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Evaluation of Alternative Valorization Options for Institutional and Industrial Food Wastes

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EVALUATION OF ALTERNATIVE VALORIZATION OPTIONS FOR INSTITUTIONAL AND INDUSTRIAL FOOD WASTES

by

SWATI HEGDE

A DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in
Sustainability

Department of Sustainability

Golisano Institute for Sustainability
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December 2018

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EVALUATION OF ALTERNATIVE VALORIZATION OPTIONS FOR INSTITUTIONAL AND INDUSTRIAL FOOD WASTES

by

Swati Hegde

Submitted by Swati Hegde in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Sustainability and accepted on behalf of the Rochester Institute of Technology dissertation committee.

We, the undersigned members of the Faculty of the Rochester Institute of Technology, certify that we have advised and/or supervised the candidate on the work described in this dissertation. We further certify that we have reviewed the dissertation manuscript and approve it in partial fulfillment of the requirements of the degree Doctor of Philosophy in Sustainability.

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SUSTAINABILITY PROGRAM
ROCHESTER INSTITUTE OF TECHNOLOGY

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ABSTRACT

Golisano Institute for Sustainability
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Title: Evaluation of Alternative Valorization Options for Institutional and Industrial Food Wastes

In recent years many countries and several regions in the United States have passed legislation on banning landfilling of organic waste. It is a well-known fact that organic wastes, including food scraps, generate methane under anaerobic landfill environments and contribute significantly to global warming. As more regions are mandated to follow the landfill ban, there is an increasing demand for alternative technologies for the disposal, treatment and upcycling of food wastes. Disposal and treatment may not result in any value-added products and hence are not the most efficient ways to manage food waste. As food waste has a high energy value due to the presence of organic nutrients, it can be a suitable resource to generate energy, fuels, chemicals, and materials through 'valorization' technologies. Therefore, to proactively address food waste management issues in the future, this dissertation evaluated three alternative food waste valorization options for institutional (food scraps) and industrial food wastes.

First, the food scraps and industrial food wastes were characterized for their chemical composition such as organic and inorganic nutrients. The objectives of this study were to (a) provide a detailed database on chemical characteristics of food scraps and industrial food wastes based on in-house laboratory measurements, third-party analysis, and literature data; (b) analyze the data obtained to understand the variability in characteristics between different sources of food waste. The outcomes of this chapter resulted in a comprehensive data collection and statistical analysis for food scraps from various sources and 10 different industrial food waste streams. The

developed data inventory is useful to anyone who does not have resources to carry out food waste characterization and researchers who work on food waste modeling studies.

Second, the process issues related to anaerobic digestion of food scraps were address using an experimental study. Process instability is a major issue in food scrap digestion at higher organic loading rates, and often leads to digester failure. The objectives of this study were to (a) study the effect of increasing organic loading rate on the stability of the process by monitoring several process parameters, and (b) offer a solution to the instability issues using an unconventional co-digestion approach. The experiments were carried out in semi-continuous mode with a daily feeding cycle to mimic the real-world conditions as closely as possible. Process parameters such as pH, volatile fatty acids, alkalinity, ammonia, biogas production, methane and hydrogen sulfide content of biogas were monitored on a regular basis. Results of this experiment provided useful information for digester operation on the threshold levels of various process parameters to that would help avoid a digester failure. Co-digestion of food scraps with other food sector wastes such as acid whey, wasted bread and soiled paper napkins were proven to significantly improve process stability and helped achieve high organic loading rate during the digestion of food scraps. These results are useful in the operation of non-farm digesters where conventional co-substrates (such as animal manure) are not available or not practical to haul.

Third, the use of fermentation technology in food waste management was evaluated for its technological feasibility. While anaerobic digestion is a well-developed technology for organic waste management with a few processes issues related to food scrap digestion, the use of fermentation in food waste management is not well documented. Food waste fermentation to produce value-added fuels and chemicals is taking shape only in recent years. The objective of this work was to provide ‘state-of-the-art’ knowledge on fermentation of food wastes in the production of products, specifically ethanol, 1-butanol, iso-butanol, and organic acids using experimental and published data. With a combination of experimentally obtained and previously published studies, a matrix was developed that maps the suitability of producing either alcohols or organic acids from various food wastes. The outcomes of this study provided a contemporary knowledge on the research status related to food waste fermentation. Also, the types of food wastes that can be potential feedstocks for fermentation to produce ethanol, butanol, lactic acid and succinic acid were suggested through the developed matrix. The outcomes from this work provide useful

qualitative information to the growing number of businesses in the waste management world looking for newer and more efficient options for food waste valorization.

Finally, the potential of thermochemical conversion as a food waste management strategy was explored using an exergy analysis and life cycle thinking approach. Use of thermochemical processing to produce a soil amendment called biochar is a circular economy inspired approach and needs evaluation as there is a limited number of research studies in this area. The objectives of this study were to (a) produce biochar using a small-scale commercial thermochemical processing unit and characterize the biochar for elemental composition, (b) estimate the exergy efficiency of various scenarios, and (c) estimate the global warming potential (GWP) by expanding the system boundary to use biochar as a soil amendment. Based on these results, the most practical options for management of food waste were recommended to produce biochar or thermal energy. The exergy analysis combined with GWP potential estimations can assist operators of thermochemical conversion systems to decide upon the practical operating conditions, and policy makers to consider and regulate newer technologies for food waste management.

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ABBREVIATIONS

ABE	Acetone, Ethanol, Butanol
AD	Anaerobic Digestion
AFDC	Alternative Fuel Data Center
AMPTSII	Automated Methane Potential Testing System II
AW	Acid Whey
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
ED	Energy Drinks
EPA	Environmental Protection Agency
FAO	Food and Agricultural Organization
FOG	Fats, Oils and Grease
FPW	Food Processing Wastes
FW	Food Waste
GWP	Global Warming Potential
HHV	Higher Heating Value
HRT	Hydraulic Retention Time
HTL	Hydrothermal Liquefaction
LCA	Life Cycle Assessment
LCFA	Long Chain Fatty Acids
LHV	Lower Heating Value
MSW	Municipal Solid Waste
NPV	Net Present Value
NRRL	Northern Regional Research Laboratory
OLR	Organic Loading Rate
PHA	Polyhydroxy Alkanoates

PN	Paper Napkins
RCM	Reinforced Clostridial Medium
RNG	Renewable Natural Gas
TCP	Thermochemical Processor
TS	Total Solids
UN	United Nations
USDA	United States Department of Agriculture
VFA	Volatile Fatty Acids
VGP	Volatile and Gaseous Products
VS	Volatile solids
WB	Waste Bread
YPD	Yeast extract, Peptone, Dextrose

CHAPTER 1

INTRODUCTION

1.1. Food waste

In the United States, food waste contributes to a significant fraction of the materials discarded via landfill or incineration and is larger than any other single waste stream. In September 2015, the United States Department of Agriculture (USDA) and Environmental Protection Agency (EPA) announced the first-ever goal[1] to reduce food waste quantities by half by the year 2030, in alignment with Target 12.3 of the United Nations (UN) Sustainable Development Goals[2]. Target 12.3 aims to "halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses." Food loss and food waste arise at each stage in the food supply chain as shown in Figure 1.1. Sustainable food management is a systematic approach that helps to reduce the quantity of wasted food and the environmental impacts associated with it over the entire food chain,[3] through a combination of source reduction, donation, and valorization.

According to recent literature, developing countries suffer from food loss in the early stages of the supply chain, while developed nations contribute more to food loss at the retail and consumption phases [1], [2]. Reducing food loss and food waste play a promising role in improving food security in the future, but food waste quantities vary among nations, depending on various factors. For example, in the United States, food items are cheaper than in nearly any other country, favored by subsidies to corn, wheat, milk and soybeans [3]. The wastage is also a result of cultural dynamics attributed to the obsession of the majority of consumers to the aesthetic quality of food. Other causes of food waste generation include overproduction, inefficiency in stock management at grocery stores, packaging damage, marketing strategies that encourage over-purchasing [4], [5] and abundant portion sizes at restaurants [5].

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[1] EPA, Sustainable management of food. US 2030 food loss and waste reduction goal. https://www.epa.gov/sustainable-management-food/united-states-2030-food-loss-and-waste-reduction-goal

[2] The UN- A/RES/70/1.Food security, nutrition and sustainable agriculture. https://sustainabledevelopment.un.org/index.php?page=view&type=2002&nr=282&menu=35

[3] https://www.epa.gov/sustainable-management-food/sustainable-management-food-basics

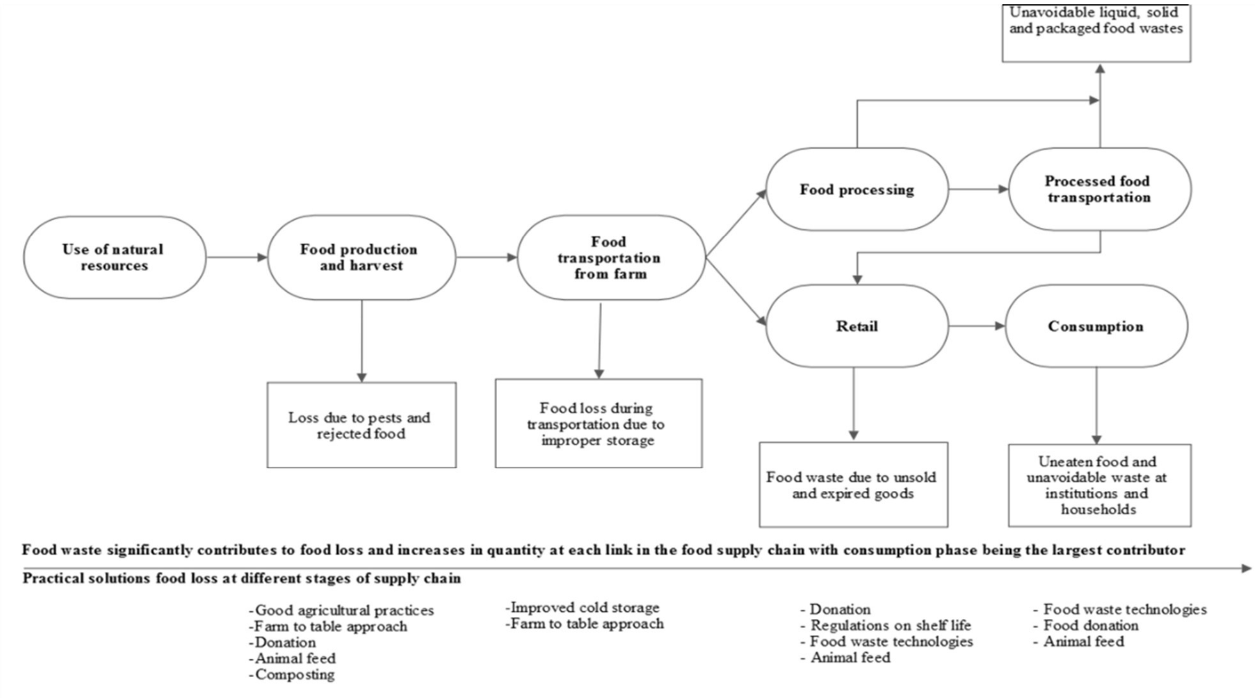

Figure 1.1 - Food loss links in the food supply chain [6]–[9]

Food loss represents the edible post-harvest food that is available for human consumption but not consumed for any reason. It includes cooking loss and natural shrinkage (e.g., moisture loss), loss from pests, or due to inadequate climate control [10], [11]. *Food waste* is a subset of food loss and occurs when an edible item goes unconsumed, such as the food discarded by retailers due to color or appearance, and plate waste by consumers. Therefore, food waste mainly occurs at the retail and consumption stages [11], [12]. Food waste generated by households and institutions is predominantly disposed of in landfills as shown in Figure 1.2. The Environmental Protection Agency estimated that in 2014, less than 7% of the total food waste generated was utilized towards beneficial uses, while more than 93% was landfilled [9], [13].

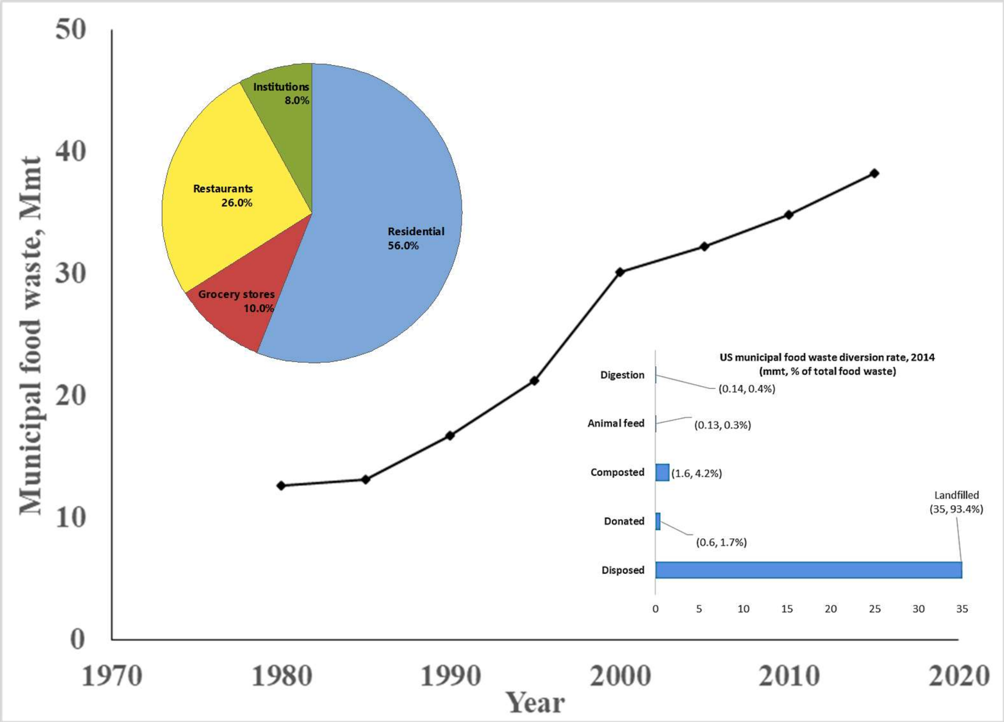

Figure 1.2 - Food waste disposal trend (line chart, Mmt: million metric ton), diversion rates (bar chart) and percent share of different sectors in municipal food waste generation (pie chart) in the U.S. [7], [9]

1.2. Food loss and food waste quantification

An approximate quantification of institutional food waste generation is possible through analysis of municipal solid waste data as shown in Figure 1.2. However, industrial food waste or food processing waste quantities and diversion rates are more challenging to estimate. The Food and Agricultural Organization (FAO) of the United Nations and Food Waste Reduction Alliance have estimated that nearly 33% of food processing waste is diverted towards animal feed applications [14]. Food processing waste has a relatively high landfill diversion rate compared to municipal food waste. However, no accurate statistics are available to estimate the actual diversion rates. A primary barrier to obtaining industrial food waste data regarding volumes produced is that it is often considered proprietary by the food manufacturers. Knowing waste volumes is essential, as substrate availability is the primary constraint in waste conversion processes (Chapter 3 through 5). However, the amount of food processing waste generated is increasing every year as food production levels rise to support a growing population.

Moreover, there is a trend of increased consumption of processed food items, primarily as standards of living rise worldwide. Therefore, an indirect approach can be used to estimate waste generation from food processing sector using food production data from existing databases (e.g., USDA's food availability database) and applying a correction factor to estimate waste quantities, as shown in Figure 1.3. The extrapolations for tomato, potato, and cheese whey indicate that "business as usual" food waste generation will continue to increase significantly. Increasing food waste volume is a serious concern regarding greenhouse gas emission, water footprint, land conversion, and economic loss. More detailed analyses of food loss and waste in the food supply chain for potatoes is given in Figure 1.4 and 1.5. The mass losses across the supply chain accounted for a total of 41% of the initial weight of the potatoes produced on the farm. These losses contain both avoidable and unavoidable wastes, with the fraction of avoidable waste exceeding that of the unavoidable waste. Various region-specific tools are available online to estimate food waste generation rates by audits and theoretical estimations. These tools are essential in understanding spatial variation in food waste generation quantities. The choice of a valorization method depends on spatial and temporal variation in food waste type, as well as abundance. Therefore, quantification of food waste resources and characterization of composition (Chapter 2) are the two critical factors to consider before evaluation of a valorization option. While different quantification methods may not yield accurate estimations, nevertheless they provide useful information to select among alternative options for food waste management.

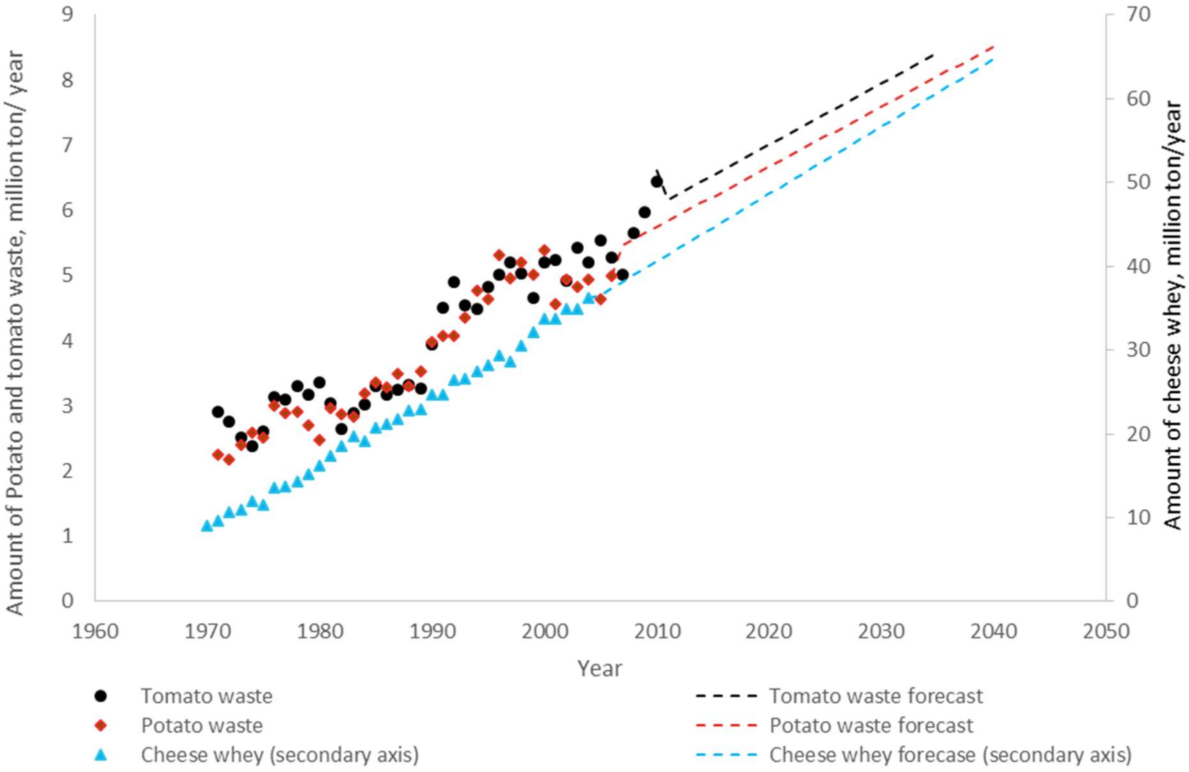

Figure 1.3 - Forecast of potential amounts of processing wastes in representative food sectors before recycling, based on linear extrapolation of 1970–2010 production data [6], [15]. Waste quantities were calculated based on the following assumptions: (i) 9 kg of whey is produced per kg of cheese [16]; ii) 46% of the weight of total processed potatoes ends up in waste streams [17]; (iii) tomato pomace accounts for up to 40% of the weight of processed tomatoes [18].

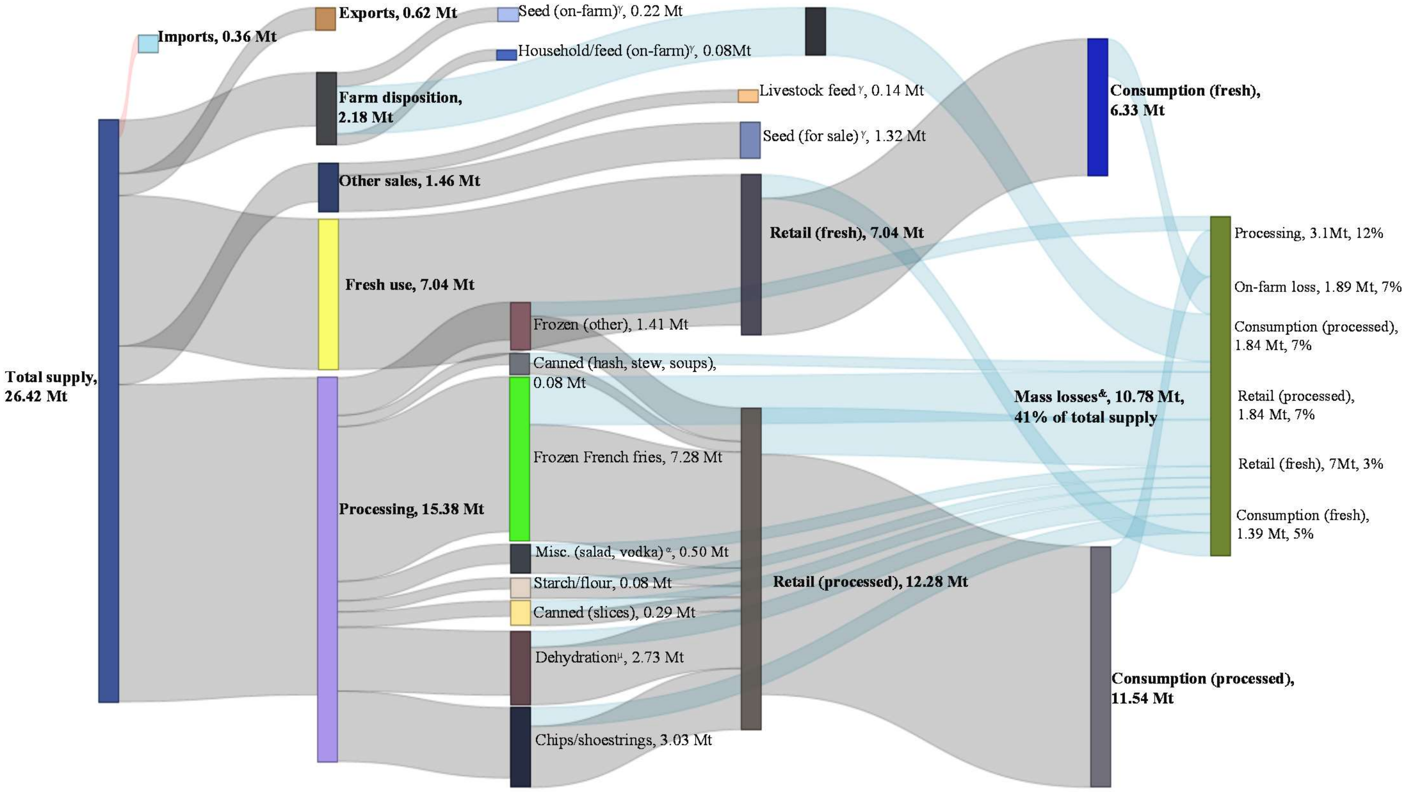

Figure 1.4 -Sankey diagram showing mass losses in the potato supply chain; All mass flows are calculated based on US potato production and utilization averaged over 2000-2006 obtained from USDA's food availability database (http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1235): Mass losses during processing are estimated using factors adapted from [19]: 15% mass loss in chips/shoestring processing, other frozen and miscellaneous products, 12% solid mass loss during dehydration, 26.5% during frozen French fries production and canning, 2.5% in starch/flour production. The mass loss factors of 10% and 6% were used for retail of fresh and processed potatoes, respectively; for consumption phase of fresh and processed potatoes 22% and 6% loss factors were used, respectively [20]

$^{\gamma}$ losses not calculated ; $^{\&}$ includes losses due to shrinkage, unavoidable waste during processing and losses due to cooking, but doesn't include losses from water evaporation $^{\mu}$ Approximately 60% of the mass is evaporated as water during dehydration [21]; however, water loss due to evaporation is not included in mass loss calculation as this water doesn't represent a waste stream; $^{\alpha}$ 2015 data [22]

Processing type	Peel waste, Mt	Waste oil, Mt	Wastewater, GL
Frozen French fries	1.1	1	84.16
Chips/shoestrings	0.37	0.89	30.02
Frozen (other)	0.14	NA	13.18
Dehydration	0.32	NA	6.13
Canned (all)	0.14	NA	1.34
Misc. (salad, vodka)	0.1	NA	0.82

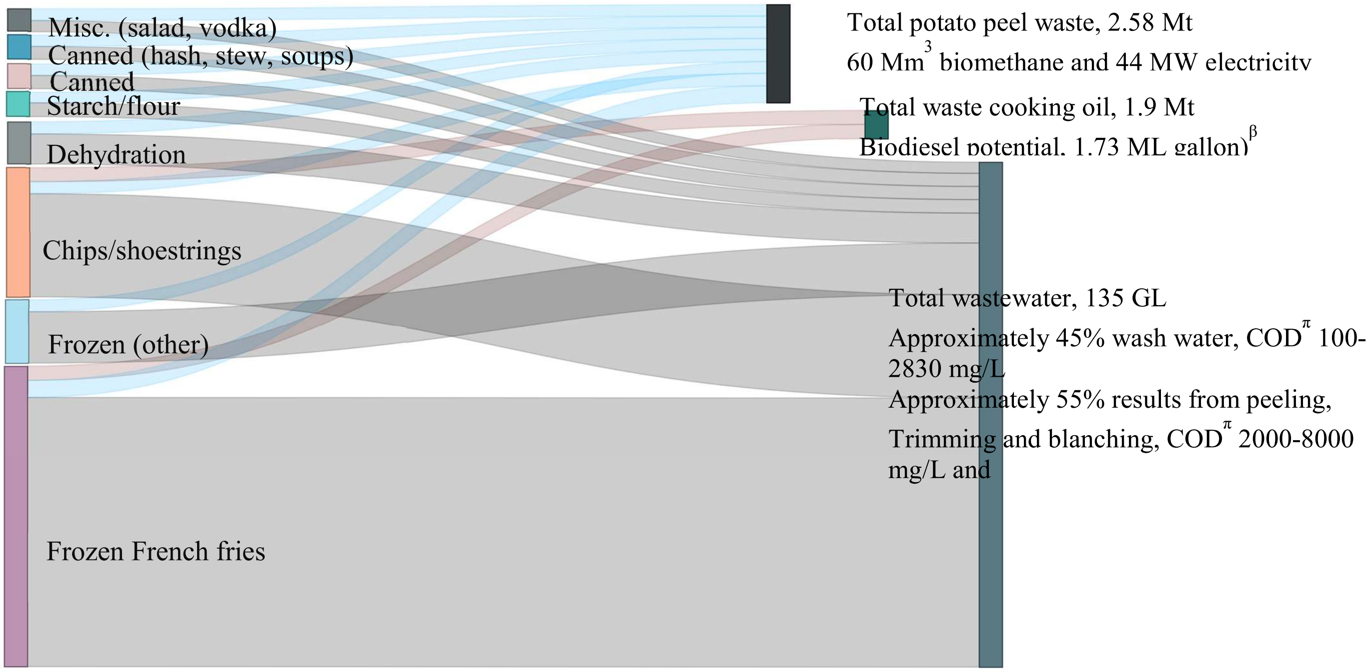

Figure 1.5 - Waste flows in potato processing; Potato peel waste quantities were calculated using a factor of 12% [19]; mass losses from trimming and blanching operations are not included in the solid waste stream as starch from these operations accumulates in the wastewater stream. The wastewater flows of 5625, 4275, 1668 and 2345 liter/raw ton of potatoes were used to calculate wastewater quantities for washing, peeling, trimming and blanching, respectively [19], [23]. In chips/shoestring production, 530 kg oil is used per ton of potatoes, and 63% is wasted; in frozen French fry production, 200 kg oil was used for pre-frying one ton of potatoes and 80% results in waste stream [23]. Potato peel waste quantities were estimated using a factor of 12% [19].

£ Biomethane potential, 23 m^3/wet ton potato peels [24]; electricity potential was calculated using an energy value of 6.4 kWh/m^3 for biomethane and 35% electric conversion efficiency [25];

β estimated using 80% conversion efficiency; biodiesel density is 874.6 kg/m^3

¥ estimated for wastewater streams (55% of the total) excluding wash water- following assumptions/data were used: starch content of wastewater is 15% [21], [23]; ethanol conversion efficiency for starch (glucose) is 51% [26]; cellulose density is 1500 kg/m^3 and ethanol density is 789 kg/m$^{3;}$ π COD values from [19], [27].

Currently, a significant fraction of institutional food waste and an unknown fraction of industrial food waste is disposed in landfills [9], and due to high biodegradability, these wastes contribute significantly to greenhouse gas emissions. Landfilling accounted for management of more than 90% of the food waste generated until 2014. Most landfills operate without energy recovery and do not provide an efficient option for food waste treatment. Technologies such as anaerobic digestion (AD), composting and animal feed production are known to convert food waste to energy and value-added products. Several other technologies like fermentation, pyrolysis and aerobic digestion have also gained increased interest due to their capability to reduce the volume of food waste. In addition to reducing chemical oxygen demand (COD) of the waste, these technologies also result in value-added products. The high solid containing food processing wastes are diverted towards animal feed, anaerobic digestion and other beneficial uses to some extent, but there is a need to explore additional benefits from FPWs. Food waste valorization or conversion offers alternative options for the most effective use of food waste resources.

1.3. Food waste policies

One of the most prominent policies that is taking shape at a faster rate is the city- or state-level bans on disposing of food waste and other organic wastes in landfills. Landfill disposal results in methane emissions due to anaerobic biodegradation of food waste. To protect the environment and improve the economics of food waste management, California, Massachusetts, Vermont, Connecticut, and Rhode Island have already implemented an organic ban policy, and Maryland, New Jersey and New York are considering such laws [28]. Most of the food waste policies allow for a "phase-in' approach [29], which means that large generators of food waste are targeted first, and slowly expanded to include medium and small generators if the target percent reductions are not reached [30]. As a greater number of food waste generators are mandated to follow the ban, especially among the commercial sector and large institutions, the amount of food waste required to be processed using alternative methods will also increase. There are also other policies related to source reduction of food waste such as food donations and rescue, date labeling laws, food donations, tax incentives, improved packaging and feeding animals[4]. In the EPA's food recovery

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[4] ReFED policy finder tool, www.refed.com/tools/food-waste-policy-finder/

hierarchy[5], source reduction of food waste is given utmost priority, while landfilling and incineration have the least priority. Industrial uses like anaerobic digestion (AD) are preferred over composting[5]. There are several policies related to AD in the US and other nations. Even though AD is technologically mature for manure management, its application in food waste management is limited either due to lack of knowledge or high cost. Therefore many countries have implemented their policies on AD capital incentives, performance incentives, carbon credits and tax credits [31]. Various options are available for the industrial uses of food waste, but most incentives are available for energy and fuel production, limiting these options to 'waste-to-energy'. However, as the organic ban policy expands geographically, the quantity of food waste requiring processing using alternative options will continue to increase. There is a need for alternative technologies which are capable of utilizing food waste as a raw material for the efficient production of value-added products to upcycle all the diverted food waste. Therefore, in addition to AD and composting, there is a potential need for policies that encourage alternative options (valorization) to produce not only electricity and fuels but also other value-added products from food waste. Some policies avoid sending packaged food wastes from food processing industries to landfills[6]. Most of the food processing waste is sent to digesters, where there is a need to depackage these wastes before digesting the organic fraction[7]. Depackaging increases the cost of operation and hence, may not be a very economical option for food processing wastes. Implementation of food waste policies in various parts of the US has led to a widespread adaption of technologies like InSinkErator, grind2energy™, and food waste dehydrators[8]. These technologies do not reduce the chemical oxygen demand of food waste, but provide food waste in a form that is suitable for treatment in wastewater treatment plants or anaerobic digesters (e.g., depackaged, slurry and reduced particle size). Newer technologies like accelerated aerobic digestion, which involves the use of enzymes or bacteria and has a faster COD degradation rate, are also being implemented[9]. Any of the technologies mentioned above do not yield a value-added product, and therefore policies supporting anaerobic digestion of pure food waste, fermentation to produce fuel and chemicals, thermochemical conversion using pyrolysis and gasification to produce fuels, heat, and

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[5] EPA, Sustainable management of food; www.epa.gov/sustainable-management-food/

[6] Based on personal interview with food industries and digester operators

[7] Based on a personal interview with local food producers

[8] www.insinkerator.com; www.grind2energy.com; www.owareco.com

[9] www.prmwastesystems.com/processes/aerobic-digestion

materials (example, biochar) must be developed. Such incentives will not only increase the food waste diversion rate using alternative options, but also help achieve a circular economy wherein essential nutrients and water used in food production ultimately return to the agricultural operation.

1.4. Food waste valorization

Valorization is defined as the process of converting food waste into useful products like fuels, chemicals, energy or materials by biotechnological [32] or thermochemical processes [33]. The most sustainable food waste management would involve the production of energy and value-added products from food waste using technologies like anaerobic digestion, fermentation, pyrolysis, and gasification. Food waste valorization technologies contribute significantly to energy and material supply, as well as reduce environmental impact, and potentially create new job opportunities. However, an effective transition to these technologies requires a thorough techno-economic assessment for using food waste as the primary feedstock. Despite ranking the food waste end-of-life options through valorization, suitable policy decisions must be integrated with technical assessments for addressing specific issues of using food waste as a feedstock. Individual technologies can be part of a centralized biorefinery (i.e., conversion of multiple feedstocks to generate multiple value-added co-products, akin to a petroleum refinery), or can be used in on-site/decentralized food waste management to produce marketable products. Production of various value-added products like biomethane [34], [35], hydrogen [36], ethanol [27], [37] butanol [38], [39], succinic acid [40], lactic acid [41], [42], acetic acid [43], [44], biochar [33], bioplastics [45] and pigments [46] have been reported in the recent literature. Landfill diversion of organic waste is a prime target of several nations, and these technologies are crucial for managing diverted food waste. Therefore, evaluation of technologies like fermentation, anaerobic digestion, and pyrolysis/gasification is a proactive step towards more efficient food waste management in the future. Composting is perhaps the most widely used food waste valorization method involving degradation of organic matter into biogenic carbon dioxide and water, with the leftover solids used as soil fertilizer [13]. However, a well-managed composting process is energy intensive, and there is still no well-developed market for compost. Animal feed production is also currently in practice and involves dehydrating specific food wastes and enriching them to obtain a required quality. Other efficient valorization options are discussed briefly below.

1.4.1. Anaerobic digestion

Anaerobic digestion (AD) involves the conversion of organic matter in the absence of oxygen to produce methane (CH_4)-rich bio-gas that can be used for heating, as a vehicle fuel, or for generating electricity. The evolution of AD systems has historically followed two distinct paths: small residential-scale systems in the developing world to provide modest bio-gas resources for heating and cooking, and large-scale facilities in the developed world for grid electricity production [47]. Production of biogas involves a series of steps, starting with hydrolysis where polymeric nutrients like proteins, carbohydrates, and lipids from the substrate convert into their monomeric form. These monomers, such as simple sugars and amino acids, further metabolize to produce volatile fatty acids (VFAs) which further break down into volatile short-chain acids like acetic acid. The formation of acetic acid by acetogenic bacteria is the acetogenesis phase. Methanogenic bacteria consume acetic acid to form methane during the methanogenesis phase. Some methanogens also use hydrogen as a substrate to produce methane. The major energy-containing component of biogas is methane, a substitute for natural gas. Also, digestate from AD can be used as a fertilizer. Most conventional AD systems use dairy manure as the primary substrate, but there have been recent efforts to include food waste as feedstock. Though some AD plants receive food waste feedstock, it is almost always co-digested with manure. As of July 2016, approximately 105 digesters[10] accepted food waste as a feedstock, and this accounts for only 6-7% of the total number of digesters in the US[11]. Out of these digesters, approximately 36% were farm-based, 17% were on-site digesters dedicated to food processing industries, 22% at wastewater treatment plants, 20% were commercial digesters, and the remaining 5% were located on a landfill site. Only commercial and landfill digesters are multi-source facilities, and others are limited in the quantity of food waste they can process. Some farm-based digesters process manure with 20-30% food waste, wastewater treatment plants mainly process fats, oils and grease (FOG) waste and are often constrained by the quantity of food scraps they can accept. On-site digesters are often dedicated to a single source of food processing waste. The overall amount of food waste processed using anaerobic co-digestion in a stipulated time duration is rather small and needs

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[10] Anaerobic Digestion Facilities Processing Food Waste; https://www.epa.gov/sites/production/files/2016-07/documents/three_types_of_ad_facilites_processing_food_waste_july_2016.pdf

[11] https://www.americanbiogascouncil.org/biogas_questions.asp

ongoing adaptation and development. Specific issues related to anaerobic digestion are discussed in detail in Chapter 3.

1.4.1.1. Methane

The primary product of AD is biogas that mainly contains methane and carbon dioxide. Methane is an energy-rich gas that can be used in the production of heat and electricity. Food waste has a biomethane potential of approximately 110 m^3/ton of food waste, while manure has the potential to produce 25 m^3/ton [35]. This means that digesting food waste in higher volumes will not only generate increased revenue through tipping fees but also increase the volume of methane production. Methane may be used to generate electricity on-site. However, it can also be used to produce thermal energy or fuels (e.g., renewable natural gas, RNG). The use of methane for any application other than electricity generation has been limited at this point, constrained by the lack of economic incentives. Food scraps, dairy processing wastewater, bakery goods, and sports drinks were reported to increase the methane potential, while apple pomace, melon rind waste and coffee grounds were found inhibitory to methane production in previous studies [35], [48]. Therefore preliminary characterization of food waste resources is critical to achieving optimum methane production (Chapter 2).

