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Review article

Bioconversion of food waste to energy: A review

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ABSTRACT

According to Food and Agricultural Organization (FAO), one third of food produced globally for human consumption is lost along the food supply chain. In many countries food waste are currently landfilled or incinerated together with other combustible municipal wastes for possible recovery of energy. However, these two approaches are facing more and more economic and environmental stresses. Due to its organic- and nutrient-rich composition, theoretically food waste can be utilized as a useful resource for production of biofuel through various fermentation processes. So far, valorization of food waste has attracted increasing interest, with biogas, hydrogen, ethanol and biodiesel as final products. Therefore, this review aims to examine the state-of-the-art of food waste fermentation technologies for renewable energy generation.

Contents

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1. Introduction

Food waste (FW) is organic waste discharged from various sources including food processing plants, and domestic and commercial kitchens, cafeterias and restaurants. According to FAO [1], nearly 1.3 billion tonnes of foods including fresh vegetables, fruits, meat, bakery and dairy products are lost along the food supply chain. The amount of FW has been projected to increase in the next 25 years due to economic and population growth, mainly in Asian countries. For example, the annual amount of urban FW in Asian countries could rise from 278 to 416 million tonnes from 2005 to 2025 [2]. Typical foods wasted in Asia–Pacific countries and around the world are summarized in Table 1 [3].

FW is traditionally incinerated with other combustible municipal wastes for generation of heat or energy. It should be realized that FW indeed contains high level of moisture and this may lead to the production of dioxins during its combustion together with other wastes of low humidity and high calorific value [8]. In addition, incineration of FW can potentially cause air pollution and loss of chemical values of FW. These suggest that an appropriate management of FWs is strongly needed [9]. FW is mainly composed of carbohydrate polymers (starch, cellulose and hemicelluloses), lignin, proteins, lipids, organic acids, and a remaining, smaller inorganic part (Table 2). Hydrolysis of carbohydrate in FW may result in the breakage of glycoside bonds with releasing polysaccharides as oligosaccharides and monosaccharides, which are more amenable to fermentation. Total sugar and protein contents in FW are in the range of 35.5–69% and 3.9–21.9%, respectively. As such, FW has been used as the sole microbial feedstock for the development of various kinds of value-added bioproducts, including methane, hydrogen, ethanol, enzymes, organic acid, biopolymers and bioplastics [10–19]. Fuel applications ($200–400/ton biomass) are usually creating more value compared to generating electricity ($60–150/ton biomass) and animal feed ($70–200/ton biomass). Due to inherent chemical complexity, FW also can be utilized for production of high-value materials, such as organic acids, biodegradable plastics and enzymes ($1000/ton biomass) [20]. However, it should be noted that the market demand for such chemicals is much smaller than that for biofuels [21]. Therefore, this article is intended to review the FW valorization techniques that have been developed for the production of various kinds of biofuels from FW, such as ethanol, hydrogen, methane and biodiesel.

2. Ethanol production

Recently, global demand for ethanol has increased due to its wide industrial applications. Ethanol is mainly used as a chemical feedstock to produce ethylene with a market demand of more than 140 million tonnes per year, a key material for further production of polyethylene and other plastics. As such, bioethanol produced from cheap feedstocks has gained interest [36,37]. Traditionally, bioethanol is produced from cellulose and starch rich crops, e.g. potato, rice, and sugar cane [38]. Starch can be easily converted to glucose by commercial enzymes and subsequently fermented to ethanol particularly by *Saccharomyces cerevisiae*. However, the hydrolysis of cellulose is more difficult. FW hydrolysis becomes much harder if large quantities of cellulosic feedstocks are present in FW. Use of abundant & cheap wastes such as lignocellulosic, municipal and FWs has been explored as alternative substrates for ethanol production [39,40].

2.1. Pre-treatments

Harsh pre-treatment may not be necessary during the conversion of FW to ethanol prior to enzymatic hydrolysis [27,41]. Instead, autoclave of FW before fermentation is often required for improving product yield and purity, but at the cost of energy and water consumption. It should be noted that thermal treatment may lead to partial degradation of sugars and other nutritional components, as well as side reactions (e.g. the Maillard reaction) through which the amounts of useful sugars and amino acids are reduced [12]. Moreover, fresh and wet FWs appear to be more effective than rewetted dried FW [42]. This is mainly due to the decreased specific surface area of the dried substrate, resulting in a decrease in the reaction efficiency between the enzymes and substrate. Therefore, the utilization of FW without a drying pretreatment is preferred as long as microbial contamination is manageable. Without thermal sterilization, acidic condition is needed to prevent microbial contamination and putrefaction [16,43]. As such, acid-tolerant ethanol producing microorganisms such as *Zymomonas mobilis*, have been employed for the fermentation of FW [28,44].

2.2. Saccharification

The conversion efficiency of FW to ethanol depends on the extent of carbohydrate saccharification as yeast cells cannot ferment starch or cellulose directly into bioethanol [45]. A mixture of α-amylase, β-amylase, and glucoamylase of various origins is more effective for substrate with higher molecular weight. Pullulanase has also been added to the list of saccharifying enzymes recently [46]. As a direct endo-acting debranching enzyme, pullulanase can specifically catalyze the hydrolysis of α-1,6-glucosidic linkages of branched polysaccharides (e.g. pullulan, dextrin, amylopectin, and related polymers), resulting in release of linear oligosaccharides. Small fermentable sugars (e.g. maltose, amylose, glucose, maltose syrups, and fructose) can be produced in saccharification process, whereas cellulases and xylanases including endoglucanase, exoglucanase, β-glucosidase and β-xylosidase, can also be employed to improve the hydrolysis of cereals for conversion of starches to glucose [47].

