparing the ratios of food waste to anaerobic digester sludge of 0.42, 1.42 and 3.0, Hobbs et al. [144] found that the highest ratio yielded the greatest volumetric methane but VFAs-induced pH inhibition required a 10-day lag period, whereas the intermediate ratio exhibited the best balance of high methanogenic yield with a short lag time. Other key parameters influencing the biogas yield include temperature, VFAs, pH, alkalinity, salinity, C/N ratio, ammonia, long chain fatty acids, solids content, and potentially toxic elements, which have been discussed in detail in previous reviews [118, 146]. Latest developments of anaerobic co-digestion can be referred to a recent review by Siddique and Wahid [147].

Food waste with low carbohydrate content and high water-soluble organic matter content tend to favor methane production, which could be related to parameters such as

total chemical oxygen demand, volatile solids, and biochemical methane potential [148]. However, regional and seasonal variations in food waste composition pose challenge to worldwide implementation of AD, which needs comprehensive characterization of food waste for specific process design. Future research efforts may focus on VFA accumulation, process instability, foaming, low buffer capacity, and high financial cost, as the critical barriers in food waste AD systems [149]. Other problems lie in biogas utilization, food waste collection and processing, and impacts of co-digestion on biosolid reuse [150].

Integration of AD and production of value-added products is a promising way to increase overall profits with less environmental impacts, for example, by combining protein extraction from whey and AD of deproteinized whey permeate [149]. A case study of biorefinery of citrus waste combined major stream lines, such as dilute-acid hydrolysis, fermentation, ethanol recovery, anaerobic digestion, and wastewater treatment, which proved to be economically feasible in producing biogas, ethanol, and limonene [151]. Another integrated food waste recycling facility employed pretreated hydrolysates for cultivation of *Rhodotorula glutinis* and used the residual solids for anaerobic digestion, yielding biogas up to $0.139 \text{ m}^3 \text{ kg}^{-1}$ volatile solids [141].

5.4 Biochar production

Biochar is one of the major by-products from thermochemical conversion of organic biomass [152, 153] (Table 5). When the temperature increases, cellulose, hemicellulose, and lignin in the food wastes thermally decompose and release volatile components (e.g., CO, CO₂, C_xH_y, C_xH_yO_z, H₂O, and NH₃). The bonds of the

complex structures (such as glycosidic bonds) in biomass break down and rearrange, capturing protons of species with weak O–H or C–H bonds and forming a more stable carbonaceous structure as biochar [127,170].

As a soil amendment, biochar shows a wide range of benefits, such as mediating acidity and increasing cation exchange capacity, water holding capacity, and nutrient retention [122, 123, 154]. With the addition of biochar, yields of diverse crops in different soil types have increased over several cropping cycles [155, 156]. In addition, the use of biochar in soil helps to safeguard healthy crop production via immobilization of various trace metals and organic pollutants [29, 157, 158]. Some recent studies have shown that biochar and/or biochar-based composts can be successfully applied as a slow-release fertilizer in soils [159-161].

The use of biochar as renewable carbon materials has spread to various advanced disciplines. For instance, biochar has proved promising as electrodes in supercapacitors, which have high specific capacitance, charge-discharge pace, cycle life, and wide range of operating temperatures for uses in green energy storage devices [162-164]. They may perform better than commercial activated carbons and ordered mesoporous carbons. Biochar also served as electrodes in microbial fuel cells due to its high porosity, surface area, and pore size [165-167]. In addition, biochar-based catalysts appear as an alternative to expensive catalysts in many industrial and biorefinery applications [30, 59, 136, 216], for the sake of its high porosity and aromaticity for electron transfer and thermal conductivity. Other advanced applications include gas and VOCs sorbent, microbial carrier material, carbon black pigment, and construction

material [124].

The abovementioned emerging applications have driven recent advances in biochar design and customization. However, research on food waste-derived biochar is scarce when compared to biochar produced from other biomass such as wood waste, sewage sludge, and livestock waste. Biochar produced via torrefaction of food wastes at 225-300 °C for 40 min - 3 h showed good fuel properties as a substitute in coal-fired boilers [169, 170]. Lee et al. [171] observed that the salt content in mixed food wastes (grains, vegetables, fruits, meat, and fish) enhanced aromatic ketones in biochar produced at 500 °C. Igalavithana et al. [126] produced biochars from vegetable wastes by torrefaction (200 °C) and slow pyrolysis (500 °C), which can supplement nutrients while immobilizing Pb in contaminated agricultural soils via (co-)precipitation, surface complexation, and electrostatic interaction. In addition, Gupta et al. [127] produced biochar from mixed food wastes (rice, noodles, pasta, meat, vegetable matters, and bones) by slow pyrolysis at 500 °C, which was ground into powder for water adsorption to reduce water-to-cement ratio and improve strength of cement mortar mixture.

6. Niche chemicals

6.1. Applications and current market

Niche chemicals may refer to chemical products targeting a particular section of industry or market for specialized uses. Recent years have seen a great increase in the production of value-added niche chemicals (e.g., chitosan, glucose, FAN, phosphate,

amino acids, and carbohydrates) from food wastes (e.g., shrimp waste, bakery waste, meat, rice, and noodles) (Table 6). For example, chitosan, known as β -D-glucosamine, is an amino polysaccharide that possesses high positive charge density and long polymeric chains to bridge aggregates; as such, it is favorable to promote precipitation in neutral and alkaline solutions [172, 173]. Chitosan is a non-corrosive, biocompatible, biodegradable, and antimicrobial polymer with excellent chelating properties extensively used as a flocculant/coagulant in pharmaceutical, agricultural, biomedical, and food processing industries (e.g., development of antimicrobial packaging) [174, 175]. It is estimated that the global market of chitosan will grow from US\$1,205 million in 2015 to US\$2,550 million in 2022 [176]. In addition to the benefit of resource recovery, niche chemical extraction can lower the organic content of food wastes before disposal in landfills [20].

6.2 Chitosan production

Cephalothoraxes and exoskeletons are the prime components that account for 50-70% of shrimp waste by weight [172]. While shells are resistant towards applications due to their low solubility [177], shrimp waste are rich in chitin (20-30%), proteins (30-40%), calcium carbonate (20-30%), and carotenoids [178]. Chitin is a highly abundant natural biopolymer, only second to cellulose in occurrence [179]. The derivatives of chitin, such as chitosan, carboxymethyl chitin, and glucosamine, are widely used in food technology, biomedical engineering, textile and chemical industries [174, 175]. Chitin is deproteinized and demineralized to obtain chitosan *via* N-deacetylation, which utilizes the major chunk of the shrimp waste (Table 6) [178,

180]. The conversion pathways from shrimp waste to chitosan are illustrated in Figure 5.

In conventional practices, proteins and minerals are removed from shrimp waste via strong alkali and acid treatments [177], which result in a high degree of depolymerization, inducing significant changes in viscosity, molecular weight, and degree of deacetylation [175, 178]. In this respect, microwave irradiation has garnered much interest for chitosan extraction [178], which reduces reaction time, facilitates homogeneous heat distribution, and yields more chitosan with lower molecular weight and higher degree of deacetylation [181, 182]. An enzymatic approach using fish protease can also deproteinize 80% of shrimp waste shells [172].

The incorporation of antimicrobial and antioxidant agents into edible films is recognized as an important advancement in food technology [183], while food packaging materials should be biodegradable, economical, and antimicrobial [184]. Concentrated caroteno-proteins extracted from shrimp waste and chitosan in concentrated astaxanthin-rich shrimp protein have displayed great antimicrobial and antioxidant capacities [185]. Mildly extracted chitosan from shrimp waste mixed with lactic acid can be used as a polymer matrix for the formation of an active film [186]. The antimicrobial properties of chitosan and its derivatives primarily result from their high cationic charge density and the resulting electrostatic stacking at the surface of microbial cell [187]. If the molecular weights of chitosan and its oligomers are below 5,000 Da, they can permeate into the microbial cell and adsorb onto DNA molecules to inhibit the RNA-DNA transcription [188]. Therefore, recent investigations have

attempted to depolymerize chitosan into oligosaccharides as a means to increase its solubility for more extensive applications [189].