1.4.1.2. Digestate

A byproduct of anaerobic digestion is so-called “digestate”, which consists of insoluble fibers and liquid effluent. The application of liquid digestate as a fertilizer has been explored in recent years and is now being commercialized[12]. If separated, digestate solids are rich fibrous materials that can either be composted as a fertilizer [49] or used on the farm as cow bedding [50]. The specific characteristics of the digestate depend on the type of feedstock and can vary significantly in solid content, physical properties, and chemical composition. Food waste digestate, on the other hand, results in a low solid content digestate owing to the low fiber content of food wastes, which makes difficult its utilization as a cow bedding. The potential applications of food waste digestate such as land application, nutrient recovery, biofuel production by growing microalgae in digestate liquid, and thermochemical conversion have been considered in various research efforts [50]–[53].

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[12] http://naskeo.com/en/biogaz/digestate-valorization/

Food waste digestate management is an ongoing area of research interest and a potential business opportunity.

1.4.2. Fermentation

Fermentation is a microbial process that breaks down complex organic nutrients into simpler low carbon molecules under aerobic or anaerobic conditions. Theoretically, the final products of the aerobic fermentation are carbon dioxide and water, as there is complete oxidation of organic matter through respiration of microbial cells [54]. Ethanol is one of the major products of yeast fermentation that has a high demand as a fuel blend. In the United States, ethanol is predominantly produced from corn fermentation, but because corn is also a food source and utilization of corn in ethanol production has increased during the last decade, the corn price for food applications has risen dramatically [55]. Even though there is a large-scale ethanol production industry, ethanol demand is fulfilled by continuously growing crops like corn, sugarcane, and other cereals. During recent years, research has focused on advanced biofuels that make use of byproducts from other processes or waste materials as the feedstock for production. These biofuels are second-generation biofuels that do not make use of purpose-grown crops like corn, or starch and sugars. Most research and development efforts have focused on lignocellulosic biomass as a renewable resource [56]–[60], but the primary challenge in using these materials is inefficiency in releasing sugars from cellulose [61]. For efficient use of lignocellulosic wastes like crop and forest residues, a pretreatment method combined with enzymatic hydrolysis is always necessary, which results in increased pretreatment cost [62], [63]. Raw materials for fermentation are generally synthetic or highly consistent, and the use of fermentation in the waste management sector is relatively unexplored. Fermentation is versatile with respect to the range of products it can yield, mainly due to the employment of an infinite number of microbial species that can convert carbon-rich materials into value-added products from their metabolism. Fermentation is an aerobic process and unlike anaerobic digestion, needs high amounts of dissolved oxygen for product formation.

1.4.2.1. Alcohols

One of the dominant classes of chemicals produced from fermentation are alcohols, which are also used as fuels. Ethanol that is produced from renewable raw materials using fermentation processes is called bioethanol. Bioethanol production has increased significantly over the last decade, indicating its growing demand as an oxygenating agent and flex fuel for transportation applications. There are 209 operating ethanol plants in the US, and as of September 2017, the total ethanol production from all the operating plants was 15.6 billion gallons/year (59 billion liters/year) [64]. The United States is the leading producer of bioethanol in the world, followed by Brazil, the Europe Union, China, and Canada. In 2015, the US produced 56.7% of the total ethanol produced globally, and Brazil's ethanol production accounted for 27.6%[13]. US ethanol plants primarily use corn as the primary feedstock, accounting for 95% of the total production, while only 1% of the total bioethanol produced comes from food and beverage waste. Therefore, there is untapped potential in using food waste as a feedstock for the production of a high-volume product like ethanol.

Food waste has a potential to be used as a feedstock, not just in ethanol production but also in advanced biofuels like butanol. Currently, butanol is synthesized chemically for industrial uses, and much of the research is based on fermentation of lignocellulosic biomass. Several researchers, however, have reported the use of food waste feedstocks, including apple pomace [65], bakery waste [66] and dairy waste [39] in 1-butanol production. Whey from cheese processing has been reported by several researchers as a potential feedstock for butanol production. In addition to 1-butanol, there are limited research efforts on the fermentative production of 3-methyl 1- butanol, also known as isobutanol. This branched chain alcohol has several properties superior to those of 1-butanol: higher heating value and carbon content, and more chemical stability as it has more side chains than 1-butanol. However, only a limited number of species of microorganisms, particularly ethanol producing yeasts and recombinant bacteria, possess the capability to produce isobutanol [67]. Although some food wastes have shown potential to produce isobutanol, the observed yields are impractically low to be economical; however, there could be a compelling research opportunity to engineer microbes to produce high amounts of isobutanol genetically. One such effort explored the production of isobutanol using genetically modified *Escherichia coli (E. coli)* to ferment protein-rich wastes from food processing operations. These researchers were able to achieve an isobutanol concentration of 4 g/L [68]. Their research is also promising in exploring the use of protein-rich food waste materials like meat processing waste in alcohol production that is otherwise unsuitable for anaerobic digestion or composting.

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[13] Ethanol statistics. US Energy Information Administration https://www.eia.gov/

1.4.2.2. Organic acids

Organic acids are commodity products that have high demand in the pharmaceutical, cosmetic, industrial and research sectors as solvents. Various organic acids such as acetic acid [44], propionic acid [69], succinic acid [70], [71] and butyric acid [72] can be produced via fermentation of high carbon feedstocks. Lactose from waste whey was reported to be a suitable raw material for the production of propionic acid, which not only acts as a precursor in the production of alcohol but is also used as an antifungal agent in food, as an intermediate in bioplastic synthesis, and as a solvent in pharmaceuticals [69]. Apple pomace has been reported as a useful raw material in the production of acetic acid [44], lactic acid [73] and citric acid [74]. Some of these acids can also be a precursor of other commodity products or converted to other products via catalytic conversion [75]. Products like succinic acid and lactic acid are used in food processing as food additives [76] and hence producing them out of food processing wastes offers an efficient recycling option.

1.4.3. Thermochemical processing

While biochemical processes like fermentation and AD can be effective options in the management of food waste, these are somewhat slow due to their dependency on microbes. Also, biochemical processes, since they depend on microbial metabolism, can be inconsistent and unstable due to heterogeneity and variation in food waste composition. AD has a retention time of as high as 30 days which limits the quantity of food waste that can be treated in a given amount of time. Also, both fermentation and AD result in a byproduct that needs secondary waste management or beneficial uses. Thermochemical processes, on the other hand, can be very efficient in energy production and allow faster conversion of food waste with a significant volume reduction and minimal waste streams. Thermochemical processes come under three main categories: incineration, gasification, and pyrolysis and the primary distinction are based on the amount of air used during the process. Incineration uses excess stoichiometric air, and due to this, the process temperatures are above 900-1000^{0}C. At these temperatures, harmful greenhouse gases like nitrogen and sulfur oxides are formed. Therefore, incineration is not considered a practical option for waste conversion by governmental agencies in most countries. Two other efficient options for food waste management are pyrolysis and gasification which are discussed below.

1.4.3.1.Pyrolysis

Pyrolysis is the thermal decomposition of materials (fuels) at an elevated temperature in the absence of oxygen. Pyrolysis is historically used to produce chemicals from coal and natural gas, but the application of pyrolysis to waste biomass and food waste conversion has only been widely researched in the current decade. Pyrolysis has two variations, fast and slow pyrolysis, based on the mechanism by which the process is carried out, and these variations yield different products. Nevertheless, both the variations yield three primary products in varying proportions: biochar, syngas, and bio-oil. Hydrothermal liquefaction is also a variation of pyrolysis, where the process is carried out in an aqueous medium at elevated pressures.

Fast pyrolysis

During fast pyrolysis, food waste is rapidly heated to 450 - 600 °C in the absence of air with a retention time of a few seconds. Under these conditions, volatile compounds, pyrolysis gases and charcoal (biochar) are produced[14]. The primary product from fast pyrolysis is bio-oil, which results from the condensation of volatile products and accounts for an average 60-70% of the initial feedstock mass [33], [77]. Due to the higher oxygen content of bio-oil, it is unstable for long-term use and requires energy intensive refining. Fast pyrolysis of kitchen waste and digested kitchen waste [33], fruit pomaces [78], spent coffee grounds [79] and raw potatoes [80] have been reported in the literature, and a maximum bio-oil yield of 88% was observed among these studies. Syngas and biochar are produced in small quantities during fast pyrolysis, and hence generally do not yield revenue-generating byproduct streams. Commercial bio-oil refineries exist for wood and other biomass, but the application of fast pyrolysis to food waste management is still in the research stage. Bio-oil, just like crude oil, contains a number of fuel and chemical fractions [33] which need further refining to obtain useful products. Therefore, bio-oil production from food waste may not be very efficient in the immediate future since the product obtained requires expensive downstream processing.

Slow pyrolysis

Another variation of pyrolysis is slow pyrolysis which is predominantly studied for the valorization of waste biomass. In slow pyrolysis, food waste is heated at similar temperatures as fast pyrolysis

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[14] Fast pyrolysis, http://www.btgworld.com/en/rtd/technologies/fast-pyrolysis

in the absence of oxygen, but for longer durations. The typical residence time for slow pyrolysis varies from a few minutes to hours. In slow pyrolysis, the primary product is biochar which can be used as a high energy fuel or in several other applications, such as soil amendment or as a replacement of activated charcoal. Small amounts of bio-oil and syngas are also formed during slow pyrolysis. Slow pyrolysis is a technology of interest because, if the main product biochar is used as a soil amendment it can help attain a circular economy in food waste management sector and return essential nutrients to farm soil. Biochar from food waste as a byproduct of fast pyrolysis has been reported in the literature. However, there are no literature studies on exclusive production of biochar from food waste. Food waste thermochemical processing is concentrated towards fast pyrolysis research, but slow pyrolysis for the production of char has been reported for wood and waste biomasses and is considered as a feasible technology with high energy efficiency [81]. Only one recent study reported slow pyrolysis of the organic fraction of municipal solid waste for the production of biochar and use of liquid byproducts from bio-oil condensation in an anaerobic digester [82]. Even though slow pyrolysis is a promising option for obtaining higher biochar yield, it produces other byproducts (including ash) that may need further waste treatment.

1.4.3.2. Hydrothermal liquefaction

In hydrothermal liquefaction (HTL), food waste is heated at temperatures between 150-300^{0}C at high pressures [83]. It is a growing area of interest in food waste research since HTL requires an aqueous medium for the reactions, unlike pyrolysis where the feedstock must be dry; this avoids the need to dry the food waste before processing, which helps to improve the economics significantly. The primary product from HTL is also bio-oil which has its associated problems as discussed in 1.4.4.1. The possibility of co-production of hydro-char and bio-oil and using it as a soil amendment are also reported in the recent literature [84]–[86]. Even though various possibilities have been researched for HTL, it requires excessive energy input due to high-pressure and endothermic nature of the process. Also, the exact nature of the products and their applicability are not understood at the moment and need further research.

1.4.3.3. Gasification

During gasification, food waste is heated to elevated temperatures of 700-800^{0}C, in the presence of small amounts of air or oxygen[15], well less than the stoichiometric level needed to support full combustion. Gasification is a mature technology used for the production of hydrogen from biomass or other conventional fuel and is a promising technology in food waste management as the primary product is an energy-rich syngas which can be used in the production of heat or electricity. Gasification needs a gasifying agent (either steam or air) to catalyze reactions that lead to the production of syngas. Air gasification can be advantageous in food waste management, as it results in very low or no bio-oil yield. Eliminating a byproduct can be economical, as it reduces the waste management cost as well as increases the amount of energy value of the fuel available for production of the primary products. Air gasification of biomass, municipal solid waste, and food waste has been studied for various reactor configurations and process conditions for syngas production [87], [88]. Air gasification uses approximately 25% of the stoichiometric air required for full combustion to produce syngas and char. Biochar yields in general range between 5-15% of the feedstock mass, depending on the air-to-fuel ratio. For food waste management, it is reasonable to consider combinations of slow pyrolysis and air gasification to obtain an optimum co-production of biochar and syngas, and eliminate bio-oil from the product stream (Chapter 5).

1.4.4. Specialty products from food waste

Bioplastics are valuable biomaterials that can be produced using fermentation of food waste. The most widely researched bioplastics are in the category of poly hydroxyl alkanoates (PHAs). Conventional production of PHAs involves high-cost carbon sources such as glucose [89]. Hence, food waste has been recommended as a low-cost carbon source for the production of PHAs [90]. Organic acids from the fermentation of food waste make good precursors for bioplastics, such as polybutylene succinate which uses succinic acid[16], polylactic acid from lactic acid monomers [91] and 2-hydroxy propionic acid from propionic acid[17]. A recent study reported the production of cellulose-like bioplastic using cocoa pod husk and spinach waste using simple acid digestion [92]; such studies are promising in exploring the efficient valorization options for food waste.

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[15] https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification
[16] Succinity, Biobased polybutylene succinate. http://www.succinity.com/images/succinity_broschure.pdf
[17] Bioplastics, https://mediathek.fnr.de/media/downloadable/files/samples/b/r/brosch.biokunststoffe-web-v01_1.pdf

Production of high-value compounds like bioplastics not only help mitigate the problems related to food waste but also nullify the harmful environmental impacts of petroleum-based plastics. Even though there is a reasonable amount of literature for PHA production, production of other bioplastics from food wastes has not been explored. Food packaging based on waste potato and whey to replace coated paper and cardboard packaging has been researched in the past [93]. Use of apple pomace in producing regenerative bone and cartilage tissue scaffold [94] was found to be the optimum choice for biofuel production, pectin and antioxidant production and tissue scaffold production. Use of carbon black produced from waste tomato peels and eggshells is being researched as a filler to replace conventional carbon black in tires [95]. Even though research in the production of biomaterials and bioplastics from food waste is being conducted at a faster rate, these must be considered as 'technologies of future' due to current economic and environmental limitations.

1.4.5. Integrated bioprocessing

As most of the technologies applicable to food waste management (except AD) are manufacturing technologies, raw materials play an essential role. Since food waste is often mixed with packaging materials and other impurities, processing of food waste negatively affects the economic potential due to the labor and infrastructure required in sorting and depackaging. Integrated bioprocessing is a developing concept whereby more than one technology is used for the processing of food waste, and the byproduct from one process serves as a raw material for the other, or multiple products are obtained from a single process. Evaluation of alternative valorization options serves a useful input in moving towards the concept of integrated bioprocessing (also called a biorefinery) in the waste management sector. Figure 1.6 shows a flowchart of conceptual integrated bioprocessing (biorefinery) for food waste management prepared using the available knowledge from various resources. Since by-products and waste streams from one process remain within the biorefinery boundary and are fed as an input to another process, there will be limited waste flow out of the biorefinery. This concept is essential to attain sustainability goals and circular economic concepts related to the food supply chain.

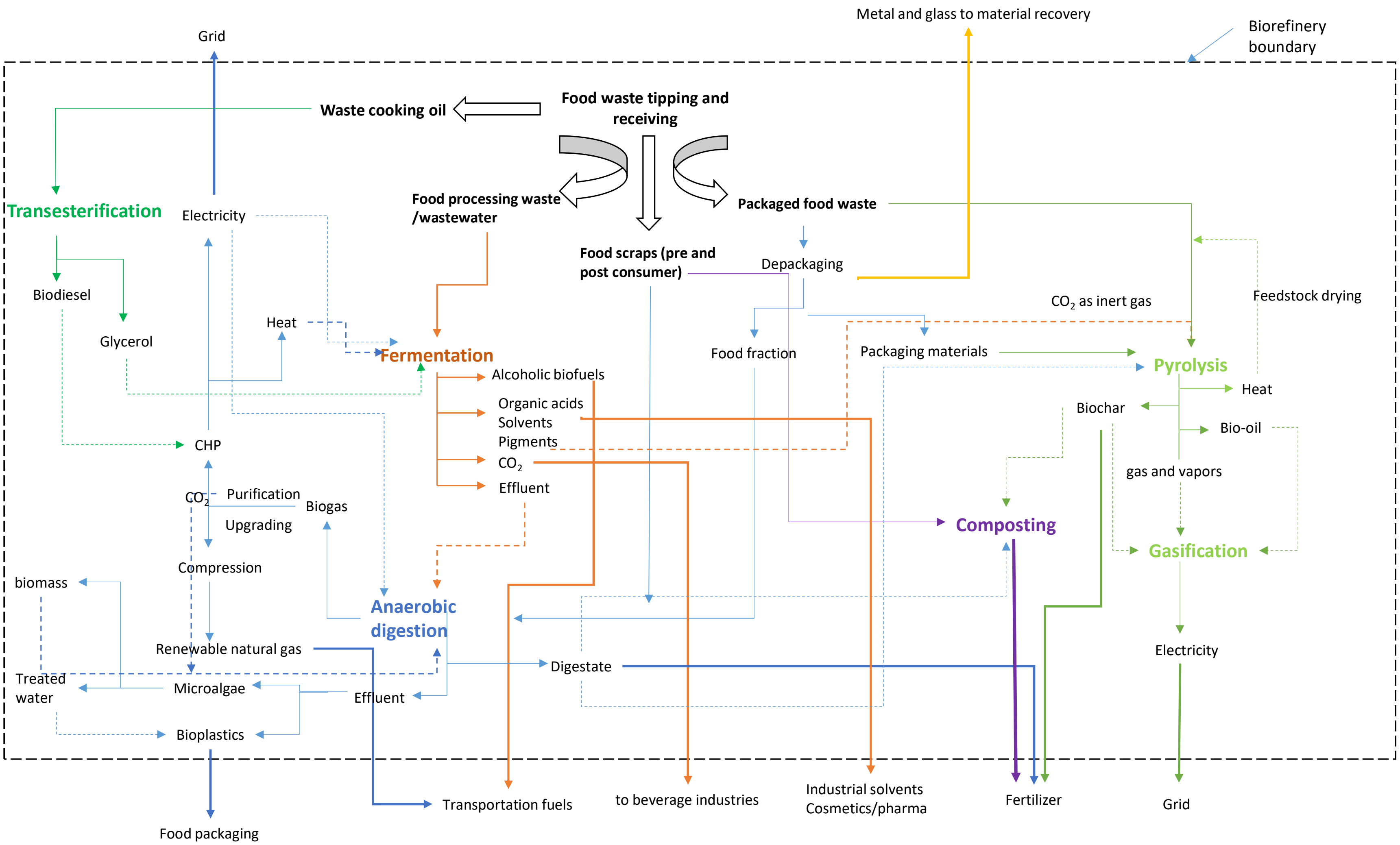

Figure 1.6 - Conceptual biorefinery for food waste valorization

1.5. Dissertation structure

Though several options are available for food waste valorization, not all of them are feasible at the moment. Technologies like anaerobic digestion to produce methane, fermentation to produce alcohols and thermochemical conversion to produce energy have immediate importance. The specific research gaps related to these technologies are discussed in detail in respective chapters. In this dissertation, research-specific pathways for conversion of food waste to energy and value-added products, with a particular focus on waste generated by institutions (e.g., hospitals and universities) and industrial food processing facilities were evaluated. The evaluation involved detailed experimental studies, case studies, real-time data analysis from food waste treatment plants, and a systems approach to assess the energy efficiency of each. The feedstocks chosen for the experiments were representative food wastes generated in the upstate region of New York State. This combination of experimental study and systems analysis will provide operating guidelines for treatment facilities and a potential bio-refinery concept for food waste diversion.

The dissertation evaluates three valorization options as a proactive measure to address the problems related to food waste, and address the overall research question: "What factors affect the use of food waste as a feedstock in biochemical and thermochemical valorization technologies?". The following research objectives are documented in Chapter 2 through 5:

Chapter 2 - Characterize the chemical and physical properties of food scraps and industrial food wastes to provide a comprehensive database of food waste properties.

Chapter 3 - Optimize anaerobic digestion of institutional food waste for achieving a stable process at high organic loading rates.

Chapter 4– Screen various food waste resources for their suitability as a feedstock for fermentation to produce alcohols (ethanol, 1-butanol, and isobutanol) and organic acids

Chapter 5 - Assess the feasibility of using thermochemical processing (pyrolysis/gasification) in food waste management for biochar production and energy generation using exergy analysis and life cycle thinking approach.

Food waste is generated at households, institutions, and food processing operations in various forms. The food waste generated because of kitchen preparation work and post-consumption classified as “food scraps” that have high solids content and contain a variety of food components like vegetables and fruits, bread and cereals, meat and poultry. On the other hand, industrial food wastes result from processed food production and can be in the form of either wastewater or high solid wastes. Examples of industrial food wastes include fruit pomaces from juice industries, bakery wastes, potato processing wastes, tomato serum and pomace, raw and cooked vegetables from soup processing, wastewater from pressing of cheese, tofu and yogurt, and other specific waste streams resulting from unavoidable waste fraction, washing the process equipment, cooking and straining. To evaluate food waste as a feedstock for industrial uses, it is of utmost importance to characterize different materials for their physical and chemical characteristics. Since food waste is highly biodegradable, its valorization is strongly dependent on microbial processes like fermentation and anaerobic digestion which are influenced by the nutritional value of the food waste feedstock. Even though many publications have reported data on food waste characteristics, it is required to explicitly characterize locally available food wastes when evaluating these materials as feedstocks for the production of value-added products. A thorough understanding of waste characteristics not only helps to map out the suitability of food waste to alternative valorization options but also offers a mechanism to trace back any changes in process behavior due to the varying composition.

Chapter 2 provides a compilation of the data on physical and chemical characteristics of representative food waste materials. The quantifications were based on literature data, in-house laboratory testing, and third-party laboratory analysis. The food waste materials characterized were food processing wastes, including tofu processing wastewater, dairy whey, potato processing waste, coffee grounds, bakery waste, apple and grape pomace, and institutional food wastes that include a mixed stream of pre- and post-consumer wastes. Different properties of these waste materials such as pH, solid content, macronutrients like carbohydrates, lipids, and proteins, and micronutrients such as metal ions were also studied. The analysis from this chapter provided a comprehensive data inventory of food waste characteristics and discussed the relevance of various characteristics on the choice of valorization method.

Food waste, when anaerobically digested at high organic loading rates using only food waste, can lead to an unstable process due to lack of trace elements, accumulation of volatile acids or ammonia [96]. While both ammonia stripping [97] and trace element supplementation [98] have been demonstrated to be effective in achieving process stability, these methods add significantly to the process cost by requiring additional infrastructure or chemicals. In Chapter 3, the possibilities of adapting these regimens by using only food waste without any synthetic chemicals or conventional feedstocks like manure to attain improved process stability were assessed through an experimental study. Other food sector waste materials, including acid whey (AW), energy drinks (ED), wasted bread (WB) and paper napkins (PN) were used as co-substrates to evaluate stability issues in food scrap digestion. While food waste is commonly co-digested in small amounts with manure, there is a need for significant developments in achieving food waste-only digestion to accommodate increasing rates of landfill diversion. The majority of the studies have used animal manure and sludge as the co-substrates, except for a few studies which involved rice straw [99] and fats, oils, and grease [100]. There are specific challenges associated with food waste-only digestion because, without any co-substrates, food waste digestion results in process instability due to insufficient trace elements that regulate enzyme reactions and ammonia formation. Therefore, the conventional practice has been to digest food waste at a relatively low fraction with primary substrates of animal manure or sewage sludge. The specific research contributions related to anaerobic digestion of pure food waste are discussed in detail in Chapter 3.

The literature on conversion of food waste using fermentation has mainly concentrated on the utilization of household food scraps [61], [101] and starchy food wastes like bakery and potato wastes [102], [103]. A few industrial food wastes like cheese whey [104] and apple pomace [105], [106] were also reported as suitable for ethanol production. Most research studies published used these wastes with the purpose of general screening and improving the ethanol yield using pretreatment or product recovery techniques. While some of these food wastes have proven to be promising for ethanol production, there is a need to systematically evaluate a variety of food wastes originating from the food processing sector. Butanol research has primarily focused on using corn and lignocellulosic biomass as feedstocks since this product is still in its early period as a fuel. A few research groups have reported the process of producing 1-butanol from bakery waste [66], agricultural wastes [107], domestic organic waste [108], apple pomace [109] and crude whey [16], with or without nutrient supplements. Two publications also reported the production of iso-butanol from cheese whey permeate [110] and apple pomace [111]. Due to the limited literature available on using fermentation as a food waste management technology, screening of various food wastes and products from food waste conversion was identified as an important research gap. Fermentation is a versatile technology regarding the number of products that can be produced by using numerous microbial species. Therefore, fermentation can offer a higher efficiency of waste valorization. Preliminary screening of food wastes as feedstocks for a spectrum of products (e.g., ethanol, 1-butanol, isobutanol, propanol, and organic acids) was carried using a combination of experimental and literature data. Therefore, this chapter provides 'state-of-the-art' knowledge on the application of fermentation in food waste valorization. Through a comprehensive data analysis and review, a qualitative metric was developed for screening the suitability of food waste as a feedstock in the production of ethanol, butanol and organic acids. The experimental studies involved a co-fermentation approach using solid food waste in combination with wastewater to replace the fresh water requirement of the process. Yeast-based aerobic fermentation was used for ethanol production, while iso-butanol production and bacterial anaerobic fermentation were used for butanol production. Tofu wastewater replaced potable water in pomace media to satisfy the water requirement of the process and provided essential nutrients for the growth of microbes. Because these waste materials are all available in large volumes within the close proximity (using the Finger Lakes region of NYS as an example), combining them as a single waste-to-alcohol feedstock was a reasonable option to consider.

The use of thermochemical processing in food waste management is relatively new, as evidenced by a relatively small number of research papers published in recent years. Food waste conversion to biochar is reported in a few studies as part of general product analysis [33], [77], [112], [113]. Various approaches such as thermogravimetric analysis [114], slow pyrolysis [82] and gasification [115] have been proposed in the recent years for food waste and other organic wastes, and are discussed in Chapter 5. Biochar research publications have predominantly focused and continue to focus on waste biomass, wood and forest residues with a primary objective of biochar characterization as a soil amendment. Since biochar is used as a soil amendment, producing biochar from food waste not only helps to close the food supply chain nutrient loop, but also significantly reduces food waste volume. On the other hand, bio-oil is a mixed fraction of various hydrocarbons that need further energy intensive refining. Therefore, the production of bio-oil from food waste may not be the most sustainable option. There is a gap in understanding the exergy efficiency of the system to produce biochar or thermal energy from food waste. A combination of experimental measurements, exergy analysis and life cycle thinking approach was used to evaluate the suitability of thermochemical processing as a food waste management option.

In Chapter 5, the most practical scenarios for the application of thermochemical processing in food waste management were developed through process optimization. This chapter provides the exergy and environmental feasibility of thermochemical processing of food waste. The scenarios were analyzed for a process that is a hybrid of slow pyrolysis and gasification. The effects of feedstock composition and process variables have been experimentally evaluated for lignocellulosic biomass [105–107]. However, there is no known reported literature on net exergy balance for a process of producing biochar and syngas using food waste as the feedstock. In Chapter 5, the effects of variables such as feedstock moisture and process temperature were evaluated by using experimental and literature data. The operating parameters to achieve the highest exergy efficiency were proposed, combined with analysis of the global warming potential of this technology.

CHAPTER 2

CHARACTERISTICS OF INSTITUTIONAL AND INDUSTRIAL FOOD WASTE RESOURCES

Abstract

This chapter provides a detailed discussion of institutional and industrial food waste characteristics. The characterization data presented here is a result of in-house measurements, third-party laboratory analysis and review of literature data. The variation among characteristics of food waste resources and their effect on the choice of valorization methods were analyzed and reviewed. Characterization data is essential to assign a suitable valorization option and to understand any instability or variation during the process. For anyone who does not have the resources to carry out food waste characterization, the data provided in this chapter serves as a useful resource and provides a reasonable range of values for food waste characteristics. The data inventory also provided important foundational data needed for consideration of alternate valorization options explored in Chapters 3-5 of this dissertation.

2.1. Introduction

Most current food waste management practices depend on biochemical processes such as AD and composting. The variation in food waste properties such as nutrient content, the presence of inhibitory compounds, pH and chemical oxygen demand (COD) can have a significant impact on microbial populations [116]. The food waste characteristics may vary significantly depending on the geographical locations and time. Despite the existence of a large number of publications on food waste properties, there is no clear understanding among the research community and waste management facilities about the average characteristics, how these characteristics might affect the valorization pathway and the variation in these characteristics among different types of food wastes. By knowing the physical and chemical properties, it would be possible to assign a suitable valorization method for a food waste stream of interest and hence provide a customized solution to maximize the resource use. Since newer technologies such as thermochemical conversion, aerobic digestion and other valorization options are being developed, the information on food waste characteristics is useful to the operators of these facilities. Even though databases like NOSHAN[18] provide a list of detailed characteristics, these are specific and detailed biochemical characteristics of food waste components (such as cabbage, celery etc.; see Appendix Table A2.1. for sample data) that would have a metabolic relevance in animal feed production. This Chapter attempts to provide a comprehensive database of institutional and industrial food waste characteristics by analysis of measured and previously published data and hence serves as a data inventory for food waste characteristics.

2.2. Food waste characteristics

The characteristics reported in this chapter are pH, chemical oxygen demand, moisture content, the organic nutrients such as carbohydrates, proteins and lipids, inorganic nutrients such as metal ions and elemental composition of carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S). All the methods used in characterization are given in Appendix 2 (Table A2.1). Understanding specific physical and chemical characteristics is essential when deciding among valorization options for food wastes. For example, the presence of optimum levels of carbohydrates in the form of free sugars is necessary for fermentation of food waste [27], while a high lipid content could be inhibitory to anaerobic digestion [117]. Specific properties like pH are fundamental parameters for all biochemical valorization options, and heating value of the food waste is a primary factor in thermochemical processing operations, which is a function of elemental composition [84]. The relevance of food waste characterization data to fermentation, anaerobic digestion and thermochemical processing options are discussed in brief in this chapter.

The food waste is generally characterized for organic nutrient composition and metal ions for specific applications such as animal feed production [65], [118]–[120]. The metal ion concentration of different food waste has been reviewed in this chapter, but their importance in valorization technologies is not discussed in detail. For example, the presence of Mg^{2+}, Mn^{2+}, Fe^{2+} and K^+ were shown to be important for stabilizing the yeast strain and improving ethanol production using mango residues [121]. Magnesium and zinc were found to be key metal ions in ethanol fermentation, because they act as modulators of important enzymes in the glycolytic

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[18] NOSHAN Food Waste Database
http://www.noshan.eu/index.php/en/food-waste-database-register/food-waste-database

pathway and regulate yeast stress, dynamics and stability of cell membranes [122]. A food waste rich is zinc could make a good cosubstrate for fermentation of low-value products and hence avoid procurement of expensive supplements. It might be necessary to supplement these minerals in the form of micronutrient solution to achieve higher alcohol yield in cases where the food waste does not contain these minerals at sufficient concentration. Mineral supplementation in the form of trace elements was suggested as a mechanism to improve stability of food waste digestion [96], [123]. The effects of other metal ions such as Fe have proven to increase biomethane production [124], [125]. The type and concentration can strongly affect the yield and quality of products due to catalytic action [126], [127]. In pyrolysis, a high mineral content of the feedstock was found to increase the biochar and syngas yield, while reducing the oil yield [128]. Food wastes are generally rich in chlorine, as food often contains salt (NaCl); chlorine can interact with vaporized species and form hydrochloric acid (HCl) or dioxins. However, this occurs when the process temperature is in the higher range of combustion temperatures [129], [130]. The metal ions tend to pose specific effects as opposed to organic nutrients and hence it is challenging to generalize the effects of these nutrients. Therefore, inorganic nutrient composition may not be a decisive factor in choice of valorization.

2.3. Institutional food wastes

Municipal solid waste (MSW) contains approximately 14-15% food waste, as discussed in Section 1.1. However, commercial food services and dining operations contain more than 30% food scraps in their waste as shown in Table 2.1. Source segregation of food waste is labor intensive if an appropriate collection system is not in place. Even though the waste composition is dependent on recycling rate, for the reviewed audit studies, the food waste content ranged between 31 and 50% for commercial food sector [1-6] and 55-63% [7-9] in university dining services. Therefore, based on the audit data presented in Table 2.1, it seems reasonable to choose a median value of 45% by weight of the total waste generated as food waste. Using median values among the listed studies, paper and paperboard would comprise 23% of the total waste stream, while recyclable (plastic, glass, and metal) and residual wastes make about 16% each as shown in Figure 2.1. Due to a higher fraction of food waste, source separation of food waste from the commercial sector and other institutions would be relatively less challenging than in the household sector and hence achieve better diversion from landfills.

Table 2.1- Composition of solid waste generated in different types of food services

Waste components	Institution type$											
	Quick service restaurant	Hospitality	Hotels	Restaurant	Restaurant	Restaurant	Wholesale	Hospitality	Resort	University dining	University dining	University dining
Food waste and soiled paper	43%	41%	37%	44%	31%	59%	40%	46%	72%	60%	55%	63%
Paper and paperboard	35%	22%	25%	24%	44%	20%	28%	20%	6%	NR	15%	NR
Plastic/glass/metal recyclables	3%	19%	25%	23%	NR	16%	11%	34%	16%	NR	11%	NR
Landfill /other	20%	18%	13%	9%	NR	5%	22%	NR	6%	20%	19%	12%
Location	Texas, USA	UK	UK	UK	UK	Chicago, USA	Chicago, USA	Toronto, Canada	Malaysia	W Virginia, USA	NC, USA	NC, USA
Time point	2012	2009-2010			2013	2010	2010	1990	2006	2017	2010	2014
Reference	[131]	[132]			[133]	[134]		[135]	[136]	[137]	[138]	[139]

$terminologies as reported by authors; blank cells indicate no reported data available; NR: not reported

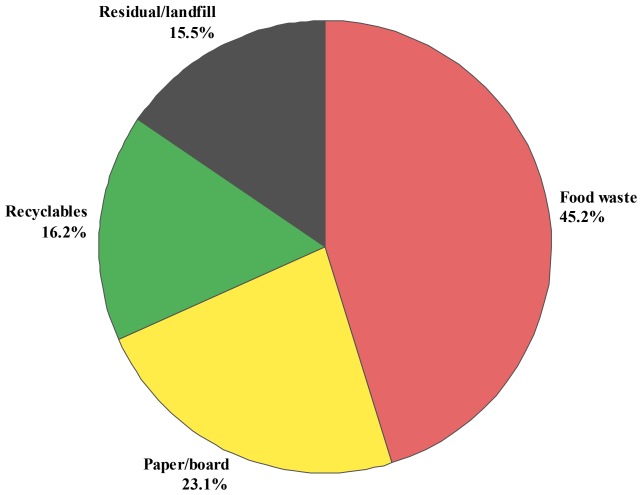

Figure 2.1 - Median composition of solid waste in commercial food service operations

Once the possibility of source segregation is established, the food waste fraction needs further characterization for its chemical composition. The food waste generated at RIT's dining halls was characterized by collecting the samples at 5 different time periods. The range of characteristics of different samples are presented in Table 2.2.

Table 2.2 - Average characteristics of food waste collected from RIT's dining halls (n=5)

Properties	Value (%)	Metal ions	Value (ppm)
Total solids	18-28	Calcium	2000 - 2200
Volatile solids	16 -25	Potassium	8800 - 10,100
Total proteins	27 - 33	Magnesium	600 - 700
Lignin	0.1 -2	Phosphorus	3000 - 3300
Starch	3 - 19.3	Sodium	6100 - 7300
Simple sugars	3.5 - 10.6	Zinc	19 - 21
Crude fat	3.6 - 23.4	Iron	13 - 40
Ash	4.1 - 5.1	Sulfur	2400 - 2600
COD, g/kg	168-227	Chlorine	10,700-12,500

Table 2.2 provides the food waste composition in terms of its macro and micro nutrients. These results were comparable to the macronutrient composition reported in literature as summarized in Table 2.3.

Table 2.3- Macronutrient composition of food waste from literature

Properties, % dry basis	**Food waste type**$^{\$}$						
	Average of 5 food waste samples	Kitchen waste	Kitchen waste	Kitchen waste	Kitchen waste	Post-consumer food waste	Preparation waste$^{\#}$
Moisture	75.9	80.3	82.8	79.2	61.3	64.4	85.7
Total sugars	42.3	59.8	62.7	NR	69	59	NR
Starch	29.5	NR	46.1	34.7	NR	NR	NR
Lignin	NR	0.8	NR	NR	NR	NR	NR
Lipids/fat	NR	15.7	18.1	22.3	6.4	21	3
Proteins	3.9$^{\&}$	21.8	15.6	29.3	4.4	17	15
Ash	1.3	1.9	2.3	NR	1.2	3	0
References	[140]	[141]	[142]	[142]	[143]	[48]	[48]

$^{\$}$ Terminologies as reported by the authors; $^{\&}$ converted from wet basis to dry basis using the reported moisture content; $^{\#}$ pre consumer waste generated in kitchen; NR: not reported

The data reported in Tables 2.2 and 2.3 comprises 17 different measurements from literature and the present study. The range of organic nutrients obtained from these data sets are plotted in Figure 2.2. The range obtained for carbohydrates, proteins and lipids were 42-69%, 3.9-29% and 3-22.3% respectively. This is a reasonable range to use when the characteristics of food waste of interest are not known. The protein concentration tends to lean towards the upper limit when the food waste is rich in meat and towards the lower limit when the food waste is a result of preparation work and mainly contains vegetable and fruit fraction. Similarly, the lipid content tends to be higher or lower depending on the food operation (e.g., fast food, farm-to-fork etc.).

