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Abstract

Consistent material and substance flow diagrams for five alternative biorefinery scenarios for treating Chinese food waste were obtained by combining reported experimental research data and material flow analysis. The biorefinery alternatives produced biogas, biomethane, bioethanol and biodiesel in various combinations. The compiled statistical data compiled showed that 100 t of Chinese food waste could produce 16 ± 1.1 t of biogas as a single technology and that other advanced biorefinery concepts could produce 5 ± 0.4 t of biomethane, 4 ± 1.6 t of bioethanol and/or 3 ± 0.2 t of biodiesel. In terms of substance flow, biorefinery scenarios transfer up to 75% of the total initial carbon in the food waste into bioproducts, while 22% of carbon is emitted, primarily as carbon dioxide. The compost obtained by composting the dewatered digestate contained about 75% of input P, 27% of input K and 6% of input N. About 15% of input N was lost to the air during composting. The remaining C, N, P and K were in the wastewater. Introducing biorefinery concepts to the management of Chinese food waste can facilitate the generation of high-value bioproducts. However, biorefinery concepts are technologically complicated and the energy consumption may triple relative to that of only biogas production. The issue of a considerably large liquid fraction in all cases still needs to be addressed. The material flow diagrams in this work constitute a consistent platform for assessing future scenarios for treating Chinese food waste from a technical, economical as well environmental perspective.

Key words

Food waste, biorefinery, material flow analysis, substance flow analysis, scenario inventory

1 Introduction

Food waste (FW) is a major issue in waste management globally; according to the Food and Agriculture Organization of the United Nations more than 1.3×10^9 t of FW is generated around the world every year (FAO, 2018). In China, 130 million tonnes of FW are generated yearly and are mainly treated by anaerobic digestion with utilization of biogas for electricity and heat production. A range of other approaches has been proposed for FW treatment in China, and they include the use of a biorefinery concept in which biofuels are produced from FW (Wen et al., 2016).

The biorefinery concept is analogous to traditional petrochemical refinery that maximizes valuable outputs from the processing of crude materials (Lin et al., 2013). As refineries, biorefineries can provide multiple chemicals by fractioning an initial raw material (biomass) into multiple intermediates (carbohydrates, proteins, lipids) that can be further converted into value-added product (Cherubini, 2010).

Apart from the direct conversion of biogas into heat or electricity, which is a technology that already exists in full scale, other alternatives in the area of FW are attracting increasing attentions (Miezhah et al., 2017; Hao et al., 2015; Sawatdeenarunat et al., 2016). The report of the International Energy Agency Bioenergy Task (IEA, 2012) gives a detailed list of potential value-added products, including bioethanol, biodiesel, succinic acid, lactic acid, levulinic acids, furfural alcohol and hydroxymethylfurfural. These products from FW has received strong support from researches in recent years (Coma et al., 2017; Gaudino et al., 2019; Lavelli et al., 2018; Rudroff and Chem, 2017; Sherwood and Shang, 2018; Yu et al., 2017).

Bioethanol and biodiesel production based on other organic substrates (corn, used cooking oils, etc.) has become available and biorefining of woody biomass has received much research attention. However, the biorefining of Chinese FW remains challenging because of the mixed organic content (carbohydrates, proteins and lipids) and the data available are scarce (Hao et al., 2015).

Tang et al., (2008) produced bioethanol and biogas from kitchen waste at laboratory scale. Hao et al., (2015) established an integrated biorefinery process with outputs of biolipids and biogas via laboratory experiments. Field case studies have also been conducted in China with feasible results (Jin et al., 2015; Wen et al., 2016), but the information available about material and nutrient flows as well as amount of products produced is rudimentary and does not provide a consistent basis for comparing alternative FW biorefinery systems.

Our research aims to fill this research gap and provide a consistent framework for

analyzing FW-based biorefinery exploitation routes. For the first time, this study provides a systematic analysis of the material and nutrient flows of a range of potential biorefinery concepts for treating Chinese FW. On the basis of a comprehensive survey of technical data from the literature and from technical reports, statistical distributions were established in this work to determine the key technical parameters. Material and nutrient flows were estimated for five scenarios for treating Chinese FW. The baseline scenario is anaerobic digestion as this technology is already in place in many areas of China. The four other hypothetical biorefinery scenarios are modeled with biomethane, bioethanol and biodiesel in different combinations with anaerobic digestion. The material flow analysis, including the estimation of associated uncertainties, provides a systematic estimate of the quantity of products and residues generated by the biorefinery scenarios. The results should form an important engineering platform for assessing the future potential of biorefinery concepts for treating Chinese FW in technical, economic and environmental terms.