6.3 Enzymatic or fungal hydrolysis

Food wastes, such as bakery wastes, contain carbohydrates (60%), proteins (20%), and lipids (10%) [190]. Enzymatic and fungal hydrolysis is used extensively as an efficient strategy for the recovery of valuable nutrients from food wastes (Table 6) [191-193]. In fungal hydrolysis, fungi secrete hydrolytic enzymes in situ and avoid costly addition of extra enzymes [190]. Fungal species such as *Aspergillus oryzae* and *Aspergillus awamori* (recognized as secretors of phosphatase, protease, and glucoamylase) are effective for the hydrolysis of mixed food wastes (containing rice, noodles, meat, and vegetables) [190, 194, 195]. The food waste hydrolysates are rich in phosphate, FAN, and glucose, serving as a promising source of nutrients and feedstocks for the production of succinic acid (through *Actinobacillus succinogenes*) and ethanol (through *Sacharomyces cerevisiae*) [196, 197].

Biomass obtained from microalgae has been widely proposed as an alternative source for biodiesel production and aquaculture feed [198, 199]. However, the cultivation of microalgae is uneconomical owing to the requirement of large quantities of carbon source and nutrients (~80% of the total operational costs) [190]. In this regard, the carbon- and nutrient-rich food waste hydrolysates emerges as a sustainable media for microalgae cultivation [190]. For instance, the amylolytic and proteolytic hydrolysates of restaurant and bakery wastes were mixed with specific inorganic nutrients (e.g., ammonium to stimulate the synthesis of phycocyanin) for successful

cultivation of heterotrophic microalgal strain *Galdieria sulphuraria* [200]. This provides a beneficial strategy for the management of food waste through simultaneous and economical production of microalgae [201, 202].

7. Economic considerations of food waste valorization

The economics of food waste utilization have yet to be studied in detail. The costs of food waste processing largely depend upon the type of technique utilized [9, 203], and the associated economics is region-specific in many cases. The involved techno-economics are regulated by the relationship between the waste types and available methodologies [204]. The majority of wastes generated by the food processing industry are landfilled [205], in which organic carbon decomposes contributing to greenhouse gas emission and global warming [10, 206]. Landfilling is also uneconomical owing to high transportation costs and landfill disposal fees [207].

Economic feasibility was frequently demonstrated on techno-economic evaluations of food waste valorization. For example, AD of food waste producing biogas and electricity is a cost-effective and sustainable alternative [10, 208, 209]. A recent techno-economic case study in Canada indicated that the food waste AD facility (100,000 ton/year and 30-year service life) was uneconomical at a 10% internal rate of return and US\$0.035/kWh price of electricity [210]. A techno-economic assessment in China proved bioprocess of hydrogen production from food waste with an overall revenue at US\$146474/year in an industrial scale [237]. As for the conversion of food waste into biochar, the biomass cost and the associated transportation cost are

responsible for the largest share in the production costs [211]. The methods of biochar application in soil (e.g., broadcast-and-disk and trench-and-fill) also play a pivotal role in biochar economics. For example, an application cost of US\$300 was reported for the broadcast method at 50 tons per acre, whereas that of US\$512 was reported for a trench-and-fill process at 75 tons per acre [212].

Food waste valorization exhibited considerable industrialization interest, whereas the integrated biorefinery was more cost-efficient. For example, sequential lactic acid and biogas productions showed more competency in minimizing energy demands as well as enhancing yields of valuable products than either single process [238]. To obtain higher profits, on-site treatment (or on a local/regional industrial site) of food waste is encouraged to minimize transportation for food waste-based biorefineries [6]. In addition to economic benefit, food waste recycling behavior also depends on incentives from administrative and corporate support as well as logistics, management, and economic benefit [236]. Therefore, stakeholder-oriented policy is suggested to foster corporate behavioral change towards food waste recycling for sustainable resource circulation.

Condition optimization plays an important role in achieving sustainability and feasibility in the development of large-scale valorization systems. For example, in a life cycle assessment study of food waste conversion under different catalytic conditions, catalyst depletion and the toxicity of organic co-solvent are proved to incur the most significant environmental impacts [9]. Accordingly, it is encouraged to adopt less polluting co-solvent (e.g., acetone) and catalyst (e.g., aluminum) while ensuring

high yield of HMF (27.9 Cmol%) from bread waste. Therefore, future techno-economic analysis as well as life cycle cost analysis are encouraged to quantify the economic profits from scaled-up food waste valorization in a greener and sustainable manner.

8. Perspectives for future development

Value-added chemicals can be yielded from food waste. This valorization approach in dealing with wastes has a great prospect in the recycling industry, as it shows economic merits and values in closed-loop resource utilization. As indicated in Table 7, the chemical products derived from food wastes have a wide spectrum of applications, ranging from personal care products to bioenergy production. Among these products, the economic value and production cost vary widely. It was reported that the average product prices of basic chemicals, agricultural chemicals, specialty chemicals, consumer products, and pharmaceuticals are <US\$0.8, US\$0.3-1.5, >US\$1.75, >US\$2, and >US\$20 per pound, respectively [213]. Scientists and engineers need to strike a balance between the economic value of food waste-derived products and the consumption of energy and material inputs, by which we will be in a position to suggest practitioners and stakeholders more feasible pathways for scaling up operation. In addition to market value, the selection of target products should depend on the types of food wastes collected, which could be regionally specific due to the wide variation in culture, political agenda, education, and industrial activities in different communities. For example, significant generation of shrimp waste can be

expected in China as it is one of the largest producers in global fishery industry [214].

Hence, chitosan production from shrimp waste could be economically feasible in China, in view of the local and centralized provision of shrimp waste saving costs associated with sorting and logistics.

Most of the available studies have stressed the independent production of a specific value-added chemical and have explored approaches to increase the yield and selectivity. It is crucial to maneuver the reaction parameters and ensure technical sustainability and resiliency. For instance, bioconversions employing microbial communities depend on species and activity of microorganisms, while thermochemical processes depend on temperature, pressure, and reagents. These processes often vary during the course of scale-up which should be carefully evaluated through experimental-computational analysis [227]. Process flow engineering is thus required as a recent study demonstrated that successive fermentations of microalgae can improve energy recovery [228].

Integrated biorefinery, i.e., implementing various conversion approaches in tandem or in series, is drawing more attention from scholars in recent studies [215]. In this way, valorization of food wastes forms a circular bio-economy with more efficient recovery of each reusable stream (e.g., higher carbon efficiency) to obtain diverse range of products, such as biofuels, platform chemicals, and advanced biomaterials. For instance, a syrup containing 89 g/L fructose was produced from enzymatic saccharification and isomerization of food and beverage waste, which was then subjected to catalytic reaction and produced 71 mol% HMF at 140 °C within 40 min

using Amberlyst 36 catalyst [168]. Another recent study proposed the supercritical CO₂ extraction of high-value products (e.g., esters, fatty acids) from vegetables, from which the solid residues were utilized as feedstock for HMF synthesis [215]. Another possibility is to combine waste-to-energy technologies, which are commercially mature in market, with emerging biorefineries. The chemicals produced can be used in existing infrastructure, which benefits closed-loop resource management and sustainable utilization.

While most of the literature emphasize the design of production process, there is insufficient discussion about selective, efficient, and low-cost separation of desired products from the complex resultant matrix. Solvent extraction can be performed after conversion or simultaneously take place during catalysis in a biphasic system, which contains a reactive (aqueous) and extractive (organic) layer [17]. In biomass conversion to LA using 2-methyltetrahydrofuran (2-MeTHF) as the process solvent, 20-fold less energy was consumed compared to methyl isobutyl ketone (MIBK), or 180-fold less energy compared to direct distillation from an aqueous stream [217]. For the conversion of bread waste to HMF, the use of water-acetone medium with the Al catalyst was more environmentally friendly than the use of DMSO medium and Sn catalyst, because of significant less resource depletion and impacts on human health and ecosystems [9]. Solvents with low boiling points are favorable for room-temperature vacuum distillation and flash separation, while using those with high boiling points tend to be energy-intensive [17]. The applicability of green solvents derived from biomass or CO₂ should be evaluated, which show greater environmental

merits than common industrial solvents [67].

