Bioconversion of food waste to energy: a review

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ABSTRACT

According to the 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~~heat or other forms of energy. The residual ash is disposed of in landfills~~. However, these two approaches are facing more and more economic and environmental stresses. ~~incineration is an expensive waste conversion technique and can potentially cause air pollution. From an environmental viewpoint, there is urgent need for appropriate management of food waste.~~ Due to its organics- and nutrients-rich composition, theoretically food waste can~~ould~~ be utilized ~~viewed~~ as a useful resource for production of biofuel through various fermentation processes. So far, ~~Such conversion of food waste is potentially more profitable than the conventional waste recycling efforts. Food waste~~ valorisation of food waste has ~~therefore~~ attracted increasing ~~gained~~ interest, with ~~bio-fuels such as~~ biogas~~methane~~, hydrogen, ethanol and biodiesel as final products. Therefore, this review aims to ~~The aim of this review is to~~ examine ~~provide information on~~ the ~~food waste situation with emphasis on the in Asia-Pacific countries and the~~ state-of-the-art of food waste fermentation technologies for ~~developed around the world which may be applicable for~~ renewable energy generation.

1. Introduction

Food waste (FW) is organic waste discharged from various sources including food processing plants, and domestic and commercial kitchens, cafeterias and restaurants. ~~It accounts for a considerable proportion of municipal solid waste all over the world (Lundqvist et al., 2008).~~ According to FAO (2012), nearly 1.3 billion tonnes of foods including fresh vegetables, fruits, meat, bakery and dairy products are lost ~~in developing and developed countries~~ along the food supply chain~~; from initial agricultural production to consumer~~. 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, ~~T~~the annual amount of urban FW in Asian countries could rise from 278 to 416 million tonnes from 2005 to 2025 (Melikoglu et al., 2013). Typical foods wasted in ~~several~~ Asia-Pacific countries and around the ~~globe~~ world are summarized ~~are listed~~ in Table 1 (FAO, 2008).

~~To reduce its volume,~~ FW is traditionally incinerated with other combustible municipal wastes for generation of heat or energy~~, the residual ash is then disposed of in landfills~~. It should be realized that ~~However, incineration is an expensive waste conversion technique. The fact is that~~ FW indeed contains high level~~s~~ of moisture and this may lead to the production of dioxins during its combustion ~~when burned~~ together with other wastes of low humidity and high calorific value (Katami et al., 2004). In addition, ~~Besides,~~ incineration of FW can potentially cause air pollution and loss of chemical values ~~functionalities~~ of FW~~s~~. These suggest that ~~From an environmental viewpoint, there is a need for~~ an appropriate management of FWs is strongly needed (Ma et al., 2009a). 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 ~~components~~ may result in the breakage of glycoside bonds with releasing polysaccharides ~~emerging~~ as oligosaccharides and monosaccharides, which are more amenable to fermentation ~~into valuable products~~. Total sugar and protein contents in FW are in the range of 35.5-69% and 3.9-21.9%, respectively. ~~Compared to agro-industrial raw materials, FW should be a better raw material for microbial fermentation without nutrients supplement.~~ 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 (Han & Shin, 2004; He et al., 2012b; Koike et al., 2009; Ohkouchi & Inoue, 2007; Pan et al., 2008; Rao & Singh, 2004; Sakai & Ezaki, 2006; Wang et al., 2005; Yang et al., 2006; Zhang et al., 2013). The value of biofuels ($200-400/ ton biomass) is higher than electricity ($60-150/ton biomass) ~~and~~ 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) (Sanders et al., 2007). However, it should be noted that the market demand for such chemicals is much smaller than that for biofuels (Tuck et al., 2012). Therefore, this article ~~eview~~ is intended to review ~~summarize and discuss recently reported~~ 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 ~~because of~~ its wide industrial applications ~~in the chemical and motor fuel industries.~~ 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 ~~that is converted in~~ polyethylene and other plastics. ~~Ethylene is by far the largest bulk chemical (more than 140 million tonnes per year) used for the production of around half of all plastics.~~ As such, ~~The demand for ethylene is continuing to rise, hence~~ bioethanol produced from ~~tion using~~ cheap feedstocks has gained ~~is gaining~~ interest (International-Renewable-Energy-Agency, 2013; Lundgren & Hjertberg, 2010). Traditionally, ~~B~~bioethanol is ~~traditionally~~ produced from cellulose and starch rich crops, e.g. ~~such as~~ potato, rice, and sugar cane (Thomsen et al., 2003). Starch can be ~~is~~ 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 (Jensen et al., 2011; Kim & Dale, 2004).

2.1. Pre-treatments

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

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

2.2. Saccharification

The conversion ~~E~~efficiency of ~~t conversion of~~ FW to ethanol depends ~~-~~on the extent of carbohydrate saccharification as yeast cells cannot ferment starch or cellulose directly into bioethanol (Tubb, 1986). ~~Various enzymes can be utilized depending on the FW composition.~~ A mixture of α-amylase, β-amylase, and glucoamylase of various origins is more effective for ~~A synergistic effect may be observed and this usually involves α-amylase, β-amylase, and glucoamylase of various origins as this is more beneficial in the case of~~ substrate with higher molecular weight. Pullulanase has also been added to the list of saccharifying enzymes recently (Tomasik & Horton, 2012). As a direct endo-acting debranching enzyme, pullulanase can specifically catalyze the hydrolysis of α-1,6-glucosidic linkages of branched polysaccharides (e.g. ~~, such as~~ pullulan, dextrin, amylopectin, and related polymers), resulting in release of ~~giving~~ linear oligosaccharides. Small fermentable sugars (e.g. ~~, such as~~ maltose, amylose, glucose, maltose syrups, ~~high-purity glucose~~ and fructose) can be produced in saccharification process, whereas ~~. C~~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 (Ducroo, 1987).