2 Materials and methods

This section describes how data on Chinese FW composition were obtained and how we defined the biorefinery technologies and compiled key data for the material and nutrient flow analysis.

2.1 Composition of FW

FW originates from households, canteens, restaurants, food shops and markets. The composition of Chinese FW is summarized in Table 1. Most of the data on FW composition come from canteens and restaurants. The water content ranges from 73% to 83%, with the average being 79%. Carbohydrates, proteins and lipids are the main components, averaging 51%, 16% and 22% of dry matter (DM), respectively. Whereas biogas is produced by anaerobic digestion of all three organic compounds, biodiesel is produced by converting lipids and bioethanol production requires carbohydrates to be saccharified into glucose.

Table 1. Composition of Chinese food waste

Source of information.	Water (%)	TS (%)	VS (% TS)	Ash (% TS)	Carbohydrate (% TS)	Protein (% TS)	Lipid (% TS)	TC (% TS)	TN (% TS)
(Ma et al., 2008)	82.8	17.2	85.0	14.9	64.9	15.6	18.1	-	-
(He et al., 2012)	81.7	18.3	87.5	12.5	35.5	14.4	24.1	48.4	0.8
(Sun et al., 2013)	80.3	19.7	86.3	13.7	51	14.5	20.9	-	-
(Shen et al., 2013)	77.4	22.6	79.2	20.8	41.9	14.7	28.9	30.3	2.6
(Zhang et al., 2013)	81.5	18.5	91.9	8.1	-	-	22.8	46.5	2.2
(Zhou et al., 2014)	77.3	22.7	91.2	8.8	-	-	30.4	48.3	2.6
(C. Wu et al., 2015)	72.8	27.2	93.8	6.3	61.1	23.0	13.2	-	-

(Yong et al., 2015)	79.9	20.1	95.8	4.2	40.6	14.0	25.3	-	-
(Li et al., 2016)	80.9	19.1	93.2	6.8	61.8	13.2	18.3	46.1	3.2
Average	79.4±2.9	20.6±2.9	89.3±4.9	10.7±4.9	50.9±10.9	15.6±3.1	22.4±5.2	43.9±6.9	2.3±0.8

TS: total solid; VS: volatile solid; TC: total carbon; TN: total nitrogen

2.2 Data collection and analysis

Data on the parameters related to bioprocesses were extracted and compiled from a range of sources: scientific literature, technical reports, statistical yearbooks and in a few cases supplemented by specific sampling and theoretical calculation. The latter was needed for the estimates of energy uses in full-scale plants where actual data were missing or only available for laboratory experiments. The statistical distributions of the related parameters (i.e., biogas yield, carbohydrate saccharification ratio, solid liquid separation ratio, glucose fermentation ratio and yield of transesterification) were established to estimate average flows and their associated uncertainties (average $\pm$ standard deviation). The parameters are shown in Table 2 together with their sources. Additional information is available in the Appendix A, B and C. The technologies and the most critical technical parameters are summarized in the subsequent sections.

2.3 Biogas production

The technology route for biogas production is well known and could be described as two main sub-processes: anaerobic digestion and digestate dewatering (Fuldauer et al., 2018). After digestate dewatering, the liquid and solid fractions (SFs) of the digestate are utilized separately. Each fraction of the FW (proteins, carbohydrates and lipids) has biogas production potential (Lopez et al., 2016). The technical parameters related to methane yield and dewatering are referred from relevant published literature. External water is added to adjust the solid content to 8-10% as a typical wet anaerobic digestion (Lv et al., 2017).

Biogas consists of a mixture of methane and carbon dioxide. The theoretical methane potential of Chinese FW, calculated by the Buswell equation (see Appendix Eq. (A.1)) is 580 m³ CH₄/t VS. The measured methane production of Chinese FW (as mono-digested) based on the literature (Appendix Table A.1) is in the range of 372-455 m³/t VS, with an average yield of 407 m³/t VS. This value suggests that a 70% (with a standard deviation of 5%) utilization of the theoretical methane potential is realistic in a continuous-flow reactor. Along with biogas production, a large amount of digestate is produced. The solid fraction of digestate can be used for soil amendment after composting and aging.