The triphasic product profile (liquid-, solid-, and gas-phase) of a biorefinery system is a concern in downstream separation and purification processes. Waste by-products generated alongside the biorefinery process are seldom considered, such as wastewater effluents, greenhouse gas emissions, and humin-like solid residues. It is essential to perform life cycle assessment of all product streams when studying the value of food waste valorization, and it is imperative to resolve how much waste is generated and how to properly utilize or dispose of it. Green chemistry and engineering routes with minimal environmental impact are highly encouraged in future food waste valorization. System boundary of life cycle analysis should also include any necessary pretreatments which are usually applied for improved production.

At present, it is of great significance to scale up from the proof-of-concept research stage to field-relevant industrial-scale applications, where the thermodynamics of a specific reaction might be changed. Manufacturing appeal needs to be considered, such as further requirements on efficiency, selectivity, mass transfer, and throughput rate. Manufacture-level analysis on overall cost and profitability are needed to evaluate the optimum design, fixed capital investment, equipment service life, material and energy balance, transportation and logistics, and product sensitivity analysis [151]. When more field-scale data become available in the future, it is recommended to establish mathematical models to simulate corresponding processes and optimize the operational parameters [218].

The global decline in primary resources and increase of food waste arouse a

strong public need for transition from a linear to a circular economic model in the world. In this regard, green synthesis of recyclable products from renewable resources is of great significance [234]. Advanced technologies of converting food waste into value-added chemicals reviewed in this paper offer sustainable alternatives to transform waste from environmental threats into economic products. These research studies promote and develop the techno-economic feasibility of sustainable biorefineries by optimizing raw materials, process options, mass and energy integration, and market constraints [235]. Therefore, food waste valorization is a sustainable and promising approach for achieving green chemistry and closed-loop economy.

9. Conclusions

Food wastes have caused severe loss of resources, including water, land, and energy. They have led to significant environmental impacts, such as secondary pollution and greenhouse gas emissions. While conventional treatments cannot meet the sustainable need for resource recovery, a wide range of physical, chemical, and biological approaches with value-added products are emerging. These innovative ways recycle or refine food wastes by converting them into consumer, specialty, commodity, and niche chemicals. This comprehensive review summarizes different pathways of converting food waste conversion into various value-added products, by presenting the state-of-art technologies and research insights. The above discussions on green synthesis and biorefinery has shed light on sustainable ways of both waste reduction and resources utilization. Further research is required for optimizing the reaction

parameters, elucidating and maneuvering the underlying mechanisms, developing greener and sustainable approaches, and performing life cycle and techno-economic assessment of these novel biorefinery strategies. Integrated biorefinery of food waste into a wide spectrum of value-added products is promising, while laboratory-level proof-of-concept studies should be scaled up for commercial manufacturing in the industry. Concerted efforts from scientists and engineers are needed to develop holistic supply and demand chains that are technologically and economically viable for food waste valorization for the sake of sustainable biorefinery and circular bio-economy.

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Table 1. Consumer chemicals

Food waste	Pretreatment	Treatment approach	Product chemicals	Yield	Application	Reference
A. Biochemical converted chemicals						
Canteen based food waste	-	Electrofermentation in the reactors operated in fed batch mode with suspended growth configuration and constant mixing (160 rpm) using a magnetic stirring at ambient temperature (28 ± 2 °C).	Volatile fatty acids, biogas (biohythane)	53-58% (VFA)	Dietary and medical application	[26]
Food waste and cheese whey	-	Acidogenic fermentation using anaerobic sludge as inoculum at different combinations of substrate to inoculum (S/I) ratio (2, 4, and 6) and initial pH (5, 7, and 9)	Hydrogen, metabolites (acetate, butyrate, propionate, valerate, lactate, and ethanol)	93.1 m ³ t ⁻¹ VS (H ₂); 58g/L (metabolites)	Platform chemical	[43]
Waste activated sludge and food waste	-	Cathodic Electro-Fermentation using mixed microbial consortium.	Lactic acid	0.6578 g L ⁻¹ h ⁻¹	Pharmaceutical and cosmetic applications	[47]
Cottonseed meal and corncob residues	-	Enzymatic saccharification for CCR hydrolysate and Fed-batch fermentation by <i>S. inulinus</i> YBS1-5 at 37 °C	D-lactic acid	0.85 g/g glucose	Pharmaceutical and cosmetic applications	[25]
<i>Curcuma longa</i> waste		Simultaneous saccharification and cofermentation by <i>L. paracasei</i> LA104 at 37 °C	L-lactic acid	69.38%	Pharmaceutical and cosmetic applications	[35]
		Simultaneous saccharification and cofermentation by <i>L. coryniformis</i> ATCC 25600 at 34 °C	D-lactic acid	65.43%		
Wheat bran	2% (w/v) sulfuric acid protease hydrolysis at 50 °C	Enzymatic hydrolysis at 50 °C for 48h and fermentation at 37 °C for	D-lactate	0.89 g/g glucose,	Pharmaceutical and cosmetic	[38]

		96 h with recovered nutrient and hydrolysate (SHF)			applications	
	Dilute acid pretreatment at bioreactor for 8 h at 50 °C	Saccharification with cellulose at 50 °C for 8h, followed by <i>S. inulinus</i> YBS1-5 inoculation and incubation at 40 °C (SSF)		0.65 g/g glucose,		
Kitchen waste	Chemical hydrolysis (i.e. H ₂ SO ₄ , HCl, NaOH, H ₂ SO ₃) by different solute concentration (0.7%, 1.5%, 3%) at three temperatures (50, 75, 120 °C) and a range of residence times (30-120 min)	Fermentation (not included in this study)	Soluble sugars (glucose and fructose)	120% increase of soluble sugars	Platform chemicals	[42]
Banana peels	-	Inoculation with the <i>Aspergillus niger</i> UABN 210 suspension at 30°C in a rotary shaking incubator for 5 days	Citric acid	8.2%	Cosmetics, pharmaceuticals, dietary supplements, and foods	[219]
Bakery waste, including cakes and pastries	Incubation with <i>A. awamori</i> and <i>A. oryzae</i> for 5 days at 30 °C.	Enzymatic hydrolysis at 55 °C for 24 h; bacterial fermentation under 37 °C with external CO ₂ at pH 6.6-6.8	Succinic acid	35% (pastry); 28% (cake)	Precursor to polymers, resins, solvent, food and dietary supplement	[44]
Food waste hydrolysate	Pre-hydrolysis of food waste in bioreactor by consortium of enzymes	Bench-top scale fermentation at 28 °C with engineered <i>Y. lipolytica</i>	Succinic acid	76%	Precursor to polymers, resins, solvent, food and dietary supplement	[45]
Bread waste	-	Enzymatic hydrolysis by enzyme complexes from solid-state fermentations with <i>A. awamori</i> and <i>A. oryzae</i> to produce glucose and free amino nitrogen; <i>A. succinogenes</i> fermentations to produce succinic acid	Succinic acid	55%	Precursor to polymers, resins, solvent, food and dietary supplement	[36]
Fermented pomegranate wastes	Wine production by yeast fermentation	70 mL 6M HCl hydrolysis at 100 °C overnight; extraction with methanol (20 mL)	Ellagic acid	53%	Nutraceutical applications	[46]