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 ~~using~~ α-amylase~~-~~ at a dose of 120U/g dry substrate, glucoamylase (120U/g dry substrate), cellulase (8 FPU/g dry substrate) and β-glucosidase (50 U/g dry substrate) (Cekmecelioglu & Uncu, 2013). In a study of Hong and Yoon (2011), 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~~s of glucose~~ is achievable ~~can be obtained~~ by increasing enzyme concentration and temperature at different solid loads, agitation speeds and hydrolysis times in ~~during~~ the saccharification processes (Ado et al., 2009; Sharma et al., 2007; Shen et al., 2009; Zhang et al., 2010). High glucose concentration may result in catabolite repression of the enzymes (Oberoi et al., 2011). Therefore, fed-batch and simultaneous saccharification and fermentation (Ssf) methods have been developed for achieving high ethanol yield from FW (Ma et al., 2009b; Oberoi et al., 2011).

The ~~In~~ fed-batch culture has been commonly employed for the the production of high concentration reducing sugars which can be ~~hydrolysis, solid FW and enzymes are added into reactors stepwise and the FW is gradually degraded (Rudolf et al., 2005). The fed-batch approach can generate high concentrations of reducing sugar which can then be~~ further fermented to ~~high concentration~~ ethanol (Ballesteros et al., 2009). Compared to batch culture, Yan et al. (2012) ~~compared the performances of batch and fed-batch cultures~~found that ~~. Results clearly showed 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 ~~reduce~~ 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 ~~and~~ so as to ~~helping to~~ mitigate ~~-~~inhibition to ~~on~~ enzymatic hydrolysis (Hari Krishna et al., 2001). This combined process can be performed in a single tank, with lower energy consumption~~costs~~, higher ethanol productivity, in shorter processing time using less enzyme (Ballesteros et al., 2009). 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 (2011), about 60 g RS and 36 g ethanol were produced from 100 g of FW in 48-h fermentation. Koike et al. (2009) also reported production of ethanol from non-diluted FW (garbage) in a continuous Ssf process with an ethanol productivity of 17.7 g/Lh. Ma et al. (2009a) 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 sugar was obtained within 14 hours, giving an ethanol yield of 10.08 g/Lh.

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 (He et al., 2009; Wang et al., 2012) and cell recycle through sedimentation or membrane retention (He et al., 2012a). Recombination of bioethanol producing strains with the amylase-producing gene or development of new strains with improved ethanol tolerance have also been reported (Li et al., 2011). 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 (Wang & Lin, 2010).

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 litres of ethanol could be produced from one ton of municipal solid wastes, while the residual by-products could be further used for biogas production (Japan-for-Sustainability, 2013). 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 (Energy-Enviro-Finland, 2013; ST1, 2013). In Spain, citrus wastes have been converted to ethanol with a yield of 235 L/ton dry orange peel (BEST, 2013; Citrotechno, 2013). E-fuel developed a home ethanol system supported with microsensors to convert sugar/starch rich liquid wastes into ethanol for homeowners and small businesses (E-fuel, 2009). ~~Considering the data in Table 1 and the maximum~~

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

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 ~~and~~ H_2 production from FW~~yields achieved using FWs~~. It can be seen that ~~T~~the hydrogen yields ranged from 0.9 mol H_2/mol hexose to 8.35 mol H_2/mol hexose (Patel et al., 2012). The factors such as ~~T~~the composition of FW, pre-treatments and process configurations may affect ~~are the important parameters affecting~~ H_2 production.

3.1. Substrate composition

Hydrogen production potential of carbohydrate-based waste was reported to be ~~as~~ 20 times higher than that of fat-based and protein-based waste (Show et al., 2012). This ~~observation~~ was partially attributed to the consumption of hydrogen towards ammonium using nitrogen generated from protein biodegradation. Kim et al. (2010) reported that the H_2 yield was maintained at around 0.5 mol H_2/mol hexose at ~~when~~ the C/N ratio ~~is~~ lower than 20, while ~~at higher C/N ratio ,~~ H_2 yield was found to drop at higher C/N ratio ~~ped~~ because of the increased production of lactate, propionate, and valerate ~~production~~. 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 (Li & Fang, 2007). Seed biomass is generally pretreated with heat to suppress hydrogen-consumers (Elbeshbishy et al., 2011). FW itself can be a source of H_2-producing microflora. Kim et al. (2008a) have applied several pre-treatments to select microflora for hydrogen production. Lactic acid bacteria are ~~were~~ the most abundant species in untreated FW,

while H_2-producing bacteria are ~~were~~ dominant in the pre-treated FWs. Heat treatment i~~was~~s effective for ~~at~~ suppressing lactate production and increasing H_2/butyrate production. However, heat treatment is likely to increase costs in large scale operations. Luo et al. (2010) investigated different pre-treatment methods~~s~~ of ~~on inoculum~~inoculums, and concluded that ~~. During the first few days, the highest hydrogen production was obtained with heat pretreated seeds. However, the differences in hydrogen yields disappeared later on, suggesting that~~ pre-treatment would only have ~~had only~~ short-term effects on hydrogen production, and ~~. In another study, a yield of 65 mL H_2/Lh was obtained using microflora from unsterilized FW, showing that~~ the pretreatment is not very crucial (Wang & Zhao, 2009).