2.4 Biomethane production

Biomethane is produced from biogas after the removal of the CO₂ content through biogas upgrading (Pöschl et al., 2010).. A range of upgrading technologies are available (pressure swing adsorption, water scrubbing, membrane separation etc.). Energy consumption is a significant and major factor in selecting technologies. Water scrubbing was chosen in the present study because it has the lowest energy consumption as described by both Hahn et al., (2014) and Patterson et al., (2011) (0.20-0.43 kWh/Nm³; gas leaking rate of 0.5-2%). The pure CO₂ after biogas upgrading could be sold for industrial applications (Esposito et al., 2019; Ryckebosch et al., 2011) or applied in construction material production (Wang et al., 2018).

2.5 Bioethanol production

The technical route for bioethanol production can be described as saccharification, solid liquid separation, fermentation and distillation (Sun et al., 2013). Bioethanol is obtained after converting the carbohydrates in FW into sugars (saccharification by means of glucoamylase) and subsequently converting the sugars into bioethanol (fermentation by *Saccharomyces cerevisiae*) (see Appendix B for details). The solid content is adjusted to 10-15% total solid (TS) by adding water to obtain the maximum efficiency of saccharification (Ma et al., 2016; Tang et al., 2008); in our work, we used an average of 12% of TS with an addition of 50 t of water per 100 t of FW. The efficiencies are 62-100% (of carbohydrate) for saccharification, 66-89% (of glucose) for solid-liquid separation, and 72-100% (of glucose) for glucose fermentation to ethanol. Bioethanol can be separated from the liquid mixture via distillation. Data on distillation was adopted from (Balat, 2011). Bioethanol is distilled off as a product; in our work, we used a distillation efficiency of 96.5% (of bioethanol) (Ebner et al., 2014).

2.6 Biodiesel production

The technical route for biodiesel production can be described as two main sub-processes: transesterification and washing (Wen et al., 2016). Biodiesel, which comprises mono-alkyl esters of fatty acids, is produced from the lipid content of FW through transesterification with methanol in the presence of lipase converted into triglyceride (lipid from FW), methyl esters (biodiesel) and glycerol (by-product) (Heimann, 2016). Details are provided in Appendix C. After the transesterification, biodiesel is purified and washed with water to remove residues. The biodiesel production constitutes 81-100% of the lipids; in our work, we used an average value of 91.5%.

Table 2 Technical data used in the modeling based on the literature. The numbers in brackets reflect the number of referenced papers; the absence of a bracket indicates that only one paper is referenced.

Process	Parameter	Value	Unit	Reference
Centrifugation	Efficiency for lipids	83	%,w of lipids	Anaerobic digestion plant in Jiangsu, China, 2017
	Energy consumption	4.5	kWh/t TWW	(Jin et al., 2015)
Transesterification	Biodiesel productivity	91.6±6.1 (7) ^a	%, w of lipids	(Yang et al., 2012)(Torres et al., 2013)(Karmee et al., 2015)(Sakuragi et al., 2016)(Wen et al., 2016)(Karmee, 2016)(Wang et al., 2017)
	Lipase consumption	40	kg/t lipids	(Jin et al., 2015)
	Energy consumption	137	kWh/t TWW	(Jian et al., 2010)
Saccharification and fermentation	Saccharification Efficiency	84.0±16.7 (4)	%, w of carbohydrate	(Tao et al., 2005)(Tang et al., 2008)(Koike et al., 2009)(Yan et al., 2013)(C. Wu et al., 2015)(Uçkun
	Solid-liquid separation Efficiency	85.0±10.8 (5)	%, w of glucose	Kiran et al., 2015)(Ma et al., 2016)
	Bioethanol fermentation Efficiency	90.4±9.1 (7)	%, w of glucose	(Ma et al., 2016)
	Glucoamylase consumption	2.4	kg/t carbohydrate	(L. J. Wu et al., 2015)
	Energy consumption	66	kWh/t TWW	(Ebner et al., 2014)
	Ethanol distillation Efficiency	96.5	%, w of bioethanol	(Quiroz-Arita et al., 2017)
	Energy consumption of distillation	420	kWh/t EtOH	(Zhang et al., 2011) (Zhang et al., 2012) (Zhang et al., 2013) (Li et al., 2016)
Anaerobic digestion	Methane yield	70%±5 (6) of theoretical value	mL/g-VS	(Jensen et al., 2016)
	Biogas leaking	1.5	%, v of biogas	(Jin et al., 2015)
	Energy consumption	26	kWh/t TWW	(Hahn et al., 2014)
Biogas upgrading	Biogas leaking	1.5	%, v of biogas	(Patterson et al., 2011) (Sin et al., 2016)
	Energy consumption	0.30	kWh/m ³ CH ₄	(Stoknes et al., 2016)
Digestate dewatering	C (to liquid fraction)	20.8	%	(Stoknes et al., 2016)
	K (to liquid fraction)	73.9	%	(Stoknes et al., 2016)
	N (to liquid fraction)	79.3	%	(Stoknes et al., 2016)