		for 1 h at room temperature under magnetic stirring						
B. Thermochemical converted chemicals								
Bread waste	Freeze-drying, grinding, and sieving through a 0.2-mm-mesh. Prepared samples were then stored in an airtight storage container at 4 °C in the dark	Microwave heating with SnCl ₄ catalyst at 140 °C from 1 to 120 min in polar aprotic solvent-water mixture	DMSO/H ₂ O (1:1 v/v)	HMF ¹	27.4 mol%	C	Precursor of medicines, polymers, solvents, and biofuel resins, and	[54]
			ACN/ H ₂ O (1:1 v/v)		26 mol%	C		
			Acetone/ H ₂ O (1:1 v/v)		26 mol%	C		
			THF/ H ₂ O (1:1 v/v)		8 C mol%			
Bread waste	Freeze-dried, stored in air-tight storage containers at 4 °C in the dark after grinding and sieving through a 0.2-mm-mesh	Microwave heating under metal chloride catalyst, i.e., SnCl ₄ , AlCl ₃ , or FeCl ₃ , 140, 150, and 160 °C from 3 to 120 min		HMF	30%			[55]
Cooked rice and penne produced	Freeze-dried, (except that watermelon flesh was blended and dewatered before freeze-drying), ground, sieved through a 0.2-mm-mesh, and stored in air-tight storage containers at 4 °C in the dark	Microwave heating at 140 °C for 20 min over SnCl ₄ catalyst	Glucose	HMF	46.0-64.8 wt%			[66]
Kiwifruit and watermelon			Microwave heating Sn catalyst		HMF	13 wt%		
			Raw mixed vegetables		Microwave heating at 140°C for 20 min over SnCl ₄ catalyst	HMF	4.9 wt%	
Food and beverage waste					Hydrolysis and isomerization using glucoamylase, sucrase glucose isomerase to yield high-fructose syrup	Mild microwave heating at 140 °C within 40 min. under Amberlyst 36	HMF	
Bread waste	Freeze-dried, ground, sieved through a 0.2 mm mesh, and stored in an air-tight container at 4 °C.	Microwave heating at 120 °C over SnCl ₄ catalyst at 7.5 and 20 min in the PC/H ₂ O and GVL/H ₂ O (1 : 1 v/v) systems		HMF	~20 mol%			[67]
Bread waste	Freeze-dried, stored in air-tight storage containers at 4 °C in the dark after grinding and sieving	Microwave heating in the medium of DMSO/DIW solution (3:1, v/v) using biochar catalyst sulfonated		HMF	30.4%			[59]

	through a 0.25-mm-mesh	from concentrated sulfuric acid at 180 °C for 20 min				
Cooked rice and bread crust	Freeze-dried, sieved through a 0.2-mm-mesh, and stored in air-tight storage containers at -4 °C in the dark.	Microwave heating in DMSO/water (1:1 v/v) under metal chloride catalyst (SnCl ₄ , AlCl ₃ , FeCl ₃ or CrCl ₃) at 140 °C for 20 min	HMF	8.1–9.5%	Platform chemicals, synthesis polymers, pharmaceuticals, and fuel	[58]
			Glucose	44.2–64.8%		
Vegetable waste	Stored in air-tight containers at 4 °C after freeze-drying followed by grinding and sieving through a 0.2-mm mesh	Microwave heating with Amberlyst 36 catalyst at 135-150 °C for 5 min in aqueous medium	Levulinic acid	13-17 C mol%	Precursor for pharmaceuticals, plasticizers, and various other additives	[48]
			HMF	17 C mol %		
		Microwave heating with Amberlyst 36 catalyst 120–150°C in DMSO-water (1:1 v/v) mixture				

¹ Hydroxymethylfurfural

Table 2. Specialty chemicals

Food waste	Pretreatment	Treatment approach	Product chemicals	Yield	Application	Reference
Citrus fruit	-	Cold press system extraction. (The peel of fresh fruits was cold-pressed, and then the EO was separated from the crude-extract by centrifugation and stored in sealed glass vials at 4 °C in the dark until used)	Essential oils (e.g., Limonene)	59-85%	Essential oils with antimicrobial activity to improve pasteurization process	[83]
Orange peel	-	Microwave accelerated distillation	Essential oils (e.g., Limonene)	76.7%		[86]
	-	Hydro-distillation		78.5%		
Citrus wastes	-	0.5% (v/v) sulfuric acid hydrolysis at 150°C, fermentation, recovery of ethanol, anaerobic digestion	Ethanol, methane, and limonene	3.1% (ethanol) 0.8%(limonene)	Essential oil, solvent	[151]
Spent coffee ground	Air dry	70 mL of 6 M HCl under stirring at 100 °C overnight; add to 0.2 mM solution of DPPH in methanol	HSCG (hydrolyzed spent coffee ground) as an all-natural polymer with multipotent intrinsic antioxidant properties	31%	Antioxidant biomaterial in biomedical, industrial, and technological applications	[71]
Waste orange peel	-	Microwave irradiation (800 W) at temperatures of 180°C and 200°C	D-limonene, α -terpineol, pectin sugars, mesoporous cellulose	60%	Biochemicals and nanoporous materials	[64]

Waste pomegranate seed	-	Incubation with protease at a concentration of 50 U/g for 14 h, at 45 °C and pH 7.2	Oil, protein, insoluble fibres	22.9% (oil); 13.2% (protein)	Pharmaceutical and cosmetic industries	[116]
Citrus processing waste	Pretreatments at 160 °C for longer than 4 min with steam purging	Simultaneous saccharification and fermentation with dry <i>Saccharomyces cerevisiae</i> yeast at 37 °C for 48 h	Ethanol	30%	Solvent	[41]
Food waste	-	Separate enzymatic hydrolysis and ethanol fermentation	Ethanol	43%	Solvent	[220]
		Simultaneous saccharification and ethanol fermentation		using enzyme and <i>S. cerevisiae</i> at pH 4.5 and 35°C		
Fruit peel waste	-	Cultivation with <i>Aspergillus niger</i> for 7 days at 30 °C in an incubator shaker at 125 rpm.	Invertase	12.5 μ M/ g biomass	Enzyme that catalyzes the hydrolysis of sucrose	[221]
Banana waste	-	Solid substrate fermentation by bacterial consortia (<i>Cellulomonas cartae</i> , <i>Pseudomonas fluorescens</i> , <i>Pseudomonas putida</i> , <i>Bacillus megaterium</i>) at 32 \pm 2°C in incubator for 40 day.	Cellulases	-	Lignolytic and cellulolytic enzyme that convert cellulose into soluble sugars	[222]

Table 3. Commodity chemicals – biofuel

Food waste	Pretreatment	Reaction	Catalyst	M:O ¹ ratio	Temperature (°C)	Time	Biodiesel Yield (%)	Reference
Solid food waste from restaurants	Sample oil extraction using Soxhlet method in a 500 mL Soxhlet apparatus	Pre-esterification	1% (w/w) H ₂ SO ₄	8:1	65	2 h	84-88	[131]
		Transesterification	1.5 (% w/w) KOH	6:1	65	1 h		
Waste cooking oil (containing triglycerides and free fatty acids)	-	Primary esterification	Acid-type grafted fibrous catalysts	10:1 (ethanol: oil; w/w)	50	24 h	~100	[129]
		Subsequent transesterification	Alkaline-type grafted fibrous catalysts			3 h		
Waste palm oil	-	Esterification and transesterification simultaneously	Sulfonated carbon catalyst derived from coconut meal residue	12:1	65-70	8 h	92.7	[139]
Waste cooking oil (WCO)	Activated carbon was added WCO and kept in a shaker flask at 150 rpm for 30 min under room to remove excess FFA	Transesterification	KBr impregnated CaO	12:1	65	1.8h	82.48	[132]
Bakery waste	Fungal hydrolysis of food waste to prepare lipid	Transesterification	KOH	10:1	60	2 h	100	[134]
Waste cooking oil	-	Transesterification	Calcined scallop shell	6:1	65	2 h	86	[133]
Waste cooking oil	Removal of suspended solid materials	Transesterification	Copper doped zinc oxide nanocomposite	8:1 (v:v)	55	50 min	97.71	[138]
Waste cooking oil	Separation to remove non-oil components	Esterification	Ferric sulfate	10:1	95	4 h	97.22	[223]
		Transesterification	Potassium hydroxide					

¹ Methanol to oil ratio.