3.3. Process Configurations

Various fermentation systems, such as the batch, semi-continuous, continuous, one or multiple stages, have been developed for ~~used to~~ production of ~~e~~ H_2 from FWs (Hallenbeck & Ghosh, 2009). High H_2 production rates have been reported ~~achieved~~ in~~using~~ the anaerobic sequencing batch (ASBR) and upflow anaerobic sludge blanket (UASB) reactors due to their high reactor biomass concentrations (Kim et al., 2008a). In these processes, ~~T~~the solid~~s~~ retention time (SRT) determines the substrate uptake efficiency, microbial size & composition and metabolic pathway. A long~~high~~ SRT favours the growth of H_2 consumers, while a short~~low~~ SRT may reduce substrate uptake efficiency, active biomass retention, and ~~therefore,~~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 (Wang & Zhao, 2009). Kim et al. (2008) investigated the effects of SRT in the range of 24-160 h and HRT of 24-42 h on hydrogen production from ~~using~~ FW. It was found that ~~T~~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 ~~determined~~ at ~~an~~ SRT of 126 h and HRT of 33 h. Wang and Zhao (2009) ~~have~~obtained~~-~~ a hydrogen yield of 65 mL H_2/g VS at a long ~~also reported that the high~~ SRT of ~~(~~160 days~~)~~ ~~provides the optimum H_2 production (65 mL H_2/g VS)~~ in a two-stage process.

It is still debatable as for the effect of ~~T~~the organic loading rate (OLR) on ~~is also affecting the H_2~~ bioconversion of FW to H_2. ~~. There are disagreements in the literature as to whether higher H_2 yields are achieved with lower or higher organic loading rates (OLRs).~~ In some studies, ~~cases~~ lower ~~higher OLRs decreased the~~ H_2 yield~~s~~ were

observed at higher OLRs, whereas the opposite trend was also reported in the literature. ~~in others higher OLRs increased the H_2 yield.~~ It appears that an ~~In the latter case, as OLRs increased the H_2 yield usually became constant or eventually began to decrease thereby providing an~~ optimal OLR would exist for the ~~(~~maximum H_2 yield~~)~~ (Wang & Zhao, 2009). Wang et al. (2009) reported that hydrogen fermentation pathway became dominant and H_2 yield was steady at lower OLR (≤22.65 kg VS/m^3d), 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 (Yu et al~~;~~. 2002; Shin and Youn ~~(~~2005). ~~reported that H_2 production was increased as OLR increased up to 8 g VS/Ld and reached 2.4 mol H_2/mol hexose, but drastically decreased at 10 g VS/Ld. This might be related to inhibitory effects of increased organic acids (Yu et al., 2002).~~ Therefore, it is important to determine the optimum OLR and SRT for improving ~~to improve~~ 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 (Kyazze et al., 2007). The accumulation of fermentation products, i.e. CO_2, increases the acidity and then inhibits the microbial growth. Such fermentation products ~~It~~ can be removed from the fermentation medium by simple gas sparging and mixing. Addition of ~~A~~alkaline ~~buffer addition~~ or inoculum recycling are also frequently used for pH control (Kim et al., 2010; Lee et al., 2010b). Compared to addition of ~~using~~ alkali~~ne buffers~~, sludge recirculation is an economically ~~preferr~~preferable approach ~~ed~~ for pH control. ~~Lee et al. (2010b) achieved~~ The long-term stability of a ~~the~~ continuous two-stage process was maintained by recirculating high-alkalinity sludge (Lee et al. 2010b), e.g. ~~. A~~at a ~~the~~ OLR of 39 g COD/Ld and HRT of 1.9 days, the system was stabilized at 2.5 mol H_2/mole hexose, 114 mL H_2/g VS and 462.5 mL H_2/Lh over a period of 96 days ~~operation~~.

The bioconversion yield of FW to ~~main barrier for commercial~~ H_2 production is low, e.g. ~~the low efficiency of bioconversion (Gómez et al., 2011). O~~only about 33% of COD in organic materials can be harvested as H_2, while most of the energy content in the feedstock ~~is~~ mainly end up as ~~converted into~~ organic acids, such as acetic, lactic and butyric acids (Gómez et al., 2011). In other words, actual H_2 yield ~~obtained~~ is much smaller than its theoretical

value of 12 mol H_2/mol glucose (Kim & Kim, 2013). As a result, commercial value of ~~Therefore,~~ organic acids particularly lactic acid should be further explored.~~could be of commercial interest.~~ To improve economic viability of ~~the efficiency~~ of the bioconversion process, H_2 production should also be ~~is sometimes~~ combined with the methane, organic acids and ethanol production processes (Lin et al., 2013). Kyazze et al. (2007) reported that the efficiency of H_2 production process was improved using two-stage H_2-methane production process. Lee et al. (2010a) ~~have~~ 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, ~~Still,~~ only 2.5 mol H_2/mol hexose was ~~could be~~ obtained due to the ~~metabolic~~ limitations of ~~in~~ anaerobic metabolism.