Table 3 shows the glucose and ethanol yields of different types of FWs. The highest glucose concentration of about 65 g reducing sugar (RS)/100 g FW was obtained with α-amylase at a dose of 120 U/g dry substrate, glucoamylase (120 U/g dry substrate), cellulase (8 FPU/g dry substrate) and β-glucosidase (50 U/g dry substrate) [32]. In a study of Hong and Yoon [48], a mixture of commercial enzymes consisting of α-amylase, glucoamylase, and protease resulted in60 g RS/100 g FW.

2.3. Process configurations

High glucose yield is achievable by increasing enzyme concentration and temperature at different solid loads, agitation speeds and hydrolysis times in the saccharification processes [50,57–59]. High glucose concentration may result in catabolite repression of the enzymes [53]. Therefore, fed-batch and simultaneous saccharification and fermentation (Ssf) methods have been developed for achieving high ethanol yield from FW [53,60].

The fed-batch culture has been commonly employed for the production of high concentration reducing sugars which can be further fermented to ethanol [61]. Compared to batch culture, Yan and Yao [62] found that saccharification and subsequent ethanol fermentation were both improved significantly using fed-batch configuration, e.g. the glucose bioconversion yield reached 92% of its theoretical value.

Alternatively, Ssf can be deployed to mitigate risk of catabolite repression. This combines enzymatic hydrolysis and ethanol fermentation into a single operation for keeping the concentration of enzymatically-produced glucose at a low level so as to mitigate inhibition to enzymatic hydrolysis [63]. This combined process can

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Table 1
Typical wasted foods in several Asia–Pacific countries and around the globe.

Waste (KT)	World	Asia	South-eastern Asia	Australia	Cambodia	China	Indonesia	Japan	Malaysia	New Zealand	North Korea	Philippines	South Korea	Thailand	Vietnam
Cereal	95,245	52,374	12,599	1380	506.1	18,990	4.6	413.4	183.4	28.6	253.0	215.7	628.4	1999	2,706
Rice	26,738	22,668	10,792	0.4	506.0	6046	3.3	139.4	50.2	NR	NR	162.7	458.2	1997	2,478
Sugar	459.9	188.9	151.7	93.6	NR	0.4	NR	20.8	NR	NR	NR	NR	NR	151.7	NR
Pulses	2735	1134	241.6	36.0	0.9	142.3	38.0	7.1	NR	1.2	10.3	NR	2.0	7.0	8.6
Oil crops	18,424	13,590	2515	3.9	3.8	9017	2238	69.6	1.4	0.1	15.2	NR	12.7	159.4	30.5
Vegetable oil	616.1	269.3	116.9	NR	NR	133.4	NR	13.0	116.9	NR	NR	NR	NR	NR	NR
Vegetables	81,441	59,949	2710	54.1	46,9	39,286	755.0	1224	64.8	73.2	414.2	242.5	1555	339.5	777.2
Beans	1049	447.3	218.1	1.1	0.9	49.1	37.2	6.5	NR	0.2	10.3	2.2	1.6	3.7	5.2
Onions	5891	3877	186.0	14.6	NR	2107	99.9	68.1	NR	NR	3.5	6.9	139.5	5.5	22.7
Peas	412.7	145.1	2.1	7.2	NR	39.9	NR	0.4	NR	1.1	NR	0.3	0.1	0.1	NR
Tomatoes	12,874	7415	104.2	NR	NR	3181	85.3	100.7	1.6	9.5	8.3	9.9	57.6	7.3	NR
Potatoes	62,229	12,912	466.1	23.6	NR	7501	250.0	177.0	NR	10.9	156.0	34.4	95.3	9.0	83.3
Fruits	53,796	28,328	4529	30.9	30.5	8323	2706	749.0	89.1	43.4	153.5	1,183	276.6	786.4	531.0
Apples	5742	4116	13.2	5.9	NR	3192	3.1	84.6	NR	22.4	72.8	3.8	49.0	1.2	5.1
Banana	13,532	8544	1896	5.4	7.8	949.3	637.4	213.0	56.1	7.6	NR	901.3	NR	153.7	137
Coconut	3038	2488	2159	NR	NR	20.5	2066	NR	1.3	NR	NR	7.8	NR	69.1	0.9
Pineapple	1829	579	431.9	NR	2.2	97.7	NR	15.4	NR	0.3	NR	109.9	2.8	189.5	50
Coffee	105.0	33.3	28.3	NR	NR	0.03	20.9	NR	0.6	NR	NR	6.4	NR	NR	NR
Milk	16,560	10,887	183.3	NR	1.6	1447	45	NR	3.8	164.8	4.9	NR	42.4	25.2	9.5
Cream	33.9	0.1	NR	NR	NR	0.1	NR	NR	NR	NR	NR	NR	NR	NR	NR
Butter	84.0	1.7	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	23.1	NR
Animal fats	174.1	1.8	NR	NR	NR	0.1	NR	NR	NR	NR	NR	NR	NR	NR	NR
Meat	1184	183.2	NR	NR	NR	NR	NR	107.2	NR	NR	NR	NR	107.2	23.1	NR
Offal	63.0	19.6	NR	8.7	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Poultry meat	97.5	61.2	NR	NR	NR	NR	NR	34.5	NR	NR	NR	NR	NR	23.1	NR
Annual waste production per capita (T)	0.184	NR	0.130	0.277	0.173	0.061	0.130	0.129	0.113	0.280	0.211	0.130	0.098	0.130	0.130
Population (millions)	7067	4175	610	22.9	14.5	1354	237.6	127.5	29.6	4.5	24.6	92.3	50.0	65.9	88.8
Total FW (MT)	1300[a]	278[b]	⩾793[a]	⩾6.34[a]	2.50[c]	82.80[d]	⩾30.90[a]	16.40[d]	3.36[a,e]	⩾1.25[a]	5.19[d]	⩾12.00[a]	4.91[d]	⩾8.6[a]	⩾11.55[a]

FW, food waste; T, ton; KT, kilotons; MT, million tonnes; NR, not reported.
[a] Gustafsson, Wills [5].
[b] Melikoglu, Lin [3].
[c] Seng, Kaneko [6].
[d] OECD [7].
[e] Noor, Yusuf [8].

