

1 **Bioconversion of food waste to energy: a review**

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1 **ABSTRACT**

2 According to [the Food and Agricultural Organization](#) (FAO), one third of food produced globally for human
3 consumption is lost along the food supply chain. In many countries food waste are currently landfilled or incinerated
4 ~~together~~ with other combustible municipal wastes for possible recovery of ~~energy~~~~heat or other forms of energy~~. ~~The~~
5 ~~residual ash is disposed of in landfills~~. However, ~~these two approaches are facing more and more economic and~~
6 ~~environmental stresses~~. ~~incineration is an expensive waste conversion technique and can potentially cause air~~
7 ~~pollution~~. ~~From an environmental viewpoint, there is urgent need for appropriate management of food waste~~. Due to
8 its organics- and nutrients-rich composition, ~~theoretically~~ food waste ~~can~~~~ould~~ be ~~utilized~~ ~~viewed~~ as a useful
9 resource for ~~production of biofuel~~ through ~~various~~ fermentation ~~processes~~. ~~So far, Such conversion of food waste is~~
10 ~~potentially more profitable than the conventional waste recycling efforts~~. Food waste valorisation ~~of food waste~~ has
11 ~~therefore attracted increasing~~ ~~gained~~ interest, with ~~bio-fuels such as~~ ~~biogas~~ ~~methane~~, hydrogen, ethanol and biodiesel
12 ~~as final products~~. ~~Therefore, this review aims to~~ ~~The aim of this review is to~~ ~~examine~~ ~~provide information on the~~
13 ~~food waste situation with emphasis on the~~ ~~in Asia Pacific countries and the state-of-the-art~~ ~~of~~ food waste
14 fermentation technologies ~~for~~ ~~developed around the world which may be applicable for~~ renewable energy
15 generation.

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1 1. Introduction

2 Food waste (FW) is organic waste discharged from various sources including food processing plants, and domestic
3 and commercial kitchens, cafeterias and restaurants. ~~It accounts for a considerable proportion of municipal solid~~
4 ~~waste all over the world (Lundqvist et al., 2008).~~ According to FAO (2012), nearly 1.3 billion tonnes of foods
5 including fresh vegetables, fruits, meat, bakery and dairy products are lost ~~in developing and developed countries~~
6 along the food supply chain; ~~from initial agricultural production to consumer.~~ The amount of FW has been
7 projected to increase in the next 25 years due to economic and population growth, mainly in Asian countries. For
8 example, ~~the~~ annual amount of urban FW in Asian countries could rise from 278 to 416 million tonnes from 2005
9 to 2025 (Melikoglu et al., 2013). Typical foods wasted in ~~several~~ Asia-Pacific countries and around the globe world
10 are summarized are listed in Table 1 (FAO, 2008).

11
12 ~~To reduce its volume,~~ FW is traditionally incinerated with other combustible municipal wastes for generation of heat
13 or energy, ~~the residual ash is then disposed of in landfills.~~ It should be realized that ~~However, incineration is an~~
14 ~~expensive waste conversion technique. The fact is that~~ FW indeed contains high levels of moisture and this may lead
15 to the production of dioxins during its combustion when burned together with other wastes of low humidity and high
16 calorific value (Katami et al., 2004). In addition, Besides, incineration of FW can potentially cause air pollution and
17 loss of chemical values functionalities of FWs. These suggest that ~~From an environmental viewpoint, there is a need~~
18 ~~for~~ an appropriate management of FWs is strongly needed (Ma et al., 2009a). FW is mainly composed of
19 carbohydrate polymers (starch, cellulose and hemicelluloses), lignin, proteins, lipids, organic acids, and a remaining,
20 smaller inorganic part (Table 2). Hydrolysis of carbohydrate in FW components may result in the breakage of
21 glycoside bonds with releasing polysaccharides ~~emerging~~ as oligosaccharides and monosaccharides, which are more
22 amenable to fermentation into valuable products. Total sugar and protein contents in FW are in the range of 35.5-
23 69% and 3.9-21.9%, respectively. ~~Compared to agro-industrial raw materials, FW should be a better raw material for~~
24 ~~microbial fermentation without nutrients supplement.~~ As such, FW has been used as the sole microbial feedstock for
25 the development of various kinds of value-added bioproducts, including methane, hydrogen, ethanol, enzymes,
26 organic acid, biopolymers and bioplastics (Han & Shin, 2004; He et al., 2012b; Koike et al., 2009; Ohkouchi &
27 Inoue, 2007; Pan et al., 2008; Rao & Singh, 2004; Sakai & Ezaki, 2006; Wang et al., 2005; Yang et al., 2006; Zhang
28 et al., 2013). The value of biofuels (\$200-400/ ton biomass) is higher than electricity (\$60-150/ton biomass) and