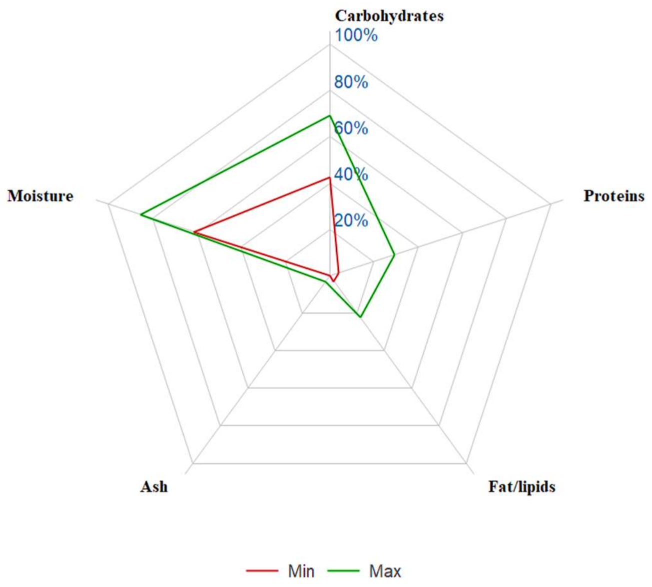

Figure 2.2- The minimum and maximum of main biochemical properties from 17 measurements compiled from this study and literature data

The food waste properties in terms of organic nutrients did not vary significantly for the food waste collected from a single source as shown in Table 2.2, but the average characteristics varied especially in protein and lipid concentration. These variations can results from the geographical location, time of collection and food habits. To obtain average data on elemental composition, ten different food waste samples from university dining halls, farmer's market, restaurant and grocery store were collected, dried and homogenized before estimating the elemental composition. The detailed description of the food wastes used for single source characterization are given in Table A2.2 and multi-source characterization are given in Table A2.3. The overall composition of the food wastes hence collected is given in Table 2.4 and compared with food waste collected from a single source. The composition was grouped into 3 categories: fruits and vegetables, meat, and rice and cereals. The elemental composition for the food waste collected from multiple sources is given in Table. 2.5.

Table 2.4- Composition of the institutional food waste collected from single and multi-sources in Upstate, NY

	Single source (n=3)	**Multisource (n=10)**
Fruits and vegetables	61%	73%
Meat (cooked/uncooked)	14%	5%
Bread/cereals	22%	25%

Table 2.5 - Selected average characteristics of food waste collected from multi-sources in Upstate, NY compared with reported studies

Properties, %	Food waste type							
	Mixed food waste (multiple sources)$^{¥}$	Food waste rich in Rice, noodles, pasta	Food waste rich in Meat and eggs	Vegetable waste	Mixed food waste	Canteen waste (average of	Mixed (rich in vegetables and fruits)	Kitchen waste
Moisture	64	66	54	82.7	85.7	75.8	97	NR
Ash	4.8	2.7	1.9	2.5	3.8	NR	NR	NR
Carbon	48.9	44.1	52.9	60.7	47.5	48	44.5	46.1
Hydrogen	7.2	6.3	8.5	9.1	12.2	NR	NR	6.9
Nitrogen	3.2	1.9	2.1	4.9	2.9	7.2	1.5	3.2
Sulfur	0.7	0.6	0.5	0.5		0.03	NR	0.3
Oxygen	32.5	44.5	34.2	22.3	29.7	NR	NR	37.8
References	This study	[115]			[112]	[144]	[145]	[146]

$^{¥}$no replicate measurement available; NR: Not reported

The elemental composition ranged between 44.1-60.7% for carbon, 6.3-12.2% for hydrogen, 1.5-7.2% for hydrogen, 0-0.7% for sulfur and 22.3-44.5% for oxygen as shown in Figure 2.3. The upper limit of the carbon composition corresponded to vegetable waste [115]. Based on this data, it is reasonable to assume a carbon composition of 44.5-52.9% as only one study reported a higher concentration of 60.7%, however this data corresponded to a simulated food waste [115]. Among the reviewed studies, the majority of mixed food waste had a carbon content of less than 50%. The composition ranged between 1.5-4.9% for nitrogen and 6.3-12.2% for hydrogen. Oxygen content is typically calculated using a ‘difference’ method after measuring C, H, N, and S, and hence the reported ranges in the literature may not be accurate for oxygen composition and tend to have a large variation. The effect of oxygen content on thermochemical conversion is briefly discussed in Section 2.5.3.

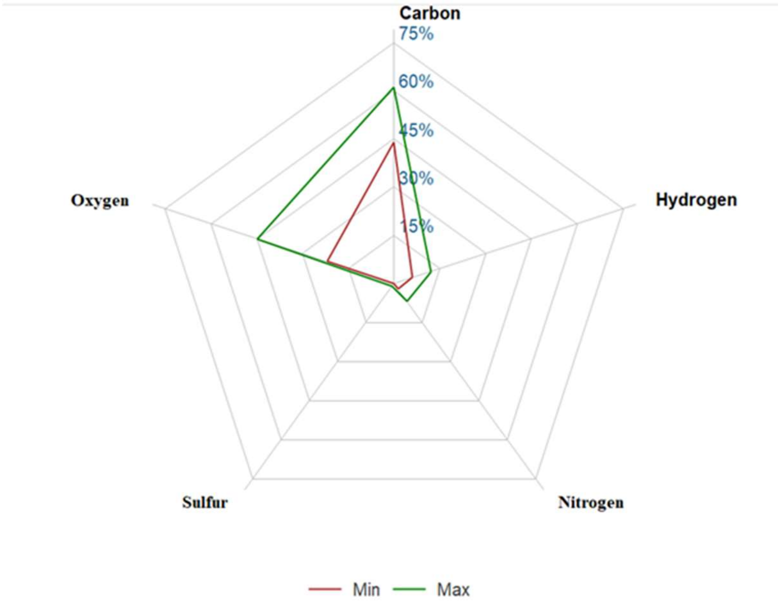

Figure 2.3 - Minimum and maximum values of the elemental composition of food wastes of 17 measurements compiled from this study and literature data

2.4. Industrial food wastes

In food processing industries, waste is produced from the separation of desired items from undesired ones [147] . Such food industry wastes are product specific and contain biodegradable residues, therefore the composition of the waste does not vary much as the final product must have a consistent quality [148]. Numerous efforts have been made to utilize industrial food wastes to produce useful products, because this practice not only offers economic benefits but also provides a solution to nuisances created by food waste degradation in the environment and landfills. Generation of significant volumes of food waste has an adverse impact on natural resources like water, land and biodiversity [1]. Food processors use large amounts of water for many applications, including temperature control, cleaning, process water, sanitation, transportation, cooking and as auxiliary water, accounting for the major sources of wastewater generation [149]. The characteristics and quantities of the wastewater generated in the food industry vary because of diverse utilization. The effluent may consist of suspended solids, organic matter and nitrogen in several forms, fats, oils and grease (FOG), and other inorganic materials [150]. Some of the major solid wastes include tomato waste, apple pomace, inedible dough, waste bread, potato waste, soybean curd residue and grape pomace from wineries. Common liquid effluents include whey from cheese and yogurt production, whey from tofu production, bakery effluent resulting from washing equipment, brewery effluent, oil mill effluent, soda industry effluent, potato processing wastewater, and apple pomace sludge. Solid food wastes are often rich in starch, lignin, cellulose and monosaccharides, mainly fructose and glucose, whereas the nutrients in liquid food wastes are available in diluted form. The composition of liquid waste varies based on the type of food processing, and its high moisture content is a major obstacle to industrial food waste management. Inorganic content of food waste is contributed by various metal ions that play an important role in metabolism of all organisms, as they take part in a variety of biocatalytic reactions, and act as co-factors for enzymes responsible for growth and product formation. They also maintain osmotic pressure of the cells in the production medium , hence both metal limitation and overload can cause cell death [151] and hence limit alcohol production. Therefore, mineral composition of a substrate can significantly affect the yield of products. Representative characteristics of 10 waste streams from food processing operations are given in Tables 2.6 and 2.7.

Table 2.6 - Characteristics of liquid effluents from food processing operations[%]; Md-Median; Mn-Mean; SD-Standard Deviation; N- number of reported studies

Characteristics	**Tofu processing wastewater**				**Sweet whey**				**Acid whey**				**Potato processing effluent**				**Sweet beverage (soda) industry effluent**			
	Md	***Mn***	***SD***	*N*	***Md***	***Mn***	***SD***	*N*	***Md***	***Mn***	***SD***	*N*	***Md***	***Mn***	***SD***	*N*	***Md***	***Mn***	***SD***	*N*
Carbohydrates,g/L	6.6	8.3	7.1	4	33.5	33.1	13	10	44	41.5	6.0	8	16.8	16.8	0.3	2	4.5	8.0	8.8	3
Proteins, g/l	1.2	1.2	0.8	6	4.5	4.9	2	11	7.9	7.6	1.7	8	2.4	3.3	2.5	4		0.2		1
Lipids, g/l		3.8		1	3.9	3.9	2.6	10	5.5	5.6	2.5	7		0.2		1				0
pH	5	5.2	0.4	5	4.2	4.4	0.9	9		4.7		1	5.8	5.5	0.7	5	9.8	9.8	0.8	6
Ash, %w/w	1.7	1.7	0.4	3	0.7	1.0	0.6	7	0.5	0.5	0.1	7	0.2	0.2	0	2	0.1	0.1	0.1	5
Total solids, % w/w		1.7		2	6.7	6.3	0.9	6	6.4	6.6	0.5	6	0.8	1.0	1.0	4		0.1		2
COD, g/l	20	22.6	13	7	69.3	67.1	4.8	4		79.5		1	5.9	6.0	3.8	4	7.4	1.3	1.3	8
Calcium		34.6		1	341	340	84	4	1100	1110	85	4		100		1		3.7		1
Magnesium		16.3	2	2	49	55	22	3		230		1		91.2		1		3.1		1
Sodium		127		1	386	366	82	4		1785	2	2		40		1		21.6		1
Potassium		861		1	1300	1250	240	3	1400	1367	153	3		35		1		4.3		1
Iron		9	1	2		2		1				0		0.2		1		0		1
Manganese		0		1				0		0.1		1		0.2		1		0		1
Phosphorous		15	1	2	440	700	521	3	540	540	198	3	169	268	295	3		1.3		1
Sulfur		2240	1	1				0				0	58	67	30	3		300		1
Zinc		0.5	0	2		0.3		2		2.2		1		0.5		1		0		1
References	[52], [152]–[159]				[16], [160]–[166]				[16], [160], [164], [165], [167]				[37], [168]–[170]				[171], [172]			

[%] Blank cells indicate data were not reported.

Table 2.7 - Characteristics of high solid wastes from food processing operations[%]; Md-Median; Mn-Mean; SD-Standard Deviation; N- number of reported studies

	Tomato pomace				**Apple pomace**				**Grape pomace**				**Spent coffee grounds**				**Bread waste**			
	Md	***Mn***	***SD***	***N***	***Md***	***Mn***	***SD***	***N***	***Md***	***Mn***	***SD***	***N***	***Md***	***Mn***	***SD***	***N***	***Md***	***Mn***	***SD***	***N***
Carbohydrates, %w/w	33.9	36.1	10.3	9	42.8	44	6	10	29.2	28.1	5.0	5	49.5	51.2	6.5	6	54.6	58.9	14.4	6
Proteins, %w/w	21	16.4	9.1	13	4.3	4.3	1.3	11	10.5	9.9	2.5	7	16.4	17	4.6	8	11.8	11	2.1	8
Lipids, %w/w	13.4	11.3	5.3	7	2.7	2.9	1.2	9	6.7	6.9	1.8	7	24	22.2	5.7	8	1.8	1.8	0.4	4
pH		2.9		1		3.9		1		4.4	0.8	2		5.3	0.6	2				
Ash, %w/w	4.1	5.0	2.1	6	1.5	1.5	1.0	9	4.8	4.8	2.0	6	1.5	1.5	0.2	5	1.80	1.7	0.5	7
Total solids, %	14.5	17.8	7.1	3	27.7	28.3	2.2	4		35.0		1	29.2	28.3	7.7	4	89	80.7	13.4	7
COD, g/kg	87.0	86.7	9.5	3	14.3	14.4	6.1	3		14.4		1		160		1				
Calcium	5700	5297	1922	7	675	808	366	6	4400	4570	1164	3	777	1020	625	5	1358	1252	553	6
Magnesium		2310		2	388	390	174	6	1500	1643	682	4	1900	1515	820	5	700	731	519	4
Sodium		1820		2	100	855	1045	5	440	420	92	3	267	317	282	4	3150	3438	644	4
Potassium		8740		2	2300	3098	2649	5	1880	2027	711	3	8100	7635	3062	5	1600	2270	1521	5
Iron		384		2	30	30	6	3	50	41.3	31	3	85	136	131	4	93	230	239	5
Manganese		366		2	6	7	2	4	106	106	34	3	33	34	6.7	4		1.7		1
Phosphorous	4750	5466	1921	8	850	973	435	5	3400	3077	1120	3	1534	1442	394	5	1890	1945	420	4
Sulfur				0		1100		1		890		1	1600	2000	872	5				
Zinc		54		1	13	11	6	4		9800		1	12	12	3			20.5	8	2
References	[119], [173]–[189]				[106], [195]				[198]–[209]				[199], [210]–[220]				[65], [89], [102], [103], [190], [221]–[230]			

[%]Blank cells indicate data were not reported.

2.5. Significance of food waste characteristics in valorization

The relevance of food waste characterization for valorization options studied in this dissertation is discussed in this section.

2.5.1. Anaerobic digestion

For any biochemical valorization method, specifically for anaerobic digestion, the substrate should always provide a balanced carbon-to-nitrogen ratio (C/N). The C/N ratio generally tends to be lower than a required range of 20-30 for institutional food wastes [231], [232], mainly because of the high nitrogen content resulting from protein-rich diets. Figure 2.3 shows the elemental composition of food wastes and C/N ratios varied between 8.5-29 for food wastes from various sources with a median of 15.6 and average of 14.9. These values agreed with the measured value of 15.6 for mixed food waste and 16.3 for vegetable waste in this study. Since this is lower than the range required for optimal biogas production, a high carbon containing co-substrate would be necessary to achieve a stable process. The co-substrates such as waste bread and soiled paper napkins have a higher C/N than the optimum as shown in Table 2.8 and using these in food scraps digestion as co-substrates is a practical option.

Table 2.8 - Properties of high carbon food sector wastes

Physical and chemical properties, n=3	Waste bread	Soiled paper napkins	Cow manure
pH	NM	NM	6.8±0.5
TS, %	95.6±0.7	94.5±3.5	10.3±1.4
VS/TS, %	89.4±2.9	86±6.9	83.5±0.8
VS, %	85.4±2.3	81.4±9.4	8.6±1.2
COD, kg/L	1167±97	1176±142	97±6
ash, %	10.2±2.8	13.1±5.9	1.7±0.3
Elemental composition[#]			
Carbon, %	45.2	44.8	54.8
Hydrogen, %	6.6	6.1	NM
Nitrogen, %	1.5	0.3	3.6
Oxygen, %	42.6	47	NM
Sulfur, ppm	1700	300	2600
Phosphorus, ppm	1854	29	3000
C/N	30	149	15

[#] no replicate measurements available

If food waste is used in anaerobic digestion, distinguishing between available and input chemical oxygen demand (COD) is essential, as a considerable fraction of input COD may not be available for biogas production [233]. While studies on co-digestion recommend inclusion of food waste, using food waste as a single substrate was often found to be unstable [234], [235]; this means that food waste composition has a significant impact on the metabolism of anaerobic microbes. Trace element supplementation has been proposed as one of the methods to increase the stability of food scrap digestion process [WRAP-UK[19]][236], [237]. Biological oxygen demand (BOD) represents the available COD that can be utilized by microbial population and converted into biogas; a BOD value of 580 g/kg of food waste was reported, while the COD was 1210 g/kg [238]. BOD is always lower than COD and hence it is never possible to achieve a 100% degradation through biological processes. Even though COD and BOD are essential parameters that help avoid overloading the digester with nutrients, they are often tedious to measure and require resources and expertise. Therefore total solids and volatile solids estimations are commonly used as a part of feedstock characterization for AD.

Another advantage of knowing the characteristics is that the maximum theoretical yield of biomethane from food waste can be calculated either by using macronutrient or elemental composition. Currently, the majority of food waste processed in anaerobic digesters is industrial food wastes that are more consistent compared to institutional food wastes. As long as the composition is consistent, food waste digestion can be achieved without significant problems, and food waste characterization data is primarily used to estimate theoretical biogas composition and methane potential. However, the methane potential can vary significantly depending on the types of nutrients available. Certain nutrients can adversely impact the methane potential of food waste. Considering the variability of food waste macronutrient composition from Table 2.5, the biomethane yield can vary between 0.9 to 2.2 L per kg food waste processed according to Buswell's equation [48], [239]. The biomethane potential is sensitive to lipid content, and the large threshold estimated is attributed to a large difference between the minimum and maximum values observed for lipids. Lipid content, however, is purely a result of the food operation type (e.g., fast food, farm-to-fork etc). Due to this high variability in composition, the digestion of institutional

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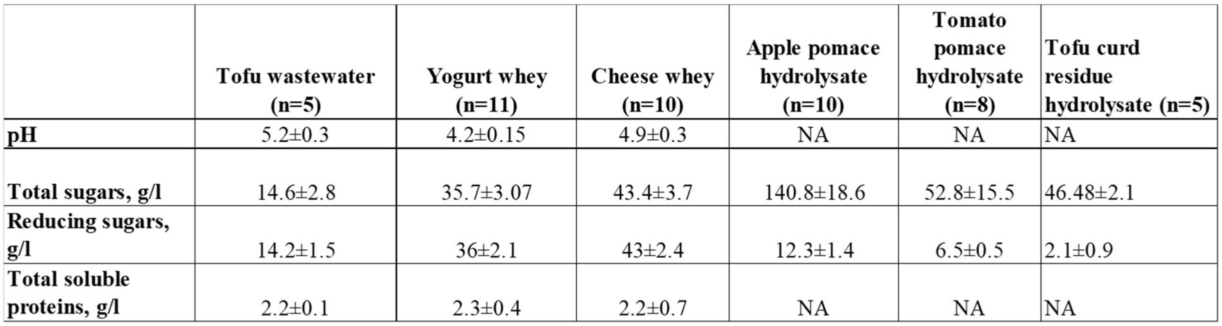
[19] Trace element supplementation for stable food waste digestion; http://www.wrap.org.uk/sites/files/wrap/110109%20%20Trace%20element%20supplementation%20-%20final%20.pdf

food wastes tends to be highly unstable. Conversely, industrial food waste, if obtained from similar sources, can have much lower variability in biomethane production. If industrial food wastes are co-digested with food scraps or with manure, they can provide a regular regime of operation in terms of nutrients, and minimize the water requirement to dilute manure or food scraps to the required solid content and supply required minerals for microbial action [35]. Increased protein concentration in food waste can lead to excessive ammonia production and inhibit the process [240], however institutional food wastes do not contain high enough protein to produce inhibitory concentrations of ammonia as long as the loading of the digester is kept within the acceptable range [35](see Chapter 4).

2.5.2. Fermentation

The most critical parameter that affects fermentation is the quantity of carbohydrates present in food waste. Carbohydrates can be complex polysaccharides like starch and cellulose, oligosaccharides like lactose and sucrose, or monosaccharides like glucose and fructose [241]. Therefore, before choosing fermentation as a valorization option for food waste, it is essential to know the composition in terms of types of available sugars. Sometimes, it is also required to know the food waste characteristics to the level of individual sugars, as all the sugars are not reducing sugars and not all reducing sugars can be utilized by all available microbes. Table 2.9 lists the measured values of total and reducing sugars and total soluble protein present in the specific liquid and solid industrial food wastes. The amount of reducing sugar can be a small fraction of total sugars available. Most of the literature tends to report total carbohydrate concentration, which includes soluble or insoluble fibers as well as reducing and non-reducing sugars. Fibers contain non-degradable lignin or less degradable pectin and polymers like cellulose and hemicellulose that require special enzymes for degradation. Apple pomace is made up of approximately 55-68% fibers [73] and needs pretreatment to release simple sugars from complex polysaccharides, which increases the cost. Therefore, even though the maximum theoretical yield of fermentation products can be estimated using measured feedstock sugar concentration, care must be taken to calculate how much of the total sugars are actually available for the production of ethanol or other products of interest.

Table 2.9 - Characteristics of industrial food wastes showing reducing and total sugar concentrations (measured); $^{\alpha}$ hydrolysate are acid extracted fraction of the solid wastes that is ready to be used in fermentation; NA- data not available/ not measured



	Tofu wastewater (n=5)	Yogurt whey (n=11)	Cheese whey (n=10)	Apple pomace hydrolysate (n=10)	Tomato pomace hydrolysate (n=8)	Tofu curd residue hydrolysate (n=5)
pH	5.2±0.3	4.2±0.15	4.9±0.3	NA	NA	NA
Total sugars, g/l	14.6±2.8	35.7±3.07	43.4±3.7	140.8±18.6	52.8±15.5	46.48±2.1
Reducing sugars, g/l	14.2±1.5	36±2.1	43±2.4	12.3±1.4	6.5±0.5	2.1±0.9
Total soluble proteins, g/l	2.2±0.1	2.3±0.4	2.2±0.7	NA	NA	NA

Even though the amount of reducing sugars is high, it is possible that the food waste fermenting microbes are not capable of utilizing these sugars. Not all species of yeast are capable of utilizing all class of sugars, for example, the most widely used yeast *Saccharomyces cerevisiae* cannot utilize lactose as a source of carbon [242], [243]. Table 2.10 lists the sugar profile of a few selected liquid waste streams. For example, in cases of acid and cheese whey, a major fraction of reducing sugar available is lactose and hence it is obvious to choose a pathway that efficiently converts lactose into useful product such as lactic acid.

Table 2.10 - Concentrations of different sugars in liquid food processing wastes (measurement average and standard deviation)

	Lactose	**Glucose**	**Arabinose**	**Xylose**
Tofu wastewater (n=3)	0.8±0.1	1.1±0.1	0.4±0.1	0.3±0.1
Acid whey (n=4)	42.2±1.5	0	0	4.8±0.3
Feta cheese whey (n=4)	39.6±0.4	0.9±0	0	0.4±0

2.5.3. Thermochemical processing

Thermochemical processing of food waste is not very well understood. One of the most critical parameters for thermochemical processing is the lower heating value (LHV), which depends directly on moisture content. LHV can be deduced from food waste composition and is explained in detail in Chapter 5 (Equations 5.1 and 5.2). Most of the energy requirement in drying and thermochemical processing depends on the specific heat of the food waste converted. While measuring specific heat capacities can be cumbersome, it can be estimated with reasonable accuracy using empirical relations that make use of macronutrient composition [244]; these relationships are discussed in Appendix 5.2. In addition to impacting the heating value, the feedstock characteristics can affect product yield and properties [130]. A higher yield of lignin (or fibers) was found to be more beneficial to the production of biochar than syngas or oil in a fast pyrolysis process [127]. High lignin content is not preferable in biochemical valorization methods, as lignin-degrading enzymes are limitedly produced in certain classes of plant pathogenic fungi and not in other classes of microbes [245], [246]. Oxygen composition could play a prominent role when the food waste management is based on a thermochemical conversion. With higher oxygen content, the food waste can be gasified at a lower temperature which helps to reduce the overall energy requirement. However, higher oxygen content also reduces the yield of biochar. A detailed understanding of the food waste characteristics on biochar production is not available due to the limited literature on the thermochemical processing of food wastes. At present, correlations must be drawn based on available data for waste lignocellulosic biomass.

2.5. Conclusions

Irrespective of the valorization methods, food waste characteristics can have a significant impact on the operational aspects and the yield and quality of products. In this study, institutional and industrial food waste characteristics were analyzed from various sources. Even though it is challenging and risky to generalize this data, a reasonable attempt was made to provide a range of general characteristics of different types of food wastes, mainly food scraps. Through this chapter,

- A comprehensive data inventory was developed to generalize characteristics of food scraps and industrial food wastes.
- The relevance of food waste characterization on food waste valorization options was provided, with a focus on the most crucial parameter required to be characterized for each option.

Even though this research provided a general range of values of organic nutrient and elemental composition for different types of food wastes, the number of samples may be relatively small to ensure broad applicability outside the scope of the present study. The available food waste data has a high degree of uncertainty depending on geographical and seasonal variations which were not considered as sensitivity factors in this study.

CHAPTER 3

ANAEROBIC DIGESTION OF FOOD WASTE WITH UNCONVENTIONAL CO-SUBSTRATES FOR STABLE BIOGAS PRODUCTION AT HIGH ORGANIC LOADING RATES

Abstract

In this chapter, the effect of increasing organic loading rates (OLR) for achieving 'food waste only' digestion were evaluated. The effect of increasing organic loading rates (OLR) was studied using food scraps as the main substrate and acid whey, waste bread, waste energy drink, and soiled paper napkins as cosubstrates in a semi-continuous mode. During digestion of FS without any co-substrates, the maximum specific methane yield (SMY)[20] was 363 mL $gVS^{-1}d^{-1}$ at an OLR of 2.8 $gVSL^{-1}d^{-1}$, with reactor failure occurring at an OLR of 3.5 $gVSL^{-1}d^{-1}$. Co-substrates of acid whey, energy drinks, and waste bread resulted in maximum SMY of 455, 453 and 479 mL $gVS^{-1}d^{-1}$, respectively, with OLR as high as 4.4 $gVSL^{-1}d^{-1}$. These results offer a potential approach to high organic loading rate digestion of food waste without using animal manure. Process optimization for the use of unconventional co-substrates may help enable deployment of anaerobic digesters for food waste management in urban and institutional applications.

3.1. Introduction

Residential, institutional and industrial sectors generate large volumes of food waste throughout the year. Though some fraction is productively utilized, most of the generated food waste is landfilled. As mentioned in Section 1.3, in the United States a few regions have moved towards legislation that bans sending food waste to landfills, and it is expected that this practice will decline as it is the most inefficient use of the material and does not adequately utilize its embodied energy and water content. Anaerobic digestion is currently the most efficient commercial-scale use of food waste, as the end-products are nutrient-rich digestate and biofuel which can be converted to electrical or thermal energy. Food waste not only provides an inexpensive substrate for anaerobic digestion but also significantly improves biogas production relative to systems that convert manure

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[20] Also called biomethane potential (BMP)

or sewage sludge alone [247]. However, a relatively small fraction of anaerobic digester plants worldwide co-digest food waste with manure, sewage sludge or lignocellulosic biomass. Most digesters in the U.S. are farm-based and digest dairy manure and agricultural residues. While food waste is co-digested in small amounts with manure (generally less than 30% of total influent), there is a need for major developments in achieving food waste-only digestion to accommodate increasing rates of landfill diversion. There are specific challenges associated with food waste-only digestion because, without any co-substrates, process instability can result from insufficient trace elements that regulate enzyme reactions. Therefore, the conventional practice has been to digest food waste with at a relatively low fraction with primary substrates of animal manure or sewage sludge.

3.1.1. Literature review

Use of co-substrates in anaerobic digestion of food waste helps to attain process stability, either by balancing the carbon-to-nitrogen ratio (C/N) or by providing trace minerals and buffering action. Table 3.1 provides a sample of the literature exploring the various co-substrates used in food waste digestion. The majority of the studies have used animal manure and sludge as the co-substrates, except for a few studies which involved rice straw [99] and fats, oils, and grease [100]. It is essential to explore newer co-substrates as food waste generation continues to rise, and existing digesters that co-digest food waste with manure cannot handle all the additional waste generated. There are two classes of methane-forming bacteria: acetoclastic and hydrogenotrophic methanogens [248]. Food waste is rich in nitrogen, generally attributed to the presence of proteins. Therefore, food waste digestion often leads to ammonia formation which is toxic to acetoclastic methanogens [98]. While hydrogenotrophic methanogens continue to produce methane, food waste often lacks trace elements which leads to accumulation of volatile fatty acids. Therefore, ammonia formation and volatile acid accumulation are the major process challenges in food waste digestion which can be addressed by ammonia stripping or trace element supplementation. There were several efforts reported at laboratory and pilot scale for *in situ* removal of ammonia using side-stream gas stripping [97], gas mixing [249], ultrasonication [250], microwave irradiation [251] and other physical and chemical methods [252]. Various researchers and organizations have also proposed trace element and mineral supplementation as a mechanism to achieve a stable process [98], [123], [236], [253].

Table 3.1 - Selected literature studies on co-digestion of food waste; NR: not reported, NA: not applicable

Food waste type	**co-substrate**	**Reactor volume, L**	**OLR, gVS^{-1} d^{-1}**	**Operation mode**	**Ratio: FW/Co-sub**	**SMY, mL/kg VS d**	**HRT, d**	**Reference**
Cafeteria food waste	Chicken manure	5	2.5	Semi continuous with only FW fed on day 1 and 2, CM fed on day 3; the sequence repeated	NA	508	50	[254]
Cafeteria food waste	Cattle manure	1	15	Semi continuous with once a day feeding and discharge	2	317	NR	[255]
Defibered kitchen waste	Biowaste	NR	10.9	Semi continuous with two times a day feeding, five days a week	NR	420	7	[256]
Cafeteria food waste	Sewage sludge	5	1	Batch	0.5	494	21	[257]
Cafeteria food waste	Rice straw	1	5	Batch	5	392	NR	[99]
Greasy food processing waste	Municipal sludge	0.5	2	Semi continuous with once a day feeding and discharge	1	633	20	[258]
Organic fraction of MSW	Fat, oil and grease	5	4	Semi continuous with once a feeding and discharge	6.7	318	16	[100]

NR: not reported

3.1.2. Factors affecting food waste digestion

Anaerobic digestion involves a synergistic metabolism between different classes of microbes: hydrolyzing bacteria, acetogens, acidogens, and methanogens. These microbial communities differ significantly in their morphology, optimum conditions for growth and product formation, and sensitivity to changing microenvironments. Therefore, it is necessary to monitor different process parameters to maintain a healthy balance between microbial populations and achieve a steady process. Some of the parameters of interest for growth and product formation are pH, volatile fatty acid (VFA) concentration, alkalinity, VFA-to-alkalinity ratio, dissolved ammonium concentration, daily biogas production, daily methane, carbon dioxide and hydrogen sulfide composition of biogas, and specific methane yield.

3.1.2.1. pH

The average daily pH is known to affect digester performance by influencing the mass transfer rate. In a substrate containing a high concentration of ammoniacal nitrogen, pH affects the ratio of free ammonia (NH_3) to ionized form of ammonia (NH_4^+) [117]. As the pH increases, ammonia toxicity increases due to the increase in free ammonia. Methanogens are susceptible to higher concentrations of ammonia, and therefore they consume VFAs at a slower rate. Slower VFA consumption leads to their accumulation and creates a low pH environment in the digester. Methanogens consume VFAs produced by acetogens to produce methane. Therefore, if acetogens outnumber methanogens, pH will drop, which can inhibit methanogens, and ultimately lead to digester failure. A balanced metabolism of acetogens and methanogens helps in maintaining the pH of a digester within the optimum range. The pH in an anaerobic digester must be between 6.8 and 7.5 for a healthy population of methanogens [259]. The pH, however, cannot be a single parameter that determines digester stability.

3.1.2.2. Volatile fatty acids

It is important to monitor on a regular basis other parameters like total VFAs. Though pH is not an early indicator of process instability, it is essential to maintain a constant digester pH at all times. Maintaining lower concentrations of VFAs helps both in attaining higher methane production and better waste conversion efficiency. The lipid component of food waste breaks down into long chain fatty acids (LCFAs) in the digester by microbial hydrolysis. The LCFAs further break down into smaller volatile fatty acid molecules like acetic acid, which methanogens consume to produce biogas. In the case of digester overload, the LCFAs incompletely hydrolyze into acetic acid. This incomplete hydrolysis leads to LCFA accumulation over time, ultimately causing inhibition of microbial activity [116]. The methanogens are highly sensitive to LCFA concentration even though all types of microbes are affected to some degree. The LCFA molecules bind to the bacterial cell membrane and cause mass transfer limitations, cell membrane disruption (lysis) and enzyme inhibition. Under the appropriate condition, LCFAs break down into short chain fatty acids: acetic acid, propionic acid, butyric acid, caproic acid, valeric acid, and enanthic acid [260] with acetic acid being the most abundant. Accumulation of short-chain fatty acids as a result of the change in pH or alkalinity can be inhibitory to methanogens. Because of the inhibitory effects of volatile fatty acids, it is essential to monitor the VFA concentration in the digester on a regular basis. Consistently elevated levels of VFAs indicate digester overload and leads to digester failure. Therefore, organic loading rate (OLR) of the digester must be reduced for stable digester operation. Researchers have studied different strategies to decrease the adverse effect of VFAs, including co-digestion, the addition of specific metal ions like Ca^{2+} [261], and reagents that increase alkalinity [262]. Another approach suggests that a discontinuous feeding profile can avoid VFA accumulation in the digester [263].

3.1.2.3. Alkalinity

Alkalinity represents the buffering capacity of the digester contents. Optimum alkalinity level in the digester will resist the pH change due to VFA accumulation and helps in achieving process stability. Alkalinity is a result of the release of cations like NH_3 and NH_4^+ in aqueous environments of the digester [117]. Ammonia-N and carbon dioxide react to form ammonium bicarbonate that contributes to alkalinity in the digester [264]. Alkalinity levels of lower than the optimum indicate VFA accumulation. Alkalinity can be maintained by using an appropriate co-substrate that has the natural buffering ability or by using external agents like calcium carbonate or sodium bicarbonate. The use of waste materials like egg shells and lime mud from pulp and paper processing was proposed as a medium for maintaining digester alkalinity [262]. In a manure-only digester maintained at pH = 7.4, normal alkalinity levels were observed to be 5500 mg $CaCO_3L^{-1}$ to maintain stable operation [265]. As manure-only digesters are stable for a long time, this can also be a basis for average required alkalinity levels in ‘food waste-only’ digestion. Alkalinity also affects the digestate characteristics by changing the phosphorus (struvite) removal efficiency [266].

3.1.2.4. Ammoniacal nitrogen

Ammoniacal nitrogen refers to the nitrogen from free ammonia (NH_3), and ammonium ions (NH_4^+) in the digester are the end products of protein, amino acid, and urea degradation. Nitrogen, in the form of free ammonia, can freely diffuse through the bacterial cell membrane and cause a pH change in the microenvironments of the cell. This pH change, in turn, results in VFA accumulation and reduced methane production. Free ammonia is known to affect methanogenic activity by inhibiting the methane producing enzymes or by diffusing into the microbial cells, causing proton imbalance or potassium deficiency [267]. An NH_4^+-N concentration of 1000 mg L^{-1} or higher was observed to be inhibitory in anaerobic digestion of municipal solid waste leachate using an expanded granular sludge anaerobic reactor [268]. These authors also achieved a higher COD removal efficiency by maintaining the NH_4^+-N concentrations below 500 mg L^{-1}. A lower concentration of NH_4^+ or free ammonia is beneficial to anaerobic digestion, as these compounds serve as a nitrogen source for microbes. Inhibition effects of ammoniacal nitrogen depend on the type of substrate, the presence of other metal ions [255] and process conditions like temperature and pH.

3.1.3. Scope of work

It was clear from the literature review that food waste digestion often leads to unstable processes, resulting in digester failure at higher organic loading rates. Even though this is a well-known factor, the solutions that were recommended to this problem are either co-digestion with cow manure, regular trace element supplementation or ammonia stripping. The availability of manure for a non-farm digester is limited, but other methods present an additional operation and maintenance cost. Based on these aspects, the following research gaps were identified:

- While both ammonia stripping and trace element supplementation are proven to be effective in achieving process stability, these methods add significantly to the process cost by requiring additional infrastructure or chemicals. Therefore there is a need for a cost-effective regime that could enable stable 'food waste only' digestion.

- Food scrap digestion leads to process failure at higher OLRs. Therefore, some process modifications are required to digest food waste at higher OLRs without any process instabilities.

To address these research gaps, the main research question that should be answered is *"What factors affect the anaerobic digestion of food scraps at higher organic loading rates?"* Therefore, experiments were conducted to test the possibility of using unconventional co-substrates as stabilizing agents that would both provide consistent feeding regime and aid digestion of food scraps at higher OLR. This study evaluated the effect of organic loading rates on non-manure based unconventional co-digestion of food scraps (FS), using available food sector waste materials, including acid whey (AW), energy drinks (ED), wasted bread (WB) and paper napkins (PN) as co-substrates to evaluate stability issues in food waste digestion. Also, the digestion of FS was studied without using any co-substrate and using cow manure as a co-substrate to obtain a comparison with the conventional process. The process parameters indicative of process stability were monitored on a regular basis. Use of unconventional co-substrates can offer a potential advantage in situations where it is not practical to haul digestate long distances for field spreading, for example, decentralized digesters at universities, hospitals or food processing plants.

3.2. Methods

The term 'reactor' is used to explain the experimental setup used in this study, whereas the term 'digester' is used in a real-world sense to emphasize the practical importance of this research. 'Food scraps' refer to mixed pre- and post-consumer waste from dining halls and 'food waste' is a generic term that relates to both FS and food processing waste. The term 'food waste-only digestion' is used to emphasize the importance of unconventional (non-manure) substrates originating from the food sector to produce energy using anaerobic digestion. The co-digestion mixes used in each reactor are listed in Table 3.2.