Alternatively, ~~On the other hand, p~~photofermentation has also been explored ~~allows~~ for the conversion of organic acids to H_2. ~~Therefore, i~~In order to increase the overall H_2 yield, combined ~~fermentation systems consisting of both~~ dark- and photo-fermentation system has ~~have~~ been proposed~~recently attempted~~. In this ~~such a~~ process, lactic acid produced from FW is utilized by photofermentative bacteria, particularly ~~using~~ purple non-sulfur bacteria and finally converted ~~in~~to H_2 while the remaining residue is converted to CH_4 (Show et al., 2012). Overall, via the three-stage fermentation system, 41% and 37% of the energy content in the FW could be harvested as ~~converted to~~ H_2 and CH_4, respectively, corresponding to the electrical energy yield of 1146 MJ/ton FW (Kim & Kim, 2013). Lee and Chung (2010) conducted a ~~presented the~~ cost analysis of hydrogen production from FW using two-phase hydrogen/methane fermentation, and suggested that ~~. T~~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 ~~Besides~~ the technological and economic challenges associated with ~~during~~ the fermentative H_2 production and its ~~processes explained above, technological and economic challenges in~~ purification, storage, and distribution may also slow down wide application of bio ~~are also limiting the utilization of~~ H_2 as green energy. ~~These aspects require intensive research and technical innovation to make the purification and storage of H_2 convenient and affordable.~~

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/m^3d, 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

digestion provides lower methane production and VS reduction due to the volatile fatty acid (VFA) transport limitation (Nagao et al., 2012). El-Mashad et al. (2008) 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 (Lee et al., 1999).

4.2. Two-Stages Anaerobic Digestion

In contrast to single stage anaerobic digestion, two-stages anaerobic digestion has often been used for producing both hydrogen and methane in two separate reactors (Chu et al., 2008). 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. (2008), single-stage and two-stages 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/Ld. 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. (2013) 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 (2010) 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 (Kastner et al., 2012). Parawira et al. (2005) 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 (Moon & Song, 2011). This also allows for high OLR and the maintenance of long retention time. Latif et al. (2012) 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 55ºC and OLR of 12.5 g COD/L with 4 day HRT supported a maximum biogas production of 1.37 L/g COD. Continuously Stirred Tank Reactor (CSTR) and an Fluidized Bed Reactor (FBR) were also investigated for methanogenesis (Kastner et al., 2012). 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. (2009). Koike et al. (2009) who 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 (Chen et al., 2009;

Mahmood & Hussain, 2010; Papanikolaou et al., 2011; Yaakob et al., 2013). 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 (Uçkun Kiran et al., 2013). Recent publications on the production of microbial lipids from various FWs using different microbial strains are listed in Table 6. Pleissner et al. (2013) 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 FW hydrolysate leading to the production of 10 to 20 g biomass. The majority of fatty acids present in lipids of both strains were reported to be suitable for biodiesel production. Papanikolaou et al. (2011) 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 ~~can~~ generate $24.5*10^6$ GJ energy per year globally.

6. Conclusions

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

FWs. It appears from this review that bioconversion of FW to energy in terms of The publications discussed above indicated that wide range of products such as ethanol, hydrogen, methane and biodiesel is economically viable. can be produced from various FWs using biological treatment strategies. Thanks to nutrient rich and easily accessible nature of FWs, many products can be produced in high yields without a form of pre-treatmentHowever, 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.

REFERENCES

Ado, S.A., Olukotun, G.B., Ameh, J.B., Yabaya, A. 2009. Bioconversion of cassava starch to ethanol in a simultanenous saccharification and fermentation process by co-cultures of *Aspergillus niger* and *Saccharomyces cerevisiae*. *Science World Journal* **s4**, 19-22.

Ballesteros, M., Oliva, J.M., Manzanares, P., Negro, M.J., Ballesteros, I. 2009. Ethanol production from paper materials using a simultaneous saccharification and fermentation system in a fed-batch basis. *World Journal of Microbiology & Biotechnology*, **18**(6), 559-561.

BEST. 2013. Bioethanol from orange in Spain in: *Bioethanol for sustainable transport*, Vol. 2013, EU. http://www.best-europe.org/Pages/ContentPage.aspx?id=549.

Cekmecelioglu, D., Uncu, O.N. 2013. Kinetic modeling of enzymatic hydrolysis of pretreated kitchen wastes for enhancing bioethanol production *Waste Management* **33**(3), 735-739.

Chen, Y., Xiao, B., Chang, J., Fu, Y., Lv, P., Wang, X. 2009. Synthesis of biodiesel from waste cooking oil using immobilized lipase in fixed bed reactor. *Energy Conversion and Management*, **50**(3), 668–673.

Cho, J.K., Park, S.C., Chang, H.N. 1995. Biochemical methane potential and solid state anaerobic digestion of Korean food wastes. *Bioresource technology*, **52**(3), 245-253.

Chu, C., Li, Y., Xu, K., Ebie, Y., Inamori, Y., Kong, H. 2008. A pH- and temperature-phased two-stage process for hydrogen and methane production from food waste. *International Journal of Hydrogen Energy*, **33**(18), 4739-4746.

Citrotechno. 2013. Second generation bioethanol. in: *Citrotechno*, Vol. 2013. http://www.citrotecno.com/subproductos_bioetanol.php.

Ducroo, P. 1987. Improvements relating to the production of glucose syrups and purified starches from wheat and other cereal starches containing pentosans. in: *Chem. Abstr.*, (Ed.) E.P. EP, Vol. 228, pp. 4704.

E-fuel. 2009. Earth's first home ethanol system. 2009 ed, Vol. 2013. http://www.microfueler.com/t-technology.aspx.