1 animal feed (\$70-200/ton biomass). Due to inherent chemical complexity, FW also can be utilized for production of
2 high-value materials, such as organic acids, biodegradable plastics and enzymes (\$1000/ton biomass) (Sanders et al.,
3 2007). However, it should be noted that the market demand for such chemicals is much smaller than that for biofuels
4 (Tuck et al., 2012). Therefore, this ~~article review~~ is intended to ~~review summarize and discuss recently reported the~~
5 FW valorization techniques ~~that have been developed~~ for the production of ~~various kinds of~~ biofuels ~~from FW~~, such
6 as ethanol, hydrogen, methane and biodiesel.

8 2. Ethanol Production

9 Recently, global demand for ethanol has increased ~~due to because of its wide industrial applications in the chemical~~
10 ~~and motor fuel industries.~~ Ethanol is mainly used as a chemical feedstock to produce ethylene ~~with a market~~
11 ~~demand of more than 140 million tonnes per year, a key material for further production of that is converted in~~
12 ~~polyethylene and other plastics. Ethylene is by far the largest bulk chemical (more than 140 million tonnes per year)~~
13 ~~used for the production of around half of all plastics. As such, The demand for ethylene is continuing to rise, hence~~
14 ~~bioethanol produced from ~~tion~~ using cheap feedstocks has gained is gaining interest~~ (International-Renewable-
15 Energy-Agency, 2013; Lundgren & Hjertberg, 2010). ~~Traditionally, B~~bioethanol is ~~traditionally~~ produced from
16 cellulose and starch rich crops, ~~e.g. such as~~ potato, rice, and sugar cane (Thomsen et al., 2003). Starch ~~can be is~~
17 easily converted to glucose by commercial enzymes and subsequently fermented to ethanol particularly by
18 *Saccharomyces cerevisiae*. However, the hydrolysis of cellulose is more difficult. FW hydrolysis becomes much
19 harder if large quantities of cellulosic feedstocks are present in FW. Use of abundant & cheap wastes such as
20 lignocellulosic, municipal and FWs has been explored as alternative substrates for ethanol production (Jensen et al.,
21 2011; Kim & Dale, 2004).

23 2.1. Pre-treatments

24 ~~Harsh pre-treatment may not be necessary during the conversion of FW to ethanol Where FW is used as substrate,~~
25 ~~harsh pre-treatment methods are typically not employed~~ prior to enzymatic hydrolysis (Kumar et al., 1998; Tang et
26 al., 2008). ~~Acid and alkali pre-treatments are therefore not necessary for the production of high glucose levels from~~
27 ~~kitchen waste (Cekmecioglu & Uneu, 2013).~~ Instead, autoclave of FW before fermentation is often required for

1 ~~improving usually autoclaved before the fermentation process in order to increase product yield and to ensure~~
2 ~~product purity, but at the cost of energy and water consumption. However, this process is energy intensive and~~
3 ~~requires water for cooling the autoclaved substrate. It should be noted that FW processing without sterilization has~~
4 ~~some other advantages besides reducing the requirement for heat and water. Furthermore, thermal treatment may~~
5 ~~lead to partial also degradation of e the sugars and other nutritional components, as well as elements, and cause side~~
6 ~~reactions; (e.g. such as the Maillard reaction) through which leading to decreases in the amounts of functionally~~
7 ~~useful sugars and amino acids are reduced; and increase in the production of unfavourable furfural compounds~~
8 ~~inhibitory to microbial growth (Sakai & Ezaki, 2006). Moreover, fresh and wet FWs appear to be more effective~~
9 ~~than rewetted dried FW (Kim et al., 2005). This is mainly due to the decreased specific surface area of the dried~~
10 ~~substrate, resulting in a decrease in the reaction efficiency between the enzymes and substrate. Therefore, the~~
11 ~~utilization of FW without a drying pre-treatment is preferred as long as if the microbial contamination is~~
12 ~~manageable can be managed. Without thermal sterilization, In order to make the non-sterilized medium applicable,~~
13 ~~acidic condition is needed controlled to prevent microbial the contamination and putrefaction by bacteria (Koike et~~
14 ~~al., 2009; Ye et al., 2008). As such, Acid-tolerant ethanol producing microorganisms such as *Zymomonas mobilis*,~~
15 ~~have been employed for the fermentation of FW are utilized (Tao et al., 2005; Wang et al., 2008), or lactic acid~~
16 ~~bacteria are sprayed to prevent putrefaction (Koike et al., 2009; Ye et al., 2008).~~