Table 4. Commodity chemicals – biogas

Food waste	Pretreatment	Treatment approach	Product chemicals	Yield	Application	Reference
Citrus wastes	-	0.5% (v/v) sulfuric acid hydrolysis at 150 °C, fermentation, recovery of ethanol, anaerobic digestion	Ethanol, methane, and limonene	3.2% (methane)	Biogas	[151]
Food waste leachate	Collection leachate from food waste recycling facilities	Anaerobic digestion at 35 °C for 20 days	Methane	70%	Biodiesel	[143]
Canteen based food waste	-	Electrofermentation in the reactors operated in fed batch mode with suspended growth configuration and constant mixing (160 rpm) using a magnetic stirring at ambient temperature (28 ± 2 °C).	Volatile fatty acids, biogas (biohythane)	23-30% (biogas)	Biogas	[26]
Mixed food waste	Chemical hydrolysis with 2 M HCl and incubated at room temperature for 24 h;	An integrated bio-refinery approach including cultivation of <i>R. glutinis</i> , anaerobic digestion by activated sludge	<i>R. glutinis</i> biomass, FAME (palmitic, stearic and oleic acids), biogas (methane)	8.51 (fatty acids/°); 0.411 (biogas/m ³ kg ⁻¹ VS)	Biogas	[141]
	Thermal hydrolysis by autoclaving procedure at 121 °C and 1 atm for 30 min			7.60 (fatty acids/°); 0.587 (biogas/m ³ kg ⁻¹ VS)		

	Thermo-chemical hydrolysis beginning with the acidic hydrolysis and ending with the thermal treatment			6.36 (fatty acids/%); 0.493 (biogas/m ³ kg ⁻¹ VS)			
Kitchen waste	-	Anaerobic digestion at 55 °C for 19-36 days	Methane	6.5 L L ⁻¹	Biogas	[142]	
	Acid pretreatment			2.2 L L ⁻¹			
	Thermal pretreatment			7.2 L L ⁻¹			
	Thermo-acid pretreatment			7.7 L L ⁻¹			
	Pressure-depressure pretreatment			8.8 L L ⁻¹			
	Freeze-thaw pretreatment			8.3 L L ⁻¹			
Mixed food waste	Enzymatic pretreatment in the fungal mash rich in hydrolytic enzymes produced by solid state fermentation (SSF) of waste cake	Anaerobic digestion with inoculum and anaerobic biomedium on an orbital shaker operated at 35 °C and 150 rpm	Methane	440 ml/g	Biogas	[224]	
Food waste	-	Anaerobic co-digestion with an optimum food waste (FM) to cattle manure (CM) ratio of 2	Methane	388 mL/g-VS	Biogas	[145]	
Food waste	Mixing and grinding food scraps with water in a food processor to get a paste	Anaerobic digestion using anaerobic digester sludge (ADS) as inoculum at ratios of 0.42, 1.42, and 3.0 g chemical oxygen demand/ volatile solids	Methane	0.42	Biogas	[144]	
				1.42			69%
				3.0			90%
				57%			

Food waste and cheese whey	-	Acidogenic fermentation using anaerobic sludge as inoculum at different combinations of substrate to inoculum (S/I) ratio (2, 4, and 6) and initial pH (5, 7, and 9)	Hydrogen, metabolites (acetate, butyrate, propionate, valerate, lactate, and ethanol) productions.	93.1 m ³ t ⁻¹ VS (H ₂); 58 g/L (metabolites)	Biogas	[43]
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Table 5. Commodity chemicals – biochar

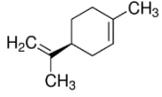
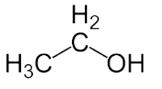
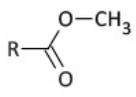
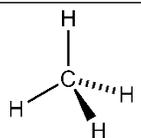
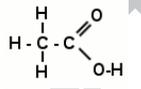
Food waste	Pretreatment	Treatment approach	Product chemicals	Yield	Application	Reference	
Food waste containing raw vegetables, fruits and peelings	Oven-dried at 105 °C for over 24 h then ground by means of a cutting mill pulverisette with mesh size of 9 mm	Torrefaction between 225 and 300°C for 1 and 3 h at a fixed heating rate of 15 °C /min.	Bio-oil and biochar	9.68-28.45(bio-oil); 48.32-85.16 (biochar)		[170]	
Vegetable waste	Air dried	Torrefaction at 200°C and slow pyrolysis at 500 °C, heating rate 7 °C min ⁻¹	biochar		Soil amendment to immobilize heavy metals	[126]	
Food waste, rice waste	-	Pyrolysis at 500 °C for 60 min in a muffle furnace	Biochar		Carbon sequestering additive in mortar	[127]	
Food wastes containing grains, vegetables, fruits, and meat and fish	Dried at 80 °C for 48 h and then ground into powder form and added with 1%, 3%, 5% NaCl	Pyrolysis for 1 h and 30 min with 10 L/min nitrogen at	300 °C	Biochar	56	Soil amendment	[171]
			400 °C		38		
			500 °C		32		
Food waste	The dry sample was crushed using a cone crusher and sieved through 750 mm	Torrefaction at a constant residence time of 40 min and 10 °C/min heating rate at	200 °C	Biochar	89.5	Biomass co-firing	[169]
			225 °C		86		
			250 °C		65		
			275 °C		60		
			300 °C		50		

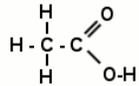
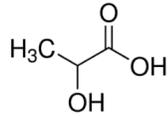
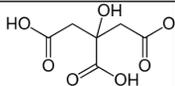
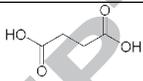
Table 6. Niche chemicals

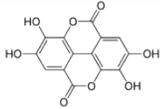
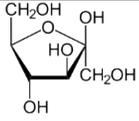
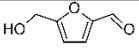
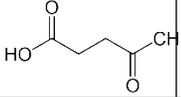
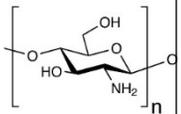
Food waste	Pretreatment	Treatment approach	Products	Yield	Application	Reference
Food waste containing rice, noodles, meat, and vegetables	Incubation with <i>A. awamori</i> and <i>A. oryzae</i> for 5 days at 30 °C	Fungal hydrolysis at 55 °C at pH 4.0 - 4.5 for 24 h	Glucose, free amino nitrogen, and phosphate	31.9%, 0.28%, 0.38%	Nutrient recovery or culture medium for microalgae cultivation.	[190]
Restaurant and bakery food waste	Suspended in water and autoclaved for 30 min at 121 °C	Hydrolysis with Stargen 002, Dupont (amylolytic enzyme preparation) to produce a hydrolysate rich in sugars, and with Fermgen, Dupont (proteolytic enzyme preparation) for 24 h at 50 °C and pH 4.5 to produce a hydrolysate rich in amino acids/peptides	Carbohydrates and amino acids	-	<i>Galdieria sulphuraria</i> 074G (Rhodophyta) growth for phycocyanin synthesis	[200]
Persian Gulf shrimp waste	Chitin extraction by deproteinization with 2% (w/w) sodium hydroxide solution for 2 h at 80 °C; demineralization with 10% (w/w) acetic acid 40:1 (v/w) for 4 h at 50 °C	Microwave irradiation at 50% NaOH solution, 720 W microwave power and 20 s reaction time	Chitosan	19.47%	Medicine, pharmaceutical, biomedical, biological, agriculture, environment and in food technology	[178]
Shrimp waste	Incubation at 40 °C for 4 h with constant stirring and thermal and organic extraction with an acetone:ethanol mixture (1:1 v/v) at 40 °C for 2 h with	Demineralization with lactic acid (75.6 g/L), ratio 1:3 (w/v) for 36 h at 21 °C; deproteinization by enzymatic hydrolysis with <i>Viscozyme L</i> (pH 4.5, 50 °C) and <i>Alcalase 2.4 L</i> (pH 8.5, 50 °C) (enzyme inactivation at 90 °C for 10 min); deacetylation with 10%	Chitosan	-	Antimicrobial packaging with the food and pharmaceutical industries	[186]

	constant stirring to get chitinous material	NaOH solution, ratio 1:7 (w/v) for 72 h at 100 °C with constant stirring				
Shrimp waste	Chitin extraction by deproteinization with fish proteases (incubation for 3 h at 40 °C, and stopped by heating the solution at 90 °C for 20 min to inactivate the enzyme) and demineralization with HCl in 1:10 (w/v) ratio for 6 h at 25 °C under constant stirring	Deacetylation of chitin to chitosan with 50 % (w/v) NaOH at 80°C for 4 h	Chitosan	14.65%	Treatment of unhairing effluents	[172]
Shrimp shell	Shells were washed and boiled in water for 1 h to remove the tissue, followed by drying in an oven at 160 °C for 2 h	Feedstock demineralization with HCl and deproteinization with NaOH from 10 to 400 min at 20 to 100 °C	Chitin	-	Bioactive material of antimicrobial activity	[188]
		Decolourant chitin deacetylation with NaOH at 90-100 °C under constant stirring for 3-5 h	Chitosan			
		Chitin is hydrolyzed by 50 ml 7 N HCl at 70 °C for 3 h.	N-acetyl chito-oligosaccharides			
		Chitosan is hydrolyzed by 50 ml HCl 6.27 N at 56 °C for 3 h	Chito-oligosaccharides			