El-Mashad, H.M., McGarvey, J.A., Zhang, R. 2008. Performance and microbial analysis of anaerobic digesters treating food waste and dairy manure. *Biological Engineering Transactions*, **1**(3), 233–242.

Elbeshbishy, E., Hafez, H., Dhar, B.R., Nakhla, G. 2011. Single and combined effect of various pretreatment methods for biohydrogen production from food waste. *International Journal of Hydrogen Energy*, **36**(17), 11379-11387.

Energy-Enviro-Finland. 2013. First plants producing ethanol from food waste in progress. 27.02.2007 ed, Vol. 2013, EnergyEnviroFinland. Finland, pp. http://www.energy-enviro.fi/index.php?PAGE=569.

FAO. 2008. FAOSTAT.

FAO. 2012. Towards the future we want: End hunger and make the transition to sustainable agricultural and food systems. Food and agriculture organization of the United Nations

Forster-Carneiro, T., Pérez, M., Romero, L.I. 2008. Influence of total solid and inoculum contents on performance of anaerobic reactors treating food waste. *Bioresource Technology*, **99**(15), 6994-7002.

Gómez, X., Fernández, C., Fierro, J., Sánchez, M.E., Escapa, A., Morán, A. 2011. Hydrogen production: Two stage processes for waste degradation. *Bioresource Technology* **102**(18), 8621–8627.

Gunaseelan, V.N. 2004. Biochemical methane potential of fruits and vegetable solid waste feedstocks. *Biomass and Bioenergy*, **26**(4), 389-399.

Hallenbeck, P.C., Ghosh, D. 2009. Advances in fermentative biohydrogen production: the way forward? *Trends in Biotechnology*, **27**(5), 287-297.

Han, S.K., Shin, H.S. 2004. Biohydrogen production by anaerobic fermentation of food waste. *International Journal of Hydrogen Energy* **29**(6), 569 – 577.

Hari Krishna, H., Reddy Janardhan, T., Chowdary, G.V. 2001. Simultaneous saccharification and fermentation of lignocellulosic wastes to ethanol using a thermotolerant yeast. *Bioresource Technology*, **77**(2), 193-196.

He, M., Sun, Y., Zou, D., Yuan, H., Zhu, B., Li, X., Pang, Y. 2012a. Influence of temperature on hydrolysis acidification of food waste *Procedia Environmental Sciences*, **16**, 85-94.

He, M.X., Feng, H., Bai, F., Li, Y., Liu, X., Zhang, Y.Z. 2009. Direct production of ethanol from raw sweet potato starch using genetically engineered *Zymomonas mobilis*. *African Journal of Biotechnology*, **3**(11), 721-726.

He, Y., Bagley, D.M., Leung, K.T., Liss, S.N., Liao, B. 2012b. Recent advances in membrane technologies for biorefining and bioenergy production. *Biotechnology advances*, **30**(4), 817-858.

Hong, Y.S., Yoon, H.H. 2011. Ethanol production from food residues. *Biomass Bioenergy* **35**(7), 3271-3275.

International-Renewable-Energy-Agency. 2013. Production of bio-ethylene. IRENA-ETSAP.

Japan-for-Sustainability. 2013. Public-Private-Academic Partnership in Kyoto to Convert Municipal Solid Waste into Ethanol. 17.12.2011 ed. in: *Japan for Sustainability*. http://www.japanfs.org/en/pages/031484.html.

Jensen, J.W., Felby, C., Jørgensen, H. 2011. Cellulase hydrolysis of unsorted MSW. *Applied Biochemistry and Biotechnology*, **165**(7-8), 1799-1811.

Kastner, V., Somitsch, W., Schnitzhofer, W. 2012. The anaerobic fermentation of food waste: A comparison of two bioreactor systems. *Journal of Cleaner Production*, **34**, 82-90.

Katami, T., Yasuhara, A., Shibamoto, T. 2004. Formation of dioxins from incineration of foods found in domestic garbage. *Environmental Science and Technology*, **38**(4), 1062-1065.

Kim, D., Kim, S., Kim, H., Kim, M., Shin, H. 2011a. Sewage sludge addition to food waste synergistically enhances hydrogen fermentation performance *Bioresource Technology* **102**(18), 8501-8506.

Kim, D.H., Kim, M.S. 2013. Development of a novel three-stage fermentation system converting food waste to hydrogen and methane. *Bioresource Technology*, **127**, 267-274.

Kim, D.H., Kim, M.S. 2013 Development of a novel three-stage fermentation system converting food waste to hydrogen and methane. *Bioresource Technology*, **127**, 267–274.

Kim, D.H., Kim, S.H., Kim, H.Y., Shin, H.S. 2010. Experience of a pilot-scale hydrogen-producing anaerobic sequencing batch reactor (ASBR) treating food waste. *International Journal of Hydrogen Energy*, **35**(4), 1590-1594.

Kim, D.H., Kim, S.H., Shin, H.S. 2008a. Hydrogen fermentation of food waste without inoculum addition. *Enzyme and Microbial Technology* **45**(3), 181–187.

Kim, J.H., Lee, J.C., Pak, D. 2011b. Feasibility of producing ethanol from food waste. *Waste Management* **31**(9-10), 2121–2125.

Kim, K.C., Kim, S.W., Kim, M.J., Kim, S.J. 2005. Saccharification of food wastes using cellulolytic and amylolytic enzymes from *Trichoderma harzianum* FJ1 and its kinetics. *Biotechnology and bioprocess engineering*, **10**(1), 52-59.