18 2.2. Saccharification

19 ~~The conversion Efficiency of t conversion of FW to ethanol depends on the extent of carbohydrate saccharification~~
20 ~~as yeast cells cannot ferment starch or cellulose directly into bioethanol (Tubb, 1986). Various enzymes can be~~
21 ~~utilized depending on the FW composition. A mixture of α -amylase, β -amylase, and glucoamylase of various origins~~
22 ~~is more effective for A synergistic effect may be observed and this usually involves α amylase, β amylase, and~~
23 ~~glucoamylase of various origins as this is more beneficial in the case of substrate with higher molecular weight.~~
24 ~~Pullulanase has also been added to the list of saccharifying enzymes recently (Tomasik & Horton, 2012). As a direct~~
25 ~~endo-acting debranching enzyme, pullulanase can specifically catalyze the hydrolysis of α -1,6-glucosidic linkages of~~
26 ~~branched polysaccharides (e.g., such as pullulan, dextrin, amylopectin, and related polymers), resulting in release of~~
27 ~~giving linear oligosaccharides. Small fermentable sugars (e.g., such as maltose, amylose, glucose, maltose syrups,~~
28 ~~high purity glucose and fructose) can be produced in saccharification process, whereas C cellulases and xylanases~~

1 including endoglucanase, exoglucanase, β -glucosidase and β -xylosidase, can also be employed to improve the
2 hydrolysis of cereals for conversion of starches to glucose (Ducroo, 1987).

3
4 Table 3 shows the glucose and ethanol yields of different types of FWs. The highest glucose concentration of about
5 65 g reducing sugar (RS)/100 g FW was obtained ~~with using~~ α -amylase- at a dose of 120U/g dry substrate,
6 **glucoamylase** (120U/g dry substrate), cellulase (8 FPU/g dry substrate) and β -glucosidase (50 U/g dry substrate)
7 (Cekmecelioglu & Uncu, 2013). In a study of Hong and Yoon (2011), a mixture of commercial enzymes consisting
8 of α -amylase, **glucoamylase**, and protease resulted in 60 g RS/100 g FW.

10 2.3. Process Configurations

11 High glucose yields of glucose is achievable can be obtained by increasing enzyme concentration and temperature at
12 different solid loads, agitation speeds and hydrolysis times in during the saccharification processes (Ado et al., 2009;
13 Sharma et al., 2007; Shen et al., 2009; Zhang et al., 2010). High glucose concentration may result in catabolite
14 repression of the enzymes (Oberoi et al., 2011). Therefore, fed-batch and simultaneous saccharification and
15 fermentation (Ssf) methods have been developed for achieving high ethanol yield from FW (Ma et al., 2009b;
16 Oberoi et al., 2011).

17
18 The In-fed-batch culture has been commonly employed for the the production of high concentration reducing sugars
19 which can be hydrolysis, solid FW and enzymes are added into reactors stepwise and the FW is gradually degraded
20 (Rudolf et al., 2005). The fed batch approach can generate high concentrations of reducing sugar which can then be
21 further fermented to high concentration ethanol (Ballesteros et al., 2009). Compared to batch culture, Yan et al.
22 (2012) compared the performances of batch and fed batch cultures found that -Results clearly showed that
23 saccharification and subsequent ethanol fermentation were both improved significantly using fed-batch
24 configuration, e.g. the glucose bioconversion yield reached 92% of its theoretical value.

25
26 Alternatively, Ssf can be deployed to mitigate reduce risk of catabolite repression. This combines enzymatic
27 hydrolysis and ethanol fermentation into a single operation for -keeping the concentration of enzymatically-

1 produced glucose at a low level ~~and so as to helping to mitigate~~ inhibition ~~to on~~ enzymatic hydrolysis (Hari Krishna
2 et al., 2001). This combined process can be performed in a single tank, with lower energy ~~consumptioneests~~, higher
3 ethanol productivity, in shorter processing time using less enzyme (Ballesteros et al., 2009). Optimization of
4 fermentation conditions is vital for the success of the Ssf process as enzymes and fermenting microorganisms may
5 have different optimum pH and temperatures. In a study by Hong and Yoon (2011), about 60 g RS and 36 g ethanol
6 were produced from 100 g of FW in 48-h fermentation. Koike et al. (2009) also reported production of ethanol from
7 non-diluted FW (garbage) in a continuous Ssf process with an ethanol productivity of 17.7 g/Lh. Ma et al. (2009a)
8 investigated the Ssf process using kitchen garbage by acid tolerant *Zymomonas mobilis* without any sterilization.
9 15.4 g sugar per 100 g of garbage and 0.49 g ethanol per g sugar was obtained within 14 hours, giving an ethanol
10 yield of 10.08 g/Lh.