Composting	P (to liquid fraction)	29.6	%	(Stoknes et al., 2016)
	Energy consumption	0.83	kWh/t TWW	(Tampio et al., 2016)
	Water (to emissions)	87.95	%	(Zhao et al., 2015)
	VS (to emissions)	89.84	%	(Zhao et al., 2015)
	C (to emissions)	97.68	%	(Zhao et al., 2015)
	N (to emissions)	76.54	%	(Zhao et al., 2015)
	Amount of Wood chips	25	%, w of digestate	(Zhao et al., 2015)
Emissions from composting	Energy consumption	38	kWh/t TWW	(Design et al., 2006)
	C (transformed to CH ₄)	1.6	%	(Møller, 2016)
	C (transformed to CO ₂)	98.4	%	(Møller, 2016)
	N (transformed to N ₂ O)	6.3	%	(Møller, 2016)
	N (transformed to NH ₃)	59	%	(Møller, 2016)

^a When more than one source of data was found, value was presented as average $\pm$ standard deviation.

TWW: total wet weight; EtOH: ethanol; VS: volatile solid; w: weight

2.7 Material flow modeling

The material and substance flows of the alternative biorefinery scenarios were modeled with the EASETECH model (Environmental Assessment System for Environmental TECHNOlogies, v2.4.5) (Clavereul et al., 2014) while the results were fed to the software STAN for graphical presentation (subSTance flow ANalysis, 2.6) (Cencic and Rechberger, 2008a).

EASETECH, a waste-LCA model focusing on the management of complex waste streams (Christensen et al., 2015), can be used to handle the flow of complex heterogeneous fractions in various bioprocess systems. Clavereul et al., (2014) described the framework and the calculation structure in detail. STAN is used to analyze material flow (Cencic and Rechberger, 2008b).

The modeling of the material and substance flows involved more than 30 modules in EASETECH. The modules represent centrifugation, transesterification, saccharification, bioethanol fermentation, anaerobic digestion, biogas leaking from the digester, biogas upgrading, digestate dewatering, composting, and emissions from composting. Transport was not included. The scenarios established in EASETECH are shown in Appendix D.

2.8 Scenarios

The five alternative scenarios for biorefining Chinese FW are described below. The material and nutrient flow modeling assumed that all scenarios received 100 t of wet Chinese FW. The establishment of scenarios are referred from various previously studies. Cesaro and Belgiorno, (2015), Miezah et al., (2017) and Tan et al., (2014) made an effort to produce biogas as well as bioethanol from FW. Hao et al., (2015), Li et al., (2016b) and Wen et al., (2016) provided examples of converting FW into biogas and biodiesel. S. Karmee and Lin, (2014), Zhang et al., (2016) and Sawatdeenarunat et al., (2016) also explained ways to convert FW into various biofuels.

The parameters listed in Table 2 are applied in all scenarios. The reaction efficiencies are specific: the efficiency of transesterification reaction relates to the amount of lipids, while for the bioethanol production processes the parameters relate to the amount of carbohydrates or glucose.