3.2.1. Food waste characterization

The substrates utilized in this study were analyzed for physical and chemical characteristics. Physical parameters included pH, total solids (TS) and volatile solids (VS). The pH of the substrates was recorded using a Mettler Toledo pH meter. The TS and VS were analyzed according to standard EPA method 1684 [269]. The chemical oxygen demand (COD) was examined for each substrate using a standard COD analyzer (Hach DR 3900, Method 8000). Other characterization methods were discussed in detail in Chapter 2.

3.2.2. Inoculum and substrates

The inoculum used in the experiments was obtained as an effluent from a running digester that co-digests industrial food waste with cow manure. As the effluent contains certain unused nutrients, it is necessary to pre-incubate the inoculum under anaerobic conditions to minimize the amount of biogas produced by these available nutrients during the experiment. The pre-incubation stage helps to deplete the residual biodegradable organic material in the effluent. The effluent was incubated in a BOD incubator for 7 days at 37^0C to obtain a degassed inoculum. After the pre-incubation step, the inoculum was analyzed for TS, VS, and pH. The primary substrate used in this study was mixed cafeteria food waste. Food scraps were obtained from the university dining hall and contained 50% by weight of pre- and post-consumer wastes. The mixed food waste was weighed and ground using a blender (Vitamix) to a particle size sufficiently small to pass through a 2 mm sieve. The co-substrates studied in this work were acid whey, energy drinks, waste bread, paper napkins and cow manure. The substrates were chosen based on local generation quantities and local digester operations. There are several cheese and yogurt manufacturing plants in upstate NY that generate large quantities of acid whey (based on discussions with digester operators and food processing industry representatives). The energy drink was chosen based on a local digester that revealed large quantities of this waste being sent to the digesters (~40-80 tons/week, based on personal communication with a hauler). Cow manure was used as a control substrate. Paper napkins and bread were chosen due to their higher carbon content that was assumed to help balance the carbon-to-nitrogen ratio during food waste digestion. Acid whey was obtained from a local cheese manufacturer and stored at 4^0C in several small vials to avoid repeated thawing. A local digester provided the energy drink cartons; this digester co-processes large volume of caffeinated drinks with cow manure and vegetable waste. The packaged food and drinks contribute to a significant amount of the food sector waste processed by digesters in upstate New York. Week-old store-bought white bread was used to simulate the waste bread. The bread was cut into small pieces and dried at 75^{0}C for 6 hours and powdered for long-term storage. Paper napkins used in this study were unsoiled Tork H1 ® white paper towels. Paper towels were milled to 2-4 mm particle size before using in experiments. Cow manure was obtained from a local farm-based digester and stored in several small containers in the refrigerator. Vegetable waste (VW), in an independent experiment, was prepared by grinding only pre-consumer vegetable waste from the cafeteria.

3.2.3. Reactor start-up

A total of 6 reactors were used in this study, each with 2.2 L total volume and 1.8 L working volume. Six reactors were used in a standard configuration as provided by Bioprocess Control (Lund, Sweden), and connected to the Automated Methane Potential Test System (AMPTSII). The AMPTSII system continuously measures biomethane production and is designed to work in a semi-continuous mode, with manual feeding at discrete time intervals. During the start-up, the reactors were filled with 1.8L of pre-incubated inoculum. The reactors were purged with nitrogen gas to create anaerobic conditions before start-up. All the reactor outlets were connected to the AMPTSII detector system. A gas sampling T-valve with a self-closing septum was connected between each reactor outlet and detector to obtain biogas samples for daily compositional analysis. The volume of the biogas withdrawn for sample analysis was ignored when calculating total daily biogas production. A 30-day hydraulic retention time (HRT) was maintained for all experiments, and the influent and effluent flow rates were adjusted manually at 60 mL d^{-1}. All the reactors were incubated at 37±2^{0}C in a water bath incubator. The digester contents were mixed using a built-in stirrer shaft rotating at 160 rpm with 10 sec 'ON' and 50 sec 'OFF' cycles. During the first 14 days of the startup phase, all the reactors were fed with FS at an organic loading rate (OLR) of 0.5 gVSL^{-1}d^{-1}. On the 15th day, the OLR was increased to 1.4 gVSL^{-1}d^{-1} and maintained at this level until 45 days had elapsed. The experiments conducted to test the effect of OLR started after the 45-day start-up phase. The HRT was kept constant throughout the experiment period. As the feeding and effluent withdrawal were carried out manually, exact volumes of the feed and effluent were recorded. The reactor working volume was calculated on a daily basis accordingly, to account for any error in feeding and withdrawal of reactor contents.

3.2.4. Semi-continuous anaerobic digestion experiments

The OLR ranged from 1.4 $gVSL^{-1}d^{-1}$ to 5.5 $gVSL^{-1}d^{-1}$ after the startup phase described above. The starting OLR was chosen based on personal communications with operation personnel and data analysis from a local digester. From analysis over 93 days of digester operation processing approximately 30% food waste with 70% cow manure, the median and mean values of OLR were 1.5 $gVSL^{-1}d^{-1}$ (see Appendix 3, Table A3.8). Therefore, OLR of 1.5 $gVSL^{-1}d^{-1}$ was chosen as the starting point, although the reported starting OLR value of 1.4 $gVSL^{-1}d^{-1}$ in this studywas due to sample preparation errors associated with manual weighing and feedin. OLR was increased at regular intervals for further experiments to study the effect on reactor stability through measurements of pH, total volatile acids, biogas production rate, etc. In the first reactor (R1), the ground FS was diluted with tap water to attain the required OLR. The pH and mineral composition of tap water were not accounted for in calculating the feed composition. In the second reactor (R2) containing FS: AW mix, acid whey was used instead of water, however, VS content of AW was adjusted for calculating OLR. The third reactor (R3) contained a mixture of FS and ED. As the ED contains negligible VS, it was directly used to dilute the FS to the required OLR instead of water. The nomenclature for each reactor and corresponding co-substrates are listed in Table 3.2. The FS to co-substrate ratios for WB (R4), PN (R5), and CM (R6) were chosen based on a pre-optimization study, conducted soon after the startup phase. In this pre-optimization work, all the reactors were maintained at 1.4 $gVSL^{-1}d^{-1}$, and different combinations of test mixtures were studied for biogas production, each observed for 7 days. Based on these results, FS co-digestion with 10±2% WB, 70% CM and 5-8% PN by weight were selected to investigate further the effect of increasing OLR; see Appendix 3 (Table A3.2). Each of the four combinations of substrate and co-substrate was studied for seven days. The combinations of substrates and co-substrates were fed every 24 hours according to the experimental design presented in Table A3.3. These experiments continued for approximately 100 days, including the time required for recovery of the FS-only reactor after failure. Slight variations in daily HRTs due to sample preparation error are reported in Table A3.4.

Table 3.2 - The co-substrates mixes used in each reactor

Reactor	Substrate	Co-substrate
R1	Food scraps (FS)	None
R2	Food scraps (FS)	Acid whey (AW)
R3	Food scraps (FS)	Energy drink (ED)
R4	Food scraps (FS)	Waste bread (WB)
R5	Food scraps (FS)	Paper napkins (PN)
R6	Food scraps (FS)	Cow manure (CW)

3.2.5. Process monitoring

The effluent from the digesters was monitored on a regular basis for several process parameters. The biogas production, biogas composition (methane, carbon dioxide, and hydrogen sulfide) and pH were measured daily. The biogas volumes were measured through the in-line detectors of the AMPTSII system. The total and volatile solids, total volatile acids, alkalinity, ammoniacal nitrogen, and COD were measured 3 to 4 times at each OLR. Methane (CH_4) and carbon dioxide (CO_2) content of the biogas were measured using a gas chromatograph (Shimadzu 2014 GC) equipped with a Hayesep Q column with 4 m x 2.1 mm analysis column with a thermal conductivity detector for routine biogas analysis. Helium was used as carrier gas at a flow rate of 40 mL min^{-1}. The temperatures of the injector, column and detector were 120, 70 and 200^0C, respectively. Hydrogen sulfide was measured in parts per million (ppm) using a portable gas measurement device (Sewerin Multitec 540). The meter could detect only up to 2000 ppm, and any H_2S concentration above the detection limit was reported as '>2000 ppm'. The pH of the effluent was measured using a Mettler Toledo Seven compact pH/ion meter. The effluent was centrifuged at 8000 rpm for 20 mins to separate the solids from liquids. The liquid part of the effluent was analyzed using standard assay kits from Hach for total volatile acids (TNTplus 872, method 10240), total alkalinity (TNTplus 870, method 10839), and total ammoniacal nitrogen (N tube vials, method 10031). The unseparated effluent was used in COD analysis (HR Plus, method 8000).

3.3. Results and Discussion

Selected characteristics of the food scraps used in this study are listed in Table 3.3. All the other characteristics of food scraps as well as co-substrates were discussed in detail in Chapter 2 (Tables 2.2 and 2.7)

Table 3.3 - Characteristics of food scraps used in the study

Physical and chemical properties, n=5	
pH	3.5±0.3
TS, %	23.8±2.9
VS/TS, %	90.9±2.4
VS, %	22.9±1.2
COD, kg/L	197±42
ash, %	1.8±0.8

Figure 3.1 shows the average pH of each reactor at different OLRs. In R1, the daily pH dropped to 6.2 on the seventh day from an initial pH of 7.3 at OLR of 4.4 $gVSL^{-1}d^{-1}$. The pH drop caused reactor failure and led to an excessive CO_2 fraction in the produced biogas. The reactors with acid whey, waste bread, energy drinks and cow manure as co-substrates maintained the daily pH between 7.3 and 7.5 throughout the experimental duration. There were no major issues with process stability with these co-substrates. With paper napkins as the co-substrate, the reactor pH varied between 6.8 and 7.3 at different OLRs. However, pH variation was minimal at each OLR, indicating a steady process. If the pH drops below 6.8, it is advised to reduce the OLR as lower pH values correspond to VFA accumulation that implies the reactor is undersized for a given OLR. Analyzed at discrete time intervals, the pH of all the digesters reduced by 0.2 to 0.3 units immediately after feeding and recovered within 2 hours.

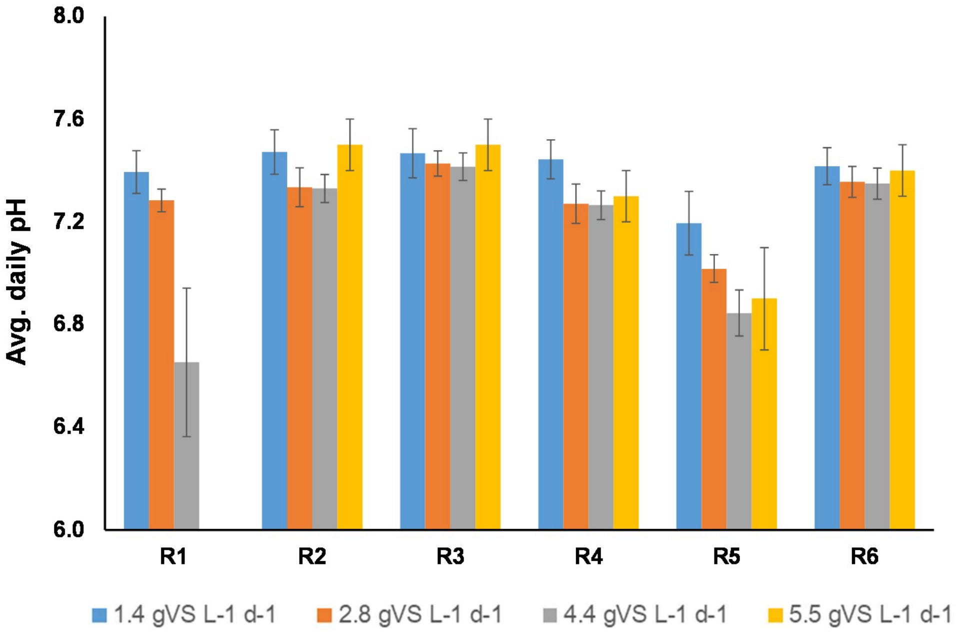

Figure 3.1 - Average of daily pH at different OLRs; For R1, the results above 4.2 gVSL^{-1}d^{-1} (yellow bar) is not shown for R1 due to a reactor failure at this OLR

At OLR of 4.4 gVSL^{-1}d^{-1}, R1 reached a total VFA concentration of 3375 mg (CH_3COOH) L^{-1} on the 7th day, where the reactor produced less than half of the daily methane, leading to reactor failure. Therefore, the OLR of FS reactor was reduced to 3.5 gVSL^{-1}d^{-1} for further experiments after an initial pH adjustment; however, a high average VFA concentration of 2288 mg (CH_3COOH) L^{-1} at this OLR indicated reactor overload. Therefore, it is recommended to keep the OLR between 1.4 and 2.8 gVSL^{-1}d^{-1} to anaerobically digest the FS without any co-substrates. The other reactors (R2 - R6) maintained an acceptable VFA concentration at 4.4 gVSL^{-1}d^{-1}, ranging between 508 and 818 mg (CH_3COOH) L^{-1}. When the OLR was increased further to 5.5 gVSL^{-1}d^{-1}, only R2 had a VFA concentration lower than 600 gVSL^{-1}d^{-1}, whereas all the other reactors had VFAs ranging between 1087 and 1307 mg (CH_3COOH) L^{-1}. These results (Figure 3.2) indicate that acid whey is a viable non-manure substrate to co-digest FS at high OLR where it is not convenient to haul manure, for example in institutional applications such as hospitals and universities. Acid whey is rich in minerals like Ca^{2+} and Na^{+} which act as co-factors for enzyme catalysis, hence improving the synergism. Co-digesting FS with cow manure is well known to help maintain process stability. In this work, non-manure based substrates also contributed to achieving process stability, higher methane production, and better waste conversion efficiency. While the existing literature is ambiguous on acceptable levels of VFA, a total VFA concentration of below

800 mg (CH_3COOH) L^{-1} at all times would be recommended to maintain optimum digester operation.

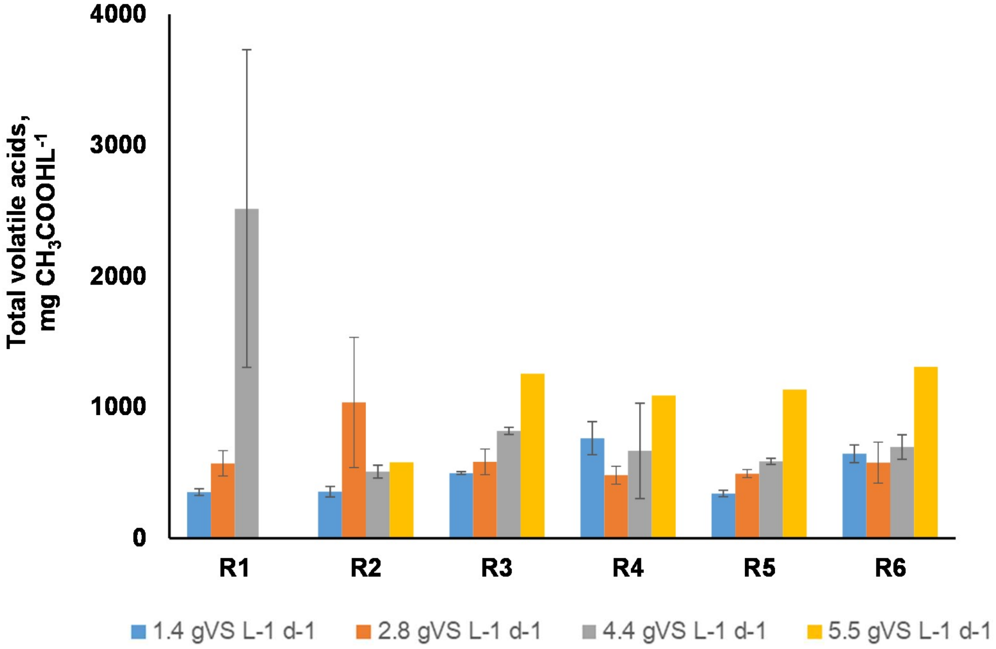

Figure 3.2- Average of total volatile acid concentration in mg (CH_3COOH) L^{-1} at different OLRs; For R1, the results above 4.4 $gVSL^{-1}d^{-1}$ (yellow bar) is not shown for R1 due to a reactor failure at this OLR

The average alkalinity levels of each reactor are shown in Figure 3.3 for different OLRs. When R1 failed to produce methane at higher OLR, it had alkalinity of 2488 mg $CaCO_3$ L^{-1}. At lower OLRs, the alkalinity ranged between 3700 and 4200 mg $CaCO_3$ L^{-1}, which is lower than that observed in manure digesters; however, there were no observed instability issues. For other digesters with co-substrates, the alkalinity levels ranged between 4324 and 7307 mg $CaCO_3$ L^{-1}. At alkalinity levels above 6500 mg $CaCO_3$ L^{-1}, the reactors did not perform well concerning methane production even though there was no observed reactor failure. Methane production did not increase significantly in R2 and R3 and reduced in R4, R5, and R6. It is essential to maintain an acceptable VFA to alkalinity ratio (V/A) during digester operation. Municipal digesters typically operate at a V/A ratio below 0.3.[21] The FS reactor had a V/A of 1 when it failed. In R4

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[21] Aquafix, Anaerobic digester upset and troubleshooting, https://teamaquafix.com/anaerobic-digester-upset-troubleshooting/

and R5, the methane production rate was reduced when V/A reached a value of 0.3. The other reactors R2, R3, and R6 maintained acceptable V/A at all times.

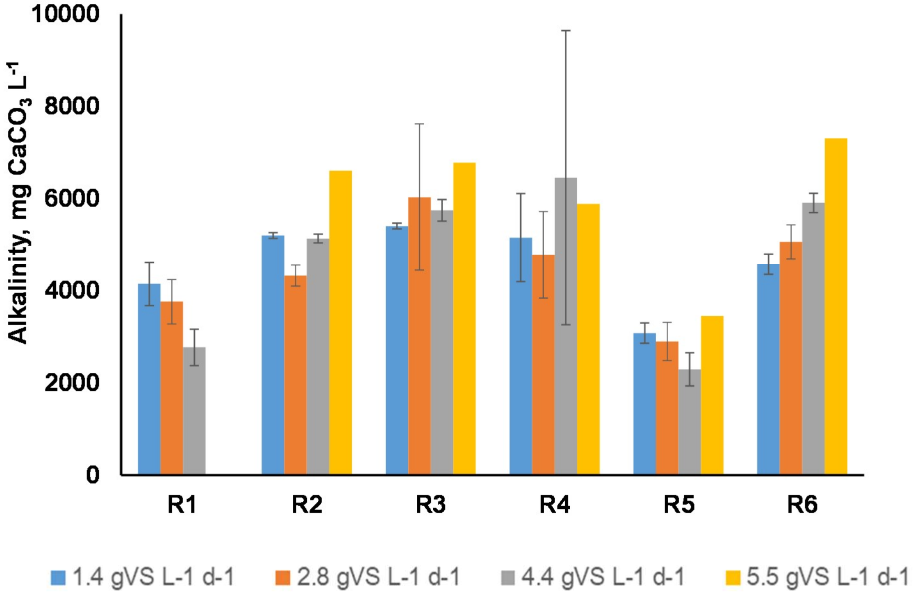

Figure 3.3- Average of total alkalinity in mg $CaCO_3$ L^{-1} at different OLRs; For R1, the results above 4.2 $gVSL^{-1}d^{-1}$ (yellow bar) is not shown for R1 due to a reactor failure at this OLR

The NH_3-N concentration throughout the experimental duration varied from 368 to 1132 mg L^{-1} in all the reactors, as shown in Figure 3.4. Ammoniacal nitrogen levels did not change significantly in any reactor, even at higher OLRs, and remained relatively stable throughout the experimental period. In a review article [117], it was reported that a broad range of ammoniacal nitrogen concentrations are inhibitory, ranging from 1700 mg L^{-1} to 15,000 mg L^{-1}. Methanogens can acclimate to increasing ammonia concentration with time. Therefore, it was difficult to recommend a safe operating zone for ammonia during biogas production.

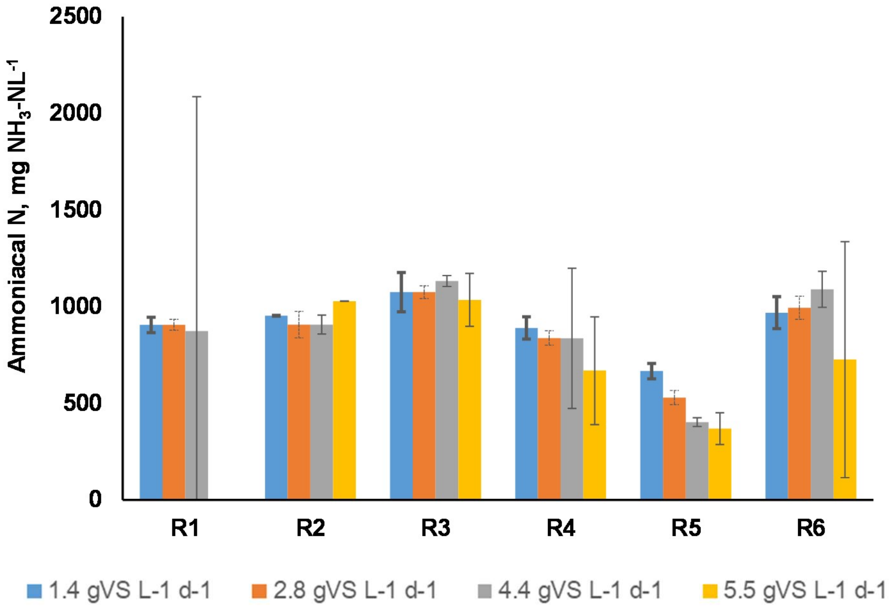

Figure 3.4- Average of total ammoniacal nitrogen in mg NH_3-N L^{-1} at different OLRs; For R1, the results above 4.2 $gVSL^{-1}d^{-1}$ (yellow bar) is not shown for R1 due to a reactor failure at this OLR

Biogas production is by far the most critical parameter to monitor in anaerobic digestion. Measuring the biogas production on a daily basis helps to identify any stability issues arising during the process. Biogas contains two main components, methane and carbon dioxide. Small amounts of hydrogen sulfide, ammonia, nitrogen, and hydrogen are also present in biogas. In a well-controlled digester, the methane percentage of biogas varies between 55% and 65%. In a continuously fed digester at steady-state, daily biogas composition should remain constant over time. Methane content below 55%, or CO_2 content above 35-40%, indicate VFA accumulation and inhibition in the activity of methanogens. Methane, which is a result of volatile solids destruction, is the final product of the anaerobic digestion pathway, suggesting that higher methane production indicates better waste processing efficiency of the digester. The average daily biogas production rate and methane and carbon dioxide composition of biogas are shown in Figure 3.5 through 3.7. In R1, the average methane level reached a high of 62% at 2.8 $gVSL^{-1}d^{-1}$. The methane level was reduced to 44% at 4.4 $gVSL^{-1}d^{-1}$, indicating a need to stop feeding and let the reactor stabilize for several days to attain a normal methane production level. In R2, the methane level reached as high as 71% at 4.4 $gVSL^{-1}d^{-1}$ with a daily average of 66%, and this reactor maintained higher than 62% methane at any given time during the study period.

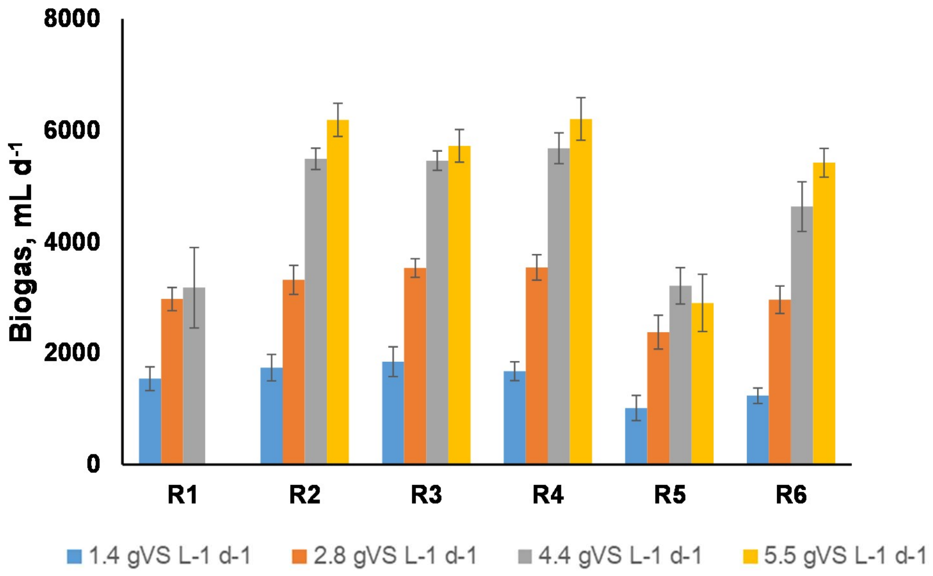

Figure 3.5- Average of daily biogas production in mLd^{-1} at different OLRs; For R1, the results above 4.2 gVSL^{-1}d^{-1} (yellow bar) is not shown for R1 due to a reactor failure at this OLR

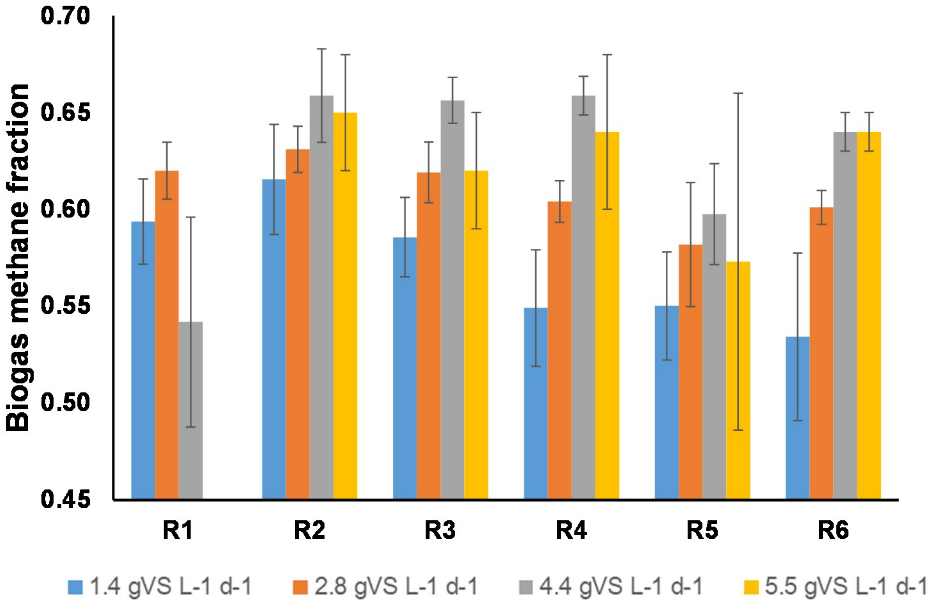

Figure 3.6- Average of daily methane fraction in biogas at different OLRs; For R1, the results above 4.2 gVSL^{-1}d^{-1} (yellow bar) is not shown for R1 due to a reactor failure at this OLR

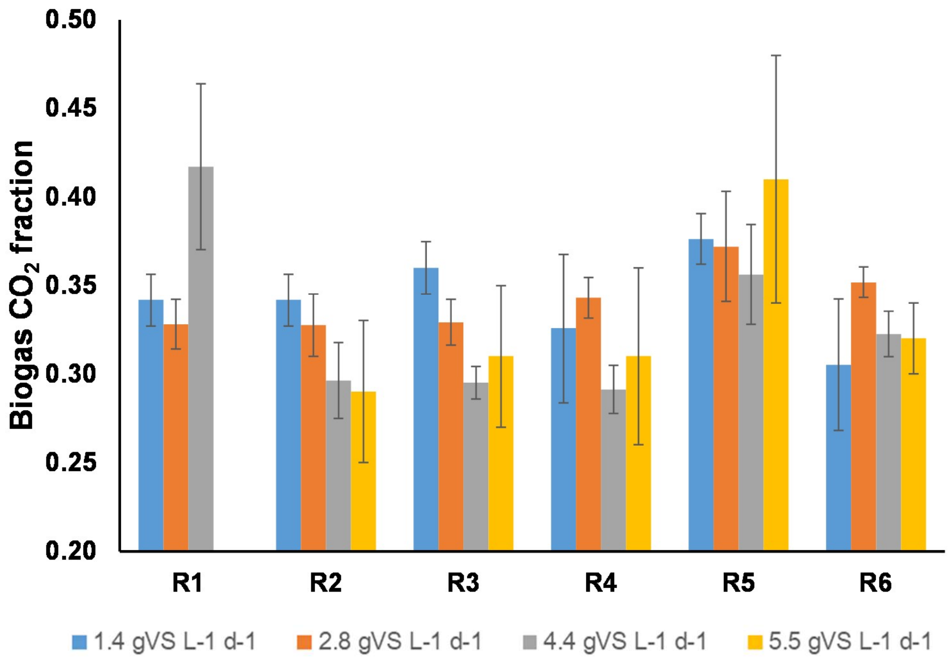

Figure 3.7- Average of daily CO_2 fraction in biogas at different OLRs; For R1, the results above 4.2 $gVSL^{-1}d^{-1}$ (yellow bar) is not shown for R1 due to a reactor failure at this OLR

In addition to methane, it is necessary to monitor the H_2S concentration of biogas. Though sulfides help in maintaining the alkalinity similar to ammonia, higher sulfide concentrations are toxic to methanogenic bacteria. Also, higher H_2S concentration in biogas demands additional infrastructure to purify biogas before its use. With ED as co-substrate, the biogas contained a high concentration of H_2S, even though it showed higher methane levels of 60 to 66%. The H_2S concentration was greater than 2000 ppm for the first three OLRs and reduced to 1194 ppm at 5.5 $gVSL^{-1}d^{-1}$ as shown in Figure 3.8. The higher H_2S levels with this co-substrate may be attributed to the presence of taurine in energy drinks. Taurine, or 2-aminoethanesulfonic acid, acts as a source of sulfur for anaerobic bacteria. These microbes dissimilate taurine to produce sulfite, which is a nutrient source. The microbes then carry out sulfite respiration through sulfate reductase enzyme and sulfides are excreted out of the cells [270]. Sulfide, excreted as hydrogen sulfide gas, makes a major component of biogas. The energy drink also contains caffeine that is a well-known stimulant of biogas production [271]. Therefore, it is important to characterize the feedstocks for the presence of specific substrates that may cause unusual problems even after being stimulatory to biogas production. The average daily H_2S concentrations ranged from 78 to 83 ppm for R2, 82 to 326 ppm for R4, 91 to 391 for R5 and 139 to 810 ppm for R6. The H_2S levels of R2, R4, and R5 were significantly lower than R6. Daily average biogas production was higher with acid whey and waste bread compared to cow manure as a co-substrate. Therefore, acid whey and waste bread can potentially make better co-substrates than cow manure for FS digestion.

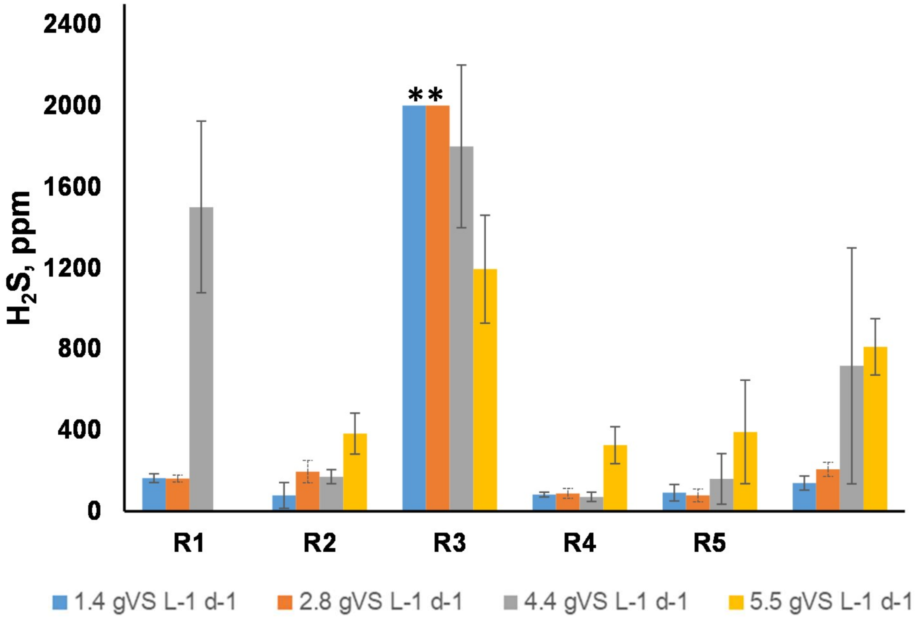

Figure 3.8- Average of daily concentration of hydrogen sulfide (ppm) in biogas at different OLRs; For R1, the results above 4.2 gVSL^{-1}d^{-1} (yellow bar) is not shown for R1 due to a reactor failure at this OLR; * the instrument reached a limit of detection of 2000ppm

Specific methane yield is the volume of the methane produced per gram of the volatile solids added per day. Figure 3.9 shows the average methane production rate and Figure 3.10 depicts the SMYs of different reactors at each given OLR. The SMY relates to the extent of biodegradability of each substrate. Babaee and Shayegan (2011) investigated the effect of OLR on vegetable waste digestion in a pilot-scale reactor operating at steady-state [272]. They suggested an OLR of 1.4 gVSL^{-1}d^{-1} as the design criterion, with an SMY of 250 mL gVS^{-1} d^{-1}. Their results also recommended an OLR of 1.4 gVSL^{-1}d^{-1} for vegetable waste digested in semi-continuous mode, as elevated VFA concentration was observed at higher OLR. Vegetable waste had an SMY of 198±48 mL gVS^{-1}d^{-1} when mixed continuously, and 350±90 mL gVS^{-1}d^{-1} with intermittent mixing in an independent experiment (not included in the graphs; see Table A3.6. Specific methane yield is subjected to waste composition and process conditions. An OLR limit of 1.5 gVSL^{-1}d^{-1} was suggested in a previous study for mixed food waste digestion without any co-substrates, yielding an SMY of 371 mL gVS^{-1} d^{-1} [273]. In FS digestion without any co-substrates, observed SMY was 352±46 mL gVS^{-1}d^{-1} at 1.4 gVSL^{-1}d^{-1} and 363±28 mL gVS^{-1}d^{-1} at 2.8 gVSL^{-1}d^{-1} with all the other process parameters within the acceptable range. Therefore, if FS has to be digested alone, it is recommended to keep the OLR below 2.8 gVSL^{-1}d^{-1}, preferably between 1.5 and 2.0 gVSL^{-1}d^{-1}. Food waste digestion at considerably higher OLR of up to 5.6 gVSL^{-1}d^{-1}was achieved using particular strategies like lipid removal [274] and thermophilic digestion [273]. In the present study, it was possible to digest food waste at high OLRs using the previously identified unconventional co-substrates. With paper napkins as the co-substrate, a maximum SMY of 381±30 mLgVS^{-1}d^{-1} was observed at 2.8 gVSL^{-1}d^{-1}. The reactors R2, R3, R4 and R6 showed maximum SMYs of 455±31, 453±20, 479±29 and 372±41 mL gVS^{-1}d^{-1}, respectively, at OLR of 4.4 gVSL^{-1}d^{-1} with all other process parameters within acceptable ranges. Acid whey, energy drinks, and waste bread were the most efficient co-substrates with higher methane yield and lower VFA levels. The SMYs of all the reactors reduced significantly at 5.5 gVSL^{-1}d^{-1} compared to lower OLRs, indicating reactor overload. A higher SMY from all the co-digestion mixtures compared to FS indicated a synergistic relationship between FS and co-substrates. Reactors R2, R3, and R4 showed a higher observed SMY compared to R6 where cow manure was the co-substrate.