11 12 **2.4. Other Strategies to Improve Ethanol Yield**

13 To improve ethanol productivity, various strategies have been explored, including use of strains with high ethanol
14 tolerance (He et al., 2009; Wang et al., 2012) and cell recycle through sedimentation or membrane retention (He et
15 al., 2012a). Recombination of bioethanol producing strains with the amylase-producing gene or development of new
16 strains with improved ethanol tolerance have also been reported (Li et al., 2011). However, stability of the
17 recombinant gene has not been proven yet. Cell recycling has been known to improve performance of the
18 continuous fermentation process significantly (Wang & Lin, 2010).

19 20 **2.5. Large Scale Ethanol Production from FWs**

21 Pilot and full scale plants for ethanol production from various wastes have been reported. The pilot study by
22 Kumamoto University and Hitachi Zosen Company showed that 60 litres of ethanol could be produced from one ton
23 of municipal solid wastes, while the residual by-products could be further used for biogas production (Japan-for-
24 Sustainability, 2013). In Finland, ST1 Biofuel built a network of 7 ethanol plants converting various kinds of wastes
25 to ethanol with a total annual capacity of 11 ML (Energy-Enviro-Finland, 2013; ST1, 2013). In Spain, citrus wastes
26 have been converted to ethanol with a yield of 235 L/ton dry orange peel (BEST, 2013; Citrotechno, 2013). E-fuel
27 developed a home ethanol system supported with microsensors to convert sugar/starch rich liquid wastes into
28 ethanol for homeowners and small businesses (E-fuel, 2009). ~~Considering the data in Table 1 and the maximum~~

1 ethanol yield reported in Table 3 (0.36 g/g FW). ~~A theoretical estimate based on it can be estimated the data~~
2 ~~presented in Tables 1 and 3 suggests~~ that 36.2, 126.8 and 593 TL (Teralitres) of ethanol ~~might can be eventually~~
3 produced annually in South East Asia, Asia and in the world, respectively. ~~These values can be increased by~~
4 ~~improving the process configurations, up scaling and using genetically modified microbial strains with high ethanol~~
5 ~~tolerance.~~

7 **3. Hydrogen Production**

8 **Hydrogen (H₂) is used as compressed gas and has a high energy yield (142.35 kJ/g).** FW rich in carbohydrate is
9 suitable for H₂ production. Table 4 summarizes the recent studies ~~on and H₂ production from FW yields achieved~~
10 ~~using FWs. It can be seen that T~~the hydrogen yields ranged from 0.9 mol H₂/mol hexose to 8.35 mol H₂/mol hexose
11 (Patel et al., 2012). ~~The factors such as T~~the composition of FW, pre-treatments and process configurations ~~may~~
12 ~~affect are the important parameters affecting H₂ production.~~

14 **3.1. Substrate composition**

15 Hydrogen production potential of carbohydrate-based waste was reported ~~to be as~~ 20 times higher than that of fat-
16 based and protein-based waste (Show et al., 2012). This ~~observation~~ was partially attributed to the consumption of
17 hydrogen towards ammonium using nitrogen generated from protein biodegradation. Kim et al. (2010) reported that
18 the H₂ yield was maintained at around 0.5 mol H₂/mol hexose ~~at when~~ the C/N ratio ~~is~~ lower than 20, while ~~at higher~~
19 ~~C/N ratio, H₂ yield was found to drop at higher C/N ratio ped~~ because of the increased production of lactate,
20 propionate, and valerate ~~production~~. The H₂ yield was significantly enhanced and reached to 0.9 mol H₂/mol hexose
21 when C/N ratio was balanced with an alkaline shock.