Kim, S., Dale, B.E. 2004. Global potential bioethanol production from wasted crops and crop residues. *Biomass and Bioenergy*, **26**(4), 361–375.

Kim, S.H., Han, S.K., Shin, H.S. 2008b. Optimization of continuous hydrogen fermentation of food waste as a function of solids retention time independent of hydraulic retention time. *Process Biochemistry* **43**(2), 213–218.

Koike, Y., An, M.Z., Tang, Y.Q., Syo, T., Osaka, N., Morimura, S., Kida, K. 2009. Production of fuel ethanol and methane from garbage by high-efficiency two-stage fermentation process. *Journal of Bioscience and Bioengineering*, **108**(6), 508–512.

Kumar, J.V., Shahbazi, A., Mathew, R. 1998. Bioconversion of solid food wastes to ethanol. *Analyst* **123**(3), 497-502.

Kyazze, G., Dinsdale, R., Guwy, A.J., Hawkes, F.R., Premier, G.C., Hawkes, D.L. 2007. Performance characteristics of two-stage dark fermentative system producing hydrogen and methane continuously. *Biotechnol. Bioeng.* , **97**(4), 759–770.

Latif, M.A., Ahmad, A., Ghufran, R., Wahid, Z.A. 2012. Effect of temperature and organic loading rate on upflow anaerobic sludge blanket reactor and CH_4 production by treating liquidized food waste. *Environmental Progress and Sustainable Energy*, **31**(1), 114-121.

Lee, D., Ebie, Y., Xu, K., Li, Y., Inamori, Y. 2010a. Continuous H_2 and CH_4 production from high-solid food waste in the two-stage thermophilic fermentation process with the recirculation of digester sludge. *Bioresource Technology*, **101**(1 SUPPL.), s42-s47.

Lee, J.P., Lee, J.S., Park, S.C. 1999. Two-phase methanization of food wastes in pilot scale. *Applied Biochemistry and Biotechnology - Part A Enzyme Engineering and Biotechnology*, **77-79**, 585-593.

Lee, Y.W., Chung, J. 2010. Bioproduction of hydrogen from food waste by pilot-scale combined hydrogen/methane fermentation. *International Journal of Hydrogen Energy*, **35**(21), 11746-11755.

Lee, Z., Li, S., Kuo, P., Chen, I., Tien, Y., Huang, Y., Chuang, C., Wong, S., Cheng, S. 2010b. Thermophilic bio-energy process study on hydrogen fermentation with vegetable kitchen waste. *International Journal of Hydrogen Energy*, **35**(24), 13458-13466.

Li, C.L., Fang, H.H.P. 2007. Fermentative hydrogen production from wastewater and solid wastes by mixed cultures. *Crit Rev Environ Sci Technol*, **37**(3), 1-39.

Li, H., Yang, L., Kim, Y.J., Kim, S.J. 2011. Continuous ethanol production by the synchronous saccharification and fermentation using food wastes. *Korean Journal of Chemical Engineering*, **28**(4), 1085-1089

Lin, C.S.K., Pfaltzgraff, L.A., Herrero-Davila, L., Mubofu, E.B., Abderrahim, S., Clark, J.H., Koutinas, A.A., Kopsahelis, N., Stamatelatou, K., Dickson, F., Thankappan, S., Mohamed, Z., Brocklesby, R., Luque, R. 2013. Food waste as a valuable resource for the production of chemicals, materials