Table 2
Composition of mixed food waste.

Moisture	Total solid	Volatile solid	Total sugar	Starch	Cellulose	Lipid	Protein	Ash	Reference
79.5	20.5	95.0	NR	NR	NR	NR	21.9	NR	[10]
84.1	15.9	95.6	NR	NR	NR	NR	NR	NR	[22]
80.0	20.0	93.6	NR	NR	NR	NR	NR	1.3	[23]
85.0	15.0	88.5	NR	NR	15.5	8.5	6.9	11.5	[19]
79.1	20.9	93.2	NR	NR	NR	NR	NR	NR	[24]
75.9	24.1	NR	42.3	29.3	NR	NR	3.9	1.3	[25]
87.1	12.9	89.5	NR	NR	NR	NR	NR	NR	[26]
80.8	19.2	92.7	NR	15.6	NR	NR	NR	NR	[18]
80.3	19.7	95.4	59.8	NR	1.6	15.7	21.8	1.9	[27]
82.8	17.2	89.1	62.7	46.1	2.3	18.1	15.6	NR	[28]
75.2	24.8	NR	50.2	46.1	NR	18.1	15.6	2.3	[28]
85.7	14.3	98.2	42.3	28.3	NR	NR	17.8	NR	[29]
82.8	17.2	85.0	62.7	46.1	2.3	18.1	15.6	NR	[30]
61.3	38.7	NR	69.0	NR	NR	6.4	4.4	1.2	[31]
64.4	35.6	NR	NR	NR	NR	8.8	4.5	1.8	[32]
81.7	18.3	87.5	35.5	NR	NR	24.1	14.4	NR	[33]
81.5	18.5	94.1	55.0	24.0	16.9	14.0	16.9	5.9	[34]
81.9	14.3	98.2	48.3	42.3	NR	NR	17.8	NR	[35]

Total solid, total sugar, starch, cellulose, lipid, protein and ash contents were given in wt% on the basis of dry weight. Volatile solid contents were given as the %VS ratio on total solid basis. NR: not reported.

Table 3
Ethanol production from food wastes.

Waste	Method	Vessel type	Pretreatment	Microorganism	Duration (h)	Y (g RS/100 g FW)	Y (g/g FW)	Y (g/g RS)	P (g/L h)	Reference
Bakery waste	Simultaneous	14 L fermenter	None	*S. cerevisiae*	14	54	0.25	0.46	NR	[41]
FW	Repeated batch simultaneous	1 L fermenter with 0.8 L working vol.	None	*S. cerevisiae* ATCC26602	264	12.3	0.06	0.5	3.7	[49]
Mandarin waste, banana peel	Simultaneous	500 mL flask	Drying, steam explosion	*S. cerevisiae Anr*, *Pachysolen tannophilus*	24	25.2	0.11	0.4	NR	[50]
FW	Separate	500 mL flask 100 mL working vol.	None	*S. cerevisiae* KA4	16	23.4	0.12	0.49	NR	[22]
FW	Simultaneous	Flask with 100 g FW	None	*S. cerevisiae*	48	11.25	0.08	NR	NR	[49]
FW	Separate continuous	Tower shaped reactor, 0.45 L working vol.	LAB spraying	*S. cerevisiae* strain KF-7	15	11.7	0.03	0.26	24	[27]
FW	Simultaneous	Flask with 100 g FW	None	*S. cerevisiae*	67.6	34.8	0.23	NR	NR	[28]
FW	Continuous simultaneous	Fermenter with 4.3 kg FW	LAB spraying	*S. cerevisiae* KF7	25	36.4	0.09	0.24	17.7	[16]
FW	Simultaneous	1 L fermenter with 0.8 L working vol.	None	*S. cerevisiae* KRM-1	48	8.9	0.06	NR	10.08	[9]
FW	Repeated batch simultaneous	250 mL flask 150 mL working vol.	None	*Zymomonas mobilis* GZNS1	14	15.4	0.07	0.49	10.08	[30]
FW	Simultaneous	250 mL flask 200 mL working vol.	None	*S. cerevisiae*	48	60	0.36	0.22	NR	[48]
FW	Separate	5 L fermenter with working volume of 3 L	None	*S. cerevisiae*	24	27	0.16	NR	1.18	[51]
FW	Synchronous saccharification	Fermenter with 200 g FW	None	*Saccharomyces italicus* kJ	352	12.5	NR	NR	2.24	[52]
Mandarin waste	Simultaneous	100 mL baffled flasks	drying	*S. cerevisiae*	15	52	0.34	NR	3.5	[53]
Banana peels	Simultaneous	100-mL baffled flasks	drying	*S. cerevisiae*	15	37.1	0.32	0.43	2.3	[54]
FW	Separate	250 ml flask 100 mL working vol.	None	*S. cerevisiae*	96	50	0.2	0.39	NR	[31]
FW	Separate	250 mL flask 100 mL working vol.	None	*S. cerevisiae*	48	64.8	0.23	0.36	NR	[32]
Waste bread	Separate	300 mL flask 80 g waste bread	Drying	*S. cerevisiae* Ethanol Red	72	37	0.27	NR	NR	[55]
FW	Separate (fb)	500 mL flask 200 g FW	None	*S. cerevisiae* H058	48	29	0.14	0.47	NR	[56]