23 **3.2. Pre-treatments**

24 Typically mixed cultures have been employed for H₂ production from waste materials. However, hydrogen
25 generated by *Clostridium* and *Enterobacter*, is often readily consumed by hydrogenotrophic bacteria (Li & Fang,
26 2007). Seed biomass is generally pretreated with heat to suppress hydrogen-consumers (Elbeshbishy et al., 2011).
27 FW itself can be a source of H₂-producing microflora. Kim et al. (2008a) have applied several pre-treatments to
28 select microflora for hydrogen production. Lactic acid bacteria ~~are were~~ the most abundant species in untreated FW,

1 while H₂-producing bacteria ~~are were~~ dominant in the pre-treated FWs. Heat treatment ~~i~~was effective ~~for at~~
2 suppressing lactate production and increasing H₂/butyrate production. However, heat treatment is likely to increase
3 costs in large scale operations. Luo et al. (2010) investigated different pre-treatment ~~methodss of on~~
4 ~~inoculum inoculums, and concluded that~~. ~~During the first few days, the highest hydrogen production was obtained~~
5 ~~with heat pretreated seeds. However, the differences in hydrogen yields disappeared later on, suggesting that pre-~~
6 treatment ~~would only have had only~~ short-term effects on hydrogen production, ~~and~~. ~~In another study, a yield of 65~~
7 ~~mL H₂/Lh was obtained using microflora from unsterilized FW, showing that~~ the pretreatment is not very crucial
8 (Wang & Zhao, 2009).

10 3.3. Process Configurations

11 Various fermentation systems, such as the batch, semi-continuous, continuous, one or multiple stages, have been
12 ~~developed for used to~~ production of e-H₂ from FWs (Hallenbeck & Ghosh, 2009). High H₂ production rates have
13 been ~~reported achieved in using~~ the anaerobic sequencing batch (ASBR) and upflow anaerobic sludge blanket
14 (UASB) reactors due to their high reactor biomass concentrations (Kim et al., 2008a). ~~In these processes, T~~the solids
15 retention time (SRT) determines the substrate uptake efficiency, microbial size & composition and metabolic
16 pathway. A ~~longhigh~~ SRT favours the growth of H₂ consumers, while a ~~shortlow~~ SRT may reduce substrate uptake
17 efficiency, active biomass retention, and ~~therefore, subsequently~~ the overall process efficiency. If the optimal SRT
18 could be achieved at a low hydraulic retention time (HRT), it would enhance the productivity and technical
19 feasibility of the H₂ production process (Wang & Zhao, 2009). Kim et al. (2008) investigated the effects of SRT in
20 the range of 24-160 h and HRT of 24-42 h on hydrogen production ~~from using~~ FW. ~~It was found that T~~the
21 maximum H₂ yield of 80.9 mL H₂/g volatile solid (VS), ~~equivalent to~~ (1.12 mol H₂/mol hexose) was ~~obtained~~
22 ~~determined at an~~ SRT of 126 h and HRT of 33 h. Wang and Zhao (2009) ~~have obtained~~ a hydrogen yield of 65 mL
23 ~~H₂/g VS at a long also reported that the high SRT of~~ (160 days), ~~provides the optimum H₂ production~~ (65 mL H₂/g
24 ~~VS)~~ in a two-stage process.

25
26 ~~It is still debatable as for the effect of T~~the organic loading rate (OLR) ~~on is also affecting the H₂ bioconversion of~~
27 ~~FW to H₂~~. ~~There are disagreements in the literature as to whether higher H₂ yields are achieved with lower or~~
28 ~~higher organic loading rates (OLRs). In some studies, eases lower higher OLRs decreased the H₂ yields were~~

1 ~~observed at higher OLRs, whereas the opposite trend was also reported in the literature. In others higher OLRs~~
2 ~~increased the H₂ yield. It appears that an~~ In the latter case, as OLRs increased the H₂ yield usually became constant
3 ~~or eventually began to decrease thereby providing an optimal OLR would exist for the (maximum H₂ yield)~~ (Wang
4 & Zhao, 2009). Wang et al. (2009) reported that hydrogen fermentation pathway became dominant and H₂ yield was
5 steady at lower OLR (≤ 22.65 kg VS/m³d), while a decrease in hydrolysis rate of substrate and an increase of
6 propionic and lactic acids were observed. **These suggest possibility of co-production of organic acids if the cost**
7 **related to separation is comparable with the value of the products.** The inhibitory effect of organic acids produced at
8 high OLR was also reported (Yu et al., 2002; Shin and Youn (2005). ~~reported that H₂ production was increased as~~
9 ~~OLR increased up to 8 g VS/Ld and reached 2.4 mol H₂/mol hexose, but drastically decreased at 10 g VS/Ld. This~~
10 ~~might be related to inhibitory effects of increased organic acids (Yu et al., 2002).~~ Therefore, it is important to
11 determine the optimum OLR and SRT for improving to improve H₂ production.