2.8.1 Scenario S0 - Biogas as the targeting product (Anaerobic digestion + composting)

S0 is the baseline scenario. The separately collected FW is sent to an anaerobic digester to produce biogas. The digestate is split into a solid fraction (SF) and a liquid fraction (LF) via dewatering. The SF is subject to composting with wood

chips in an open windrow and the compost can be used, for example, as a biofertilizer. Wood chips are used as structural material to improve the aeration needed for the aerobic process (Bernstad and la Cour Jansen, 2011) (Hayes et al., 2016). The LF most likely needs treatment prior to discharge or use. The main products from Scenario S0 are biogas, compost and liquid residue.

2.8.2 Scenario S1 - Biomethane as the targeting product (Anaerobic digestion + biogas upgrading + composting)

Biogas produced as Scenario S0 is upgraded to biomethane through the removal of CO₂ and hydrogen sulfide. The digestate is treated in the same way as that described in Scenario S0. The main products from Scenario S1 are biomethane, CO₂, compost and liquid residue.

2.8.3 Scenario S2 - Bioethanol as the targeting product (Saccharification and fermentation + anaerobic digestion + composting)

Bioethanol is produced by fermentation on the liquid flow after water addition and separation of solids. The bioethanol is distilled off and the residues are subject to anaerobic digestion. The SF of the residue is composted as described in Scenario S0. The main products are bioethanol, biogas, compost and liquid residues.

2.8.4 Scenario S3 - Biodiesel as the targeting product (Transesterification + anaerobic digestion + composting)

Biodiesel is produced on the lipid fraction of the FW separated by centrifugation. After transesterification with methanol, washing with water and dehydration, three products are obtained: biodiesel, crude glycerol and asphalt. All of the residues (including the wastewater from the washing system) are anaerobically digested to produce biogas. The main products are biodiesel, bioasphalt, crude glycerol, biogas, liquid residue and compost.

2.8.5 Scenario S4 - Biodiesel and bioethanol as the targeting product (Transesterification + saccharification and fermentation + anaerobic digestion + composting)

Biodiesel is produced on the lipid fraction of FW separated by centrifugation as described in Scenario S3, while the remaining fraction is used for bioethanol production as described in Scenario S2. The residue of ethanol fermentation is subjected to anaerobic digestion for biogas production followed by composting of the solid residue. The products are biodiesel, crude glycerol, bioasphalt, bioethanol, biogas, compost and liquid residue.

3 Results and Discussion

The study addresses 100 t of wet Chinese FW; this could be the amount that a full

scale plant process each day. The FW is collected from restaurants and hotels and transported to the biorefinery plant, where impurities are removed manually prior to the actual bio-refining (Jin et al., 2015). The products produced maybe used locally or sold on the market. The current study focuses on the technological alternatives and exclude activities before and after the biorefinery.

Table 1 shows that FW composition is rather uncertain. The large standard deviation indicates that FW composition varies significantly, likely due to differences in the source, collection method, and maybe time of the year. In particular, the carbohydrate content varies significantly and future research should address this issue.

3.1 Material flow analysis

Figure 1 shows the estimated material flows originating from 100 t of wet Chinese FW subject to treatment in the five alternative biorefinery scenarios. The 100 t Chinese FW contains 4.6 t of lipids in dry matter (DM), 10.5 t of carbohydrates (DM) and 84.9 t other components, including other organic compounds (5.5 t DM) and water (79.4 t). Water (50 t), chemicals, wood chips and other supporting materials are shown as well. The flow diagrams show the complexity of the biorefinery scenarios and the variety of outputs and emissions. The amount of external water is the same in all scenarios. The small addition of enzymes/additives is not included in the mass flows. The consistency of the input materials ensures the comparability of the alternative scenarios.

Though the five scenarios generate different products of different quantities, a high amount of liquid residue is produced (124-126 t) in all scenarios. The numerical values for the flows in all scenario can be found in Table 3.

The comprehensive analysis of these five alternative flow diagrams shows that the bio-refining of 100 t of Chinese FW can produce around 3.8 ± 1.6 t ethanol, 3.0 ± 0.2 t biodiesel and from 6.3 ± 1.7 to 15.8 ± 1.1 t of biogas; a low amount of biogas is produced when bioethanol and biodiesel are produced and a high amount is produced when only biogas is produced. The upgrading of 15.5 ± 1.1 t biogas produces 5.2 ± 0.4 t biomethane ($> 98\%$ CH₄). When biodiesel is produced, 0.9 ± 0.1 t of byproducts, including bio asphalt and crude glycerol, are also produced.