NR, not reported; FW, food waste; LAB, lactic acid bacteria; RS, reducing sugar; Y, yield; P, productivity; Simultaneous, simultaneous saccharification fermentation; Separate, separate saccharification fermentation; fb, fed-batch.

be performed in a single tank, with lower energy consumption, higher ethanol productivity, in shorter processing time using less enzyme [61]. Optimization of fermentation conditions is vital for the success of the Ssf process as enzymes and fermenting microorganisms may have different optimum pH and temperatures. In a study by Hong and Yoon [48], about 60 g RS and 36 g ethanol were produced from 100 g of FW in 48-h fermentation. Koike et al. [16] also reported production of ethanol from non-diluted FW (garbage) in a continuous Ssf process with an ethanol productivity of 17.7 g/L h. Ma et al. [9] investigated the Ssf process using kitchen garbage by acid tolerant *Zymomonas mobilis* without any sterilization. 15.4 g sugar per 100 g of garbage and 0.49 g ethanol per g

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Table 4
Hydrogen production from food waste.

Waste	Vessel type	Pretreatment	Inoculum	Duration (d)	HRT (d)	OLR (kg VS/m^3 d)	OLR (kg COD/m^3)	Y (mol/mol hexose)	Y (mL/g VS)	P (g H_2/L h)	Reference
FW	Leaching bed reactor with 3.8 L working vol.	None	HSSS	7	5	NR	NR	NR	160	NR	[10]
FW with sludge	415 mL bottle with 200 mL working vol.	None	HSSS	3	Batch	NA	NA	0.9	67	9.9	[78]
FW	715 mL bottle with 500 mL working vol.	None	Acidogenic culture from CSTR	6	Batch	NA	NA	1.8	92	6.8	[79]
FW	Bioreactor with 3 L working vol.	None	Anaerobic SS	5	NR	8	NR	2.2	125	3.8	[80]
FW	Bioreactor with 3 L working vol.	None	Anaerobic SS	60	5	3	NR	2.4	NR	NR	[73]
FW	CSTR with 10 L working vol.	None	SS	150	1.3	38.4	64.4	NR	283	19.9	[81]
FW	1 L bioreactor with 500 mL working vol.	None	Anaerobic SS	2	Batch	NA	NA	NR	57	NR	[18]
FW	7.5 L bioreactor with 3 L working vol.	Heat pretreatment (90 °C, 20 min)	SS	3	Batch	NA	NA	2.05	153.5	19.2	[26]
FW	ASBR with 4.5 L working vol.	None	HSSS	NR	SRT: 5.25 HRT: 1.25	NR	NR	1.12	80.9	10.2	[82]
FW	Bioreactor with 1 L working vol.	None	SS	2	Batch	NA	NA	NR	NR	1.0	[83]
FW	Rotating drum with 200 L working vol.	None	None	30	4	22.65	NR	NR	65	NR	[84]
Apple pomace	150 mL bioreactor with 100 mL working vol.	Enzymatic pretreatment	HSSS	2	Batch	NA	NA	NR	134	NR	[74]
FW	CSTR 500 L working vol.	Heat pretreatment (100 °C, 30 min)	HSSS	90	21	NR	12.3–71.3	1.82	NR	NR	[85]
FW	CSTR with 20 L working vol.	None	SS	59	4	NR	NR	NR	NR	7.1	[86]
FW	SCR with 10 L working vol.	None	HSSS	96	1.9	NR	39	2.5	114	41.3	[87]
FW	ASBR with 0.15 m^3 working vol.	Alkaline pretreatment (pH 12.5, 1d)	HSSS	200	36	NR	NR	0.9	NR	NR	[82]
FW	Bottle with 200 mL working vol.	US with acid	None	14.6	Batch	NA	NA	NR	118	NR	[88]
FW	Bottle with 200 mL working vol.	None	None	3	Batch	NA	NA	1.79	NR	33.0	[89]
FW	500 mL bioreactor with 200 mL working vol.	None	HSSS	1	Batch	NA	NA	NR	NR	6.6	[75]
FW	300 mL bioreactor with 150 mL working vol.	None	HSSS	2	Batch	NA	NA	NR	NR	NR	[24]
FW	Bioreactor with 150 mL working vol.	Lactate fermentation	Irradiated *R. sphaeroides*	1	Batch	NA	NA	8.35	NR	NR	[90]

FW, food waste; Y, yield; P, productivity; ASBR, anaerobic sequencing batch reactor; SBR, sequencing batch reactor; SS, seed sludge; HSSS, heat shocked seed sludge; US, ultrasonication; d, day; min, minute; NR, not reported; NA, not applicable.

sugar was obtained within 14 h, giving an ethanol yield of 10.08 g/L h.

2.4. Other strategies to improve ethanol yield

To improve ethanol productivity, various strategies have been explored, including use of strains with high ethanol tolerance [64,65] and cell recycle through sedimentation or membrane retention [33]. Recombination of bioethanol producing strains with the amylase-producing gene or development of new strains with improved ethanol tolerance has also been reported [52]. However, stability of the recombinant gene has not been proven yet. Cell recycling has been known to improve performance of the continuous fermentation process significantly [66].