12
13 Acidity of the fermentation medium is another crucial parameter influencing the fermentation efficiency. It had been
14 reported that the optimum pH for H₂ production from organic waste ranged from 4.5 to 6.5 (Kyazze et al., 2007).
15 The accumulation of fermentation products, i.e. CO₂, increases the acidity and then inhibits the microbial growth.
16 Such fermentation products ~~It~~ can be removed from the fermentation medium by simple gas sparging and mixing.
17 Addition of Aalkaline ~~buffer addition~~ or inoculum recycling are also frequently used for pH control (Kim et al.,
18 2010; Lee et al., 2010b). Compared to addition of using alkaline ~~ne~~ buffers, sludge recirculation is an economically
19 preferpreferable approach ~~ed~~ for pH control. ~~Lee et al. (2010b) achieved~~ The long-term stability of a the continuous
20 two-stage process was maintained by recirculating high-alkalinity sludge (Lee et al. 2010b), e.g. ~~At a the~~ OLR of
21 39 g COD/Ld and HRT of 1.9 days, the system was stabilized at 2.5 mol H₂/mole hexose, 114 mL H₂/g VS and
22 462.5 mL H₂/Lh over a period of 96 days ~~operation~~.

23
24 The bioconversion yield of FW to main barrier for commercial H₂ production is low, e.g. the low efficiency of
25 bioconversion (Gómez et al., 2011). ~~Only~~ about 33% of COD in organic materials can be harvested as H₂, while
26 most of the energy content in the feedstock is mainly end up as converted into organic acids, such as acetic, lactic
27 and butyric acids (Gómez et al., 2011). In other words, actual H₂ yield ~~obtained~~ is much smaller than its theoretical

1 value of 12 mol H₂/mol glucose (Kim & Kim, 2013). ~~As a result, commercial value of~~ ~~Therefore, organic acids~~
2 ~~particularly lactic acid should be further explored, could be of commercial interest.~~ To improve economic viability of
3 ~~the efficiency~~ of the bioconversion process, H₂ production ~~should also be~~ ~~is sometimes~~ combined with the methane,
4 organic acids and ethanol production processes (Lin et al., 2013). Kyazze et al. (2007) reported that the efficiency of
5 H₂ production process was improved using two-stage H₂-methane production process. Lee et al. (2010a) ~~have~~
6 reported the feasibility of continuous H₂ and CH₄ fermentation in a two stage process using sludge recirculation
7 from the sludge storage tank (denitrification + digestion sludge storage) in a full-scale system. ~~Even so, Still,~~ only
8 2.5 mol H₂/mol hexose ~~was could be~~ obtained due to the ~~metabolic~~ limitations ~~of in~~ anaerobic metabolism.

9
10 ~~Alternatively, On the other hand, pp~~ photofermentation ~~has also been explored~~ ~~allows~~ for the conversion of organic
11 acids to H₂. ~~Therefore, i~~n order to increase the overall H₂ yield, ~~combined fermentation systems consisting of both~~
12 dark- and photo-fermentation ~~system has have been~~ ~~proposed~~ ~~recently attempted.~~ In ~~this such a~~ process, lactic acid
13 produced from FW is utilized by photofermentative bacteria, particularly ~~using~~ purple non-sulfur bacteria and ~~finally~~
14 converted ~~into~~ H₂ while the remaining residue is converted to CH₄ (Show et al., 2012). Overall, via the three-stage
15 fermentation system, 41% and 37% of the energy content in the FW could be ~~harvested as~~ ~~converted to~~ H₂ and CH₄,
16 respectively, corresponding to the electrical energy yield of 1146 MJ/ton FW (Kim & Kim, 2013). Lee and Chung
17 (2010) ~~conducted a presented the~~ cost analysis of hydrogen production from FW using two-phase hydrogen/methane
18 fermentation, ~~and suggested that~~. ~~T~~he abundance and low-cost of FW makes it economically more feasible than the
19 other sources for H₂ production. ~~However, the economic feasibility of process applications from FW is dependent~~
20 ~~on the cost of FW collection.~~ Besides, hydrogen production processes should be combined with an ancillary process,
21 such as methane fermentation, to achieve complete treatment and disposal of FW.