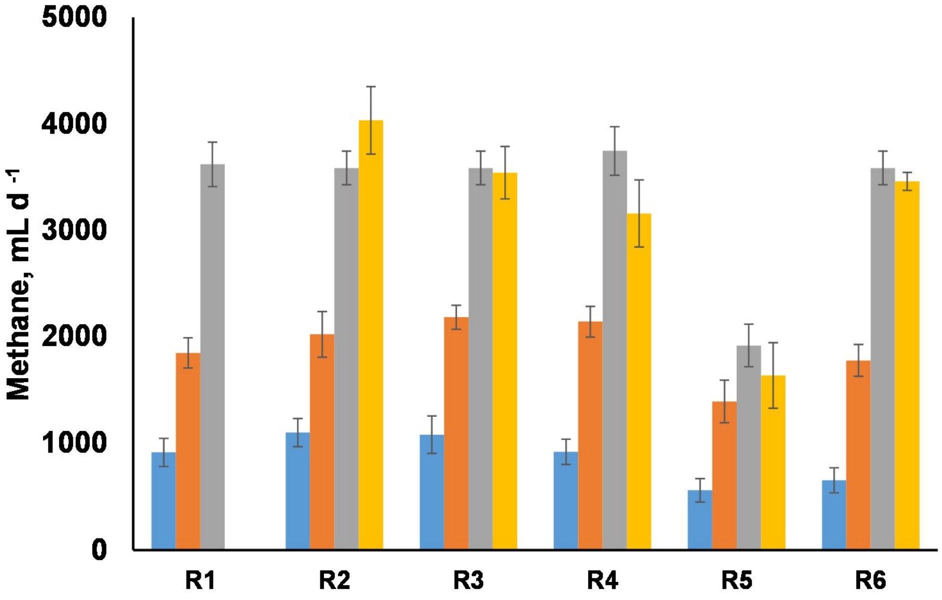

Figure 3.9- Average of daily methane production in mL at different OLRs; For R1, the results above 4.2 gVSL^{-1}d^{-1} (yellow bar) is not shown for R1 due to a reactor failure at this OLR

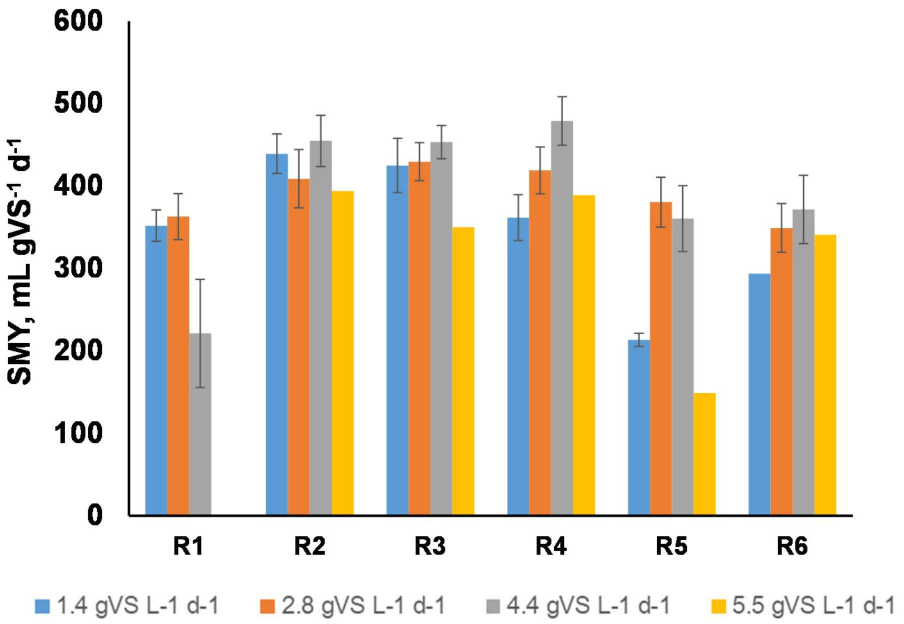

Figure 3.10- Average of daily SMY in mLCH4gVS^{-1} at different OLRs; For R1, the results above 4.2 gVSL^{-1}d^{-1} (yellow bar) is not shown for R1 due to a reactor failure at this OLR

Biogas productivity is an indicator of process stability and must be monitored on a regular basis. Reactors R2, R3 and R4 showed increasing productivities (Figure 3.11) with each increasing OLR up to 4.4 gVSL^{-1}d^{-1}, and productivity either reduced or remained the same at a loading of 5.5 gVSL^{-1}d^{-1}. No further increase in productivity emphasizes reactor overload, which implies that the OLR should be reduced for further operation. The productivity in R1 and R6 did not increase further after an OLR of 2.8 gVSL^{-1}d$^{-1,}$ and the productivity decreased in R5. Therefore it is suggested that the OLRs kept below 4.4 gVSL^{-1}d^{-1} when acid whey, bread, and energy drinks are used as co-substrates with FS, below 2.8 gVSL^{-1}d^{-1} when co-digesting FS with cow manure and paper napkins, and between 1.4-2 when digesting FS alone.

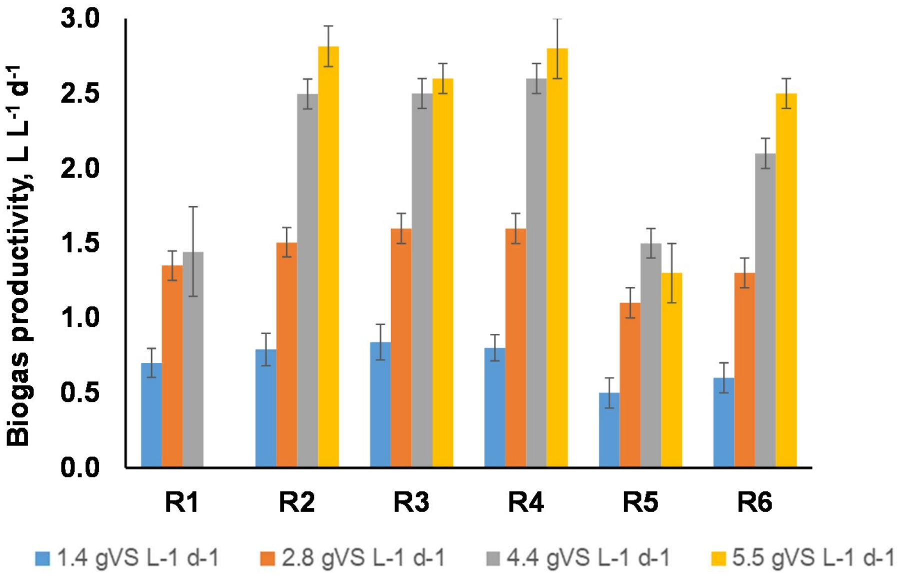

Figure 3.11- Average of daily biogas productivity in $LL^{-1}d^{-1}$ at different OLRs; For R1, the results above 4.2 $gVSL^{-1}d^{-1}$ (yellow bar) is not shown for R1 due to a reactor failure

The degradability or percent degradation signifies waste management efficiency because it is directly proportional to the amount of food waste converted into biogas. All the reactors had a lower biodegradability except for R5 at the highest OLR as indicated in Figure 3.12. A significant improvement in biodegradation from 1.4 to 2.8 $gVSL^{-1}d^{-1}$ was observed in all the reactors. However, at 4.4 $gVSL^{-1}d^{-1}$, only R2, R3, and R4 had significantly higher average COD removal. The COD removal reduced in all the reactors at 5.5 $gVSL^{-1}d^{-1}$.

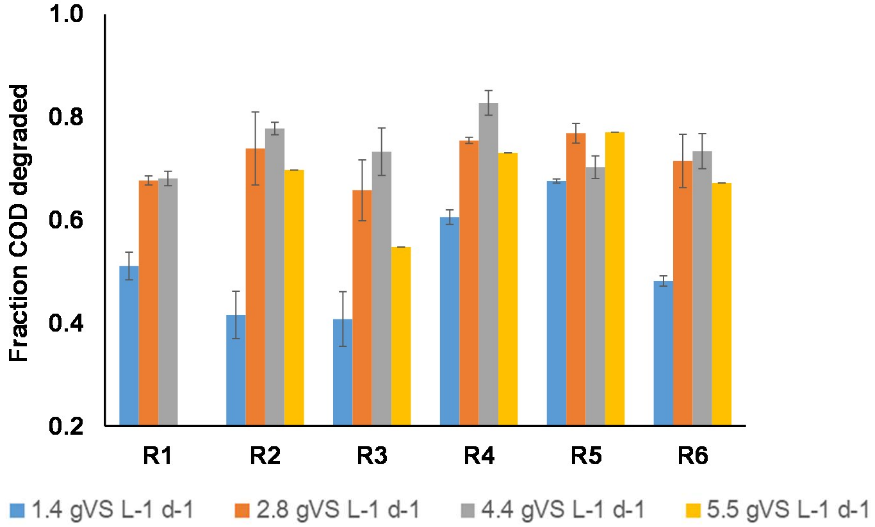

Figure 3.12- Average of fraction of COD degraded at different OLRs; For R1, the results above 4.2 $gVSL^{-1}d^{-1}$ (yellow bar) is not shown for R1 due to a reactor failure at this OLR

Based on all the above process monitoring data, the operating guidelines for 'food waste only' digestion were recommended. An OLR of 1.4 $gVSL^{-1}d^{-1}$ or lower should be maintained to when food scraps are the only feedstock and a higher OLR can be achieved when a suitable co-substrate is available. A volatile acid concentration of lower than 800 mg CH_3COOHL^{-1} is recommended and a pH of 7.2-7.8, slightly higher than conventional digestion, is necessary as the alkalinity of food waste is low and hence the pH changes are drastic. Alkalinity must be maintained around the same level as a conventional manure digestion at 5000 $mgCaCO_3L^{-1}$ [265]. A volatile acid to alkalinity ratio of above 0.35 resulted in a reactor failure and hence, calculating from the recommended volatile acid and alkalinity levels, it should be maintained below 0.16.

3.4.Conclusions

Use of unconventional co-substrates helped enhance anaerobic digestion of food waste at high organic loading rates. These co-substrates generally resulted in increased daily methane production, higher methane fraction in biogas, improved waste degradation, and process stability. Though pure food scrap digestion can be carried out at low organic loadings without much process instability, it is difficult to digest FS at high organic loading rates. Our results show a high level of volatile acid accumulation during FS digestion, indicating poor degradation. Digesting food scraps at low OLRs will need a larger reactor volume than conventional substrates for the same OLR, increasing upfront capital cost. The outcomes from this work have the following novel contributions:

- The operating guidelines for a 'food waste only' were recommended based on a long-term, experimental study with good reproducibility.

Table 3.4. "Food waste only" digestion safe operating parameters compared to standard municipal digester operation

Parameter	**Municipal Digester** [275]	**"Food waste only" digester**
Safe operating OLR, $gVSL^{-1}d^{-1}$	0.6 -1.6 [276]	1.5-4.5 food scraps with cosubstrates, 0.5-1.5 without cosubstrates
Volatile acids, mg CH_3COOH/L	50-500	<800
Alkalinity, mg $CaCO_3/L$	2000-3000	3500-6000
pH	6.5-7.5	7-8
Methane in biogas, %	50-60%	50-75%
VA/alkalinity	<0.25	<0.4

- The mechanism to achieve 'food waste only digestion' at higher organic loading rates, which otherwise would cause a process failure, were proposed and experimentally demonstrated.

In summary, it is generally not practical to build "food scrap only" digesters without improving stability to enable higher OLR. Our experiments show that, when food scraps are mixed with co-substrates like acid whey, waste bread, manure, caffeinated energy drink and paper napkins, the digestion process can be improved significantly, as well as biogas yield and biodegradability. In addition, co-digesting food waste with bread, acid whey and paper napkins have been shown to reduce ammonia and hydrogen sulfide emissions. Because of the synergistic effect offered by the co-substrates, the substrates are utilized more efficiently, leading to increased biodegradability. It is recommended to co-digest food scraps with more homogenous substrates that do not frequently change in their composition. Co-digestion has a beneficial impact on reducing the design volumes of reactors, making provisions for potentially treating large amounts of food waste.

Despite these contributions, it should be mentioned that this work was limited in the following aspects:

- Real-time digesters may process more than two food sector waste materials at the same time, in which case, the interaction between these wastes may vary.

- Since the experiments were carried out in semi-continuous mode with once daily feeding, at higher organic loading rates there is a possibility of nutrient shock soon after the feeding which could have affected some of the measured parameters like total volatile acids which is less likely in a real-time continuous digester with multiple feeding cycles in a day.

This project evaluated certain co-substrates that are generated in large amounts in New York State; the use of other potential co-substrates like waste cooking oil, grease trap waste and fruit and vegetable processing wastewater needs further evaluation. Co-digestion would, therefore, have beneficial impacts on reducing the digester volume, reducing the water footprint of anaerobic digestion processes, increasing the food waste management throughput and electricity production. The co-substrates suggested through this study may help in the deployment of decentralized digesters in settings where it is not practical to haul manure, for example in institutional or commercial installations such as hospitals, universities or restaurants.

CHAPTER 4

SCREENING OF FOOD WASTE RESOURCES FOR VALORIZATION VIA FERMENTATION

Abstract:

This chapter evaluates the applicability of fermentation in food waste management based on the yield of various products. While anaerobic digestion is versatile in converting various types of food wastes into biogas, fermentation is more versatile in the range of value added products that can be generated. Different food wastes originating from the institutional and industrial sector were screened for their suitability as feedstocks in the production of alcohols and organic acids. Through a combination of experimental measurements and analysis of data available in literature studies, institutional food wastes were found to be more suitable for fermentation than industrial food wastes. Moreover, based on the current status of research and development, ethanol is the only viable fuel product, and it is technologically challenging to produce fuels based on higher alcohols from food wastes at acceptable yields. A matrix was developed to qualitatively assess the possibility of producing ethanol, butanol, lactic acid and succinic acid from various food waste resources.

4.1. Introduction

Renewable fuels and chemicals have gained a priority because of increasing environmental concern associated with combustion of fossil fuels [16]. Alcohols are used as oxygenating blending components for gasoline, and ethanol is by far most commonly used. However, advanced biofuels like propanol, 1-butanol, and 3-methyl 1-butanol are receiving attention from alcohol producers. Ethanol is produced commercially using corn as the primary feedstock, and other feedstocks have not been widely used for large-scale ethanol production, except sugarcane molasses (primarily in Brazil). There is significant research and development efforts underway for large-scale production of butanol from lignocellulosic materials, though butanol has not yet been regulated as a fuel blend in the USA. There are limited efforts on using propanol as a fuel, possibly due to its high viscosity.

Though alcohol production from food processing waste (FPW) was explored first in the 1980s [109], [111], [277], [278], a continued research effort is required to reduce the production cost of higher alcohols and commercializing them. Food wastes are cheaper raw materials compared to all other substrates currently being used, including corn, lignocellulosic biomass, and molasses. While food waste can make a cheaper feedstock, the use of food waste in fermentation has not been completely understood as indicated by the primitive results of several research studies.

4.1.2. Literature review

The literature on conversion of food waste using fermentation has mainly concentrated around the utilization of household food scraps [61], [279] and starchy food wastes like bakery and potato wastes [102], [103]. A few industrial food wastes like cheese whey [104] and apple pomace [105], [106] were reported as suitable for ethanol production. Most research studies published used the four types of food wastes shown in Figure 4.1 with the purpose of general screening and improving the ethanol yield using pretreatment or product recovery techniques. Pretreatment methods are energy intensive as they make use of high pressure or temperature, grinding or milling, or acid hydrolysis processes [280]. Although some pretreatment methods have been shown to be technically viable, there is little known about their economic impact at commercial scale. Moreover, while some of the food wastes studied to date have proven to be promising for ethanol production, there is a need to screen a variety of waste materials originating from the food processing sector to firmly establish economic viability.

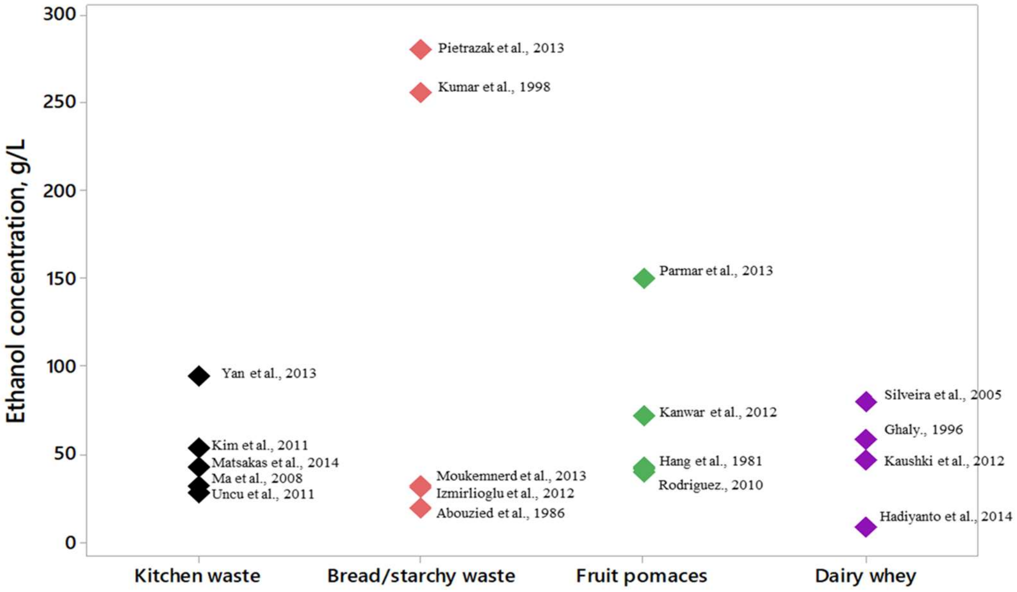

Figure 4.1 - Reported ethanol product concentrations from various food wastes

Butanol research has primarily been dedicated to using corn and lignocellulosic biomass as feedstocks since this product is still in its infancy as a fuel. Butanol is in many ways a superior fuel to ethanol, and currently classified as an advanced biofuel under the Renewable Fuel Standard[22]. Few research groups reported the possibilities of producing 1-butanol from bakery waste [66], agricultural wastes [107], domestic organic waste [108], apple pomace [109] and crude whey [16], with or without nutrient supplements. Two publications reported the production of iso-butanol from cheese whey permeate [110] and apple pomace [111]. Succinic acid and lactic acid are the organic acids that have a wide range of application as food additives [76], pharmaceutical components [281] and monomers of bioplastics synthesis [282]. The bioplastics synthesis from these organic acids is of particular importance to food waste management because the adaptation rate of bioplastics in food packaging is growing at a steady rate [283]. Use of bioplastics produced from food waste back in food packaging is a sustainable option to close the nutrient cycle loop as bioplastics can be further degraded along with food waste once they reach the end of life. Therefore, in addition to the products screened via experiments, the possibility of producing succinic acid and lactic acid were evaluated.

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[22] Biobutanol. Alternative Fuel Data Center (AFDC). https://www.afdc.energy.gov/fuels/emerging_biobutanol.html

4.1.3. Scope of work

Owing to the limited literature available on using fermentation as a food waste management technology, following research gaps were identified.

- Screening of various food wastes as feedstocks and resulting products of fermentation, as there was no clear understanding of the various options for valorization via fermentation
- Compilation of the inconsistent information available on food waste fermentation was necessary to understand the "state-of-the-art" for using fermentation as a food waste management option.

The evaluation was purely on the basis of the product concentration expressed as g/L which indicates the amount of the product produced in the aqueous fermentation broth. Higher product concentration is essential as purification involves series of unit operations- cell separation, concentration/filtration, separation and dehydration that account for more than 60% of the production cost[284]. As the application of fermentation in food waste management is not a common practice, the technical evaluation of value-added products is an essential factor to consider. A lower concentration of the product indicates that it is in it diluted form in the aqueous medium of the fermentation reactor which calls for a further need to install additional infrastructure required to concentrate the product to a level minimum required for efficient purification[285]. Therefore, before moving on to the economic and policy evaluation for the use of fermentation as a food waste management option, a detailed understanding of the technical feasibility of using fermentation as a valorization method must be available. In this work, a preliminary screening of various industrial food wastes as feedstocks for production of a spectrum of products, including ethanol, 1-butanol, isobutanol, propanol and organic acids, through a co-fermentation approach was carried out and complemented by an extensive review of the literature. Based on the data analysis, a metric was developed for a qualitative evaluation of fermentation technology to produce ethanol, butanol, lactic acid and succinic acid from various food wastes.

4.2. Methods

Though this chapter highly focuses on review and analysis of published information, several experiments were conducted to support, validate and expand the data available in the literature. This section explains the methodology used in in-house laboratory experiments and the analysis of the relevant literature data.

4.2.1. Microorganisms and culture conditions

Two yeast strains, *Saccharomyces cerevisiae* var. *ellipsoides and Kluyveromyces marxianus* NRRLB1175 were used in the study to produce ethanol and 3-methyl 1-butanol from FPWs. The inoculum was prepared in Yeast extract-Peptone-Dextrose (YPD) broth containing 1% glucose. The inoculum flasks were incubated at 30^0C for 24 hours before they were used in production. A 10% v/v culture broth was used as inoculum to begin the production culture. *Clostridium acetobutylicum* ATCC 4259 was used to study the production of 1-butanol. The inoculum was prepared in Reinforced Clostridial Medium (RCM) and the cultures were incubated at 37^0C for 36-48 hours before they were used in the production medium.

4.2.2. Preparation of substrates

Effluent from local industrial cheese and tofu processing and waste pomace from fruit and vegetable processing were used as production media. The apple pomace and tomato pomace were prepared in the laboratory by using simulated conditions. To prepare apple pomace samples, the apples were washed, weighed, cut into small pieces, and then reduced to a fine paste using a Vitamix blender with a predefined amount of water. This preparation was strained using cheesecloth to separate juice from the pomace. The retentate from cheesecloth was used as apple pomace in the experiments. Tomatoes were washed, blanched in boiling water for 10 minutes, pureed and strained using cheesecloth to separate the sauce. The retentate from cheesecloth contained tomato pomace that mainly included the peel, seeds and part of the pulp. Both apple and tomato pomace were stored at -20^0C until they were used in the experiments.

4.2.3. Production media and fermentation conditions

Apple and tomato pomace solids were re-suspended in tofu wastewater to form 10%w/v slurry for ethanol fermentation. Apple and tomato pomace hydrolysate were supplemented with 1%w/v yeast extract as a nitrogen source for Acetone-Butanol-Ethanol (ABE) fermentation. Cheese whey, yogurt whey, and tofu processing wastewater were used with no supplementation. Use of tofu wastewater for deionized water in pomace media not only provides the required water, but also includes essential nutrients for the growth of microbes. Because these waste materials are all available in large volumes within close proximity to the RIT campus, combining them as a single waste-to-alcohol feedstock was a reasonable option to consider.

Ethanol production potential was tested using 250 mL Erlenmeyer flasks with 50 mL production medium. The flasks were incubated at 30^0C with a shaking speed of 130 rpm. Initial pH was adjusted to 5.5±0.2. Sampling was performed intermittently to test ethanol production. The samples were centrifuged at 12,000 rpm for 15 minutes to remove the cells and sediments from food waste media. The supernatants were stored at -20^0C until used for analysis.

ABE fermentation was carried out in 125 mL serum bottles with 50 mL working volume. Strict anaerobic condition was maintained by using an anaerobic chamber to conduct inoculation and sampling. The serum bottles were secured after inoculation with an aluminum crimp and incubated at 37^0C under static conditions. Initial pH was adjusted to 6.5±0.2. Sterile hypodermal needles were used to extract samples from the serum bottles. The samples were centrifuged at 12,000 rpm for 15 minutes to separate the cells and sediments from the broth. The supernatants were stored at -20^0C until they were used for analysis.

4.2.4. Analysis of alcohols

Shimadzu Ultra Flow Liquid Chromatography (UFLC) with an autosampler and refractive index detector was used in the analysis of alcohols and organic acids. A Phenomenex ROA^{TM}-organic acid-H^+ column was used with deionized water as mobile phase at a flow rate of 0.6 mL/min. The detection was facilitated using a refractive index detector. The column was capable of analyzing alcohols in combination with organic acids and some sugars like glucose and lactose. This method separated ethanol, propanol, 1-butanol, 3 methyl 1-butanol, acetic acid, butyric acid and lactic acids into distinct chromatograph peaks. The same method was used to analyze free sugars before and after fermentation.

4.2.5. Analysis of carbohydrates and proteins

Total carbohydrates were analyzed using the phenol-sulfuric acid method [286] and reducing sugars were estimated using Dinitro salicylic acid assay. The liquid effluents were used in the assay after appropriate dilution. Apple and tomato pomace hydrolysate was prepared by suspending 10% w/v of the pomaces in 2%v/v sulfuric acid. This suspension was autoclaved for 20 mins at 121^0C and 100 kPa. The resulting solution was filtered and then used in total sugar and reducing sugar analyses after pH adjustment. After appropriate dilution, soluble proteins in the liquid effluents were measured using Bradford's protein assay kit from Biorad.

4.2.6. Qualitative feasibility matrix

As mentioned earlier, product concentration is a critical factor that decides the cost of production. Even though it is a standard practice in bioprocess engineering to normalize the product content to glucose or carbon content of the production media, this metric will not provide a good insight into the economics of purification. Therefore, for every food waste for which the data was available, a score was developed by normalizing the reported product concentration to the minimum required concentration to attain an economically break even or efficient process. An ethanol concentration of 42gL^{-1} based on sugarcane as the feedstock [287] was chosen as a reference, and a conservative estimate of 50 gL^{-1} was used in calculations. As ethanol yield from corn is exceptionally high, it could not be used as the reference when evaluating low-grade feedstocks like food waste. Sugarcane, on the other hand, requires nominal pretreatment and a primary feedstock used for ethanol production in developing countries [287]. The product concentration of 20 gL^{-1} for butanol [288], 55 gL^{-1} for lactic acid [285] and 56.2gL^{-1} for succinic acid [289] were chosen based on the studies that focused on the technoeconomic evaluation of these products. After the normalization, a heat table was developed to qualitatively screen various food wastes for the production of above-stated products.

4.3. Results and discussions

4.3.1. Ethanol

Out of approximately 30 experiments used in screening of food wastes with the possibility to produce ethanol, only 5 experiments yielded the best results. The experiments involved variations of food waste and nitrogen source combinations, inoculum concentration and the addition of external carbon source like waste glycerol from a biodiesel process. Ethanol product concentrations from the highest yielding experiments are shown in Figure 4.2 along with available literature data. From the experimental and literature data, it is clear that the ethanol concentration does not exceed 5-6% unless a product recovery or an efficient pretreatment method is employed.

The ethanol concentration in fermentation broth was 12.9 gL^{-1} for tofu wastewater, 29.8 gL^{-1} for Greek yogurt whey, 26.5 gL^{-1} for cheese whey, 1.3 gL^{-1} for tomato pomace and 2.5 gL^{-1} for apple pomace. The ethanol concentration from cheese whey, using *Kluyuveromyces marxianus* was significantly higher than a previously reported 8 gL^{-1}[290]. However, with an appropriate upstream concentration step to increase the lactose concentration in whey, proper choice of microorganism couple with an *in situ* product recovery, ethanol concentration of upto of 120 gL^{-1} can be obtained [291]. Ethanol concentration reached 20.9 gL^{-1} whey tofu wastewater was supplemented with 2% glycerol which indicated that, when a cheaper carbon source like glycerol is available, tofu wastewater can make a complete medium to support microbial growth. There were no known publications on the use of Greek yogurt whey and tomato pomace for ethanol production. In case of apple and tomato pomace, the reduced yield obtained were possibly because of inefficient pretreatment and hence there were no sufficient reducing sugars available to form the product. The ethanol yield from various food wastes is given in Figure 4.2. The process conditions, microorganism and type of pretreatment methods used for these studies are given in Appendix 4.1.

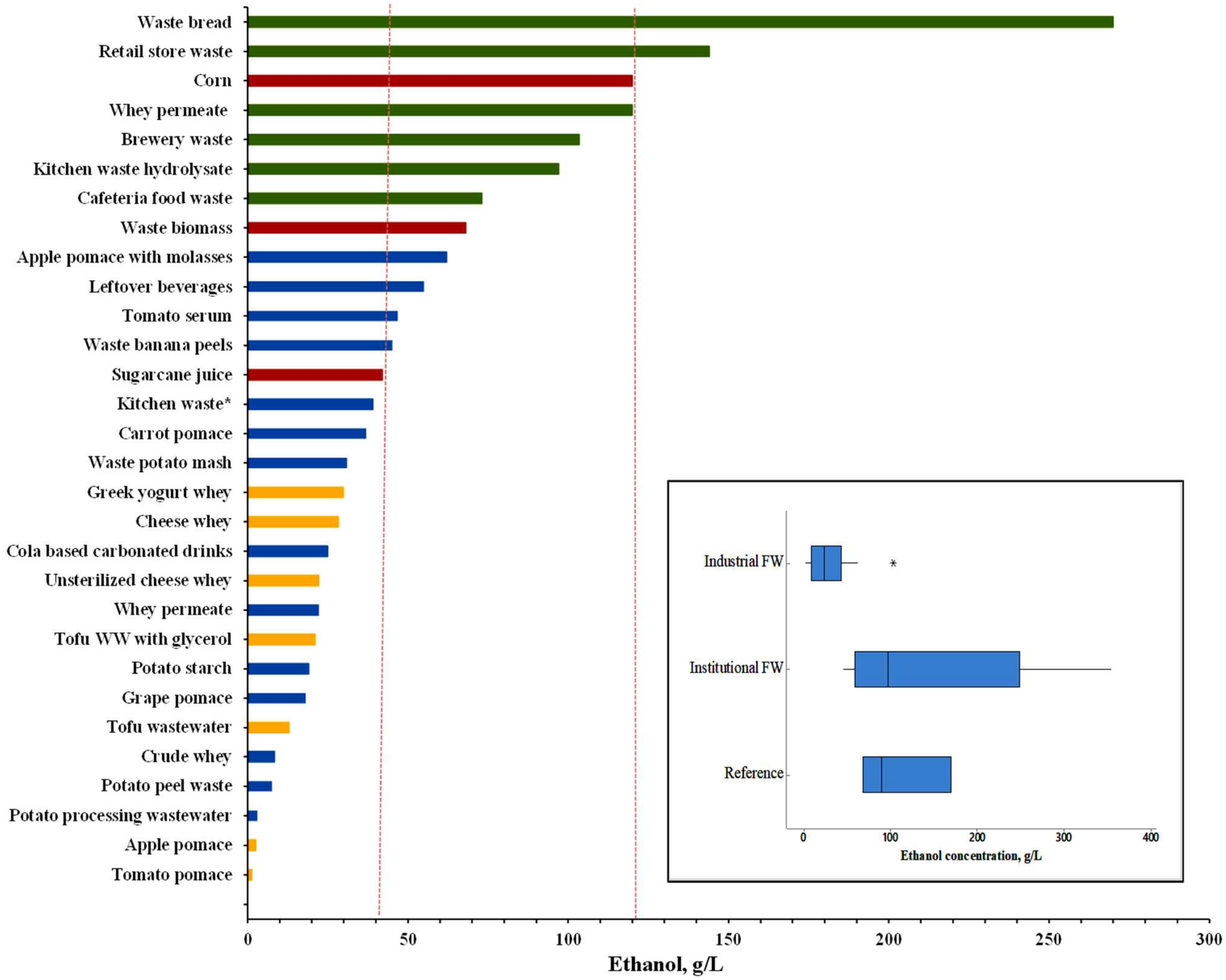

Figure 4.2- Ethanol concentration in g/L (i.e., gram of ethanol produced per liter of the fermentation medium) from various food wastes. Blue markers show reported values from literature (from top to bottom except for kitchen waste* [101], [172], [292]–[299][278][300][290][301], [302]); yellow markers indicate experimental data and red markers correspond to reference data for corn[303] , sugar cane juice [304], and waste biomass [305]. The box plot indicates the range of ethanol concentrations reported for different categories of feedstocks; * average of four studies [37], [61], [143], [306] The dotted lines indicate reference yields from corn and sugar cane juice

The institutional food wastes were reported to be better than industrial food waste for ethanol production. However, there was a large variation in the ethanol concentration obtained from institutional food wastes due to the variation in waste composition, pretreatment method used and process conditions. Industrial food waste on the other hand, had a lower ethanol concentration possibly attributed the nutrient dilution effect in these wastes, which makes utilization of industrial food wastes directly in ethanol fermentation difficult. With an appropriate and economic method to concentrate the sugars in a liquid effluent it is possible to obtain higher yield of ethanol [291], but it should be ensured that this pretreatment does not result in an additional waste stream. In summary, institutional food wastes and bread waste make a feasible feedstock for ethanol production, but it is important to consider variation in composition, process parameter and pretreatment efficiencies into account. The yield of ethanol from corn is more than 100 g/L and can be achieved only with a high starch containing waste like bread. To obtain yields higher than 50 g/L, an *in situ* product recovery would always be necessary. If a lower reference yield of 42 g/L was established based on the yields from sugarcane, a few more wastes can be used in ethanol production. Sugar cane contains higher amounts of free sugars and hence requires less extensive pretreatment steps which balances the cost of downstream processing. Even though experimental data showed 98% theoretical conversion for Greek yogurt whey and cheese whey, the yields are too low to be practical. A concentration step may be employed to increase the concentration of lactose and hence increase ethanol yield.

4.3.2. n-butanol and iso-butanol

Several researchers have reported the use of apple pomace and bakery waste in n-butanol production [38], [109], however, tomato and vegetable wastes have not been used as substrates in butanol production. Whey is one of the most widely studied food-processing liquid wastes for producing butanol. Table 4.1 shows reported and experimental 1-butanol concentrations from various FPWs. There are no reported literature for the use of tomato pomace and tofu wastewater in butanol production. The laboratory tests resulted in 1-butanol concentration of 6.06 and 6.85 g/L butanol for cheese whey and yogurt whey, respectively. Butanol concentration of 12 and 12.2 g/L for cheese whey and yogurt whey have been reported in previous studies when whey was replaced for water in reinforced Clostridial medium [16]. The RCM provides all the nutrients required for the growth of microbes, thus improving the butanol production, however from a practical standpoint this option is not economic as synthetic media add significantly to the variable production cost. Tofu wastewater, apple pomace and tomato pomace yielded 1-butanol concentrations of 2 g/L, 3.3 g/L and 0.8 g/L respectively. Even though these yields are promising, they are still not high enough to be classified as ‘feasible’ from an economic standpoint. The low concentrations of butanol from laboratory tests for apple and tomato pomace were hypothesized to result from a lack of minerals in the medium and incomplete hydrolysis of apple pomace.

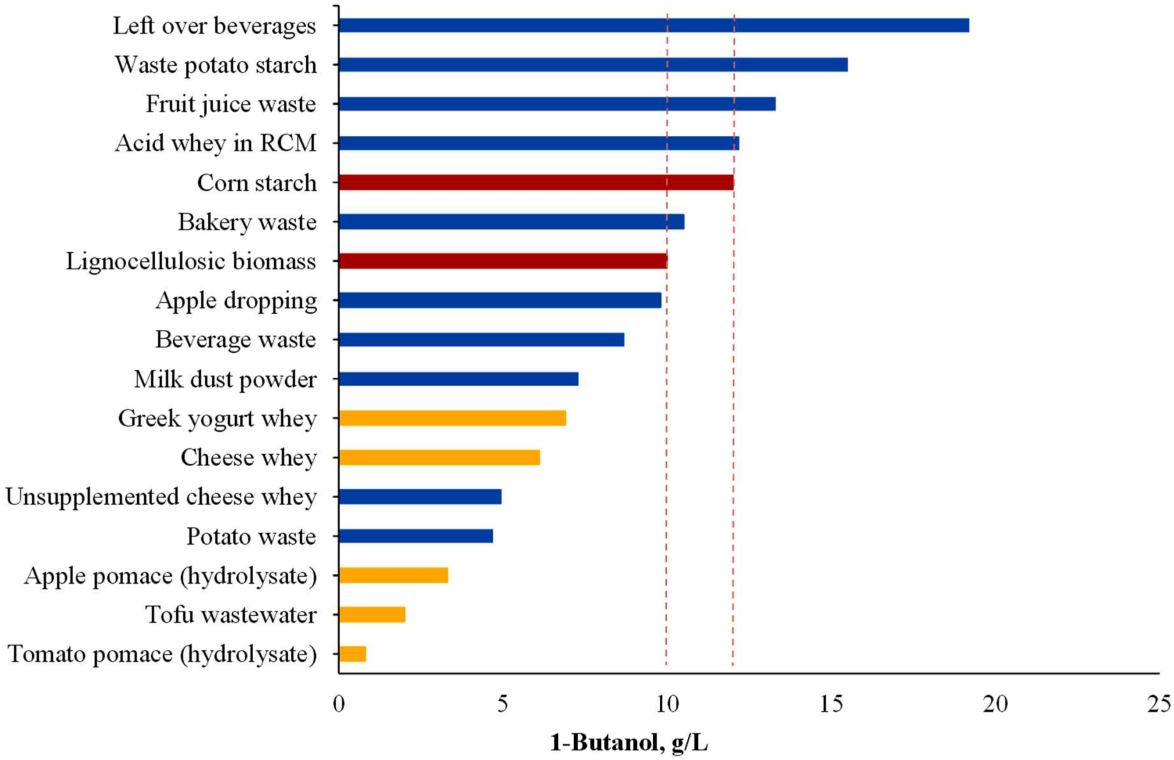

Figure 4.3- Concentration of n-butanol in g/ L; (i.e., gram of butanol per liter of the fermentation broth) Blue markers show reported values from literature (from top to bottom [307][16], [308], [309][66][107][307][39][307][310]); yellow markers indicate experimental data and red markers correspond to reference data for corn starch [311] , and waste biomass [311].

In addition to 1-butanol, several researchers have investigated the production of 3-methyl 1-butanol, and laboratory tests were also conducted in-house (Table 4.1). 3-methyl 1-butanol, commonly known as iso-butanol, has several superior properties to that of 1-butanol. The heating value of iso-butanol is slightly higher than 1-butanol, and its carbon content is higher than 1-butanol. It is also more stable, as it has more side chains than 1-butanol. Only a few microorganisms, particularly ethanol producing yeasts, possess the capability to produce iso-butanol [67]. Hence, there are only a few research efforts to produce iso-butanol from yeast using food waste. The production of iso-butanol was tested in our laboratory using cheese and yogurt whey as the main substrate for *K marxianus* NRRL Y-1175, and the results are presented in Table 4.1. The 3-methyl 1-butanol concentration was observed to be 146.5 mg/L for autoclaved crude cheese whey, 235.2 mg/L for autoclaved crude yogurt whey, and 102.9 mg/L for unsterilized crude cheese whey. These concentrations are higher than the reported value 80 mg/L for whey permeate using *K. fragilis* [110]. There are no other reports on the use of crude whey in the production of isobutanol. Though food wastes show some potential to produce iso-butanol, the observed yields were too low to be economical. However, these results could provide important foundational data to support genetically modifying yeasts to produce high amounts of isobutanol.