In the baseline scenario (S0), 18% of the input FW material appears as bioproducts (biogas and compost), 7% is emitted to the surroundings, and 75% appears in the wastewater. After biogas upgrading in S1, only 7.2% of the input FW material is transferred to bioproducts (biomethane and compost). If the removed CO₂ is considered a product (Esposito et al., 2019; Ryckebosch et al., 2011) the transformation value to bioproduct is 18%.

According to the material flow analysis, the ratios of FW transferred into bioethanol and biogas in S2 are 3.8% and 11.6%, respectively. This is a moderate estimation and similar to previously reported results from the same technical route (Tang et al., 2008). The production of bioethanol (S2, S4) entails additional CO₂ emissions during the fermentation process. Thus, the emissions in S2 and S4 are higher than in the baseline scenario.

In the biodiesel scenario (S3), about 14% of input FW material ends up in biogas, biodiesel and its by-products. The material flows are comparable to those with liquid fraction for biodiesel and biogas production, and the by-products from the lipids are also verified in other studies (Wen et al., 2016). However, given the complicated routes for FW biorefinery, the overall transfer coefficient is different from that reported in a similar biorefinery system (Jin et al., 2015). The differences are mainly attributed to the different FW composition and the different lipid separation efficiency in the biodiesel technology. This implies that not only the biorefinery route play important roles in the FW material flows, but also the specific parameters do. A comprehensive analysis of parameters from broad sources is desired in future research.

Dist: distillation; AD: anaerobic digestion; Trans.: transesterification; W&D: washing and dehydration; Dewater.: dewatering; Comp.: composting; Glu.: glucose; SF: solid fraction

Scenario S0 – Biogas (Anaerobic digestion + composting)

Scenario S1– Biomethane (Anaerobic digestion + biogas upgrading + composting)

Scenario S2 – Bioethanol (Saccharification and fermentation + anaerobic digestion + composting)

Scenario S3 – Biodiesel (Transesterification + anaerobic digestion + composting)

Scenario S4 – Bioethanol + biodiesel (Transesterification + saccharification and fermentation + anaerobic digestion + composting)

Figure 1 Material flows on five alternative biorefinery scenarios for Chinese food waste (based on 100 t wet weight of food waste)

The high water content of Chinese FW suggests that the costs of collection and transportation may be relatively high because of the low content of useful organic

solid material. However, in terms of the biorefinery processing of FW, the high water content is beneficial and reduces the demand for additional water for optimal bioprocessing (such as the bioprocesses related to carbohydrate saccharification). Nevertheless, all biorefinery scenarios deliver a liquid residue as a result of the low solid content in the biorefining reactors; in terms of weight the liquid residue exceeds the amount of FW processed (+25%). The liquid residue contains 2.5-5.0 kg/m³ of C, 3.3-3.4 kg/m³ of N, 0.18 kg/m³ of P, and 1.3 kg/m³ of K. This LF must be managed further.

3.2 Substance flow analysis (C, N, P, K)

Figure 2 shows the carbon flows through the five biorefinery scenarios. The 100 t of Chinese FW contains 9.96 t C, 0.53 t N, 0.08 t P and 0.22 t K).

The carbon flow diagrams show that 40-75% of the carbon (increasing from S1 to S4) ends up in the bioproducts, namely, biogas, biomethane, bioethanol and biodiesel; only small amounts end up in the compost. Most of the carbon (1 t) in the compost originates from the wood chips added as a bulking agent to the composting process. This result suggests that around 75% of the carbon in the FW is found in the bioproducts and that about 22% is lost through air emissions (primarily during composting) and in the liquid residue (3%).

As the nutrients, namely, nitrogen (N), phosphorus (P) and potassium (K) are absent in the carbohydrates and lipids utilized in bioethanol or biodiesel production, their fate in biorefinery is almost the same in all five scenarios. Figure 3 shows the flows of nutrients (0.53 t N, 0.08 t P and 0.22 t K) present in the 100 t FW, as determined by the transfer coefficients listed in Table 2. Given the lack of data, we neglect the possibility of a small amount of N transferring to the biogas. The fate of the nutrients downstream the digester is controlled by the separation of residue into a liquid and a solid flow and for nitrogen also on the loss during composting. Figure 3 reveals that 79% of the initial N from FW ends up in the liquid residue, 6% is found in the compost and about 15% is lost during composting. From the substance flow perspective, 25% of P and 73% of K end up in the liquid residue, while the compost contains 6% N, 75% P and 27% K from FW. This shows that all biorefinery scenarios preserve the nutrients well. The air emissions of P and K are insignificant.