22
23 ~~Lastly, it should also be realized that~~ ~~Besides the technological and economic challenges associated with during the~~
24 ~~fermentative H₂ production and its processes explained above, technological and economic challenges in~~
25 ~~purification, storage, and distribution may also slow down wide application of bio are also limiting the utilization of~~
26 H₂ as green energy. ~~These aspects require intensive research and technical innovation to make the purification and~~
27 ~~storage of H₂ convenient and affordable.~~

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4. Methane Production

The production of biogas, particularly methane via anaerobic processes is an acceptable solution for waste management because of its low cost, low production of residual waste and its utilisation as a renewable energy source (Morita & Sasaki, 2012; Nasir et al., 2012). 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. Mtz. Viturtia et al. (1989) 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. (1999), FW was converted to methane using a 5-L continuous digester fed with an OLR of 7.9 kg VS/m³d, resulting 70% VS conversion with a methane yield of 440 mL/g VS. Gunaseelan (2004) 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 (Molino et al., 2013). 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. (1995) determined the methane yields of different FWs over 28 days 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, acetogenesis, and methanogenesis) take place simultaneously in a single reactor, the system encounters less frequent technical failures and has a smaller investment cost (Forster-Carneiro et al., 2008). 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 (Nasir et al., 2012). Compared to wet anaerobic digestion, dry anaerobic

1 digestion provides lower methane production and VS reduction due to the volatile fatty acid (VFA) transport
2 limitation (Nagao et al., 2012). El-Mashad et al. (2008) reported that a digester treating FW was not stable due to the
3 VFA accumulation and low pH, leading to low biogas production. On the other hand the stability of single-stage
4 anaerobic digester for easily degradable FW is of concern (Lee et al., 1999).

5

6 **4.2. Two-Stages Anaerobic Digestion**

7 In contrast to single stage anaerobic digestion, two-stages anaerobic digestion has often been used for producing
8 both hydrogen and methane in two separate reactors (Chu et al., 2008). In such a system, fast-growing acidogens
9 and hydrogen producing microorganisms are enriched for the production of hydrogen and volatile fatty acids
10 (VFAs) in the first stage. In the second stage, slow-growing acetogens and methanogens are built-up, where VFAs
11 are converted to methane and carbon dioxide. In a study of Park et al. (2008), single-stage and two-stages
12 thermophilic methane fermentation systems were operated using artificial kitchen waste. In both systems, the
13 highest methane recovery yield of 90% (based on COD) was determined at the OLR of 15 g COD/Ld. However, the
14 propionate concentration in the single stage reactor fluctuated largely and was higher than that in the two-stage
15 process, indicating less stable digestion. Massanet-Nicolau et al. (2013) have also compared single and two stage
16 anaerobic fermentation systems on FW processing. The methane yield in two-stage fermentation was improved by
17 37% and was operating at much shorter HRTs and higher loading rates. Lee and Chung (2010) also proved that the
18 two stages hydrogen/methane fermentation has significantly greater potential for recovering energy than methane-
19 only fermentation.

20

21 **4.3. Reactor Configurations**

22 Packed bed reactors (PBR) or fixed bed systems have been developed in order to attain high loading, immobilize
23 microbial consortia and stabilize methanogenesis (Kastner et al., 2012). Parawira et al. (2005) investigated the
24 performances of two different systems, one consisting of a solid-bed reactor for hydrolysis/acidification connected
25 to an upflow anaerobic sludge blanket methanogenic reactor (UASB) while the other consists of a solid-bed reactor
26 connected to a methanogenic reactor packed with wheat straw as biofilm carriers (PBR) during mesophilic anaerobic
27 digestion of solid potato waste. Although PBR degraded the organic materials faster than UASB, the methane yield

1 (390 mL /g VS) and the cumulative methane production was equal in both systems. Among the high-rate anaerobic
2 reactors, UASB reactor has been widely used to treat various kinds of organic wastes. UASB provides the
3 immobilization of anaerobic bacteria by granulation resulting in high microbial activity and good settling
4 characteristics (Moon & Song, 2011). This also allows for high OLR and the maintenance of long retention time.
5 Latif et al. (2012) investigated the mesophilic and thermophilic anaerobic treatment of liquidized FW in UASB
6 reactor by stepwise increasing OLR and temperature. UASB reactor was efficient for COD removal (93.7%), high
7 methane production (0.912 L/g COD) due to low VFA accumulation under controlled temperature and pH. A
8 temperature of 55°C and OLR of 12.5 g COD/L with 4 day HRT supported a maximum biogas production of 1.37
9 L/g COD. Continuously Stirred Tank Reactor (CSTR) and an Fluidized Bed Reactor (FBR) were also investigated
10 for methanogenesis (Kastner et al., 2012). Fermentation yielded 670 normalized litres (NL) biogas/kg VS with the
11 CSTR and 550 NL biogas/kg VS with the FBR while the average methane concentration was approximately 60% for
12 both reactor systems. However, the stability of the process was greater in the FBR.