and fuels. Current situation and global perspective. *Energy and Environmental Science*, **6**(2), 426-464.
Lundgren, A., Hjertberg, T. 2010. Ethylene from Renewable Resources. in: *Surfactants from Renewable Resources*, John Wiley & Sons, Ltd, pp. 109-126.
Lundqvist, J., de Fraiture, C., Molden, D. 2008. Saving water: From field to fork – curbing losses and wastage in the food chain. Stockholm International Water Institute
Luo, G., Xie, L., Zou, Z., Wang, W., Zhou, Q. 2010. Evaluation of pretreatment methods on mixed inoculum for both batch and continuous thermophilic biohydrogen production from cassava stillage. *Bioresource technology*, **101**(3), 959-964.
Ma, H., Wang, Q., Qian, D., Gong, L., Zhang, W. 2009a. The utilization of acid-tolerant bacteria on ethanol production from kitchen garbage. *Renewable Energy* **34**(6), 1466–1470.
Ma, K., Wakisaka, M., Sakai, K., Shirai, Y. 2009b. Flocculation characteristics of an isolated mutant flocculent *Saccharomyces cerevisiae strain* and its application for fuel ethanol production from kitchen refuse. *Bioresource Technology* **100**(7), 2289–2292.
Mahmood, T., Hussain, S.T. 2010. Nanobiotechnology for the production of biofuels from spent tea. *African Journal of Biotechnology*, **9**(6), 858-868.
Massanet-Nicolau, J., Dinsdale, R., Guwy, A., Shipley, G. 2013. Use of real time gas production data for more accurate comparison of continuous single-stage and two-stage fermentation. *Bioresource technology*, **129**, 561-567.
Melikoglu, M., Lin, C.S.K., Webb, C. 2013. Analysing global food waste problem: pinpointing the facts and estimating the energy content. *Cent. Eur. J. Eng.* , **3**(2), 157-164.
Mohd Yasin, N.H., Rahman, N.A., Man, H.C., Yusoff, M.Z.M., Hassan, M.A. 2011. Microbial characterization of hydrogen-producing bacteria in fermented food waste at different pH values. *International Journal of Hydrogen Energy*, **36**(16), 9571-9580.
Molino, A., Nanna, F., Ding, Y., Bikson, B., Braccio, G. 2013. Biomethane production by anaerobic digestion of organic waste. *Fuel*, **103**, 1003-1009.
Moon, H.C., Song, I.S. 2011. Enzymatic hydrolysis of foodwaste and methane production using UASB bioreactor. *International Journal of Green Energy*, **8**(3), 361-371.
Morita, M., Sasaki, K. 2012. Factors influencing the degradation of garbage in methanogenic bioreactors and impacts on biogas formation. *Applied Microbiology and Biotechnology*, **94**(3), 575-582.
Mtz. Viturtia, A., Mata-Alvarez, J., Cecchi, F., Fazzini, G. 1989. Two-phase anaerobic digestion of a mixture of fruit and vegetable wastes. *Biological Wastes*, **29**(3), 189-199.
Nagao, N., Tajima, N., Kawai, M., Niwa, C., Kurosawa, N., Matsuyama, T., Yusoff, F.M., Toda, T. 2012. Maximum organic loading rate for the single-stage wet anaerobic digestion of food waste. *Bioresource Technology*, **118**, 210-218.
Nasir, I.M., Ghazi, T.I.M., Omar, R. 2012. Production of biogas from solid organic wastes through anaerobic digestion: A review. *Applied Microbiology and Biotechnology*, **95**(2), 321-329.
Oberoi, H.S., Vadlani, P.V., Nanjundaswamy, A., Bansal, S., Singh, S., Kaur, S., Babbar, N. 2011. Enhanced ethanol production from Kinnow mandarin (*Citrus reticulata*) waste via a statistically optimized simultaneous saccharification and fermentation process. *Bioresource Technology* **102**(2), 1593–1601.
Ohkouchi, Y., Inoue, Y. 2007. Impact of chemical components of organic wastes on l(+)-lactic acid production. *Bioresource Technology*, **98**(3), 546-553.
Pan, J., Zhang, R., El-Mashad, H.M., Sun, H., Ying, Y. 2008. Effect of food to microorganism ratio on biohydrogen production from food waste via anaerobic fermentation. *International Journal of Hydrogen Energy*, **33**(23), 6968-6975.

Papanikolaou, S., Dimou, A., Fakas, S., Diamantopoulou, P., Philippoussis, A., Galiotou-Panayotou, M., Aggelis, G. 2011. Biotechnological conversion of waste cooking olive oil into lipid-rich biomass using *Aspergillus* and *Penicillium* strains. *Journal of Applied Microbiology* **110**(5), 1138–1150.

Parawira, W., Murto, M., Read, J.S., Mattiasson, B. 2005. Profile of hydrolases and biogas production during two-stage mesophilic anaerobic digestion of solid potato waste. *Process Biochemistry* **40**(9), 2945–2952.

Park, Y.J., Hong, F., Cheon, J.H., Hidaka, T., Tsuno, H. 2008. Comparison of thermophilic anaerobic digestion characteristics between single-phase and two-phase systems for kitchen garbage treatment. *Journal of Bioscience and Bioengineering*, **105**(1), 48-54.

Patel, S.K.S., Kumar, P., Kalia, V.C. 2012. Enhancing biological hydrogen production through complementary microbial metabolisms. *International Journal of Hydrogen Energy*, **37**(14), 10590-10603.

Pleissner, D., Lam, W.C., Sun, Z., Lin, C.S.K. 2013. Food waste as nutrient source in heterotrophic microalgae cultivation. *Bioresource Technology* **137**, 139-146.

Rao, M.S., Singh, S.P. 2004. Bioenergy conversion studies of organic fraction of MSW: kinetic studies and gas yield–organic loading relationships for process optimisation. *Bioresource Technology* **95**(2), 173–185.

Rudolf, A., Alkasrawi, M., Zacchi, G., Liden, G. 2005. A comparison between batch and fed-batch simultaneous saccharification and fermentation of steam pretreated spruce. *Enzyme and Microbial Technology*, **37**(2), 195-204.

Sakai, K., Ezaki, Y. 2006. Open L-lactic acid fermentation of food refuse using thermophilic *Bacillus coagulans* and fluorescence in situ hybridization analysis of microflora. *Journal of Bioscience and Bioengineering*, **101**(6), 457-463.

Sanders, J., Scott, E., Weusthuis, R., Mooibroek, H. 2007. Bio-refinery as the bio-inspired process to bulk chemicals. *Macromolecular Bioscience*, **7**(2), 105-117.

Sharma, N., Kalra, K.L., Oberoi, H.S., Bansal, S. 2007. Optimization of fermentation parameters for production of ethanol from kinnow waste and banana peels by simultaneous saccharification and fermentation. *Indian Journal of Microbiology*, **47**(4), 310-316.

Shen, F., Liu, R., Wang, T. 2009. Effect of temperature, pH, agitation and particles stuffing rate on fermentation of sorghum stalk juice to ethanol, energy source part a: recovery. *Utilization and Environmental Effects* **31**(8), 646–656.

Shin, H., Youn, J. 2005. Conversion of food waste into hydrogen by thermophilic acidogenesis. *Biodegradation*, **16**(1), 33-44.

Show, K.Y., Lee, D.J., Tay, J.H., Lin, C.Y., Chang, J.S. 2012. Biohydrogen production: Current perspectives and the way forward. *International Journal of Hydrogen Energy*, **37**(20), 15616-15631.