We must note that nutrient source is essential during ethanol fermentation as it provides a balanced nutrient source for bacterial growth metabolisms. Moreover, with the C/N ratio less than 30, FW can be considered as a suitable biomedium for its ethanol fermentation without additional nutrient supply. This idea is supported by many previous studies (Ma et al., 2009; Uçkun Kiran et al., 2015; Uncu and Cekmecelioglu, 2011). All of these nutrients flow to the next technical stage (anaerobic digestion).

Dist: distillation; AD: anaerobic digestion; Trans.: transesterification; W&D: washing and dehydration; Dewater.: dewatering; Comp.: composting; Glu.: glucose; SF: solid fraction

Scenario S0 – Biogas (Anaerobic digestion + composting)

Scenario S1 – Biomethane (Anaerobic digestion + biogas upgrading + composting)

Scenario S2 – Bioethanol (Saccharification and fermentation + anaerobic digestion + composting)

Scenario S3 – Biodiesel (Transesterification + anaerobic digestion + composting)

Scenario S4 – Bioethanol + biodiesel (Transesterification + saccharification and fermentation + anaerobic digestion + composting)

Figure 2 Carbon flow of the five alternative biorefinery scenarios for Chinese food waste (based on 100 t wet weight of food waste containing 9.95 t)

Figure 3 N/P/K flow of the five alternative biorefinery scenarios for Chinese food waste (based on 100 t wet weight of food waste containing 0.53 t N, 0.08 t P, and 0.22 t K)

3.3 Material inventory

Table 3 shows the inventory of the five biorefinery scenarios in terms of all inputs and outputs when treating 100 t of Chinese FW.

Table 3 Inventory of the five biorefinery scenarios for 100 t of Chinese FW.

Inputs		Unit	Total amount				
			S0	S1	S2	S3	S4
Waste	Food waste	t	100	100	100	100	100
Additive chemicals	Water	t	50	50	50	51.8	51.8
	Wood chips	t	2.16	2.16	1.65	2.5	2
	Methanol	t	0	0	0	0.42	0.42
	Glucoamylase	t	0	0	0.027	0	0.027
	Saccharomyces cerevisiae	t	0	0	0.15	0	0.15
	Lipase	t	0	0	0	0.092	0.092
	Centrifugation	kWh	0	0	0	0.45	0.45
Energy use	Transesterification	kWh	0	0	0	0.58	0.58
	Saccharification & fermentation	kWh	0	0	9.90	0	9.65
	Ethanol distillation	kWh	0	0	1.57	0	1.57
	Anaerobic digestion	kWh	3.90	3.90	3.71	3.86	3.66
	Biogas upgrading	kWh	0	2.21	0	0	0
	Digestate dewatering	kWh	0.11	0.11	0.11	0.11	0.11
	Composting	kWh	0.46	0.46	0.34	0.51	0.40
Outputs		Unit	S0	S1	S2	S3	S4
Emissions	CH ₄ *	t	0.13 ± 0.00	0.21 ± 0.00	0.09 ± 0.02	0.10 ± 0.00	0.06 ± 0.02
	CO ₂ *	t	8.63 ± 1.34	8.79 ± 1.37	5.15 ± 1.79	7.40 ± 1.09	4.13 ± 1.68
	N ₂ O	t	8.3E-03	8.3E-03	8.3E-03	8.3E-03	8.3E-03
	NH ₃	t	6.0E-02	6.0E-02	6.0E-02	6.0E-02	6.0E-02
Products	Biogas	t	15.77 ± 1.13	0	11.62 ± 1.47	10.60 ± 0.48	6.30 ± 1.72
	Biomethane	t	0	5.19 ± 0.37	0	0	0