2.5. Large scale ethanol production from FWs

Pilot and full scale plants for ethanol production from various wastes have been reported. The pilot study by Kumamoto University and Hitachi Zosen Company showed that 60 L of ethanol could be produced from one ton of municipal solid wastes, while the residual by-products could be further used for biogas production [67]. In Finland, ST1 Biofuel built a network of 7 ethanol plants converting various kinds of wastes to ethanol with a total annual capacity of 11 ML [68,69]. In Spain, citrus wastes have been converted to ethanol with a yield of 235 L/ton dry orange peel [70,71]. E-fuel developed a home ethanol system supported with microsensors to convert sugar/starch rich liquid wastes into ethanol for homeowners and small businesses [72]. A theoretical estimate based on the data presented in Tables 1 and 3 suggests that 36.2, 126.8 and 593 TL (Teralitres) of ethanol might be eventually produced annually in South East Asia, Asia and in the world, respectively.

3. Hydrogen production

Hydrogen (H_2) is used as compressed gas and has a high energy yield (142.35 kJ/g). FW rich in carbohydrate is suitable for H_2 production. Table 4 summarizes the recent studies on H_2 production from FW. It can be seen that the hydrogen yields ranged from

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0.9 mol H_2/mol hexose to 8.35 mol H_2/mol hexose [76]. The factors such as the composition of FW, pre-treatments and process configurations may affect H_2 production.

3.1. Substrate composition

Hydrogen production potential of carbohydrate-based waste was reported to be 20 times higher than that of fat-based and protein-based waste [91]. This was partially attributed to the consumption of hydrogen towards ammonium using nitrogen generated from protein biodegradation. Kim et al. [82] reported that the H_2 yield was maintained at around 0.5 mol H_2/mol hexose at the C/N ratio lower than 20, while H_2 yield was found to drop at higher C/N ratio because of the increased production of lactate, propionate, and valerate. The H_2 yield was significantly enhanced and reached to 0.9 mol H_2/mol hexose when C/N ratio was balanced with an alkaline shock.

3.2. Pre-treatments

Typically mixed cultures have been employed for H_2 production from waste materials. However, hydrogen generated by *Clostridium* and *Enterobacter*, is often readily consumed by hydrogenotrophic bacteria [83]. Seed biomass is generally pretreated with heat to suppress hydrogen-consumers [88]. FW itself can be a source of H_2-producing microflora. Kim et al. [90] have applied several pre-treatments to select microflora for hydrogen production. Lactic acid bacteria are the most abundant species in untreated FW, while H_2-producing bacteria are dominant in the pre-treated FWs. Heat treatment is effective for suppressing lactate production and increasing H_2/butyrate production. However, heat treatment is likely to increase costs in large scale operations. Luo et al. [92] investigated different pre-treatment methods of inoculums, and concluded that pre-treatment would only have short-term effects on hydrogen production, and the pretreatment is not very crucial [84].

3.3. Process configurations

Various fermentation systems, such as the batch, semi-continuous, continuous, one or multiple stages, have been developed for production of H_2 from FWs [93]. High H_2 production rates have been reported in the anaerobic sequencing batch (ASBR) and upflow anaerobic sludge blanket (UASB) reactors due to their high reactor biomass concentrations [90]. In these processes, the solid retention time (SRT) determines the substrate uptake efficiency, microbial size & composition and metabolic pathway. A long SRT favors the growth of H_2 consumers, while a short SRT may reduce substrate uptake efficiency, active biomass retention, and subsequently the overall process efficiency. If the optimal SRT could be achieved at a low hydraulic retention time (HRT), it would enhance the productivity and technical feasibility of the H_2 production process [84]. Kim et al. [90] investigated the effects of SRT in the range of 24–160 h and HRT of 24–42 h on hydrogen production from FW. It was found that the maximum H_2 yield of 80.9 mL H_2/g volatile solid (VS), equivalent to 1.12 mol H_2/mol hexose was obtained at SRT of 126 h and HRT of 33 h. Wang and Zhao [84] obtained a hydrogen yield of 65 mL H_2/g VS at a long SRT of 160 d in a two-stage process.

It is still debatable as for the effect of the organic loading rate (OLR) on bioconversion of FW to H_2. In some studies, lower H_2 yields were observed at higher OLRs, whereas the opposite trend was also reported in the literature. It appears that an optimal OLR would exist for the maximum H_2 yield [84]. Wang and Zhao [84] reported that hydrogen fermentation pathway became dominant and H_2 yield was steady at lower OLR ($\leqslant$22.65 kg VS/m^3 d), while a decrease in hydrolysis rate of substrate and an increase of propionic and lactic acids were observed. These suggest possibility of co-production of organic acids if the cost related to separation is comparable with the value of the products. The inhibitory effect of organic acids produced at high OLR was also reported by Shin and Youn [80]. Therefore, it is important to determine the optimum OLR and SRT for improving H_2 production.

Acidity of the fermentation medium is another crucial parameter influencing the fermentation efficiency. It had been reported that the optimum pH for H_2 production from organic waste ranged from 4.5 to 6.5 [94]. The accumulation of fermentation products, i.e. CO_2, increases the acidity and then inhibits the microbial growth. Such fermentation products can be removed from the fermentation medium by simple gas sparging and mixing. Addition of alkaline or inoculum recycling are also frequently used for pH control [82–87]. Compared to addition of alkali, sludge recirculation is an economically preferable approach for pH control. The long-term stability of a continuous two-stage process was maintained by recirculating high-alkalinity sludge, e.g. at a OLR of 39 g COD/L d and HRT of 1.9 d, the system was stabilized at 2.5 mol H_2/mole hexose, 114 mL H_2/g VS and 462.5 mL H_2/L h over a period of 96 d [96].