ST1. 2013. St1 Biofuels bioethanol production. 2012 ed, Vol. 2013. http://www.st1.eu/index.php?id=12351.

Tang, Y.Q., Koike, Y., Liu, K., An, M.Z., Morimura, S., Wu, X.L., Kida, K. 2008. Ethanol production from kitchen waste using the flocculating yeast *Saccharomyces cerevisiae* strain KF-7. *Biomass and Bioenergy* **32** (11), 1037–1045.

Tao, F., Miao, J.Y., Shi, G.Y., Zhang, K.C. 2005. Ethanol fermentation by an acid-tolerant *Zymomonas mobilis* under non-sterilized condition. *Process Biochemistry*, **40**(1), 183–187.

Thomsen, A.B., Medina, C., Ahring, B.K. 2003. Biotechnology in ethanol production. 2. Riso National Laboratory.

Tomasik, P., Horton, D. 2012. Enzymatic conversions of starch. *Advances in Carbohydrate Chemistry and Biochemistry*, **68**, 59-436.

Tubb, R.S. 1986. Amylolytic yeasts for commercial applications. *Trends Biotechnology*, **4**(4), 98-104.

Tuck, C.O., Pérez, E., Horváth, I.T., Sheldon, R.A., Poliakoff, M. 2012. Valorization of biomass: Deriving more value from waste. *Science*, **337**, 695–699.

Uçkun Kiran, E., Trzcinski, A., Webb, C. 2013. Microbial oil produced from biodiesel by-products could enhance overall production. *Bioresource Technology*, **129**, 650-654.

Uncu, O.N., Cekmecelioglu, D. 2011. Cost-effective approach to ethanol production and optimization by response surface methodology. *Waste Management*, **31**(4), 636-643.

Wang, F.S., Lin, H.T. 2010. Fuzzy optimization of continuous fermentations with cell recycling for ethanol production. *Ind. Eng. Chem. Res.* , **49**(5), 2306−2311.

Wang, G., Wang, Z., Zhang, Y., Zhang, Y. 2012. Cloning and expression of amyE gene from *Bacillus subtilis* in *Zymomonas mobilis* and direct production of ethanol from soluble starch. *Biotechnology and Bioprocess Engineering*, **17**(4), 780-786.

Wang, H., Wang, J., Fang, Z., Wang, X., Bu, H. 2010. Enhanced bio-hydrogen production by anaerobic fermentation of apple pomace with enzyme hydrolysis. *International Journal of Hydrogen Energy*, **35**(15), 8303-8309.

Wang, Q., Ma, H., Xu, W., Gong, L., Zhang, W., Zou, D. 2008. Ethanol production from kitchen garbage using response surface methodology. *Biochemical Engineering Journal*, **39**(3), 604-610.

Wang, Q., Wang, X., Wang, X., Ma, H., Ren, N. 2005. Bioconversion of kitchen garbage to lactic acid by two wild strains of *Lactobacillus* species. *Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering*, **40**(10), 1951-1962.

Wang, X., Zhao, Y.C. 2009. A bench scale study of fermentative hydrogen and methane production from food waste in integrated two-stage process. *International Journal of Hydrogen Energy*, **34**(1), 245-254.

Yaakob, Z., Mohammad, M., Alherbawi, M., Alam, Z., Sopian, K. 2013. Overview of the production of biodiesel from waste cooking oil. *Renewable and sustainable energy reviews*, **18**, 184–193.

Yan, S., Wang, P., Zhai, Z., Yao, J. 2011. Fuel ethanol production from concentrated food waste hydrolysates in immobilized cell reactors by *Saccharomyces cerevisiae* H058. *Journal of Chemical Technology and Biotechnology* **86**(5), 731-738.

Yan, S., Yao, J., Yao, L., Zhi, Z., Chen, X., Wu, J. 2012. Fed batch enzymatic saccharification of food waste improves the sugar concentration in the hydrolysates and eventually the ethanol fermentation by *Saccharomyces cerevisiae* H058. *Brazilian Archives of Biology and Technology*, **55**(2), 183-192.

Yang, S.Y., Ji, K.S., Baik, Y.H., Kwak, W.S., McCaskey, T.A. 2006. Lactic acid fermentation of food waste for swine feed. *Bioresource Technology*, **97**(15), 1858–1864.

Ye, Z., Zheng, Y., Li, Y., Cai, W. 2008. Use of starter culture of *Lactobacillus plantarum* BP04 in the preservation of dining-hall food waste. *World Journal of Microbiology and Biotechnology*, **24**(10), 2249-2256.

Youn, J., Shin, H. 2005. Comparative performance between temperature-phased and conventional mesophilic two-phased processes in terms of anaerobically produced bioenergy from food waste. *Waste Management and Research*, **23**(1), 32-38.

Yu, H., Zhu, Z., Hu, W., Zhang, H. 2002. Hydrogen production from rice winery wastewater in an upflow anaerobic reactor by using mixed anaerobic cultures. *International Journal of Hydrogen Energy*, **27**(11-12), 1359–1365.

Zhang, C., Xiao, G., Peng, L., Su, H., Tan, T. 2013. The anaerobic co-digestion of food waste and cattle manure. *Bioresource technology*, **129**, 170-176.

Zhang, M., Shukla, P., Ayyachamy, M., Permaul, K., Singh, S. 2010. Improved bioethanol production through simultaneous saccharification and fermentation of lignocellulosic agricultural wastes by *Kluyveromyces marxianus* 6556. *World J. Microbiol. Biotechnol.* , **26**(6), 1041-1046.

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