	Bioethanol	t	0	0	3.85 ± 1.60	0	3.85 ± 1.60
	Biodiesel	t	0	0	0	2.99 ± 0.20	2.99 ± 0.20
	Bio asphalt	t	0	0	0	0.53 ± 0.04	0.53 ± 0.04
	Crude glycerol	t	0	0	0	0.37 ± 0.02	0.37 ± 0.02
	Compost	t	4.17 ± 0.09	4.17 ± 0.09	3.45 ± 0.13	4.6 ± 0.20	3.95 ± 0.12
Residues	Stored CO ₂ from biogas upgrading	t	0	10.34 ± 0.74	0	0	0
	CO ₂ from bioethanol production	t	0	0	3.84 ± 1.60	0	3.84 ± 1.60
	Liquid residue	t	125.4 ± 0.2	125.4 ± 0.2	123.93 ± 0.55	125.77 ± 0.15	124.3 ± 0.50

CH₄* and CO₂*from two parts: biogas leaking and air emissions from composting

Scenario S0-Biogas; Scenario S1: Biomethane; Scenario S2: Bioethanol; Scenario S3: Biodiesel; Scenario S4: Bioethanol+biodiesel

Water and wood chips are added in all scenarios. Glucoamylase and *S. cerevisiae* are the essential additives in bioethanol production while methanol and lipase are needed in biodiesel production.

Energy consumption is listed for each technological process. Centrifugation, transesterification, saccharification and fermentation, ethanol distillation, anaerobic digestion, biogas upgrading, digestate dewatering and composting are the key technological processes in the systems. The highest energy consumption takes place in the bioethanol production processes (saccharification and fermentation) for heating, followed by anaerobic digestion with heating. We note that saccharification and bioethanol-fermentation involve full FW flow, and that the transesterification for biodiesel production involves only the lipid flow obtained after the separation of oil from the FW. The energy consumption for the five scenarios is estimated to be in the range of 45-165 kWh/t FW.

The main emissions are CH₄, CO₂, N₂O and NH₃. CH₄ leaks from the anaerobic digester and is emitted during the upgrading process and composting due to unavoidable anaerobic pockets in the windrow. CO₂ leaks from anaerobic digesters and is emitted from ethanol fermentation, biogas upgrading and the composting process. N₂O and NH₃ are emitted only from the composting process. CO₂ is the largest fraction of (gas) emissions in the range of 97-99% followed by CH₄ in the range of 0.7-2.3%.

Biomethane, bioethanol and biodiesel can be used as substitutes for fossil fuel (compressed natural gas, petrol, diesel, etc.,) while crude glycerol and bioasphalt can be used as biochemicals. CO₂ from biogas upgrading can be stored and also treated as a supply for the chemical industry. Nevertheless, the liquid residue, produced in large quantities in all scenarios, constitutes a separate management issue that presents as a wastewater problem or a potentially as liquid fertilizer.

In terms of output diversity and amounts of products, scenario S4 seems to be the most promising scenario in our study. Though our study provides consistent technical engineering platforms for alternative biorefineries for FW, specific assessments in technical, economic and environmental terms must be carefully conducted before recommending any alternative for treating FW in industrial practice.

Future efforts should address other technical routes and bioproducts to expand the biorefinery platform related to material balance. Researchers are encouraged to take the full-chain, material balance and transformation, bioproducts' utilization and geographical characteristics into consideration in their future work to improve this platform. Furthermore, assessment in terms of technical feasibility, economic and environmental should be conducted to support the management of alternative FW

biorefinery systems.

4 Conclusion

This study provides a systematic modeling of material and substance flows of five alternative scenarios for treating Chinese FW on the basis of a biorefinery concept that produces valuable bioproducts (i.e., biogas, biomethane, biodiesel and bioethanol). All scenarios produce bioproducts in the range 7-18 t out of 100 t of wet Chinese FW. The bioethanol production is controlled by the carbohydrate content and biodiesel production is controlled by the lipid content of FW. Anaerobic digestion converts most of the volatile organic solids in the FW. Moreover, the value of products is a crucial consideration when introducing a complex biorefinery concept. The energy consumption of the biorefinery scenarios is estimated, and the results indicate that going from a simple biogas scenario to more complex biorefinery concepts may triple the energy consumption from 45 kWh/t FW to 165 kWh/t FW. The analysis also reveals that all scenarios result in a high volume (about 125% in weight of the FW input) of liquid residue that needs further treatment. These outcomes offer a consistent material flow analysis that is useful in comparing alternative biorefinery concepts for managing Chinese FW in terms of technical feasibility, economics and environmental issues.

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Declarations of interest

None

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