The bioconversion yield of FW to H_2 production is low, e.g. only about 33% of COD in organic materials can be harvested as H_2, while most of the energy content in the feedstock mainly end up as organic acids, such as acetic, lactic and butyric acids. In other words, actual H_2 yield is much smaller than its theoretical value of 12 mol H_2/mol glucose [89]. As a result, commercial value of organic acids particularly lactic acid should be further explored. To improve economic viability of the bioconversion process, H_2 production should also be combined with the methane, organic acids and ethanol production processes [95]. Kyazze et al. [94] reported that the efficiency of H_2 production process was improved using two-stage H_2-methane production process. Lee et al. [85] reported the feasibility of continuous H_2 and CH_4 fermentation in a two stage process using sludge recirculation from the sludge storage tank (denitrification + digestion sludge storage) in a full-scale system. Even so, only 2.5 mol H_2/mol hexose was obtained due to the limitations of anaerobic metabolism.

Alternatively, photofermentation has also been explored for the conversion of organic acids to H_2. In order to increase the overall H_2 yield, combined dark- and photo-fermentation system has been proposed. In this process, lactic acid produced from FW is utilized by photofermentative bacteria, particularly purple non-sulfur bacteria and finally converted to H_2 while the remaining residue is converted to CH_4 [91]. Overall, via the three-stage fermentation system, 41% and 37% of the energy content in the FW could be harvested as H_2 and CH_4, respectively, corresponding to the electrical energy yield of 1146 MJ/ton FW [89]. Lee and Chung [96] conducted a cost analysis of hydrogen production from FW using two-phase hydrogen/methane fermentation, and suggested that the abundance and low-cost of FW makes it economically more feasible than the other sources for H_2 production. However, the economic feasibility of process applications from FW is dependent on the cost of FW collection. Besides, hydrogen production processes should be combined with an ancillary process, such as methane fermentation, to achieve complete treatment and disposal of FW. Lastly, it should also be realized that the technological and economic challenges associated with the fermentative H_2 production and its purification, storage, and distribution may also slow down wide application of bio H_2 as green energy.

4. Methane production

The production of biogas, particularly methane via anaerobic processes is an acceptable solution for waste management because

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Table 5
Methane production from food wastes.

Waste	Inoculum	Pretreatment	Process type	Vessel type	Duration (d)	HRT (d)	OLR (kg VS/ m^3 d)	OLR (kg COD/ m^3 d)	Biogas Yield (mL/g VS)	CH_4 Yield (mL/g VS)	%CH_4	Efficiency (VS,%)	Reference
Fruit and vegetable waste	Cow manure	None	Two stage	Bioreactor with 0.5 L working vol.	29	1	1–9	NR	NR	530	70	95.1	[99]
FW	Anaerobic SS	Freeze drying of waste	Two stage	UASB with 8 L working vol.	120	NR	1,04	7–9	NR	277–482	NR	90	[102]
FW	Anaerobic SS	None	Two stage	Continuous pilot scale 5 tons/d capacity	90	NR	7.9	NR	NR	440	70	70	[100]
Fruit and vegetable waste	Anaerobic SS	None	Single stage	Serum bottles with 135 mL vol.	100	Batch	NA	NA	NR	180–732	NR	NR	[101]
FW & activated sludge	Anaerobic SS	None	Single stage	Semi continuous reactor with 3.5 L working vol.	250	13	2.43	4.71	NR	321	64.4	55.8	[103]
Potato waste	Anaerobic SS	None	Two stage	Packed bed with 1 L working vol.	38	NR	NR	1–3	NR	390	82	NR	[104]
FW	Anaerobic SS	None	Two stage	Bioreactor with 12 L working vol.	60	20	8	NR	NR	NR	68.8	86.4	[73]
FW	Bacteria isolated from landfill soil & cow manure	None	Single stage	3 Stage semi continuous with 8 L working vol.	30	12	NR	NR	NR	NR	67.4	NR	[26]
FW	Anaerobic SS	None	Single stage	Batch	28	10–28	NA	NA	600	440	73	81	[105]
FW	SS	None	Two stage	CSTR with 10 L working vol.	150	5	6.6	16.3	NR	464	80	88	[81]
FW	Landfill soil and cow manure	None	Single stage	Batch 5 L	60	20–60	NR	NR	0.49	220	NR	NR	[106]
FW	Bacteria & sludge from various sources	None	Three stage	UASB with 4800 L working vol.	NR	12	54.5	ND	ND	254	68	90.1	[107]
FW	SS	None	Two stage	Bioreactor with 4.5 L working vol.	200	1–27	NR	15	578	520	90	NR	[108]
FW	SS	LAB pretreatment & SsF	Two stage	Bioreactor with 5 L working vol.	98	7	NR	NR	850	434	51	NR	[16]
FW	No addition	None	Two stage	Rotating drum with 200 L working vol.	30	SRT 26.7 h	4.61	NR	769	546	71.5	82.2	[84]
FW	SS	Heat pretreatment (100 °C 30 min)	Two stage	UASB with 2.3 L working vol.	60	3.9–6.4	NR	NR	NR	NR	80	80	[85]
FW	SS	None	Two stage	Gas sparging type reactor with 40 L working vol.	96	15.4	NR	4.16	NR	NR	65	88.1	[96]
FW	NR	None	Single stage	Digester with 900 m^3 tank vol.	426	80	2.5	NR	643	399	62	90	[109]
FW	Anaerobic SS	Enzymatic pretreatment	Two stage	UASB with 2.7 L working vol.	75	2.2	NR	2.2	NR	NR	75	61	[110]
FW	Anaerobic SS	Homogenized using blender	Two stage	Hydrolytic reactor (10 L), methanogenic MBR (3 L)	19	23	10	NA	NR	357	63–70	81	[111]
FW	Anaerobic SS	Trace element addition	Single stage	Semi-continuous with 150 mL working vol.	368	20–30	2.19–6.64	NR	NR	352–450	51.2	NR	[35]
FW	Anaerobic SS	FW liquidized at 175 °C for 1 h	Single stage	UASB with 2 L working vol.	72	4–10	NR	2–12.5	NR	NR	63	93.7	[112]
FW	Anaerobic SS	None	Single stage	CSTR with 3 L working vol.	225	16	NR	9.2	NR	455	NR	92.2	[113]
FW & SS	Anaerobic SS	None	Single stage	Bioreactor with 6 L working vol.	NR	8–30	4–21.8	NR	1039	465	52	90.3	[114]
FW	NR	None	Single stage	Digester with 800 mL working vol.	30	Batch	NA	NA	621	410	66	NR	[15]