Table 4.1 - Production of iso-butanol from food wastes

Organism	Substrate	3-methyl 1-Butnaol conc, mg/l	Reference
Kluveromyces lactis	Synthetic medium with 4% glucose	274	[312]
Pichia pastoris		182	
Saccharomyces cerevisiae		285	
Saccharomyces cerevisiae Montrachet strain 522 w	Apple pomace	120	[111]
Kluveromyces fragilis	whey permeate	80	[110]
Kluyveromyces marxianus, NRRL Y-1175	Crude cheese whey	146.5±13	This study
Kluyveromyces marxianus, NRRL Y-1175	Crude yogurt whey	235.2±18.7	This study
Kluyveromyces marxianus, NRRL Y-1175	Unsterilized crude cheese whey	102.9	This study
Kluyveromyces marxianus, NRRL Y-1175	YPD broth	244.7±19.1	This study
Saccharomyces erevisiae ellipsoideus	Yogurt whey	141.7	This study
Saccharomyces erevisiae ellipsoideus	YPD broth	116.7	This study

4.3.3. Other alcohols and organic acids

Organic acids like acetic acid, propionic acid and butyric acid are important precursors of alcohols and commodity chemicals. These compounds can also be produced from conversion of food wastes [313]. Whey lactose was reported to be a good raw material for the production of propionic acid, which not only acts as a precursor in the production of alcohol but is also used as an antifungal agent in food, intermediate in bioplastic synthesis, and as a solvent in pharmaceuticals [69]. Apple pomace can be a useful raw material in the production of acetic acid [44], lactic acid [73] and citric acid [74]. The organic acids reported from laboratory tests in Table 4.2 were obtained as byproducts of ABE fermentation after 120 h of fermentation. The fermentation broth was analyzed at the end of fermentation to check for the presence of acids. It could be possible to achieve higher production of these acids when they are produced with specific process conditions and microorganisms, and not as byproducts. The lab results show that the organic acid concentration was less than 6 g/L for individual acids produced as byproducts, making them highly un-economical to recover. When the food wastes were used exclusively for the production of organic acid a very high yield could be achieved. For example, acetic acid concentration of 614 g/kg was achieved using apple pomace as substrate and *Acetobacter acetii* bacterium [44]. Acetic acid can be converted into ethanol using a simple catalytic processes.

Table 4.2- Production of other value-added products from food wastes via fermentation$^{\$}$

Organism	Substrate	Compounds	Concentration, [g/l]	Reference
Kluyveromyces fragilis	whey permeate	2-methyl 1-propanol	0.045	[110]
		2-methyl 1-butanol	0.027	
Lactobacillus rhamnosus	Cafeteria waste	Lactic acid	45.5	[314]
Yeast and acetic acid bacteria	Cafeteria waste	Acetic acid	25.9	[43]
Propionibacterium freudenreichii ssp. shermanii	Whey lactose	Propionic acid	22.6	[69]
		Succinic acid	1.9	
Actinobacillus succinogenes .	Mixed vegetable waste	Succinic acid	29.9	[40]
Actinobacillus succinogenes	Bakery wastes from Starbucks HongKong	Succinic acid	31.7	[71]
C acetobutylicum ATCC 4259	Crude cheese whey	Acetic acid	5.9±0.7	This study
	Crude yogurt whey	Acetic acid	5.8±0.3	This study
	Crude yogurt whey	Lactic acid	1.5±0.8	This study
	Crude yogurt whey	Butyric acid	1.1±0.0	This study
	Tofu wastewater	Acetic acid	2.2±0.1	This study
	Tofu wastewater	Butyric acid	1.6±0.0	This study
C beijerinckii NRRL B -598	Apple pomace hydrolysate	1-propanol	3.3±0.1	This study
	Crude yogurt whey	Acetic acid	1.5±0.0	This study
	Apple pomace hydrolysate	Acetic acid	3.2±0.2	This study
	Tomato pomace hydrolysate	Acetic acid	1.9±0.1	This study
	Crude yogurt whey	Lactic acid	2.7±0.0	This study

[$] The organic acids reported by this study were screened as byproducts of ABE fermentation and not as products of a dedicated process

4.3.4. Fermentation as a food waste technology-perspectives:

In literature, fermentation is never considered as a food waste management technology; rather it is considered a manufacturing technology. From the discussions above, it is clear that only a few selected food wastes can be utilized as a raw material for the production of various value-added products, and most others achieve economic value by minimizing costs through proper disposal or recycling. The qualitative metric shown in Figure 4.4 can be used to screen the applicability of fermentation in valorization of specific food wastes. The data inventory used in this analysis is shown in Appendix Table A4.4. The possibility of alcohol production using fermentation has been discussed in previous section. From the heat table presented in Figure 4.4, the production of lactic acid from food waste appears to be a better option. To analyze this situation in a real world perspective, one can assume lactic acid production from cheese or yogurt whey. The lactic production cost was estimated as a variable cost of 1.25 \$/kg per year[23] [284] using $100m^3d^{-1}$ of cheese whey as feedstock. The market price of lactic acid was reported as 1.5 \$/kg in this study and 2800 kg of purified lactic acid can be produced per year. Using this initial data and applying this to food waste management offers a saving of 375,000-832,000\$ per year at a liquid waste tipping fee[24] of 13-26\$/m^3. These cost savings can be further increased when lactic acid produced is marketed as a product offering another 896,000\$ in revenue. However, it is crucial to note that the aerobic fermenters have a lower capacity factor of approximately 50% and hence require a reactor volume double the volume of the waste generated to process. This study reported a capital cost of 2.5M \$ and an operational and maintenance cost of 1.6M \$; the operation and maintenance for the production process consumes approximately 65% of the capital cost on a yearly basis. Using these estimations, this project would have a discounted payback time of 9 years with a positive Net Present Value (NPV) [315]by assuming a 9% interest paid on loan for capital investment and a 35% paid in taxes after the plant starts to make profit [288].

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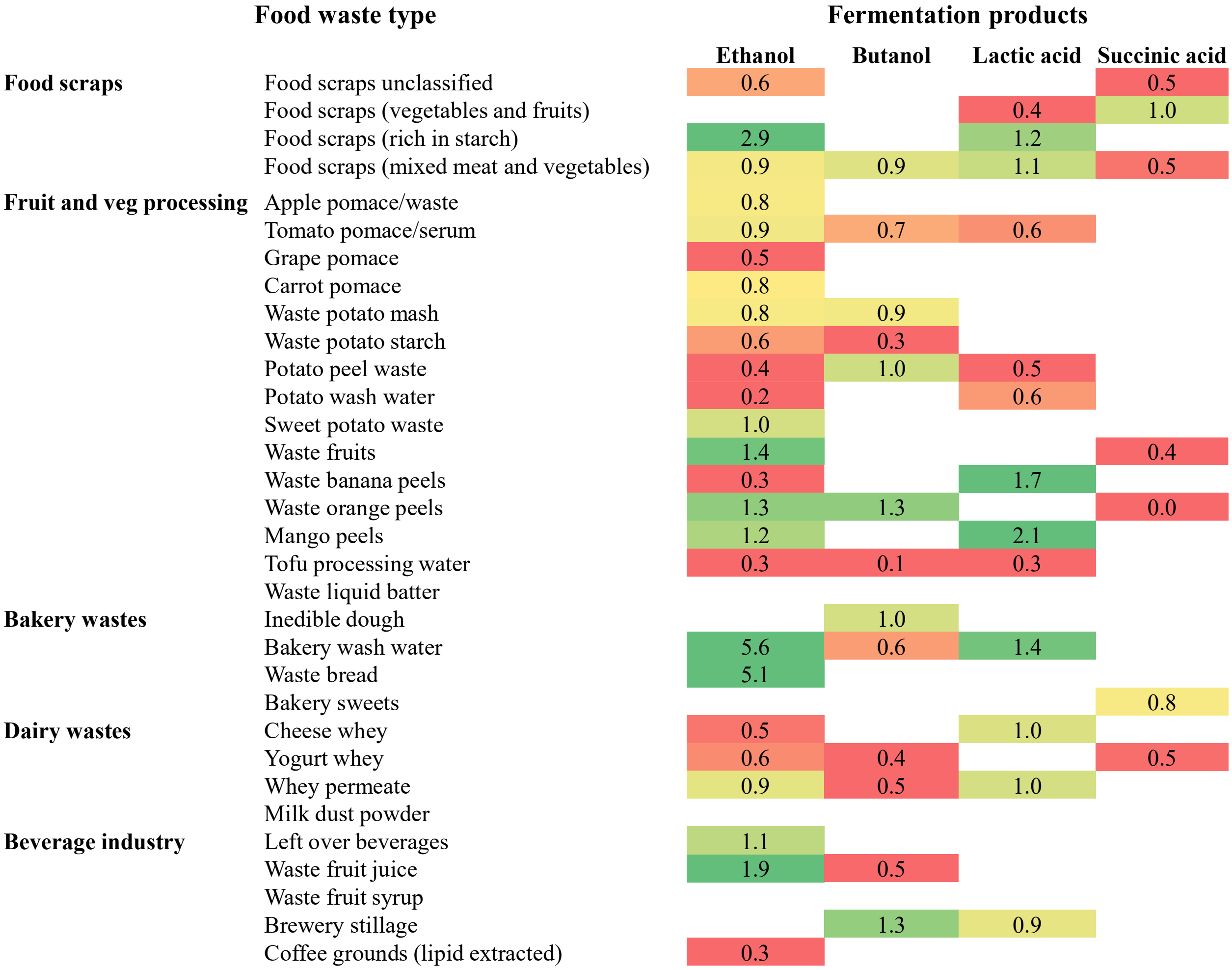
[23] Not adjusted for inflation

[24] Tipping fee data obtained through personal communication with a local digester facility



Food waste type		Fermentation products			
		Ethanol	Butanol	Lactic acid	Succinic acid
Food scraps	Food scraps unclassified	0.6			0.5
	Food scraps (vegetables and fruits)			0.4	1.0
	Food scraps (rich in starch)	2.9		1.2	
	Food scraps (mixed meat and vegetables)	0.9	0.9	1.1	0.5
Fruit and veg processing	Apple pomace/waste	0.8			
	Tomato pomace/serum	0.9	0.7	0.6	
	Grape pomace	0.5			
	Carrot pomace	0.8			
	Waste potato mash	0.8	0.9		
	Waste potato starch	0.6	0.3		
	Potato peel waste	0.4	1.0	0.5	
	Potato wash water	0.2		0.6	
	Sweet potato waste	1.0			
	Waste fruits	1.4			0.4
	Waste banana peels	0.3		1.7	
	Waste orange peels	1.3	1.3		0.0
	Mango peels	1.2		2.1	
	Tofu processing water	0.3	0.1	0.3	
	Waste liquid batter				
Bakery wastes	Inedible dough		1.0		
	Bakery wash water	5.6	0.6	1.4	
	Waste bread	5.1			
	Bakery sweets				0.8
Dairy wastes	Cheese whey	0.5		1.0	
	Yogurt whey	0.6	0.4		0.5
	Whey permeate	0.9	0.5	1.0	
	Milk dust powder				
Beverage industry	Left over beverages	1.1			
	Waste fruit juice	1.9	0.5		
	Waste fruit syrup				
	Brewery stillage		1.3	0.9	
	Coffee grounds (lipid extracted)	0.3			

Figure 4.4- Qualitative matrix for food waste fermentation; the scores above 1.0 indicate a breakeven or suitable option and score pf below 1 (yellow, orange or red) indicate that the food waste feedstock is not suitable; minimum yield required to achieve economic sustainability for each product are given in the table below

$$\text{Score} = \frac{\text{Measured yield}}{\text{Min required yield for economic viability}}$$

Product	Min yield for economic sustainability, g/L	Reference
Ethanol	45	[287]
Butanol	20	[288]
LA	55	[284]
SA	57	[289]

On the opposite side, fermentation is also efficient in reducing the strength of the waste. In yeast fermentation experiments, a sugar consumption of 80.9%, 100%, and 93% was observed within 25 hours for tofu wastewater, Greek yogurt whey and cheese whey, respectively. In this case, the sugar consumption can be approximated to an overall reduction in the strength of wastewater and the associated cost of wastewater treatment. For solid wastes like apple pomace, at an initial concentration of 10% solids, the overall sugar consumption was 78-85% in 24 hours. In anaerobic fermentation using *Clostridium,* this reduction was much slower, with 35% to 80% sugar consumption in 72 hours. Anaerobic fermentation discussed in this chapter is different from anaerobic digestion, as anaerobic fermentation is a pure culture process. If the same example of cheese whey fermentation is applied to waste management without the production of value added products, the discounted payback time was reduced to 2 years. This is mainly due to the fact that, during the production, downstream processing infrastructure and its maintenance takes up more than 65% of the overall investment. Hence, if fermentation is purely used for waste management, in which case, it should be called aerobic digestion the cost savings of 375,000-832,000 $ can still be realized with a much shorter payback time. . If a 10% solid content is assumed as a requirement for the operation of the fermenter, the process would require approximately 40-50L of water per kg of food waste at 75% moisture. Using a wastewater stream from the food industry provides the water required in the process and at the same time COD of the wastewater stream would be reduced. Also, fermentation has a temperature requirement of 25-30^{0}C, which requires lesser energy input compared to anaerobic digestion (37^{0}C). Use of fermentation as a waste management technology could benefit waste generators due to avoided tipping fee for landfilling. Because the COD reduction is relatively fast, the wastewater from the process is suitable to be discharged to the sewer for further treatment in wastewater treatment plants. While product concentration is one of the factors that dictate the feasibility of a valorization method, other economic factors must be considered before deciding to choose or not to choose a valorization option. For example, using fermentation as a waste management option at the location of a food processing operation could be economical even when it does not result in any value-added product

4.3. Conclusions

Various food waste resources were screened for the production of value-added products such as ethanol, n-butanol, iso-butanol and a few organic acids. Even though a decent number of literature studies existed, due to inconsistency in the data available, it was hard to conclude whether food waste can be a good feedstock for fermentation. Through this work,

- A state of the art knowledge was made available to the stakeholders who are interested in innovative valorization options for food waste via fermentation
- This study expanded the knowledge about fermentation of food waste through several experimental studies
- A qualitative matrix with possibility of using fermentation in waste management was developed

It was not possible to cover a wider range of food waste resources in the experimental studies due to a large number of experimental runs. The results for same food waste may vary depending on the pretreatment method and product recovery techniques. Sensitivity of product yield to these parameters was not analyzed in detail. In summary, only a few food wastes originating from institutions like kitchen waste, retail store waste, and waste bread were found to yield a higher quantity of ethanol. None of the industrial food wastes except whey permeate were found to be suitable for the production of any of the value-added products screened. At this point, food waste is not a suitable feedstock for the production of butanol or higher alcohols even though it is worth continuing the research to explore more possibilities. Since fermentation can reduce the strength of food wastes in a short span of time, it has a potential to serve as an onsite or off-site waste management strategy, even without generating any value-added products.

CHAPTER 5

EVALUATION OF THERMOCHEMICAL CONVERSION OF FOOD WASTE USING EXERGY ANALYSIS AND LIFE CYCLE THINKING

Abstract:

The feasibility of food waste management using a thermochemical conversion process that comprises combined gasification and slow pyrolysis stages was analyzed in this chapter using an exergetic lifecycle thinking approach. Exergy indicates the useful energy that is available as work and is a practical indicator of process efficiency. The exergy efficiency and global warming potential (GWP) of producing biochar and thermal energy (heat) from food waste was estimated for 36 different combinations of fuel (dried food waste) moisture, process temperature, and biochar yield. Three scenarios involving the use of biochar as a soil amendment and as a fuel were evaluated. Global warming potential increased with an increase in exergy efficiency under most circumstances. The exergy efficiency varied between 9 and 48% and the GWP ranged from -61 to 143 kg CO_2e ton FW_{wet}^{-1}.

5.1. Introduction

Mass-burn incineration has a bad reputation for its perceived energy inefficiency and environmental emissions [316]. Unlike incineration where the waste is combusted using excess oxygen, gasification and pyrolysis use very little or no oxygen, well below the stoichiometric level required for full oxidation. Due to partial oxidation of waste materials, pyrolysis and gasification yield useful products like biochar, hydrogen-rich syngas, and bio-oil while the end products of incineration are only low-value carbon dioxide and ash. Most common types of waste materials incinerated are municipal solid waste, hazardous waste and medical wastes [317]. Even though incineration can reduce the volume of waste by up to 95%, it has unjustified financial risks and has been reported to cost up to 50% more per ton than landfilling [318]. A significant percentage of the carbon from the original feedstock is sequestered during pyrolysis in the biochar co-product as recalcitrant carbon, and this helps to avoid carbon emissions into the atmosphere. Anaerobic digestion, composting, animal feed production or any other currently existing food waste technologies demands separation of paper, bones, and non-bio degradable materials. The presence of these materials can directly affect all the above-stated conversion pathways. Thermochemical conversion of food waste to value-added products has the potential to avoid food waste segregation, especially from paper- and plastic-based packaging materials, needed before treatment. Also, conventional methods like anaerobic digestion result in an effluent stream (“digestate”) that requires further management. Therefore, several food waste streams, including all their associated impurities, can potentially be pyrolyzed to achieve better conversion and energy value. Thermal conversion of food waste is proposed as an alternative and efficient pathway to reduce the volume of food waste and to obtain value-added products. Food waste can also be co-pyrolyzed or gasified with dry materials like food packaging, yard waste or agricultural waste, potentially resulting in reduced energy consumption. Using thermochemical conversion, up to a 90% volume reduction is achievable [319], which implies that these technologies can have a substantial impact in diverting a significant quantity of food waste from landfills.

5.1.1. Literature Review

The application of gasification for biomass management has been rigorously studied by many researchers, to produce gaseous fuels and electricity. Biomass contains higher oxygen compared to conventional fuels like coal, which makes the gasification of biomass possible at lower temperatures of 700-800^{0}C [320]. This is an advantage, as lower temperatures help avoid the heat losses that occur during a high-temperature process like incineration [321]. On the other hand, pyrolysis of biomass to produce ‘biochar’ is a relatively new research area. Other thermal technologies like fast pyrolysis and hydrothermal liquefaction have been reported for food waste, as these are the suitable technologies for producing bio-oil. Reports of application of fast pyrolysis to food waste [33], [322], animal wastes [323], mixed food and packaging [324] [113] and sewage sludge [325] have been found in the literature. However, production of bio-oil may not be a favorable option as bio-oil produced from waste material tends to be unstable due to the high oxygen content of waste biomass resources which ultimately needs high energy input for refining [326]. Hydrothermal liquefaction, on the other hand, is still in its infancy and due to high pressures used to thermally process the feedstock and higher moisture content of the product streams [83], is not efficient or technologically mature. Therefore, gasification and slow pyrolysis to produce biochar and gaseous products of high energy value are suitable technologies for faster waste treatment and valorization.

Since thermochemical conversion processes are associated with thermal energy production, exergy efficiency, energy efficiency, and cumulative energy demand are some of the metrics used to evaluate their feasibility. Exergy analysis is the most useful since exergy indicates the available form of energy that can be converted to work and hence provides guidelines for real-time operation. Exergy is defined as "the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interactions only with the above-mentioned components of nature" [327]. Energy is neither created nor destroyed during a process; it changes from one form to another (first law of thermodynamics). Exergy, on the other hand, can be destroyed due to process irreversibility, characterized by an increase in entropy (second law of thermodynamics [328].

A unique thermochemical conversion process for waste wood, 'chartherm' process that combines the principles of slow pyrolysis and distillation was comparable to gasification in exergy efficiency [328]. Several studies focused on fast pyrolysis of waste resources in the production of bio-oil, such as post-harvest waste biomass, [329], switchgrass, equine waste and forest residues [330], poplar wood [331] and other lignocellulosic biomasses [332], [333] either using simulated or empirical approach. The majority of the literature on exergy analysis of thermochemical conversion has considered a gasification process for the production of syngas that is used to generate electricity in most cases or heat in some cases. However, these studies have assumed various operating conditions, gasifier types, and configurations, for example, two-stage gasification combined with a solid oxide fuel cell for energy generation [334], downdraft gasifier [335] and fluidized bed reactor [336]. A number of the exergy analysis studies investigated a general Gibb's reactor and estimated the exergy efficiencies on a purely theoretical basis [337]–[340]. The energy requirement of the process vary significantly depending on the configuration [341], feedstock type [329], [330] and operating conditions [337], [339]. The thermochemical conversion can be carried out in various configurations to maximize the output energy and hence need case-specific evaluation. None of the studies reported here used food waste as a feedstock, except for one study that analyzed a hydrothermal liquefaction process [84].

While exergy analysis is useful in obtaining information on the real-time operational consideration, to evaluate the sustainability of a process, this information should be combined with life cycle thinking. It has been reported that food waste fast pyrolysis for bio-oil production had a higher negative environmental impact compared to anaerobic digestion or an integrated process combining anaerobic digestion and fast pyrolysis [342]. Some gasification LCA studies have used an attributional approach for estimating the impacts associated with syngas production [343]–[346], but none have considered biochar as a coproduct of gasification. In a comparative assessment of slow pyrolysis, fast pyrolysis and gasification for ten biodegradable wastes including food waste, the significant carbon abatement was associated with biochar yield [347]. A considerable carbon abatement was achieved for biochar production from slow pyrolysis of biomass when the system boundaries were expanded to include long-term carbon sequestration from biochar, displaced fertilizer use, energy generation and avoided conventional waste management [348]. Few studies have reported higher carbon abatement via electricity generation than biochar use as a soil amendment from slow pyrolysis systems [331], [349]. Varying effects of biomass feedstocks due to variation in heating value, bulk density and processibility on impact categories have also been investigated previously [331], [347], [349], [350]. Again, all the above studies used biomass, wood or forest residues as feedstocks except for fast pyrolysis of food waste [342]. A few comparative studies for food waste management considered incineration under thermal conversion category and compared with other management practices such as anaerobic digestion and composting [351]–[354]. Even though it is challenging to establish a general conclusion from all the reported studies due to variability in the system treatment, generally, major offsets result from biochar production in slow or fast pyrolysis processes and electricity generation in gasification. A higher biochar yield is crucial to attain a lower global warming potential (GWP).

This work analyzed a unique configuration to convert food waste into biochar and gaseous products inspired by a circular economic approach of using biochar as a soil amendment. The thermochemical conversion systems offer significant advantages in decentralizing food waste management as these systems can be operated on a small to medium scale as well as in rural or urban settings. The processing time is considerably smaller than the biochemical processes such as anaerobic digestion or fermentation and there is no need for post wastewater management. Thermochemical conversion systems can generate value-added products and energy with minimal or no waste generation and offer a mass reduction of up to 90%. However, the use of these systems is limited to dry biomass and forest residues and the sustainability of their use in food waste management is poorly understood. Since food waste is a high moisture feedstock, it is necessary to understand the operational feasibility and environmental impact of these systems owing to their practical benefits of smaller product footprint and short residence time. The operational parameters are known to have an impact on process efficiency, however the effects of these parameters on GWP have not been widely explored as most LCA studies assume a fixed standard operating condition. In this study, the feasibility of thermochemical processing of food waste was analyzed based on exergy efficiency and environmental factors.

5.1.2. Scope of work

Based on a thorough literature review, the following research gaps were identified:

- While a few studies have estimated exergy efficiency and environmental impacts of thermochemical processes, no correlation combining these two metrics was found.
- The configuration in which the process is operated, feedstock used and the reactor type has great implications on the overall process efficiency. The majority of the energy/exergy models presented in the literature apply to biomass, many of which assume general composition and properties, or relied on theoretical calculations. Therefore, it was necessary to analyze the system under study as a commercial-scale configuration where the feedstock is first 'flash gasified' before moving into the pyrolysis zone for biochar formation. There are no known reported studies on this configuration.
- While air gasification and slow pyrolysis processes are technologically mature for fuel and energy production, they do not have widespread application in the waste management sector [9]. Therefore, evaluating this technology as a food waste management option would open up new opportunities for food waste volume reduction in addition to valorization.

From the research gaps listed above, the overall research question for this part of the dissertation research was framed as: "*How do operating conditions impact exergy efficiency and global warming potential of a small scale thermochemical food waste conversion system*?"

The present work is based on a unique configuration to convert food waste into biochar and gaseous products that have not been considered elsewhere in the literature. The exergy efficiency was estimated for source segregated food waste that goes through a series of unit operations, including drying, grinding and thermochemical conversion before biochar and heat were produced as the products. The system configuration studied in this research did not utilize syngas as a separate co-product, but rather combusted the syngas for emissions control and additional thermal energy generation. This work provides useful information to the operators and decision makers on alternative options for efficient use of thermochemical conversion process in food waste management. The tradeoffs between exergy efficiency and environmental impacts are discussed.

5.2. Methods

5.2.1. Process description

A small-scale commercial thermochemical processing unit manufactured by Biomass Controls LLC (Putnam, CT, Figure 5.1) was used to produce biochar from food waste. The food waste was collected from dining halls, restaurants, retail stores and the local farmer's market. The collected food waste, containing approximately 53% vegetables, 15% fruit, 5% meat, 7% coffee grounds and 20% bread, was dried to 10% moisture and ground to a particle size of 2-25 mm.. Food waste samples collected from various places were first dried separately in a hot air oven and then mixed in a large trough to obtain a homogeneous feedstock. The thermochemical processor (TCP) contained a feed hopper where the food waste was fed at a flow rate of 10 kgh^{-1} and transported through the system by an auger with a retention time of 15-20 minutes, and then collected in the pyrolysis pot located in the "carbonizer" section (Figure 5.1). The temperature of the process measured using a thermocouple just above the pyrolysis pot was maintained at 800^0C by using food waste as a sole source of fuel and a small quantity of oxygen to help aid preheating of food waste to a predefined temperature. The experiment was also conducted at 500^0C and biochar yield was recorded at regular intervals. Only biochar yield was recorded for 500^0C due to a data acquisition issue in the control system. Oxygen was supplied to the process as air from a blower flowing perpendicular to the direction of feed flow. The equivalence ratio (i.e., ratio of actual to stoichiometric air-to-fuel ratio) was approximately 0.32 for the 800^0C process and 0.18 for the 500^0C process (see Appendix Section A5.1 for calculation of equivalence ratio). During the process, food waste is partially oxidized into volatiles and gases at the top of the pyrolysis pot and moved down to the bottom air-free zone to carbonize. A dual auger assembly at the bottom of the pot moved the biochar into a biochar collection box. The biochar samples were collected at regular intervals throughout the continuous process, and mass flow rates were recorded. The volatiles and gaseous products (VGPs) produced as a result of the partial oxidation of food waste were drawn upward (i.e., away from the biochar dropping vertically to the bottom of the pyrolysis pot) toward a catalytic converter and combusted for air pollution control. The emissions from the stack were measured using CO_2 (Wohler) and CO measurement (Testo 300) devices. The process parameters, including process temperature, electricity consumption, and variations feed and air flow rates were continuously monitored through a user interface, and 1800-2200 discrete measurements of these parameters were acquired during each run. These measurements were averaged for intervals of 20 minutes, and at the end of each 20-minute cycle biochar samples were obtained. An independent third-party laboratory analyzed the elemental composition of the biochar sample. The method used to estimate stack gas flow rate (i.e., downstream of the catalytic converter) is explained in Section 5.2.5.

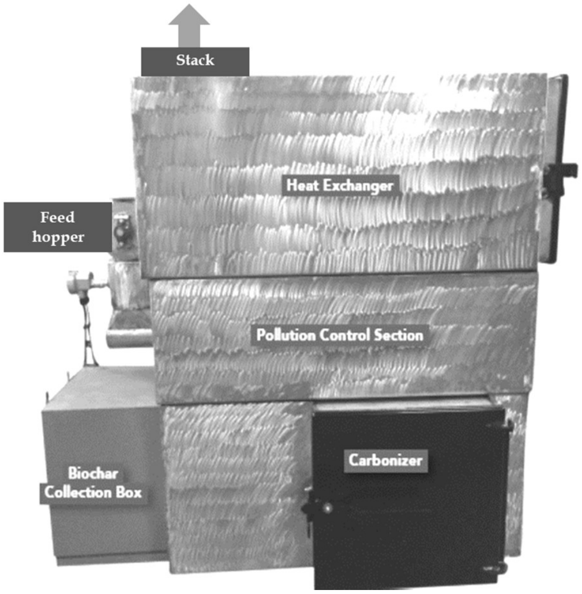


Figure 5.1- Main hardware components (dryer not shown) of the thermochemical processor manufactured by Biomass Controls (Putnam, CT)

5.2.2. System description

For analysis purposes, the system explained in section 5.2.1 was expressed as a simplified block diagram as shown in Figure 5.2. The block method was used to analyze the exergy where the system is assumed to consist of a series of interconnected blocks. Each block interacts with the surroundings via transfers of mass, heat and work [328]. For exergy analysis, the system boundary was defined for the onsite treatment of source segregated waste to produce biochar and VGPs, and no transportation of food waste or biochar was considered. For the analysis of GWP, the system boundary was expanded to include biochar transport. Each unit operation is explained in detail in the following sections.

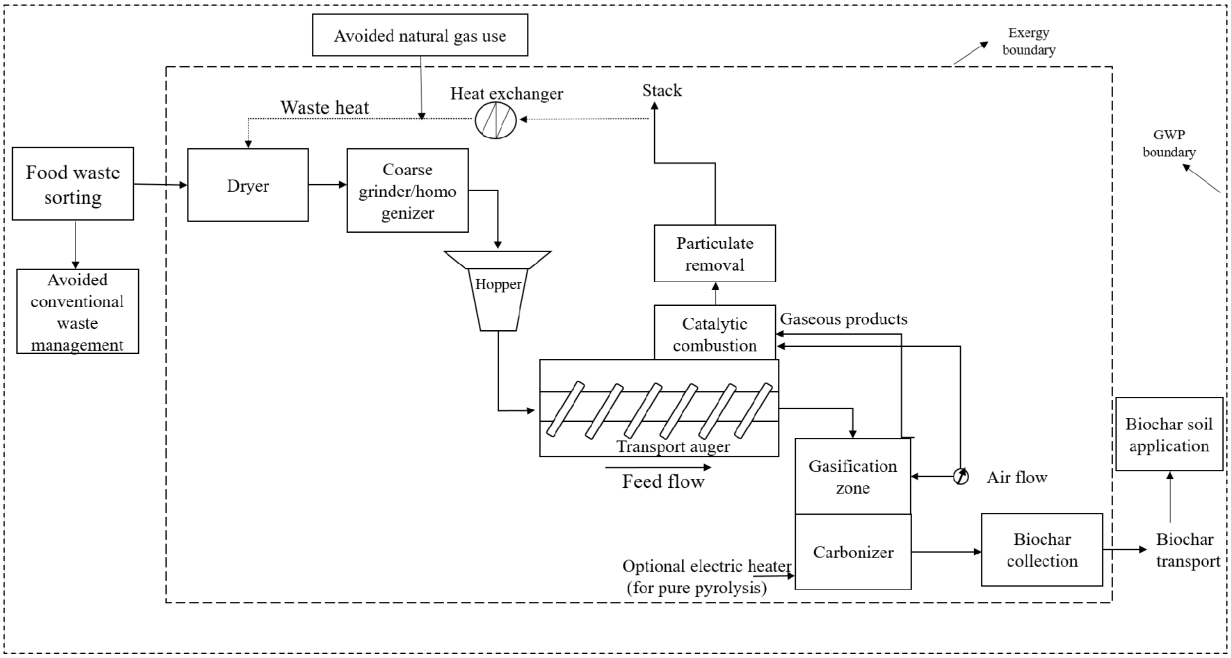


Figure 5.2. System diagram used in analysis of exergy and GWP

5.2.3. Unit operations used in exergy and environmental feasibility assessment

An overall mass balance on food waste solids and water during each unit operation was used to estimate the input and output flow rates. The exergy and environmental impacts were calculated based on food waste or product mass flows from each of the unit operation described in this section. As stated earlier, for the current experimental campaign, the food waste feedstock was separately dried and homogenized before introducing it to the thermochemical processor. Below, drying and grinding stages are modeled as front-end unit operations of the full integrated TCP system.

5.2.3.1. Drying:

A conveyer belt type perforated food dryer was employed to dry food waste in this analysis. The specified feed flow rate of 96 kg/h and drying was assumed to occur at 150^{0}C. The mass flow rates through the specified dryer were calculated by using 1 ton of wet food waste at 80% moisture as the basis for various final moisture levels. The efficiency of drying was estimated as 51% by using estimated values for biowaste (using specific heat capacity of 5 KJ kg^{-1}C$^{0-1}$;)[355] and empirical data for the energy requirement of the specified dryer to dry biowaste from an initial moisture of 77% to a final moisture of 35% [356]. Additional assumptions applied in the calculation of input energy were:

- The heat losses from the dryer body, which are typically 5-10% for convective dryers [357], was assumed to be included within the efficiency.
- A constant bed thickness of 100 mm was assumed for which Hallowell et al. [358] measured the drying energy requirement.
- No air recycling was considered, as the feedstock contained very high moisture that saturated and cooled the outlet air, requiring further energy input to recycle heated air.
- Emissions result purely from natural gas use for drying

5.2.3.2. Grinding:

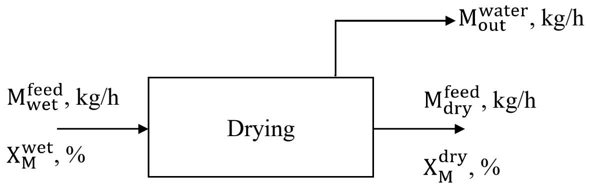
Grinding or homogenization is necessary before the feedstock is sent through the dryer and the associated grinding energy requirement depends on moisture content, initial and final particle size and other rheological properties [359], [360]. However, grinding food waste to extremely small particle size is not beneficial in biochar production, as smaller particle size does not favor the secondary biochar formation reactions, thus decreasing the biochar yield [361]. The grinding process is staged after the drying stage, as dry feedstock requires significantly lower energy to grind than wet feedstock [360] . Grinding energy requirements were calculated for a rotary hammer mill of 5 hp (3.7kW) capacity [356] capable of grinding the feedstock to a predefined mesh size (10mm-25mm required by the feed hopper in TCP unit) and a flow rate of 27 kg h^{-1}. The overall energy input was calculated based on the time required to process the dried feedstock (dryer output mass flow rate). The emissions were assumed to result purely from electricity use to run the grinder.

5.2.3.3. Thermochemical processing:

The mass flow rates of food waste through the TCP and biochar out of TCP were calculated based on the biochar yield in different scenarios. The mass flow rate of the VGPs was predicted by subtracting the mass flow rate of biochar and feed mass loss rate from the actual feed flow rate. The moisture content of feed and biochar were experimentally determined using the standard EPA method 1684[269]. The water content in VGPs was estimated by using a water mass balance on feed and product streams. The mass of food waste destroyed during preheating and steady-state operation was calculated using LHV utilization per unit weight during these stages. It was assumed that there is no friction to mass flow during any unit operation, either by trapping of feedstock on the dryer belt, grinder and feed and product transport augers or due to premature cooling of tar fraction in the flow path. In a typical run, such effects can account for up to 15-40% of losses [329]; however, only mass of feedstock lost while preheating and steady-state operation was considered in this analysis.

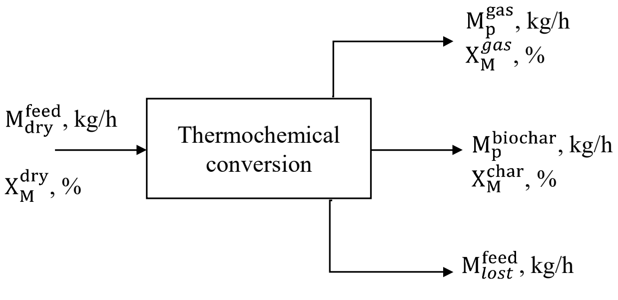
5.2.4. Overall mass balance

An overall mass balance is necessary to accurately estimate the exergy and environmental impacts. The overall mass balance for drying, grinding and thermochemical conversion is given by the schematics and equations below.



$$M_{wet}^{feed} = M_{dry}^{feed} + M_{out}^{water} \quad \textbf{Eq. 5.5}$$

$$M_{dry}^{feed} = M_{dry}^{feed} \quad \textbf{Eq. 5.6}$$



$$M_{dry}^{feed} = M_p^{biochar} + M_p^{gas} + M_{lost}^{feed} \quad \textbf{Eq. 5.7}$$

where, M_{wet}^{wet} is the mass of food waste at an initial moisture content of X_M^{wet};

$M_{dry}^{feed}$is the mass of dry food waste leaving the dryer at a final moisture level of X_M^{dry}, which is also equal to the mass flow through the grinder and mass input to the thermochemical conversion unit;

$M_p^{biochar}$ and M_p^{gas} represent the mass flows of product stream-biochar and VGPs respectively;

$M_{lost}^{feed}$is the mass of dry food waste lost due to utilization of chemical exergy to preheat the food waste to process temperature and maintain the temperature;

$X_M^{biochar}$and X_M^{gas} are moisture contents of biochar and VGPs, respectively.

5.2.4. Exergy Analysis

The thermochemical conversion of food waste was evaluated using an exergy balance approach. By using an independent mass and exergy balance of an individual block, the exergy performance of each unit operation was estimated. Exergy, like energy, can be in the form of heat or work, however, unlike energy it can be destroyed. The energy balance represents the energy input and outputs of the system assuming that the system is at equilibrium (1st law of thermodynamics). However, it does not give information on the quality of the energy [328]. Therefore, an exergy analysis provides estimates of the energy that can be derived as useful work to run the process, or as an output from the process. Exergy balance also provides an estimate of the irreversibility of the process due to the creation of entropy in the system [84]. Equation 5.8 represents a general exergy balance on the system.

$$\sum E_x^{in} - \sum E_x^{out} = \sum E_x^{destroyed} \qquad \textbf{Eq. 5.8}$$

The reference state used for calculations was 25^0C and 1 atm (0.1 MPa) pressure. The exergy input to the process was calculated as the sum of chemical exergy of the fuel, heat energy required during drying and electrical energy requirement during drying, grinding and thermal processing of the feedstock using Eq. 5.9.

$$E_x^{in} = E_{x,chem}^{feed} + E_{x,heat} + E_{x,electric} \qquad \textbf{Eq. 5.9}$$

Exergy is destroyed during the process because of the energy required to preheat the food waste to required process temperature and the energy required to maintain the equipment at steady state temperature. A fraction of exergy is also destroyed after the food waste is converted into VGPs due to the presence of water in vapors.

$$E_x^{destroyed} = Q_{preheat} + Q_{steady} + Q_{CC} \qquad \textbf{Eq. 5.10}$$

where, Q_{CC} represents the exergy loss during catalytic combustion as LHV or heat.