13
14 As a summary, the two-stage process could attain higher OLR and higher methane generation. In addition, it is less
15 vulnerable to fluctuations in OLR than a single methanogenic process. The efficiency of digestion could be
16 improved by co-digesting different wastes, trace element addition, and using active inoculum as start-up seed. The
17 highest methane yields from FWs were reported by Koike et al. (2009). Koike et al. (2009) who obtained a biogas
18 production of 850 L/g VS during the two-stage hydrogen and methane production processing of FW. Approximately
19 85% of the energy of the garbage was converted to fuels, ethanol and methane by this process.

20
21 Considering the data in Table 1 and Table 2 and the maximum methane yield of (546 mL/g VS) reported in Table 5,
22 it can be estimated that 1.32×10^9 m³ methane can be produced annually which can generate 2.6×10^7 GJ energy using
23 the total food waste generated in the world.

24 25 **5. Biodiesel Production**

26 FW was also converted to fatty acids and biodiesel either by direct transesterification using alkaline or acid catalysts
27 or by the transesterification of microbial oils produced by various oleaginous microorganisms (Chen et al., 2009;

1 Mahmood & Hussain, 2010; Papanikolaou et al., 2011; Yaakob et al., 2013). Microbial oils can be produced by
2 many yeast strains and they can be used as the substitute of plant oils due to their similar fatty acid compositions.
3 Alternatively they can be used as raw material for biodiesel production (Uçkun Kiran et al., 2013). Recent
4 publications on the production of microbial lipids from various FWs using different microbial strains are listed in
5 Table 6. Pleissner et al. (2013) have revealed the potential of FW hydrolyzate as culture medium and nutrient source
6 in microalgae cultivation for biodiesel production. The FW hydrolyzate was prepared using *Aspergillus awamori*
7 and *Aspergillus oryzae* and then used as culture medium for the growth of heterotrophic microalgae *Schizochytrium*
8 *mangrovei* and *Chlorella pyrenoidosa*. The microorganisms grew well on the FW hydrolysate leading to the
9 production of 10 to 20 g biomass. The majority of fatty acids present in lipids of both strains were reported to be
10 suitable for biodiesel production. Papanikolaou et al. (2011) investigated the capacities of five *Aspergillus sp* and
11 *Penicillium expansum* to produce lipid rich biomass from waste cooking olive oil in a carbon limited culture.
12 Significant amount of lipid accumulation was determined in each culture while the highest lipid yield (0.64 g/g dry
13 cell weight) with a productivity of 0.74 g/g was obtained by *Aspergillus sp.* ATHUM 3482. The fatty acids
14 accumulated were mainly C18:1 and has potential to develop food/feed supplements. From Table 6, it can be seen
15 that the studies related to mixed food waste is still very scarce and that the productivity is relatively low. In addition,
16 an extraction and a transesterification step are required to obtain biodiesel. The residual water in FW that is
17 inhibitory in the transesterification is an additional obstacle for this type of fermentation from mixed food waste.

18
19 In South East Asia, Asia and globally produced vegetable oils, butter and animal fats amounts were presented in
20 Table 1. Assuming a maximum lipid yield of 0.74 g/g oil that was obtained from waste cooking oils and with a
21 transesterification yield of 0.95 FAME/g lipid, it can be estimated that 86.5, 201.9 and 647 kT (kilotons) of biodiesel
22 can be produced annually in South East Asia, Asia and in the world, respectively. This [can potentially generate](#)
23 [24.5*10⁶ GJ energy per year globally.](#)

24

25 **6. Conclusions**

26 ~~Large amount of The management of FWs has posed a serious economic and environmental concern. are generated~~
27 ~~worldwide. Environmental concerns directed the research for alternative, environmental friendly methods to handle~~

1 ~~FWs. It appears from this review that bioconversion of FW to energy in terms of~~ The publications discussed above
2 indicated that wide range of products such as ethanol, hydrogen, methane and biodiesel is economically viable. can
3 be produced from various FWs using biological treatment strategies. Thanks to nutrient rich and easily accessible
4 nature of FWs, many products can be produced in high yields without a form of pre treatment. However, difficulties
5 associated with the collection/transportation of FW should also be taken into account. Nevertheless, the low or no
6 cost of food waste along with the environmental benefits considering the waste disposal would balance the initial
7 high capital costs of the biorefineries. The efficiency and cost base of the production could be further improved by
8 intensifying research and optimization studies on integrating different value-added product manufacturing processes.

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