FW, food waste; SS, seed sludge; UASB, upflow anaerobic sludge blanket reactor; SsF, simultaneous saccharification fermentation; MBR, membrane bioreactor; LAB, lactic acid bacteria; NR, not reported; NA, not applicable.

of its low cost, low production of residual waste and its utilization as a renewable energy source [97,98]. In addition to biogas, a nutrient-rich digestate produced can also be used as fertilizer or soil conditioner. Table 5 summarizes the studies pertaining to anaerobic digestion of various kinds of FWs. Viturtia et al. [99] investigated two-stage anaerobic digestion of fruit and vegetable wastes, in which 95.1% volatile solids (VS) conversion with a methane yield of 530 mL/g VS was achieved. In a study by Lee et al. [100], FW was converted to methane using a 5-L continuous digester fed with an OLR of 7.9 kg VS/m^3 d, resulting 70% VS conversion with a methane yield of 440 mL/g VS. Gunaseelan [101] has reported the methane production capacities of about 54 different fruit and vegetable wastes ranged from 180–732 mL/g VS depending on the origin of wastes.

Feedstock characteristics and process configuration are the main factors affecting the performance of anaerobic digestion [115]. The physical and chemical characteristics of the waste, such as moisture, volatile solid & nutrient contents and particle size affect the biogas production and process stability. Cho et al. [102] determined the methane yields of different FWs over 28 d at 37 °C, and found 482, 294, 277, and 472 mL/g VS for cooked meat, boiled rice, fresh cabbage and mixed FWs, with 82%, 72%, 73% and 86% efficiency, respectively, based on elemental compositions of raw materials.

4.1. Single stage anaerobic digestion

The process configuration is very important for the efficiency of methane production process. Single-stage anaerobic digestion process has been widely employed for municipal solid waste treatment. As all of the reactions (hydrolysis, acidogenesis, aceto genesis, and methanogenesis) take place simultaneously in a single reactor, the system encounters less frequent technical failures and has a smaller investment cost [106]. The anaerobic digestion can be wet or dry; the former uses the waste as received, while the latter needs to lower water content to about 12% of total solid [98]. Compared to wet anaerobic digestion, dry anaerobic digestion provides lower methane production and VS reduction due to the volatile fatty acid (VFA) transport limitation [113]. El-Mashad et al. [116] reported that a digester treating FW was not stable due to the VFA accumulation and low pH, leading to low biogas production. On the other hand the stability of single-stage anaerobic digester for easily degradable FW is of concern [100].

4.2. Two-stages anaerobic digestion

In contrast to single stage anaerobic digestion, two-stage anaerobic digestion has often been used for producing both hydrogen and methane in two separate reactors [81]. In such a system, fast-growing acidogens and hydrogen producing microorganisms are enriched for the production of hydrogen and volatile fatty acids (VFAs) in the first stage. In the second stage, slow-growing acetogens and methanogens are built-up, where VFAs are converted to methane and carbon dioxide. In a study of Park et al. [108], single-stage and two-stage thermophilic methane fermentation systems were operated using artificial kitchen waste. In both systems, the highest methane recovery yield of 90% (based on COD) was determined at the OLR of 15 g COD/L d. However, the propionate concentration in the single stage reactor fluctuated largely and was higher than that in the two-stage process, indicating less stable digestion. Massanet-Nicolau et al. [117] have also compared single and two stage anaerobic fermentation systems on FW processing. The methane yield in two-stage fermentation was improved by 37% and was operating at much shorter HRTs and higher loading rates. Lee and Chung [96] also proved that the two stages hydrogen/methane fermentation has significantly greater potential for recovering energy than methane-only fermentation.

4.3. Reactor configurations

Packed bed reactors (PBR) or fixed bed systems have been developed in order to attain high loading, immobilize microbial consortia and stabilize methanogenesis [118]. Parawira et al. [104] investigated the performances of two different systems, one consisting of a solid-bed reactor for hydrolysis/acidification connected to an upflow anaerobic sludge blanket methanogenic reactor (UASB) while the other consists of a solid-bed reactor connected to a methanogenic reactor packed with wheat straw as biofilm carriers (PBR) during mesophilic anaerobic digestion of solid potato waste. Although PBR degraded the organic materials faster than UASB, the methane yield (390 mL/g VS) and the cumulative methane production was equal in both systems. Among the high-rate anaerobic reactors, UASB reactor has been widely used to treat various kinds of organic wastes. UASB provides the immobilization of anaerobic bacteria by granulation resulting in high microbial activity and good settling characteristics [110]. This also allows for high OLR and the maintenance of long retention time. Latif et al. [112] investigated the mesophilic and thermophilic anaerobic treatment of liquidized FW in UASB reactor by stepwise increasing OLR and temperature. UASB reactor was efficient for COD removal (93.7%), high methane production (0.912 L/g COD) due to low VFA accumulation under controlled temperature and pH. A temperature of 55 °C and OLR of 12.5 g COD/L with 4 d HRT supported a maximum biogas production of 1.37 L/g COD. Continuously Stirred Tank Reactor (CSTR) and Fluidized Bed Reactor (FBR) were also investigated for methanogenesis [118]. Fermentation yielded 670 normalized litres (NL) biogas/kg VS with the CSTR and 550 NL biogas/kg VS with the FBR while the average methane concentration was approximately 60% for both reactor systems. However, the stability of the process was greater in the FBR.