The output exergy of the process was calculated as the sum of chemical exergies of biochar and VGP. Even the VGPs are in fluid form since the flow rates are adjusted to reference conditions, the kinetic, potential and other physical energies from product stream approach zero [84]. Therefore, the output exergy from the product stream would be a simple sum of chemical exergy values of biochar and VGPs. The chemical exergy of food waste and products was calculated by using the method described in section 5.2, and the chemical exergy of VGP was calculated by using the conserved chemical exergy of food waste and overall mass balance for water present in VPG stream.

$$E_x^{products} = E_{x,chem}^{biochar} + E_{x,chem}^{hea} \qquad \textbf{Eq. 5.11}$$

The irreversibility or percent exergy destruction was calculated using Eq. 5.12.

$$ED\ (\%) = \frac{E_x^{products}}{E_{x,chem}^{food\ waste}} \qquad \textbf{Eq. 5.12}$$

The exergy efficiency was defined as the ratio of exergy output to exergy input using Equation 5.13.

$$\eta_{ex} = \frac{E_{x,chem}^{biochar} + E_{x,chem}^{heat}}{E_{x,chem}^{food\ waste} + E_x^{electrical}} \qquad \textbf{Eq. 5.13.}$$

The energy input and outputs and exergy estimations for individual unit operations are given in Appendix sections A5.3 through A5.5.

5.2.5. Global warming potential estimation:

This section describes the methods used to estimate GWP for the system under study shown in Figure5.2.

5.2.5.1. Goal and Scope:

The global warming potential assessment and exergy analysis were carried out to understand the combined effects of process efficiency and environmental impact. Even though specific processes are exergetically feasible, it is essential to understand the sustainability of a process by estimating its environmental impact. The goal of this study is to understand the combined technological and environmental efficiency of thermochemical conversion food waste into biochar and energy-rich

Feedstock:

Source separated mixed food waste typically containing fruits, vegetables, rice and cereals and small amounts of cooked meat was considered as a feedstock. The **functional unit** used was the management of one ton of wet food waste at 80% initial moisture. The food waste was assumed to be source separated and devoid of contaminants.

System boundaries:

A simplified block diagram showing the main unit operations through which maximum exergy flow occurs is given in Figure 5.2. The system boundary was defined for the onsite treatment of source segregated waste to produce biochar and VGPs, and no transportation of food waste or biochar was considered. By using independent mass and exergy balance of an individual block, the exergy performance and CO_2e greenhouse gas emissions of each unit operation was estimated. The cumulative exergy efficiency and global warming potential were later estimated by combining all the unit operations. The system boundary was expanded to calculate GWP by including biochar transportation and its application as a soil amendment.

Processes included within the system boundary:

- Drying, grinding and thermochemical processing of source separated food waste.
- Biochar collection, transport and field application.
- Catalytic combustion of VGPs to produce heat.
- Avoided emissions associated with biochar use.

- Avoided emissions associated with natural gas by recycling heat produced during the process.
- Avoided emissions from conventional waste management, landfilling.

Processes not included within the system boundary:

- Segregation of food waste from the garbage and recyclables.
- Emissions associated with extraction of material and techno-sphere inputs.
- Emissions associated with production of process equipment and infrastructure.
- Emissions from avoided landfilling: even though it is a common practice to include avoided landfilling, sustainable technologies will be the new norm in future and landfilling will no longer be an option.

Assumptions:

- There are only two main products from the process- biochar and heat.
- No waste management is necessary after the process except for small amounts of ash, as all the products are collected for downstream application (biochar), in volatile or gaseous form, or are used to produce heat.
- Stack emissions only contain CO_2 and traces of CO.
- The heat produced by catalytically combusting VGPs is recycled to dry incoming feedstock which displaces natural gas use.

5.2.5.2. Inventory:

The biochar produced was assumed to have a primary function as a soil amendment and syngas was assumed to be combusted in a post catalytic combustor to produce heat energy. The biochar would be transported from facility to a farm for use as a soil amendment that would displace a certain fraction of nitrogen/phosphorous/potassium (NPK) fertilizer use (See Appendix 5, Table A5.4 for data inventory).

The drying energy was calculated as the energy required to evaporate water and bring the moisture levels of the food waste feedstock down from 80% to final moisture content, using a perforated plate conveyor type dryer. The emissions from the drying process were purely assumed as the direct and indirect emissions associated with natural gas and electricity use to heat the feedstock and run the machinery. Emissions associated with drying and grinding process were assumed to be purely associated with heat and electricity use and were also calculated using SimaPro 8 software. The thermochemical processing unit consisted of a hopper, transport auger, a gasification zone and a pyrolysis pot. The biochar from pyrolysis pot was collected in the char box and syngas produced in the upper gasification zone were drawn into the catalytic conversion chamber for air pollution control. The process was modeled for various operating conditions of temperature ranging between 50 and 800°C and dry feedstock moisture content ranging between 10% and 35%. The direct emissions from the process were measured using a stack gas monitoring system and the indirect emissions from the use of natural gas and electricity were estimated using SimaPro 8. The biochar produced (2% to 25% of the weight of dry feedstock) was assumed to be transported to farms for its use as a soil amendment using a medium duty truck and a distance of 100 km to the farm and back to the facility.

Direct emissions:

Direct emissions are associated with natural gas combustion in drying, diesel use in biochar transport and farm equipment and stack emissions during the process. The emissions associated with natural gas and diesel fuel were obtained from the Eco Invent 3 database. The stack emissions were measured experimentally for 500 and 800°C process and factors were used to estimate emissions for other operating conditions.

Indirect emissions:

Indirect emissions associated with biochar production resulted from electricity use in the drying of food waste, grinding and for the control system. These emissions were calculated using SimaPro Eco Invent 3 database for US country grid mix.

Avoided emissions:

The heat generation was considered as the main sources that would provide energy and GHG benefits. Also, the beneficial use of biochar as a soil amendment would offer GHG reduction by displacing the production and consumption of a certain amount of NP K fertilizer. The avoided emissions were calculated using SimaPro 8 software based on emissions from non-distributed US average mix for electricity generation, natural gas displacement for heat generation and displacement of NPK fertilizer use for biochar. Previous life cycle assessment studies have used a biochar application rate of 5-ton carbon per hectare for corn [348] and the same was used in this analysis. Food waste biochar had a total organic carbon content of 62%, and this leads to an application rate of 8.1 ton biochar per hectare.

5.2.5.3. Impact Assessment:

The impact assessment consisted of deriving the GHG carbon dioxide equivalent for the entire system and the net exergy efficiency of the process of biochar production through the steps of drying, grinding and thermochemical conversion. The exergy analysis was performed purely from the operational standpoint and the transportation was not considered.

Measured and literature data were used to estimate the global warming potential (GWP) of thermochemical processing of food waste for all the combinations of process conditions. The process emissions of CO_2 and CO per kg of wet food waste were estimated as explained in Section 5.2.5 and used in the analysis. The emissions due to electricity and heat use were estimated using SimaPro 8 software (https://simapro.com/). The only emissions associated with food waste conversion were carbon dioxide, carbon monoxide and nitrogen due to the use of excess air in catalytic combustion. There were no detectable nitrogen or sulfur oxides, as the catalytic combustion occurs at a temperature between 650-800^{0}C (measured using GUI during the experimental run) and these oxides form only at temperatures above 950-1000^{0}C [362], [363]. Emissions associated with drying and grinding process were assumed to be associated entirely with heat and electricity use, and were also calculated using SimaPro 8 software. The electricity consumption was modeled based on the country mix for the US, and heat consumption was modeled as natural gas combusted in a small-scale industrial boiler. In addition to reducing emissions, biochar can improve the water holding capacity of soil and hence reduce the water requirement of some crops[25]. Biochar also improves mineral uptake of plants due to its excellent cation exchange capacity [364]. These parameters that can potentially provide greater environmental benefits were beyond the scope of this work and not hence analyzed. The only waste stream considered was ash (at 5% of the fuel weight), which can result from process irregularities and biochar combustion due to accidental contact with air, and was modeled as treatment of scrub ash from incinerators. Biochar transportation was modeled for standard diesel truck hauling a

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[25] International biochar initiative: Environmental benefits of biochar. http://www.biobiochar-international.org/biobiochar/benefits

distance of 100 km. The global warming potential was calculated for individual unit operations using IPCC 2013 100a method and then summed to provide an estimate of overall GWP. The reference case used was landfilling of food waste, and the data were obtained from[365], where a 60% utilization of landfill gas produced as a result of food waste conversion, was used to produce energy.

5.3. Results and discussions

This section summarizes the primary findings and interpretation from the exergy and GWP analyses described above.

5.3.1. Biochar production from food waste

During the experiment, the biochar yield n averaged between 7.6 and 7.8% of the food waste fed to the system. The average values of the process parameters measured during 20-minute test intervals are summarized in Table 5.1. The biochar yields were rather low relative to many biomass pyrolysis studies [366]–[368], indicating that a majority of the feedstock LHV is utilized to maintain the process temperature and conserved in the gaseous products due to the use of air. The calculated equivalence ratio (ratio of actual to stoichiometric fuel-to-air ratio; Appendix 5.1) of the process was approximately 0.3.

Table 5.1 Observed process parameters during thermochemical processing of food waste at 800^0C; TiSj represent Test 'i', sample 'j' as the parameters were monitored continuously; T1 and T2 are duplicate runs with same operating conditions

	T1S1	**T1S2**	**T1S3**	**T1S4**	**T1S5**	**T1S6[€]**	**T1S7[€]**	**Overall Average**	
Avg Temp, C	795±37.3	805.3±31.6	806.8±37.5	800.8±32.3	802.3±39.1	642.8±72.2	542.1±23.2	**749.2±101.8**	
Avg power use, W	180±11	182.4±5.5	183.6±6.4	181.5±4.6	182.4±5.6	186±20.3	192±6	**183.4±10.7**	
Feed flow rate, Kg/h	11.8±1.7	10±1	9.3±1.7	9.3±1.4	9.2±1.6	5.8±1.3	6.7±0.8	**9.3±2.5**	
Char flow rate, kg/h	0.69	0.72	0.75	0.51	0.72	0.56	0.61	**0.66±0.1**	
Char yield, %	5.8	7.2	8	5.4	7.8	9.6	9.1	**7.6±1.5**	
*samples collected at regular 20 minutes intervals; [€] the temperature started drop, therefore experiment was stopped and repeated as Test 2									
	T2S1	**T2S2**	**T2S3**	**T2S4**	**T2S5**	**T2S6**	**T2S7**	**T2S8**	**Overall Avg**
Avg Temp, C	808.8±10.7	802.4±15.5	803.1±21.2	786.6±33.2	743.5±39.3	841±34.2	795±26.5	766.8±51.1	**797±46.8**
Avg power use, W	103.6±4.4	98.9±7.4	97.3±7.6	103.3±8.8					**159±40**
Feed flow rate, kg/h	7±0.4	6.9±0.5	5.9±1	7.6±1	12±2.3	10.4±1.6	9.3±0.8	11.1±2.8	**9.1±2.7**
Char flow rate, kg/h	0.50	0.72	0.61	0.64	0.75	0.64	0.64	0.72	**0.66±0.2**
Char yield, %	7.2	10.4	10.4	8.4	6.2	6.1	6.9	6.5	**7.8±1.8**

5.3.2. Determination of energy value of the feedstock

The elemental composition of food waste and biochar are given in Table 5.2. Even though higher heating value (HHV) gives the energy content of the feedstock, the usable energy is indicated by its lower heating value (LHV). Additional biochar properties are given in Appendix 5.7. The predicted LHV of food waste was 25.1 MJ kg^{-1} on a moisture and ash free basis which was in close agreement with the measured value of 24.8 MJ kg^{-1}. The available chemical exergy of food waste at various moisture contents is shown in Figure 5.3. The lower heating value range of 15-20 MJkg^{-1} has been reported in previous studies for food waste and other organic wastes [33], [369]. The LHV of feedstocks however, depends on the moisture content and for food waste varies between 3MJkg^{-1} at a moisture content of 75% to 21 MJkg^{-1} on a moisture-free basis.

Table 5.2. Ultimate analysis of food waste and biochar produced at 800 and 500^{0}C

	Food waste	Biochar @ 800ºC	Biochar@ 500ºC
C	48%	68%	65%
H	3%	1%	2%
O	31%	7%	8%
N	3%	3%	4%
S	0.01%	0.3%	0.3%
Moisture	11%	3%	3%
Ash	5%	23%	21%

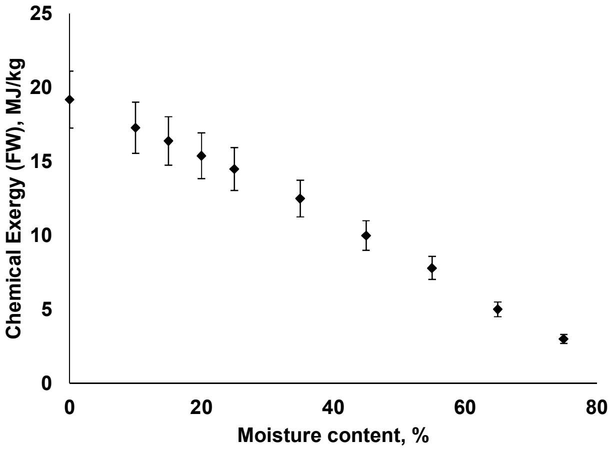

Figure 5.3. The estimated effect of moisture content on chemical exergy of food waste; the error bars represent an expected 10% deviation in lower heating value attributed to the variation in elemental composition

5.3.2. Energy requirement of food waste drying

The feedstock needs drying before grinding or homogenization. The minimum drying energy requirement of a perforated plate belt dryer was calculated as 1710 $\mathrm{MJton_{wet}^{-1}}$ to dry the feedstock from initial moisture of 80% to a final moisture content of 10%. However, after accounting for efficiency, the drying energy requirement went up to 2547 $\mathrm{MJton_{wet}^{-1}}$ for the same initial and final moisture. The latter value represents the exergy input in the form of heated air to dry 1 ton of wet food waste to a final moisture of 10%. The drying energy requirement is a function of initial and final moisture of the feedstock at constant air temperature, air velocity, and atmospheric conditions. The variation in drying energy requirement as a function of final moisture content to which the feedstock is dried to is given in Figure 5.4. An overall mass balance was used to estimate the chemical exergy content of the output waste stream. For example, when 1ton of wet food waste at 75% moisture is dried to 10%, the mass of the dried output is 278 kg by neglecting any chemical reactions or gas phase transitions of the feedstock. For the specified dryer with 96 $\mathrm{kgh^{-1}}$ input flow rate, the output flow rate was calculated as 26.5 $\mathrm{kgh^{-1}}$ by using the mass balance on water and solid streams. From Figure 5.5, the chemical exergy of food waste input is 3000 MJ while the chemical exergy of dryer output ranges between 3500-4800 MJ for final moisture of 10-35%. Therefore drying is an essential step in the thermal processing of food waste, as it improves the chemical exergy content and helps to store the food waste as a better fuel. However, drying is an energy-intensive process that requires net energy input in the form of electricity or heat. Based on the above-stated factors, the exergy efficiencies of the drying process were estimated as varied between 65-81% for drying to a final moisture of 40-10%. The exergy efficiency of drying process to dry the feedstock from an initial moisture of 80% is shown in Appendix 5 (Figure A5.1). The drying efficiency showed a sudden drop beyond 30% final moisture content, which was attributed to lower of LHV of feedstock due to higher moisture content.

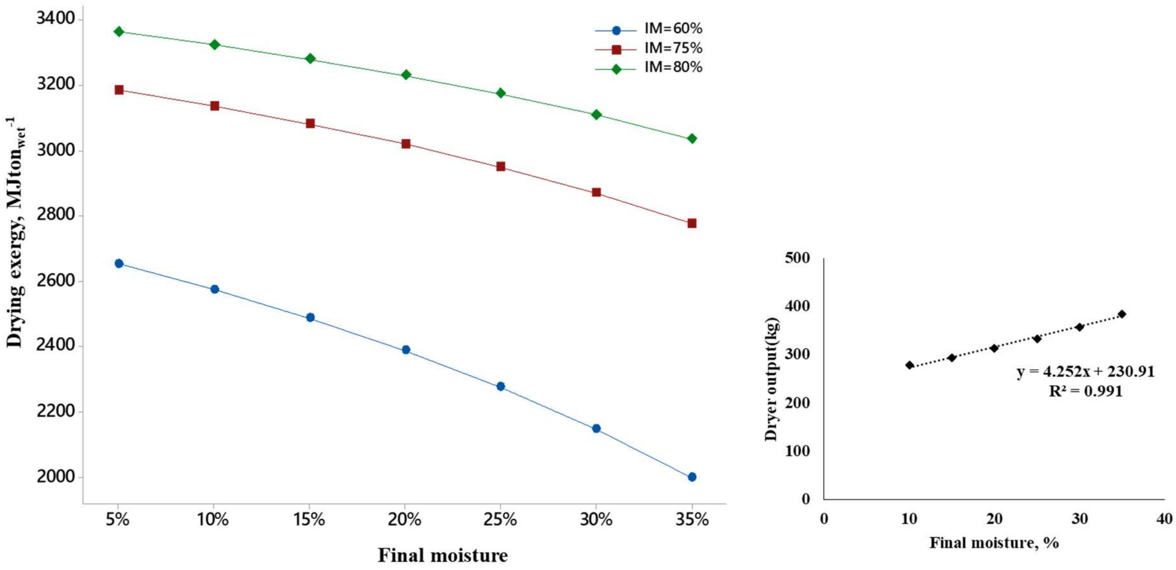

Figure 5.4. The drying energy requirement for drying 1 ton of wet food waste; the additional electricity required to run the equipment are not shown in this graph; IM-initial moisture

The drying energy requirement of a conveyor belt dryer based on empirical and theoretical studies has been reported in the literature for high moisture containing feedstocks, as listed in Table 5.3. The exergy efficiency of drying depends on various factors including drying rate, the type of dryer used, feedstock type, air flow rate, air humidity, drying temperature etc. [370].

Table 5.3: Reported energy consumption in biomass drying using conveyor air dryer (NR = not reported)

Feedstock	**Initial moisture**	**Final moisture**	**Efficiency, %**	**Energy input, MJ$\text{ton}_{\text{wet}}^{-1}$**	**Reference**
Fish residue	78%	15%	50.5%	5500	[371]
Sewage sludge	>70%	10%	NR	2520-4140	[372]
Pine wood chips	45-72%	25%	NR	1260-2500	[373]

5.3.3. Input energy requirement of size reduction

The specified thermal processing unit is capable of handling large particle size of up to 25mm. Therefore the size reduction process would be only a coarse grinding which requires lower energy than fine grinding. Grinding of dry feedstock uses significantly lower energy than grinding of wet feedstock [374]. The grinding energy increases with an increase in moisture content, however, for a coarse grinding (maceration) process, the feedstock moisture does not significantly affect the energy requirements [360]. Table 5.4 lists the reported grinding energy requirements for various feedstocks using hammer mills, widely used in biomass grinding. No mass losses were assumed during grinding and the flow rate was the same as the input mass flow rate of the thermal processing unit. A nameplate capacity of 3.7 kW [356] was used to calculate grinding energy requirement as electricity. The grinding energy requirement varied from 130-1555 MJ for the dryer output at 10%-35% moisture due to variation in feed flow rates.

Table 5.4. Grinding energy requirement of different biomass types on a hammer mill

Feedstock	Final particle size, mm	Feedstock moisture	Energy consumption, MJ/ton DM*	Reference
Miscanthus$^{\#}$	4	15-20%	184	[360]
Switch grass$^{\#}$	6	15-20%	172	[360]
Corn stover$^{\#}$	6	20%	111	[375]
Corn	4	18%	33	[376]
Canola straw$^{\$}$	19	13-15%	9	[359]
Wood chips$^{\#}$	3.2	17%	117	[377]
Peanut shell	5	13%	2.52	[378]

DM: Dry matter; * corrected for DM using moisture content where the values were reported on a wet mass basis; $^{\#}$Lignocellulosic materials are crushed in a prior step before grinding, which increases the overall grinding energy to reduce to a smaller particle size; $^{\$}$ coarse grinding is less energy intensive and does not vary significantly with moisture content

5.3.4. Energy requirement in thermochemical processing

The energy requirement during pyrolysis or gasification depends on feedstock moisture and time required to completely process unit mass of the input. Figure 5.5 shows energy required to preheat the food waste to predefined process temperatures. The higher temperature processes require a higher energy input to attain the desired temperature, which means that a higher fraction of the chemical exergy of the feedstock is lost during preheating. Both preheating and steady-state energy requirements are a function of feedstock moisture and ranged from 660 MJton^{-1} to 1900 MJton^{-1} for food waste with 10% to 35% moisture. The energy required to preheat the feedstock contributed significantly to overall exergy destruction and ranged between 5-17% and the energy required to maintain the steady-state temperature ranged between 12-24% of the feedstock LHV. The combined energy to run the slow pyrolysis process was previously reported to range between 8 and 15% of fuel LHV [81], however this study assumed the use of external heat source during steady state operation. The electrical requirement of the equipment to support the control system and augers was determined from the measured electric draw during the experiments, and was insignificant compared to the fraction of the fuel LHV required to run the process.

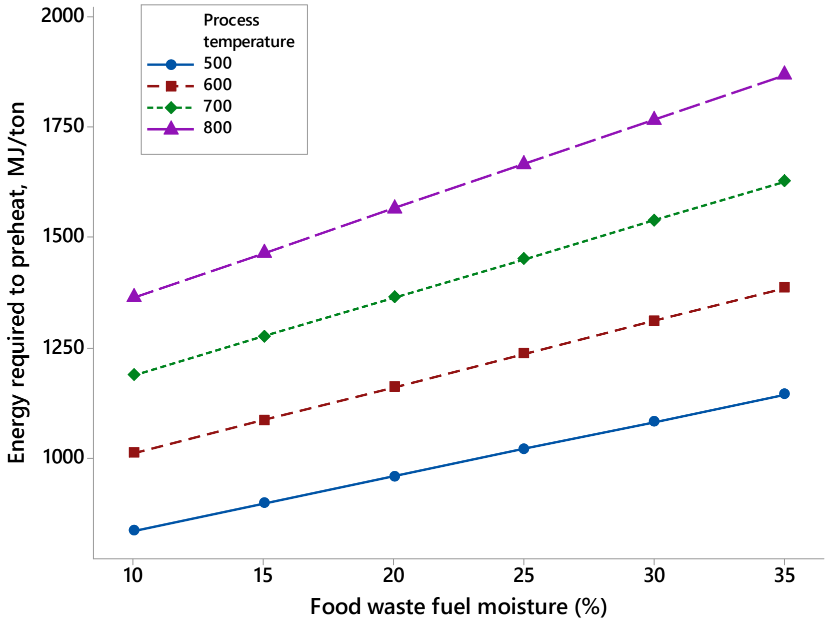

Figure 5.5. Energy required to preheat the food waste to process temperature at different final moisture contents

5.3.5. Environmental and exergetic feasibility of the process

The following scenarios were analyzed for exergy and environmental performance at different combinations of operating conditions.

- BC (soil, waste heat): Biochar produced is used as a soil amendment and waste heat is utilized in drying of the feedstock
- BC (heat, waste heat): Biochar produced is combusted to generate additional heat along with waste heat and employed in the drying of feedstock
- BC (soil, no waste heat): Biochar produced is used as a soil amendment and no waste heat utilized. The VGPs are combusted for air pollution control

Exergy analysis was conducted to study the effect of two principal operating parameters: feedstock moisture and process temperature. Biochar yield was also considered as a process variable since it can be controlled by regulating the airflow. The results from exergy analysis for various combinations of feed moisture and temperature are presented in this section. Three feed moisture levels between 10-35% and four temperature levels between 500-800^{0}C were considered. Temperatures lower than 500^{0}C were not within scope, as at these lower temperatures the pyrolysis reactions for biochar production become endothermic and are not sustainable [361].

Because food waste was used as the sole source of fuel to support thermochemical conversion completely, a significant fraction of chemical exergy of food waste was utilized during the process. This fraction accounted for 33-46% of the total LHV. The exergy destruction or process irreversibility was directly associated with fuel moisture as shown in Appendix 5 (Figure A5.3). The mass loss of feed associated with consumption of LHV leads to reduced yield of biochar. Therefore, the maximum biochar production that can be achieved using food waste was estimated at 6% to 24% of the original feedstock mass. The process was not energy efficient at a lower yield of biochar, and only biochar yields of 14% to 24% helped to achieve an energy efficient operation that could be self-sustaining and in some cases, exceed the external energy requirement. A regression analysis on the iterations showed that overall exergy efficiency of food waste management depends on the biochar yield as shown in Figure 5.6, which in turn depends on process temperature and fuel moisture. This presents a simple case for food waste management with biochar production. Table 5.5 gives predicted and measured values of biochar yield and LHV at two different process temperatures. If an external heating source were employed to preheat the fuel and maintain a steady state, this would save 33-46% of the chemical exergy of food waste which would then be distributed into products. Due to this, in the current configuration with no backup heating, biochar yield cannot be higher than 24%. The maximum stoichiometric air requirement of the food waste used in this study was 6.6 kg air per kg of food waste on a moisture-free basis. Therefore the air supply to the system must be kept lower than 25% of the stoichiometric requirement (approximately 1.5 kg air per kg moisture free food waste) to achieve higher biochar production. In the system under study, because food waste is used as a fuel, the temperature is a function of equivalence ratio or the amount of oxygen supplied (Appendix A5.1). In the current mode of operation, it is not possible to attain ideal pyrolysis conditions unless secondary electric heating is used to maintain the process temperature.

Table 5.5. Measured and estimated biochar yield and LHV at lower and higher limits of process temperature; the estimated biochar yields are from the LHV model for corresponding temperature and moisture conditions. The experimental data provides a certain degree of validation to the predictions used in this study

	Measured	**Estimated**
Process temp=800^{0}C; feed moisture=10.8%		
Biochar yield, %	7.6±1.5	7.9±0.2
Biochar LHV, MJkg^{-1}	24.8	25.1
Process temp=500^{0}C; feed moisture=10.8%		
Biochar yield, %	15.0±1.3	16.0±0.2
Biochar LHV, MJkg^{-1}	24.0	24.4

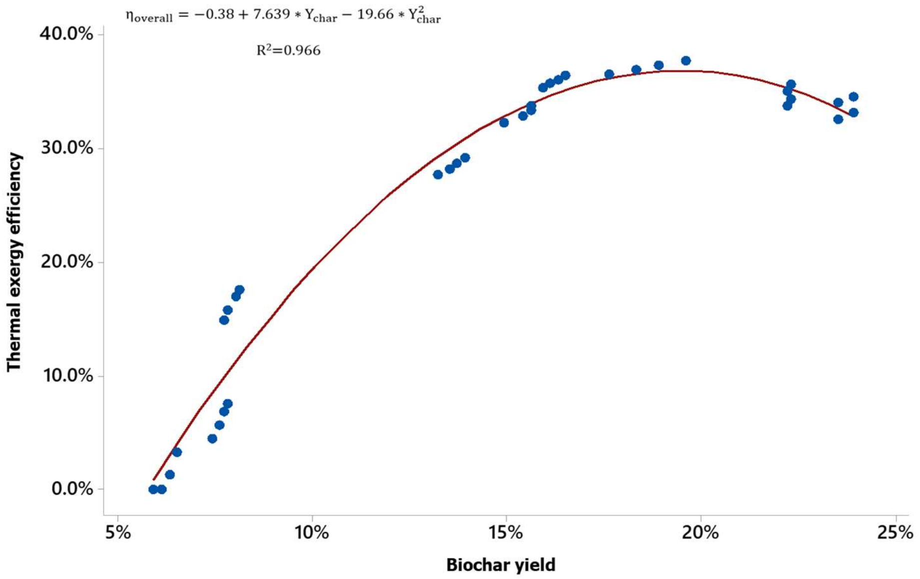

Figure 5.6. Regression analysis showing the dependency of overall exergy efficiency (excludes drying and grinding) on biochar yield

The sustainability of food waste management using thermochemical conversion depends on not just the exergy efficiency but also on the associated environmental impacts. The mass flow rates of exhaust gases were calculated by using measured composition of CO_2, CO, oxygen and water vapor, coupled with nitrogen determined by subtraction. For food waste processed at 10.8% input fuel moisture and 7.6% biochar yield, the calculated CO_2 emissions were 690 kg CO_2/dry ton food waste or 190 kg CO_2/wet ton food waste input, resulting only from the catalytic combustion of gaseous products generation during thermochemical conversion of food waste. Carbon monoxide emissions were relatively small (48 kg CO/dry ton of food waste). The exhaust emissions contain CO_2 that result from food waste processing and hence can be considered biogenic. A major percentage of the emissions resulted from the heat energy input required during the drying process corresponding to approximately 75% of the overall process emissions. The GWP of 56 to 115 $kgCO_2eton_{wet}^{-1}$ for drying, 11 to 16 $kgCO_2eton_{wet}^{-1}$ for grinding and -83 to 143 $kgCO2eton_{wet}^{-1}$ for thermal processing were estimated for all the scenarios when avoided emissions from landfilling were not considered. All the stack emissions were considered biogenic and SimaPro assigned a value of zero since these emissions resulted only from food waste. A major GWP reduction occurred because of the displaced natural gas use in both Options. The impacts associated with biochar transport and ash treatment were insignificant. The GWP resulting from landfilling of food waste have been reported in the literature before as 855 $kgCO2eton_{dry}^{-1}$ [365]. The landfill emissions calculated using EPA WARM model [379] also resulted in a similar emission factor of 840 $kgCO2eton_{dry}^{-1}$ managed in a landfill with energy generation and assigned carbon sequestration credits.

The operating parameters under different scenarios showed varying effects on GWP and exergy efficiency as shown in Figures 5.7 through 5.9. The moisture content did not have a statistically significant effect on efficiency or GWP in BC (soil, waste heat) scenario (Figure 5.7). When biochar was used for heat production along with heat utilization, an increase in efficiency at lower fuel moisture led to an increase in GWP. These estimates indicate that, if biochar is used for heat production, it would be reasonable to keep the moisture at intermediate levels to achieve a balance between exergy efficiency and GWP. On the contrary, when biochar used as a soil amendment and no waste heat utilized, the efficiency was inversely proportional to GWP. When the fuel moisture content is higher, the amount of drying energy needed is much lower which also correspond to a lower natural gas use and hence lower emissions resulting from natural gas combustion. This indicates that higher fuel moisture helps to reduce GWP since a lower amount of drying energy is required. In summary, the higher moisture content of 35% is favorable when biochar is used as a soil amendment and lower fuel moisture levels of 10-20% must be maintained if biochar must be used in heat production.

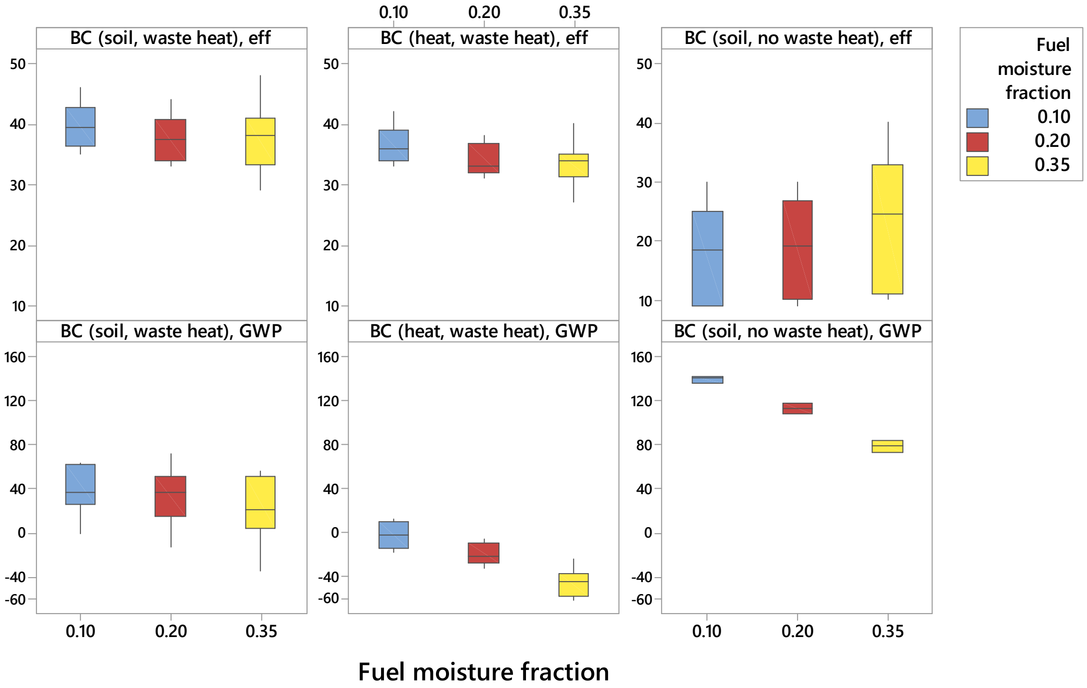

Figure 5.7- Effect of fuel moisture content on overall exergy efficiency and GWP; exergy efficiency (eff) presented as % and GWP in kg CO_2e/ton wet food waste

Unlike fuel moisture, the temperature did not have a significant effect on exergy efficiency or GWP except for BC (soil, waste heat) scenario. Lower temperatures helped reducing emission in BC (soil, waste heat) scenario and did not have a major effect on other scenarios. Maintaining a lower process temperature requires slightly smaller amounts of LHV of the feedstock and hence a higher fraction of the LHV of the feedstock would be available for biochar production. Depending on whether biochar is used as a soil amendment or as a fuel, high temperature process would increase emissions and reduce efficiency as shown in Figure 5.8. However, the difference between these results were not statistically significant. Lower temperatures favor the production of biochar and hence higher LHV of biochar will be available to generate heat. Therefore, in the BC (heat, waste heat) scenario, lower temperatures slightly increase efficiency as well as help reduce emissions. When biochar is used in heat generation, there are direct emissions associated with biochar which are considered biogenic since biochar is produced from food waste. Since reasonable exergy efficiencies are achieved even at low temperature, it is recommended to run the process at 500-600ºC especially when biochar is used as a soil amendment.

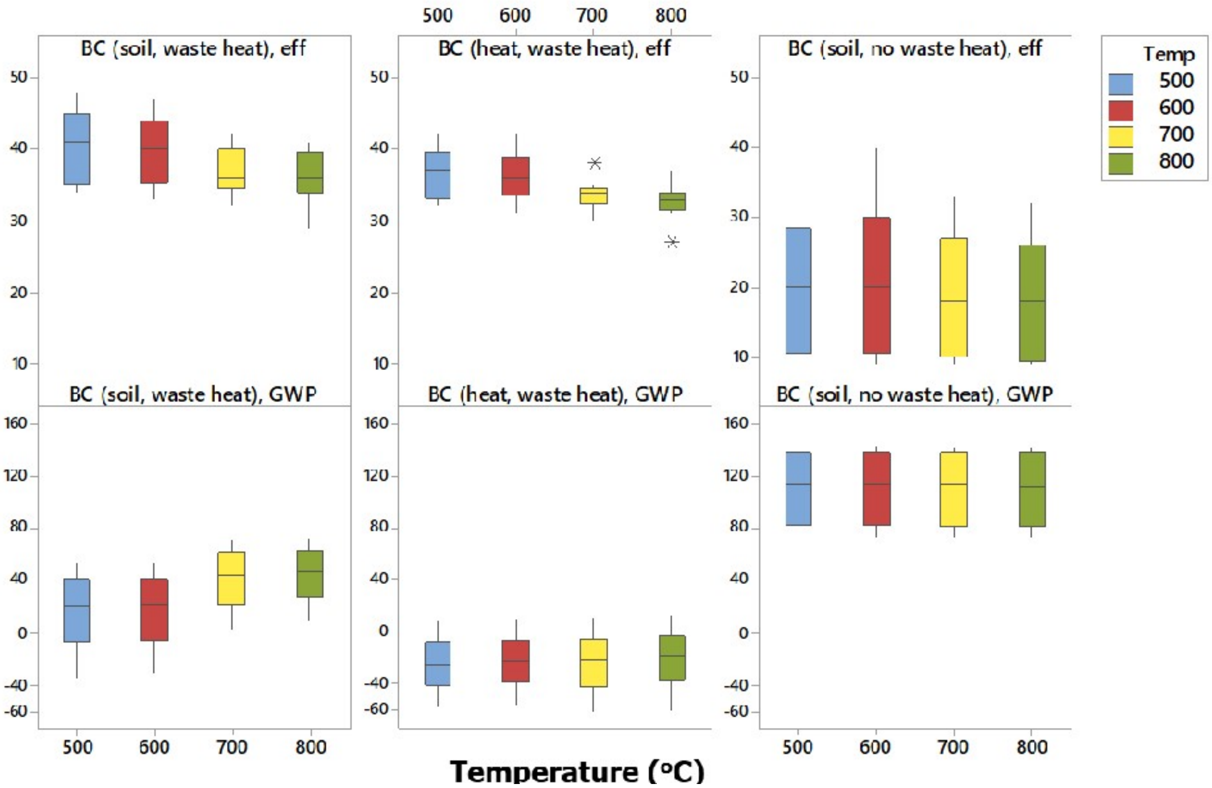

Figure 5.8: Effect of process temperature on overall exergy efficiency and GWP; exergy efficiency (eff) presented as % and GWP in kg CO_2e/ton wet food waste.