Table 7. Assessment of food waste derived chemicals

Chemicals	Valorization technology	Molecular structure	Product value (USD/kg)	Microbes/Catalyst	Key parameters	Application	References
Essential oil	Cold press system extraction, hydrolysis, incubation		11-20.5	H ₂ SO ₄	Pressure, temperature, solvent, pretreatment	Microbial activity	[64, 83, 116, 151]
Ethanol	Fermentation, SSF		0.38	<i>Saccharomyces cerevisiae</i>	Microbial dynamics, pretreatment	Solvent, biofuel	[41, 151, 220]
Enzyme	Cultivation with bacteria				Microbial dynamics	Catalyst	[221, 222]
Biodiesel	Transesterification, esterification		1.08-1.48	Activated carbon, KOH, calcined callop shell, copper doped zinc oxide nanocomposite	Catalyst Time, temperature	Alternative for petroleum	[129, 131, 139]
Methane	Anaerobic digestion		0.106 (USD/m ³)	Anaerobic sludge, <i>R. glutinis</i> , <i>A. awamori</i> , cattle manure	Microbial dynamics	Natural gas	[26, 43, 141-145, 151, 224]
Biochar	Torrefaction, pyrolysis	-	2.58	-	Temperature, medium, rate, time	Soil amendment, absorber, catalyst, carbon sequestration	[127, 169-171]
VFA (volatile fatty acid)	Acidogenic fermentation, acidogenic fermentation, SSF ¹ ,		0.384 (minimum selling price)	Mixed consortium obtained from sewage treatment plant, granular	Temperature, pH, HRT ³ , pretreatment methods	Bioplastics, bioenergy and the biological removal of	[26, 43, 225, 226]

	SHF ² , hydrolysis			sludge		nutrient from wastewater	
Lactic acid	Fermentation Electrofermentation		1.38-1.87	Waste activated sludge, <i>Sporolactobacillus inulinus</i> YBS1-5	Microbial dynamics	Acidulant, flavor enhancer, shelf-life extender in foods and beverages; antimicrobial properties, starting material for polylactic acid (PLA), a biodegradable polymer	[25, 35, 47, 182]
Citric acid			1.04-1.65	<i>Aspergillus niger</i>	Microbial dynamics, pretreatment	Food acidulant, ingredients in detergents and cleaners, personal care products, pharmaceuticals, and industrial applications, control of the growth of microorganisms, adjust acidity (pH), provide sourness and tartness, and enhance flavors.	[219]
Succinic acid	Fermentation		121-176	<i>A. awamori</i> , <i>A. oryzae</i> , <i>A. lipolytica</i> , <i>A.</i>			[36, 44, 45]

Ellagic acid	Chemical hydrolysis and extraction		25-30	<i>succinogenes</i> <i>Saccharomyces</i>	Reagent, temperature	Natural phenol antioxidant antiproliferative and antioxidant properties	[46]
Soluble sugars (fructose and glucose)	Chemical hydrolysis, microwave heating		0.9-5	H ₂ SO ₄ , HCl, NaOH, H ₂ SO ₃	Reagent, temperature, pretreatment	Precursor, polymer, medical uses	[42, 58, 66, 200]
HMF ⁴	Microwave heating		1.03	metal chloride catalyst (e.g., SnCl ₄ , AlCl ₃ , or FeCl ₃), sulfonated biochar	Temperature, solvent, time, catalyst	Precursors of medicine, polymers, solvents, biofuel	[17, 54, 55, 58, 59]
Levulinic acid	Microwave heating		5-8	Amberlyst	Feedstock choices, associated plant locations, solvent	Replacements for petroleum-based products	[48, 217]
Chitosan	Demineralization and deacetylation		21-52.3	<i>Aspergillus awamori</i> , <i>Aspergillus oryzae</i> , <i>Galdieria sulphuraria</i> 074G (Rhodophyta), NaOH, HCl	Temperature, reagent, enzyme activity	Medicine, pharmaceutical, biomedical, agricultural	[172, 178, 186, 188]

¹ simultaneous sacchrification and fermentation

² separate hydrolysis and fermentation

³ hydraulic retention time

⁴ hydroxymethylfurfural

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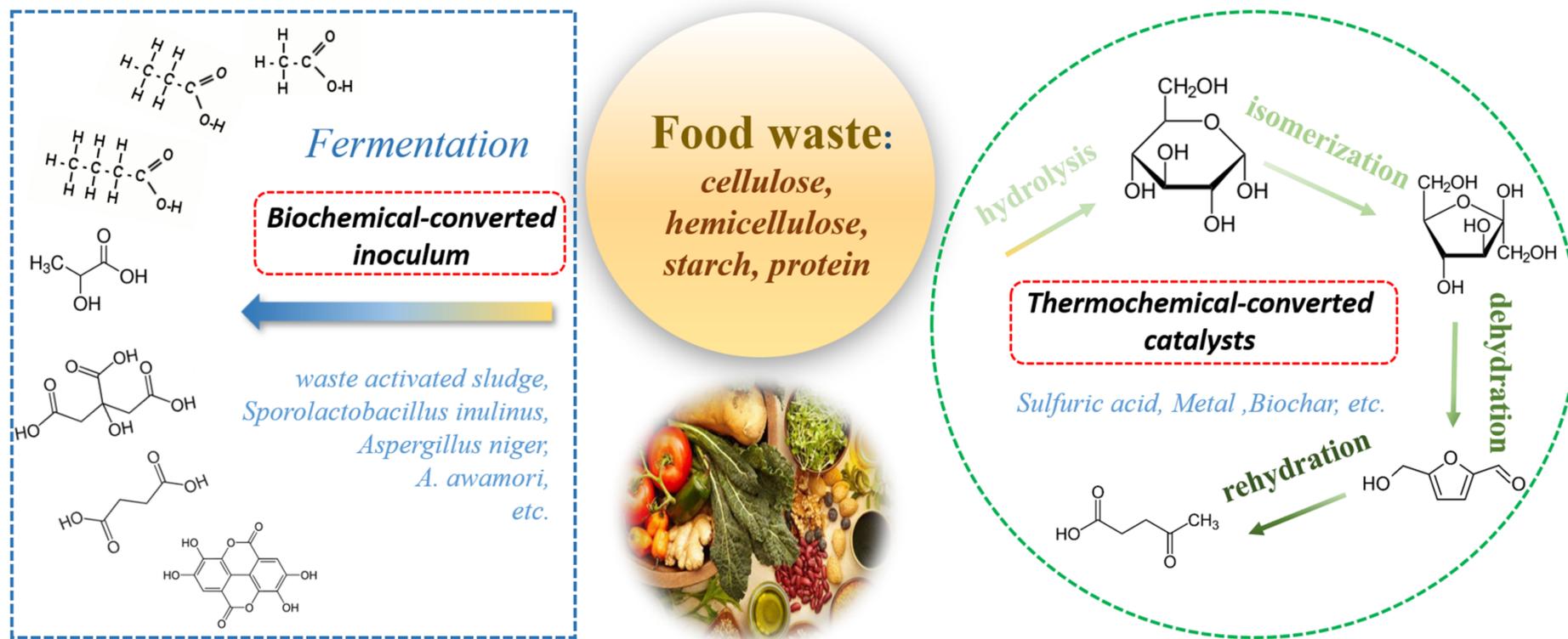


Figure 1. Consumer chemicals derived from food wastes.