As a summary, the two-stage process could attain higher OLR and higher methane generation. In addition, it is less vulnerable to fluctuations in OLR than a single methanogenic process. The efficiency of digestion could be improved by co-digesting different wastes, trace element addition, and using active inoculum as start-up seed. The highest methane yields from FWs were reported by Koike et al. [16]. They obtained a biogas production of 850 L/g VS during the two-stage hydrogen and methane production processing of FW. Approximately 85% of the energy of the garbage was converted to fuels, ethanol and methane by this process.

Considering the data in Table 1 and Table 2 and the maximum methane yield of (546 mL/g VS) reported in Table 5, it can be estimated that $1.32 * 10^9$ m^3 methane can be produced annually which can generate $2.6 * 10^7$ GJ energy using the total food waste generated in the world.

5. Biodiesel production

FW was also converted to fatty acids and biodiesel either by direct transesterification using alkaline or acid catalysts or by the transesterification of microbial oils produced by various oleaginous microorganisms [119–122]. Microbial oils can be produced by many yeast strains and they can be used as the substitute of plant oils due to their similar fatty acid compositions. Alternatively they can be used as raw material for biodiesel production [123]. Recent publications on the production of microbial lipids from various FWs using different microbial strains are listed in Table 6. Pleissner et al. [124] have revealed the potential of FW hydrolyzate as culture medium and nutrient source in microalgae cultivation for biodiesel production. The FW hydrolyzate was prepared using *Aspergillus awamori* and *Aspergillus oryzae* and then used as culture medium for the growth of heterotrophic microalgae *Schizochytrium mangrovei* and *Chlorella pyrenoidosa*. The microorganisms grew well on the

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Table 6
Fatty acids and biodiesel production from food wastes.

Waste	Microorganism	Pretreatment	Vessel type	Conditions	Duration (d)	Y (g cell/g waste)	Y (g lipid/g cell)	Y (g lipid/g fat consumed)	μ (h^{-1})	Reference
Waste cooking olive oil	*A.niger* NRRL363	Filtration	SmF-250 mL flasks	28 °C, pH6, 200 rpm	5	1.2	0.49	0.6	NR	[121]
Waste cooking olive oil	*A.niger* NRRL363	Filtration	SmF-250 mL flasks	28 °C, pH 6, 200 rpm	8	1.15	0.64	0.74	NR	[121]
FW	*Schizochytrium mangrovei*	Fungal hydrolysis by *A. oryzae* & *A. awamori*, autolysis	SmF-2 L bioreactor	25 °C, pH 6.5, 400 rpm	4	NR	0.321	NR	0.196	[124]
FW	*Chlorella pyrenoidosa*	Fungal hydrolysis by *A. oryzae* & *A. awamori*, autolysis	SmF-2 L bioreactor	28 °C, pH 6.5, 400 rpm	4	NR	0.208	NR	0.046	[124]

FW, food waste; Y, yield; P, productivity; SmF, submerged fermentation; μ, specific growth rate; A, *Aspergillus*; NR, not reported.

FW hydrolysate leading to the production of 10–20 g biomass. The majority of fatty acids present in lipids of both strains were reported to be suitable for biodiesel production. Papanikolau et al. [121] investigated the capacities of five *Aspergillus* sp. and *Penicillium expansum* to produce lipid rich biomass from waste cooking olive oil in a carbon limited culture. Significant amount of lipid accumulation was determined in each culture while the highest lipid yield (0.64 g/g dry cell weight) with a productivity of 0.74 g/g was obtained by *Aspergillus* sp. ATHUM 3482. The fatty acids accumulated were mainly C18:1 and has potential to develop food/feed supplements. From Table 6, it can be seen that the studies related to mixed food waste is still very scarce and that the productivity is relatively low. In addition, an extraction and a transesterification step are required to obtain biodiesel. The residual water in FW that is inhibitory in the transesterification is an additional obstacle for this type of fermentation from mixed food waste.

In South East Asia, Asia and globally produced vegetable oils, butter and animal fats amounts were presented in Table 1. Assuming a maximum lipid yield of 0.74 g/g oil that was obtained from waste cooking oils and with a transesterification yield of 0.95 FAME/g lipid, it can be estimated that 86.5, 201.9 and 647 kT (kilotons) of biodiesel can be produced annually in South East Asia, Asia and in the world, respectively. This can potentially generate $24.5 * 10^6$ GJ energy per year globally.

6. Conclusions

The management of FWs has posed a serious economic and environmental concern. It appears from this review that bioconversion of FW to energy in terms of ethanol, hydrogen, methane and biodiesel is economically viable. However, difficulties associated with the collection/transportation of FW should also be taken into account. Nevertheless, the low or no cost of food waste along with the environmental benefits considering the waste disposal would balance the initial high capital costs of the biorefineries. The efficiency and cost base of the production could be further improved by intensifying research and optimization studies on integrating different value-added product manufacturing processes.

7. Uncited references

Q4 [4,77].

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