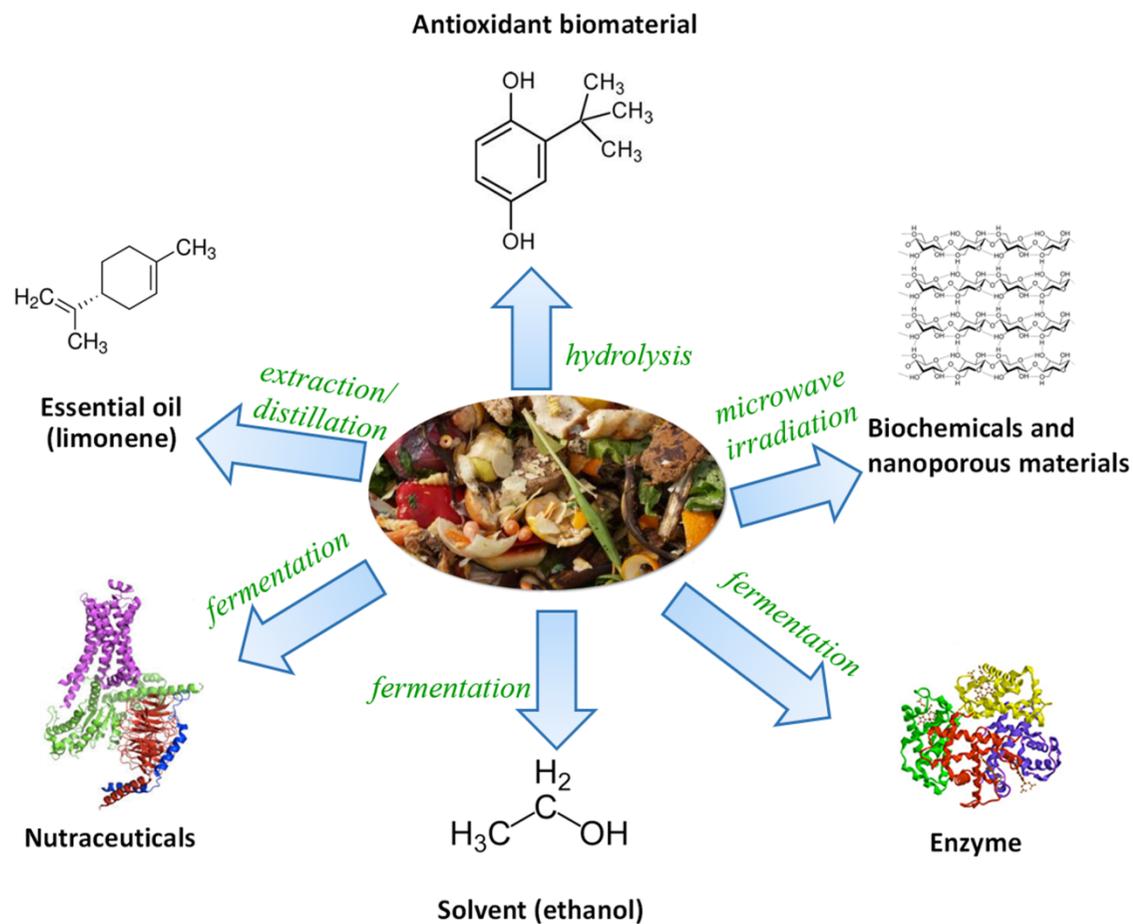


Figure 2. Specialty chemicals derived from food wastes.

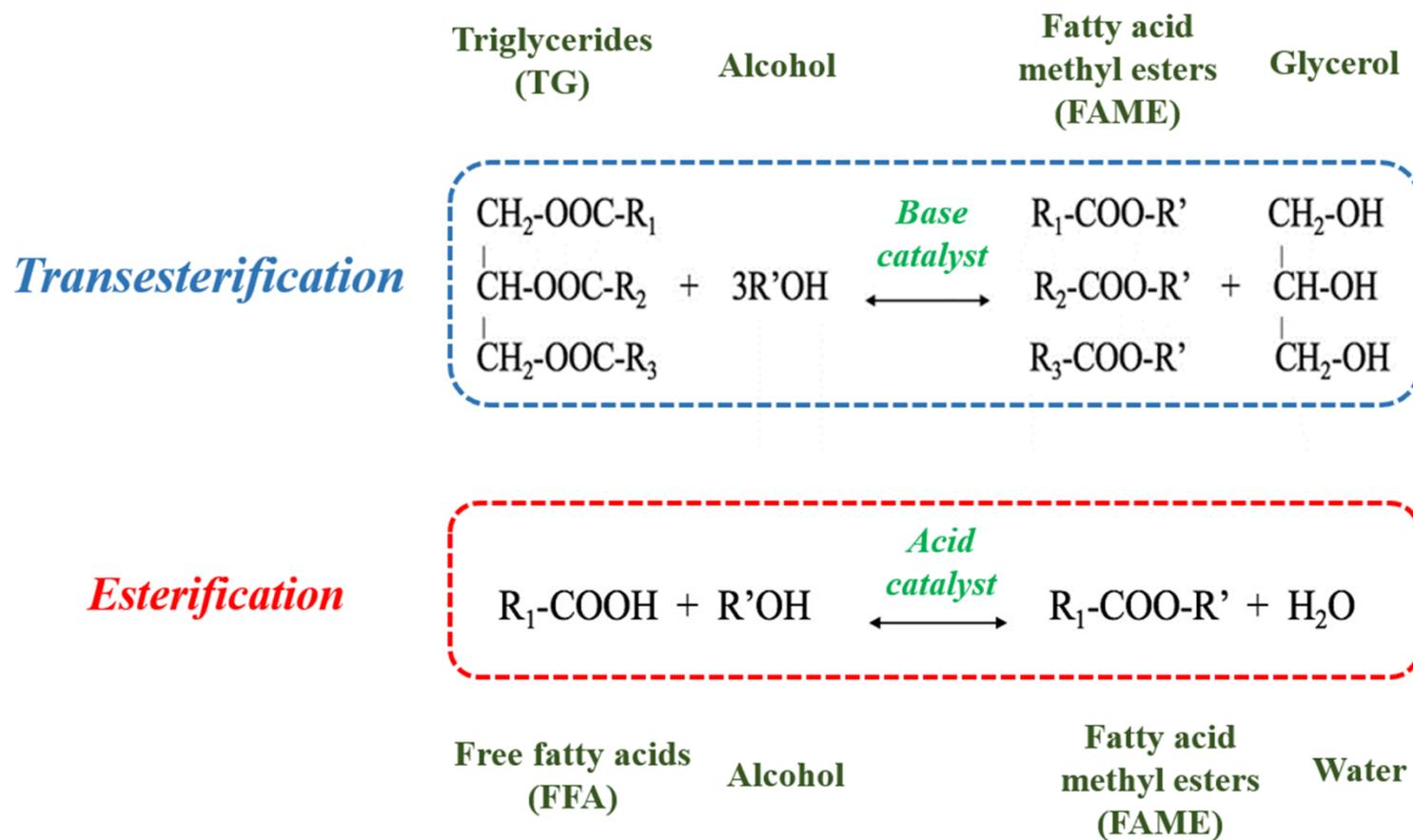


Figure 3. Transesterification and esterification.

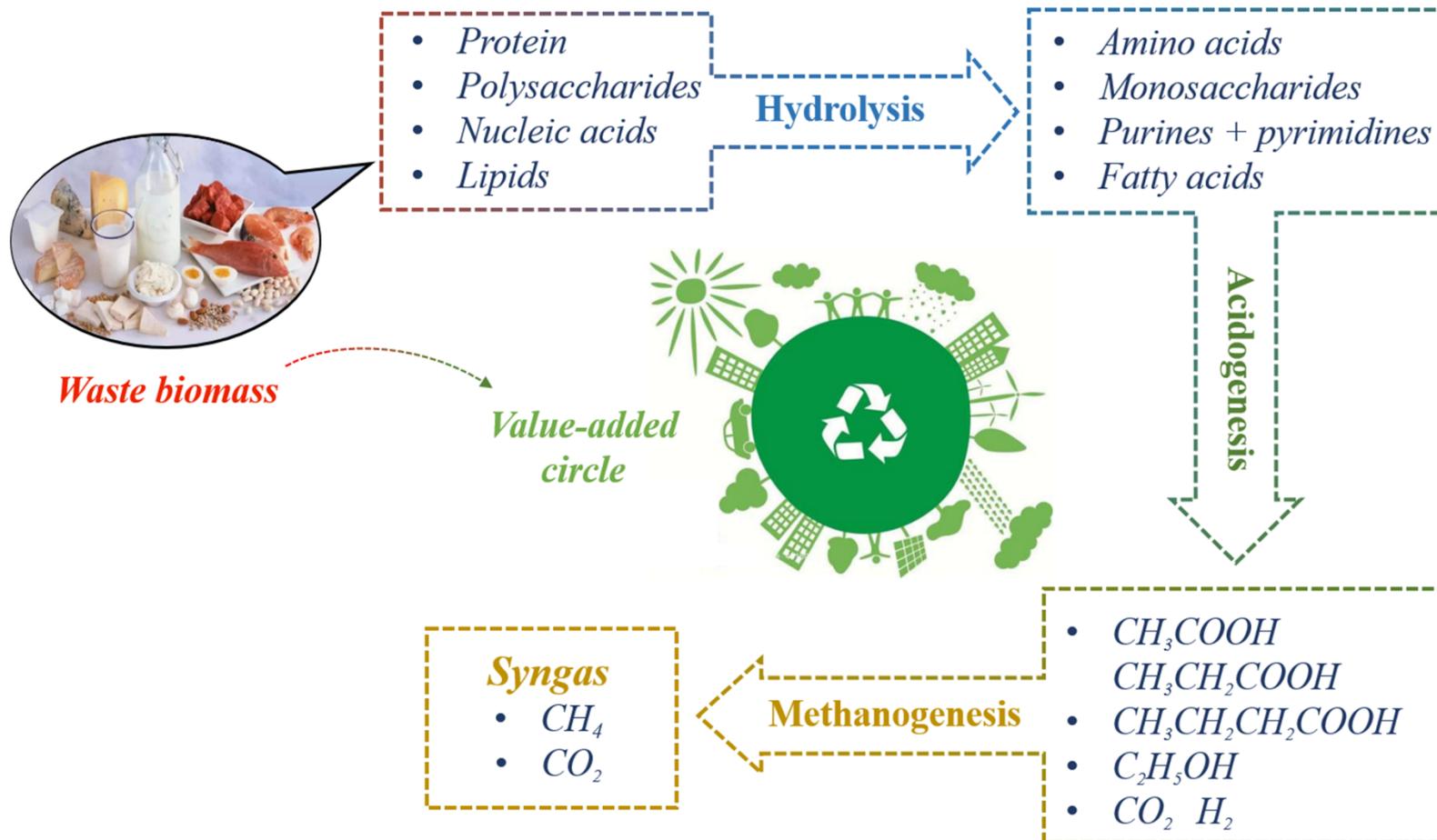


Figure 4. Process pathways of biomass anaerobic digestion.

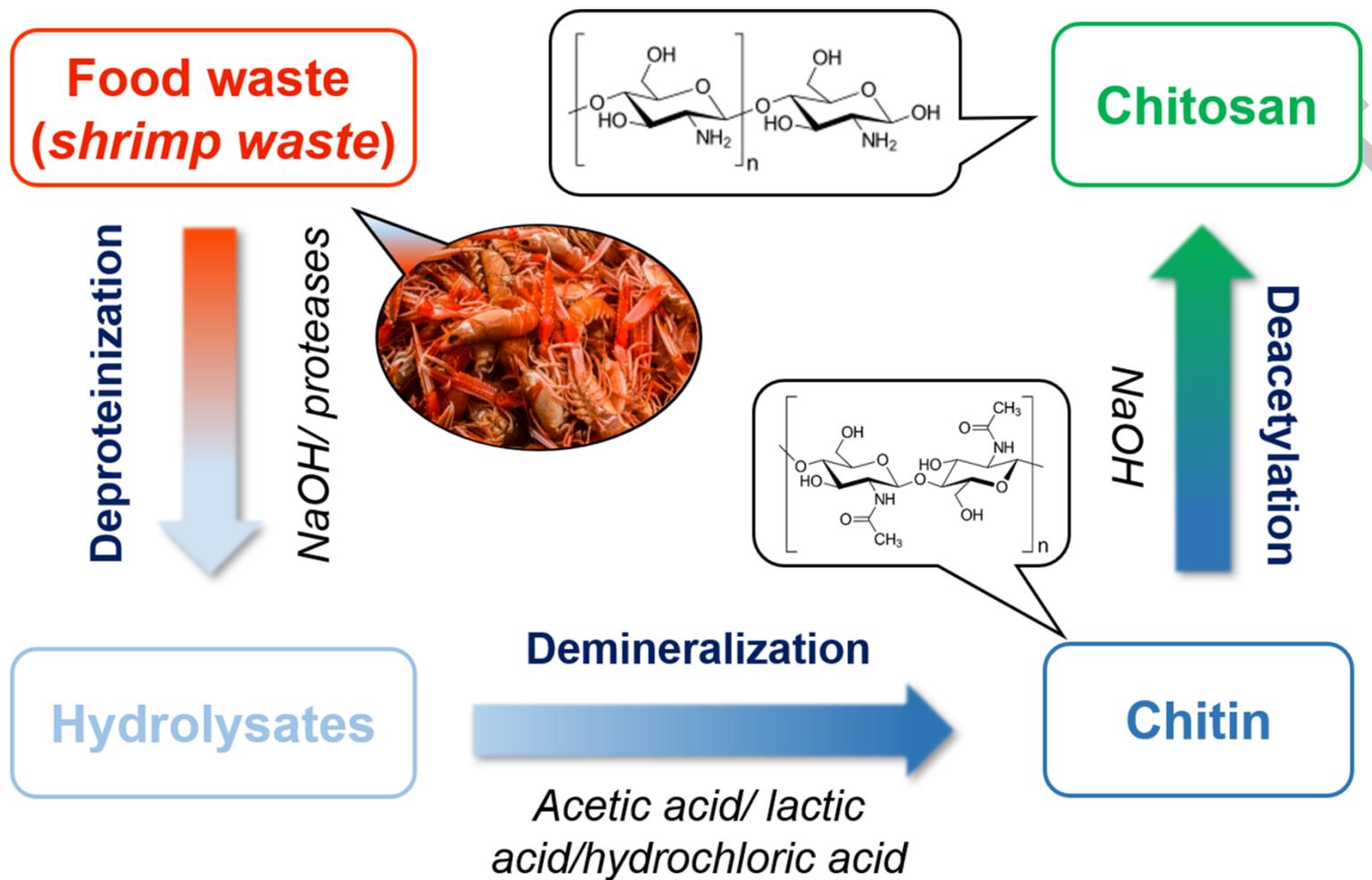
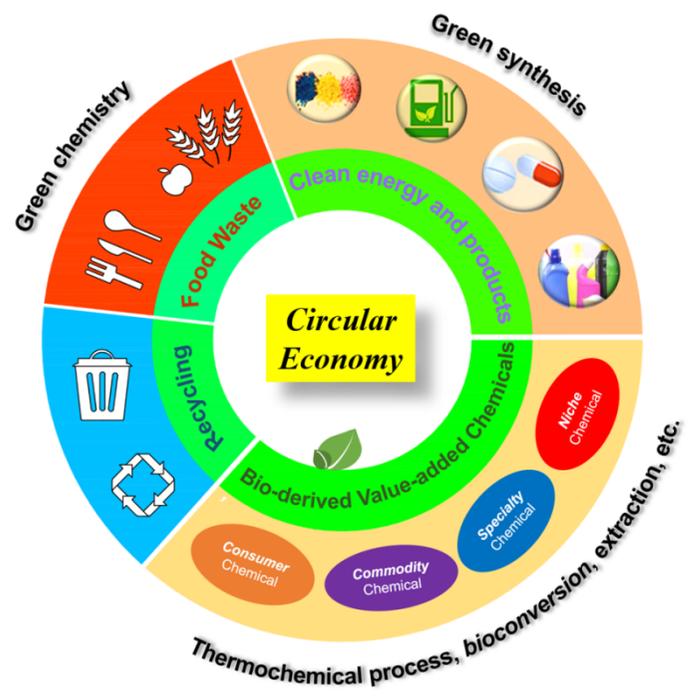


Figure 5. Conversion from shrimp waste to chitosan.

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Highlights:

- Food waste valorization is a profitable and sustainable waste management option.
- Consumer, specialty, commodity, and niche chemicals can be refined or recovered from food waste.
- Physical, chemical, and biological technologies improve outcomes of food waste conversion.
- Integrated biorefinery of food waste into a wide spectrum of value-added products is promising.