The biochar yield had the highest impact on both exergy efficiency and GWP. As shown in regression analysis in Figure 5.6, the thermal exergy efficiency is a strong function of expected biochar yield. The biochar yield reaches a thermodynamic maximum between 20-30%. Generally a maximum exergy efficiency was observed when the biochar yield was within the thermodynamic maximum range since, this also corresponds to a higher mass of biochar and hence higher LHV. Interestingly, in BC (soil, waste heat) and BC (soil, no waste heat) scenarios, an increase in efficiency also increased emissions. However, in BC (heat, waste heat) scenario, the correlation was the opposite. When biochar is used in heat generation, a significant amount of emissions from natural gas use are avoided since the heat generated is used to dry the feedstock.

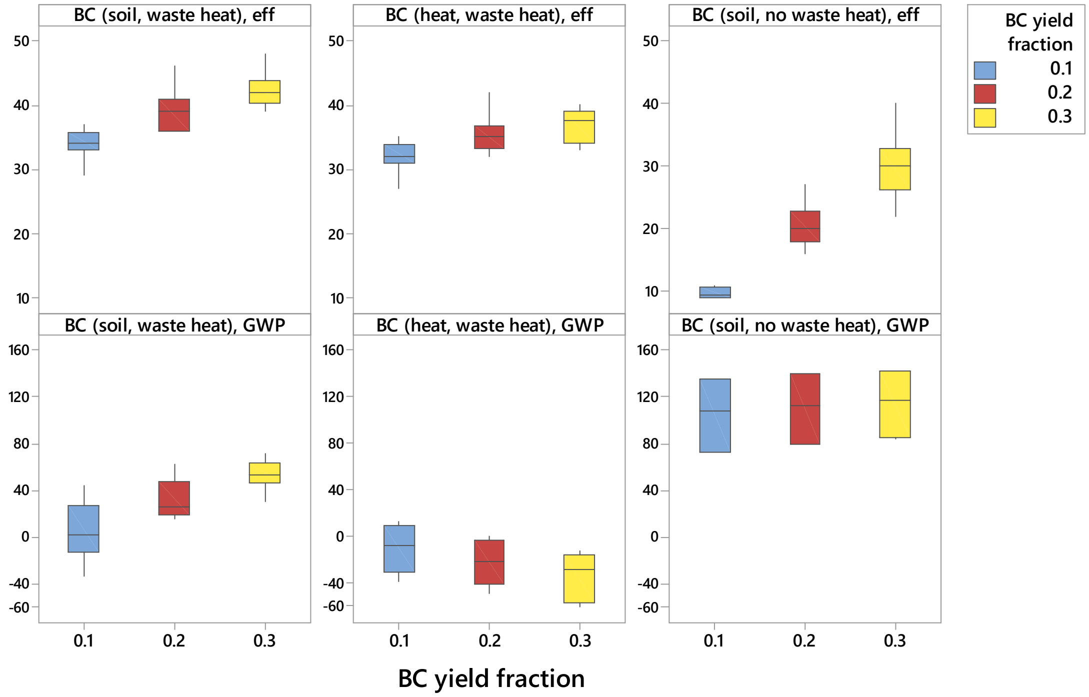

Figure 5.9: Effect of biochar yield on overall exergy efficiency and GWP; exergy efficiency (eff) presented as % and GWP in kg CO_2e/ton wet food waste.

The exergy efficiency of biochar production with waste heat utilization varied between 29 and 48% for all the combinations and GWP between -61 to 138 kg CO_2e ton FW_{wet}^{-1}. The exergy efficiency for BC (heat, waste heat) and BC (soil, no waste heat) ranged from 27-42% and 9-40% respectively and GWP from -61 to 138 and 73 to 143 kg CO_2e ton FW_{wet}^{-1}. From both exergy and environmental standpoint, the use of biochar as a soil amendment with waste heat utilization was the most suitable option and BC (heat, waste heat) was the next suitable option. Both exergy efficiency and GWP are negatively impacted when the system is purely used for waste management without any energy generation. In BC (soil, waste heat) scenario, a more clear correlation between exergy efficiency and GWP was obtained as shown in Figure 5.10.

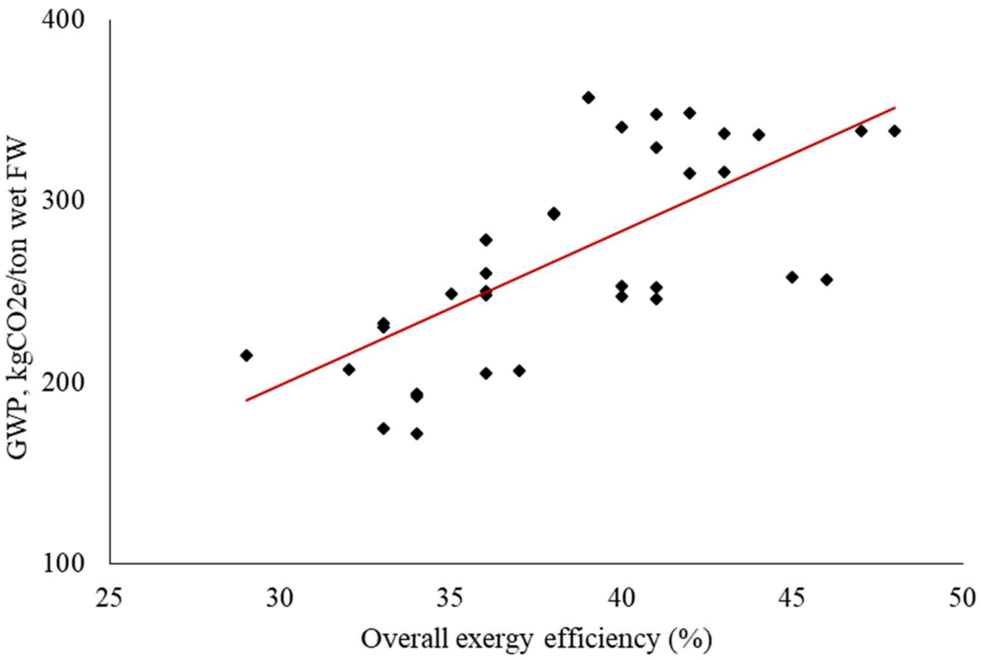

Figure 5.10. Correlation between overall exergy efficiency and GWP in BC (soil, waste heat) scenario.

As drying is the most energy intensive unit operation in the overall thermochemical process, to completely support drying, the minimum amount of heat that should be produced by thermal processing of 1-ton wet food waste is 2100-2600 MJ. Therefore, out of the chemical exergy of the feedstock, a minimum of 2100-2600 MJ must be utilized towards heat production to aid the use of waste heat in feedstock drying. However, to produce useful work in the form of heat, a higher percentage of feedstock LHV is required, which leads to further losses. The energy losses during heat production are often associated with combustion and heat exchanger efficiencies. This scenario assumes that the primary product from thermochemical conversion of food waste is thermal energy or heat. Any biochar produced during the process will be fed back along with food waste as a fuel to support heat production and 90% of the chemical exergy of biochar would be available as heat energy. When biochar is recycled back as a fuel in the system, the process becomes feasible irrespective of the process conditions. This analysis indicated that, the process can completely self-sustain when biochar is used as a supplemental fuel. Biochar yield of 2.3-7.9% can still be achieved when a fraction of biochar produced is used to produce heat.

In a study that experimentally investigated the impact of various operating conditions on the pyrolysis gas composition and energy content, it was concluded that the process temperatures above 450^{0}C were required to fulfill the minimum energy need of the process, however, temperatures above 650^{0}C were required to achieve maximum heat production [380]. They also suggested combustion of gas fraction to sustain the pyrolysis process irrespective of whether the process is optimized for biochar or bio-oil production. A universal energy model applied to a slow pyrolysis process of ‘standard biomass’[26] to produce biochar and heat and in this analysis biomass moisture content was directly found to influence the energy value of the output [81]. The combustion of biochar and non-condensable gases has been suggested as a strategy to self-sustain a fast pyrolysis process from waste biomass for bio-oil production [329]. For an air gasification process for a ‘standard biomass’ analyzed using a thermodynamic equilibrium model, drying was found to be the essential step in increasing the overall energy output and recommended the use of pressurized reactors for reducing the temperature of the process [339]. Based on the analyses done in the current study, Option 2 (soil, waste heat) was the most feasible option for a feed moisture range of 10-35% and operating temperature of 500-800^{0}C, which would still result in a biochar yield of 2.3-7.9% of the input food waste. Option 1 (soil, no waste heat) was infeasible for moisture level 10-20% and feasible for moisture levels above 20% at lower temperature range of 500-600^{0}C attributed to increased drying energy demand and reduced heat production. Therefore, if biochar production for beneficial uses other than fuel is the goal, fuel moisture of above 20% and temperature between 500-600^{0}C could be used.

A comparative assessment [347] indicated that the maximum carbon abatement can be achieved through increased biochar production both in pyrolysis and gasification system. The emission benefits associated with thermochemical processing were significant compared to current practices such as composting and landfilling, waste-to-energy incineration and anaerobic digestion. Net emissions of 100 to 239 $kgCO_2eton_{wet}^{-1}$ (approximately 357 to 853 $kgCO_2eton_{dry}^{-1}$) has been reported for composting [381]. In a comparative study for management of municipal food waste, GWPs in $kgCO2eton_{dry}^{-1}$ of -350 to -45 for anaerobic digestion, -192 to 62 for composting, -350 to -28 for waste-to-energy and -260 to 260 for a highly managed landfill were reported [351]. While there is an inconsistency in GWP of various technologies in the literature, these inconsistencies are mainly due to the methods and factors used in calculation, and treatment of byproducts. The proposed thermochemical conversion can be highly beneficial to the environment

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[26] Standard biomass does not specify the type of biomass, rather a general composition is assumed to calculate the heating values

since there are no methane and nitrogen oxide emissions. Also, all the emissions associated with the main processing step are biogenic, as food waste is the only fuel source used. These emissions may increase when a supplementary fuel like paper board or other paper products from the food industry are used. Biochar systems can potentially offer greater benefits when quantitative data on beneficial uses of biochar becomes more easily available. In summary, it is pertinent to note that systems with high exergy efficiency need not have lower GWP and vice versa. Therefore, it becomes imperative while assessing newer technologies, especially for waste management applications, to evaluate both technological and environmental performance.

The correlation between exergy efficiency and GWP is an important parameter on the operational stand point. As applications and market for biochar are not well established, it is important to carefully consider practical uses of biochar in ways that would be beneficial on energy and environmental stand point. As biochar is a major product of the proposed process, while higher yield of biochar favors the exergy efficiency, it contradicts environmental efficiency by increasing the GWP under certain circumstances. Since in this analysis, it is assumed that no external source of energy such as electricity is used to operate the pyrolyzer (or food waste is the sole source of fuel), no significant difference in the process efficiency was observed with changing temperatures.

5.4. Conclusions

Food waste valorization using a thermochemical process capable of managing 700 to 1000 ton per year was analyzed for exergy efficiency and global warming potential (GWP). The major contribution of this work were:

- This work provided the most practical scenarios for the thermochemical conversion of food waste through a combination of exergy and environmental feasibility.
- The results from these analyses provides useful information on optimum operating parameters for efficient management of food waste using a smaller scale thermochemical process that may be suitable for deployment at individual large waste generation sites, instead of in a centralized configuration.

This study however was limited in several respects:

- The type of dryer and grinder can have a significant impact on input energy due to varying efficiencies that are not included in this study. Also, belt dryers effectively dry to a final moisture of 25% in a single stage, after which there may be a need for multi-stage drying [373]. Multi-stage drying was not considered in this study for moisture content lower than 25%, however an underestimation of drying efficiency was applied to account for these cases.
- The global warming potential estimations provided preliminary data in this study. The sensitivities to dryer type and treatment of byproducts were not considered and the analysis was not performed for a base case such as landfilling or incineration.
- The exergy analysis was carried out for discrete data intervals of temperature and feedstock moisture, and may vary when the data interval is continuous.

In summary, the correlations between the process parameters and exergy efficiency as well as GWP were estimated. The exergy efficiency for BC (heat, waste heat) and BC (soil, no waste heat) ranged from 27-42% and 9-40% respectively and GWP from -61 to 138 and 73 to 143 kg CO_2e ton FW_{wet}^{-1}. Under any circumstance, a minimum of 14% biochar should be produced to make biochar production feasible, and less than 14% yields are necessary to achieve higher thermal energy efficiency. Preliminary studies indicated that when biochar was used as a fuel to produce heat energy, an increase in exergy efficiency led to a slight decrease in emissions, however this behavior was the opposite in other scenarios. Considering the existing biochar market, offering commercial pricing that is uncertain at best, dedicating such systems to producing thermal energy as a byproduct of food waste management may be the more sustainable option at the present time.

CHAPTER 6

CONCLUSIONS AND CONTRIBUTIONS

The adoption of waste to energy and valorization technologies have been increasing with time as indicated by growing number of food waste digesters[27] and a small number of newly developed food waste fermentation plants[28]. The adoption of landfill ban policy is associated with a large quantity of food waste generation that require diversion and processed using a renewable technology. Due to biodegradability of food waste, storage is not possible and hence requires a high capacity of renewable infrastructure for its management. To address these issues, this dissertation evaluated three valorization options based on technological factors such as process instabilities, product yield and exergy efficiency.

To understand the compositional variability and chemical characteristics of food wastes from institutional and industrial origin, a detailed characterization study was carried out (Chapter 2). The extensive data inventory provided here is useful for the research communities working on food waste modeling and the operators, anyone who does not have resources to characterize their waste and for the waste management facilities looking for a quick evaluation of certain types of food waste. The data presented in Chapter 2 can be used with an acceptable confidence in other studies as many of the characteristics were verified by laboratory measurements. Even though there was no contribution to the originality of data, the existing knowledge was expanded and validated through this study. The outcomes from this chapter can be used in a qualitative preliminary screening of valorization options and track any process related issues by understanding the characteristics associated with it.

In Chapter 3, anaerobic digestion of food scraps was evaluated using an unconventional co-digestion approach. Even though anaerobic digestion is a mature technology for management of organic wastes like animal manure, it often was found to lead to an unstable process when digesting

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[27] American Biogas Council. Operating biogas digesters in the US. https://www.americanbiogascouncil.org/biogas_maps.asp

[28] NREL Biofuel Atlas. https://maps.nrel.gov/biofuels-atlas/#/?aL=yilN7K%255Bv%255D%3Dt&bL=groad&cE=0&lR=0&mC=40.21244%2C-91.625976&zL=4

food scraps [98]. Currently food waste is co-digested with cow manure at 20-30% by volume. As the food waste generation continues to grow, the capacity factor of food waste processing must increase and hence there is going to be a need for dedicated food waste digesters in a non-farm environment. To address this imminent issue of instabilities associated with digestion, food scrap co-digestion was studies experimentally using unconventional cosubstrates that were chosen based on their characteristics and their local generation quantities. In Chapter 3, a solution was provided to avoid instabilities associated with food scrap digestion without using expensive methods like ammonia stripping [249] and trace element supplementation [237]. The outcomes from this Chapter provide guidelines to the operators of dedicated food waste digesters about the threshold of several operating parameters and troubleshooting in the event of a digester failure. Since a solution was provided for digestion of food scraps at higher organic loading rates, this research can have significant impact on reducing the design volume of the dedicated food waste digesters and hence achieve improved economics.

While Chapter 3 addressed a prominent issue associated with a currently existing food waste management technology, possibility of using a newer option-fermentation were evaluated in Chapter 4. Even though fermentation is technologically mature, its application in food waste management is not a common practice. In Chapter 3, various food wastes were screened for the production of value added chemicals such as ethanol, 1-butanol, iso-butanol, lactic acid and succinic acid. Through a systematic screening using experimental and published data, Chapter 3 provided a "State of the art" knowledge on possibility of using fermentation in food waste management. A matrix was developed to map the suitability of choosing a suitable production pathway for food waste. This matrix is very helpful to newer businesses that are developing in the waste management world to assess the possibility of an additional economic revenue through production of 'low value high volume[29]' products such as the ones screened in this study.

Finally, a thermochemical process comprising a hybrid gasification/pyrolysis mechanism was evaluated for the production of energy and value added material such as biochar. Use of thermochemical processing for the management of waste biomass is shaping up as evidenced by a number of research publications. The use of these technologies in food waste is not in practice and

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[29] A standard term used in bioprocessing to represent the products that have lower production cost, lower market price and high demand

not reported in literature. The feasibility of using thermochemical processing was evaluated using an exergy analysis and life cycle thinking approach using a combination of empirically obtained and estimated data inputs. Two most practical options for thermochemical processing of food waste were proposed based on exergy efficiency and their global warming potential was estimated. The outcomes from Chapter 5 provided novel contributions to fill an important knowledge gap in the field of food waste management. With the use of appropriate operating conditions, thermochemical conversion technology analyzed in this Chapter was recommended for small scale, onsite or distributed management of food waste. With further development of technology to cover a range of organic waste resources, it offers promising alternative to landfilling and other less efficient methods of food waste management. Thermochemical conversion processes have potential to offer solutions to the management of packaged food waste, digestate, the solid sludge from fermentation and a variety of other food waste. Thermochemical processes are an integral part of future biorefineries.

Further, the feasibility matrix can be extended to include other potential valorization technologies to provide a comprehensive picture of a number of options available for food waste valorization. The metrics such as lower heating value or biochar yield can be used for thermochemical conversion processes. The existing knowledge is sufficient to map AD to different food wastes, however it is important to note that the food wastes that can be processed through AD need not produce the byproduct digestate due to lower fiber content and the food wastes with higher fiber content generally do not have a higher biomethane potential. If any of the valorization methods stated are not possible, then the food waste can be composted or used in animal feed production. This dissertation via initial technical evaluation, opened up numerous research and development opportunities for the systematic assessment of food waste technologies for their economic, environmental and social performance. Economic sustainability can be achieved by combining different technologies in a synergistic manner as shown in Figure 6.1(reintroduction of Figure1.6) and this dissertation provides important pieces of information for the biorefinery concept.

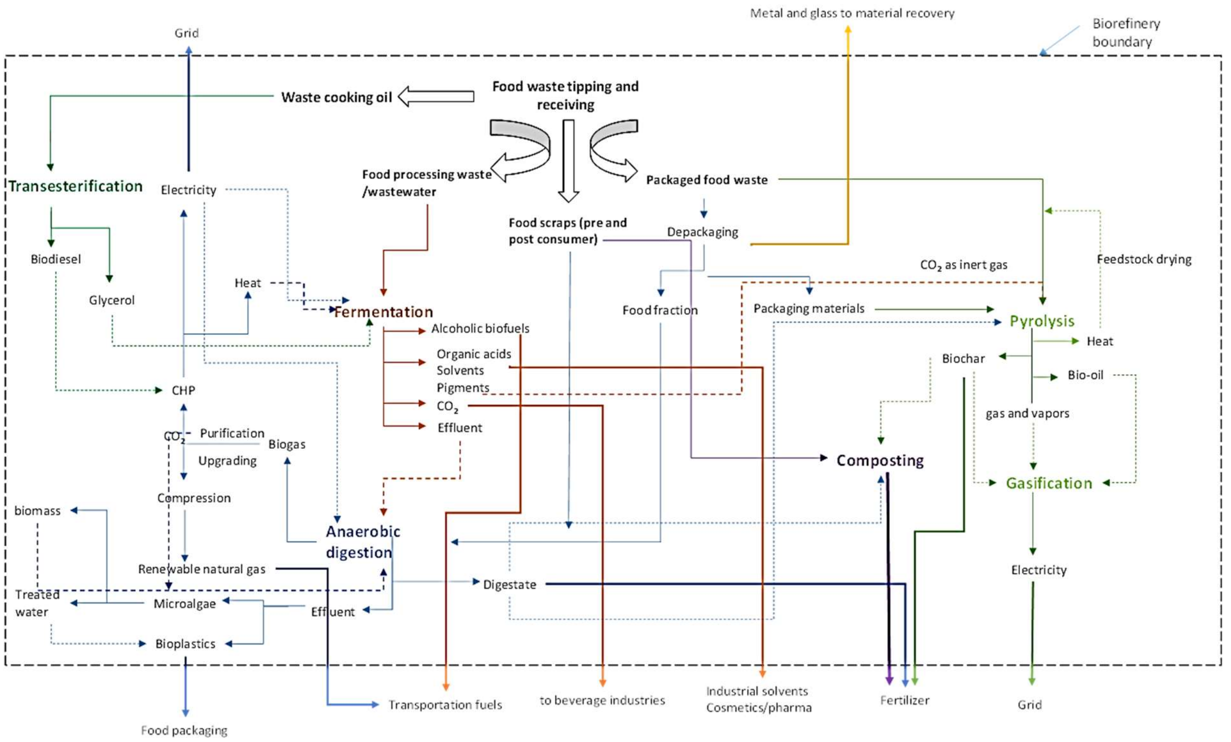

Figure 6.1. Biorefinery concept-the big picture; this dissertation provides important technical and environmental information for multiple components of the proposed food waste biorefinery.

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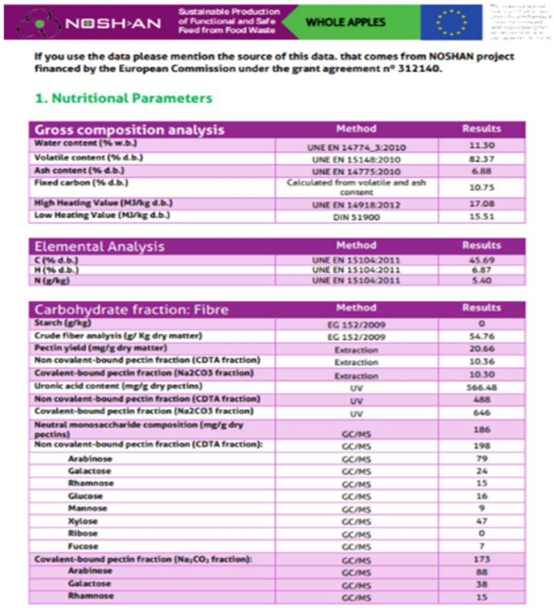
APPENDICES

This section provides supplementary materials to selected sections as referred in the main body of the chapters. Appendices are numbered corresponding to the chapters they appear in.

APPENDIX 2



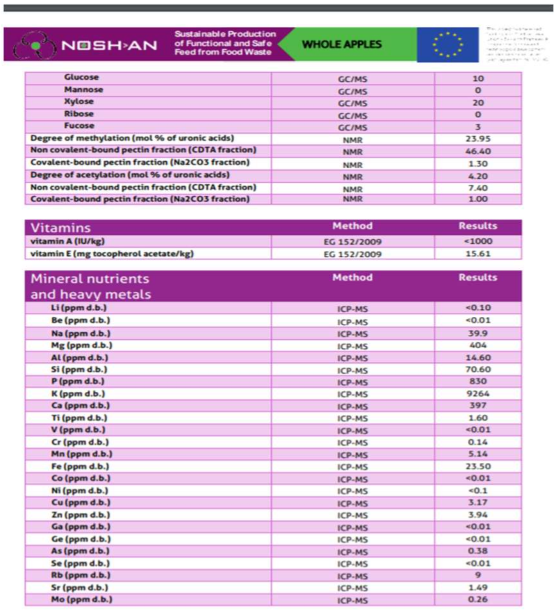
If you use the data please mention the source of this data. that comes from NOSHAN project financed by the European Commission under the grant agreement n° 312140.

1. Nutritional Parameters

Gross composition analysis	Method	Results
Water content (% w.b.)	UNE EN 14774_3:2010	11.30
Volatile content (% d.b.)	UNE EN 15148:2010	82.37
Ash content (% d.b.)	UNE EN 14775:2010	6.88
Fixed carbon (% d.b.)	Calculated from volatile and ash content	10.75
High Heating Value (MJ/kg d.b.)	UNE EN 14918:2012	17.08
Low Heating Value (MJ/kg d.b.)	DIN 51900	15.51

Elemental Analysis	Method	Results
C (% d.b.)	UNE EN 15104:2011	45.69
H (% d.b.)	UNE EN 15104:2011	6.87
N (g/kg)	UNE EN 15104:2011	5.40

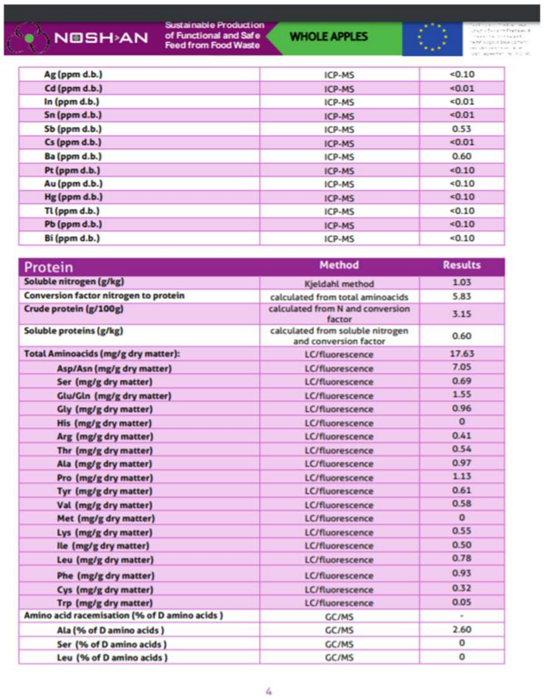
Carbohydrate fraction: Fibre	Method	Results
Starch (g/kg)	EG 152/2009	0
Crude fiber analysis (g/ Kg dry matter)	EG 152/2009	54.76
Pectin yield (mg/g dry matter)	Extraction	20.66
Non covalent-bound pectin fraction (CDTA fraction)	Extraction	10.36
Covalent-bound pectin fraction (Na2CO3 fraction)	Extraction	10.30
Uronic acid content (mg/g dry pectins)	UV	566.48
Non covalent-bound pectin fraction (CDTA fraction)	UV	488
Covalent-bound pectin fraction (Na2CO3 fraction)	UV	646
Neutral monosaccharide composition (mg/g dry pectins)	GC/MS	186
Non covalent-bound pectin fraction (CDTA fraction):	GC/MS	198
Arabinose	GC/MS	79
Galactose	GC/MS	24
Rhamnose	GC/MS	15
Glucose	GC/MS	16
Mannose	GC/MS	9
Xylose	GC/MS	47
Ribose	GC/MS	0
Fucose	GC/MS	7
Covalent-bound pectin fraction (Na_2CO_3 fraction):	GC/MS	173
Arabinose	GC/MS	88
Galactose	GC/MS	38
Rhamnose	GC/MS	15



Glucose	GC/MS	10
Mannose	GC/MS	0
Xylose	GC/MS	20
Ribose	GC/MS	0
Fucose	GC/MS	3
Degree of methylation (mol % of uronic acids)	NMR	23.95
Non covalent-bound pectin fraction (CDTA fraction)	NMR	46.40
Covalent-bound pectin fraction (Na2CO3 fraction)	NMR	1.30
Degree of acetylation (mol % of uronic acids)	NMR	4.20
Non covalent-bound pectin fraction (CDTA fraction)	NMR	7.40
Covalent-bound pectin fraction (Na2CO3 fraction)	NMR	1.00

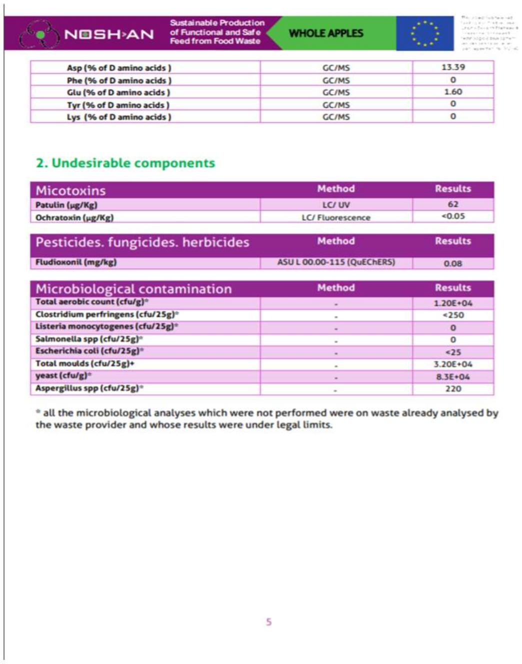
Vitamins	Method	Results
vitamin A (IU/kg)	EG 152/2009	<1000
vitamin E (mg tocopherol acetate/kg)	EG 152/2009	15.61

Mineral nutrients and heavy metals	Method	Results
Li (ppm d.b.)	ICP-MS	<0.10
Be (ppm d.b.)	ICP-MS	<0.01
Na (ppm d.b.)	ICP-MS	39.9
Mg (ppm d.b.)	ICP-MS	404
Al (ppm d.b.)	ICP-MS	14.60
Si (ppm d.b.)	ICP-MS	70.60
P (ppm d.b.)	ICP-MS	830
K (ppm d.b.)	ICP-MS	9264
Ca (ppm d.b.)	ICP-MS	397
Ti (ppm d.b.)	ICP-MS	1.60
V (ppm d.b.)	ICP-MS	<0.01
Cr (ppm d.b.)	ICP-MS	0.14
Mn (ppm d.b.)	ICP-MS	5.14
Fe (ppm d.b.)	ICP-MS	23.50
Co (ppm d.b.)	ICP-MS	<0.01
Ni (ppm d.b.)	ICP-MS	<0.1
Cu (ppm d.b.)	ICP-MS	3.17
Zn (ppm d.b.)	ICP-MS	3.94
Ga (ppm d.b.)	ICP-MS	<0.01
Ge (ppm d.b.)	ICP-MS	<0.01
As (ppm d.b.)	ICP-MS	0.38
Se (ppm d.b.)	ICP-MS	<0.01
Rb (ppm d.b.)	ICP-MS	9
Sr (ppm d.b.)	ICP-MS	1.49
Mo (ppm d.b.)	ICP-MS	0.26



Ag (ppm d.b.)	ICP-MS	<0.10
Cd (ppm d.b.)	ICP-MS	<0.01
In (ppm d.b.)	ICP-MS	<0.01
Sn (ppm d.b.)	ICP-MS	<0.01
Sb (ppm d.b.)	ICP-MS	0.53
Cs (ppm d.b.)	ICP-MS	<0.01
Ba (ppm d.b.)	ICP-MS	0.60
Pt (ppm d.b.)	ICP-MS	<0.10
Au (ppm d.b.)	ICP-MS	<0.10
Hg (ppm d.b.)	ICP-MS	<0.10
Tl (ppm d.b.)	ICP-MS	<0.10
Pb (ppm d.b.)	ICP-MS	<0.10
Bi (ppm d.b.)	ICP-MS	<0.10

Protein	Method	Results
Soluble nitrogen (g/kg)	Kjeldahl method	1.03
Conversion factor nitrogen to protein	calculated from total aminoacids	5.83
Crude protein (g/100g)	calculated from N and conversion factor	3.15
Soluble proteins (g/kg)	calculated from soluble nitrogen and conversion factor	0.60
Total Aminoacids (mg/g dry matter):	LC/fluorescence	17.63
Asp/Asn (mg/g dry matter)	LC/fluorescence	7.05
Ser (mg/g dry matter)	LC/fluorescence	0.69
Glu/Gln (mg/g dry matter)	LC/fluorescence	1.55
Gly (mg/g dry matter)	LC/fluorescence	0.96
His (mg/g dry matter)	LC/fluorescence	0
Arg (mg/g dry matter)	LC/fluorescence	0.41
Thr (mg/g dry matter)	LC/fluorescence	0.54
Ala (mg/g dry matter)	LC/fluorescence	0.97
Pro (mg/g dry matter)	LC/fluorescence	1.13
Tyr (mg/g dry matter)	LC/fluorescence	0.61
Val (mg/g dry matter)	LC/fluorescence	0.58
Met (mg/g dry matter)	LC/fluorescence	0
Lys (mg/g dry matter)	LC/fluorescence	0.55
Ile (mg/g dry matter)	LC/fluorescence	0.50
Leu (mg/g dry matter)	LC/fluorescence	0.78
Phe (mg/g dry matter)	LC/fluorescence	0.93
Cys (mg/g dry matter)	LC/fluorescence	0.32
Trp (mg/g dry matter)	LC/fluorescence	0.05
Amino acid racemisation (% of D amino acids)	GC/MS	-
Ala (% of D amino acids)	GC/MS	2.60
Ser (% of D amino acids)	GC/MS	0
Leu (% of D amino acids)	GC/MS	0



Asp (% of D amino acids)	GC/MS	13.39
Phe (% of D amino acids)	GC/MS	0
Glu (% of D amino acids)	GC/MS	1.60
Tyr (% of D amino acids)	GC/MS	0
Lys (% of D amino acids)	GC/MS	0

2. Undesirable components

Micotoxins	Method	Results
Patulin (µg/Kg)	LC/ UV	62
Ochratoxin (µg/Kg)	LC/ Fluorescence	<0.05

Pesticides. fungicides. herbicides	Method	Results
Fludioxonil (mg/kg)	ASU L 00.00-115 (QuEChERS)	0.08

Microbiological contamination	Method	Results
Total aerobic count (cfu/g)*	-	1.20E+04
Clostridium perfringens (cfu/25g)*	-	<250
Listeria monocytogenes (cfu/25g)*	-	0
Salmonella spp (cfu/25g)*	-	0
Escherichia coli (cfu/25g)*	-	<25
Total moulds (cfu/25g)+	-	3.20E+04
yeast (cfu/g)*	-	8.3E+04
Aspergillus spp (cfu/25g)*	-	220

* all the microbiological analyses which were not performed were on waste already analysed by the waste provider and whose results were under legal limits.

Figure A2.1. Screen shots of a typical food waste characterization data from NOSHAN Database

Table A2.1. Methods used in food waste characterization

Characteristics	Method	Reference
pH	The food waste was centrifuged and pH of the supernatant was measured using a Mettler Toledo pH meter	Standard method
Chemical oxygen demand (COD)	Standard assay kit (Hach)	https://www.hach.com/codguide
Total solids and volatile solids	EPA method 1684	(EPA, 2001)
Total sugars	Phenol sulfuric acid method	[286]
Reducing sugars	Dinitro salicylic acid assay	[382]
Total proteins	Bradford assay	Bradford protein assay[30]
Total lipids	Analyzed by a third party lab using ether extraction method	AAFCO[31]
Elemental analysis (organic)	Third party lab-Elemental analyzer	ASTMD5273
Elemental analysis (inorganic)	Third party lab-ICP anlyzer	ASTM D5185
Heating value	Calculated	
Sugar profiling	HPLC	See below

A2.1. Sugar profile using HPLC

Shimadzu UFLC with an auto sampler and Refractive Index detector was used in the analysis of alcohols and organic acids. A Phenomenex ROA-organic acid-H^+ column was used with deionized water as mobile phase at a flow rate of 0.6 mL/min. The detection was facilitated using a refractive index detector. The column was capable of analyzing sugars in combination with organic acids and alcohols.

A 2.2. Analysis of carbohydrates and proteins

Total carbohydrates were analyzed using phenol-sulfuric acid method and reducing sugars were estimated using Dinitro salicylic acid assay. The liquid effluents were used in the assay after appropriate dilution. Apple and tomato pomace hydrolysate were prepared by suspending 10% w/v of the pomaces in 2%v/v sulfuric acid. This suspension was autoclaved for 20 mins at 121^0C and 100 kPa. The resulting solution was filtered and then used in total sugars and reducing sugars

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[30] http://home.sandiego.edu/~josephprovost/Protein%20Assay%20Std%20Protocol.pdf

[31] https://www.aafco.org/Portals/0/SiteContent/Laboratory/Fat_Best_Practices_Working_Group/Crude_Fat_Methods_Considerations.pdf

analysis after pH adjustment. After appropriate dilution, soluble proteins in the liquid effluents were measured using Bradford's protein assay kit from Biorad.

Table A2.2. Composition of food scraps used for single source characterization, weights are in gram

Batch 1		Batch 2		Batch 3	
Preconsumer		**Preconsumer**		**Unclassified**	
Green flat beans	99.1	Potatoes	107.2	potato	211
Bell peppers	78.7	Tomatoes	170.9	carrots	216.2
Baby Corn kernels	46.6	Green peas	40.2	bell pepper	148.2
Herbs/salad	111.1	Bell peppers/carrots	301.6	corn	28
melon rinds	160.4	Baby Corn kernels	7.3	Broccoli	567.2
Pineapple rinds	102.9	Cauliflower	130	Beans	110.8
Purple cabbage	104.6	Cucumber	47.2	melon	77.2
Post consumer		Pineapple rinds	111.3	Bread	150
Fries	106.7	Cabbage/lettuce	94.7	Nuggets	284.2
Lettuce	30	**Post consumer**		Pizza	412.4
Melon/carrot/pineapples	99	Bread	102.9	wrap	301.7
Burger pattice	114.6	Fries	100.3	Sphigatti	592.7
Pasta/rice/potato mash	100	Burger pattice	99.2	tomatoes	858.7
bacon	16.6	bacon	2	onions	270.6
Fried chicken	100.1	Fried chicken	114.7	salad	199.6
Ham	38.7	Ham	68.1	butter	165.9
wrap (wheat)	53.1	Pasta/rice/potato mash	96.1	grapes	127.2
Pizza	79	wrap (wheat)	99.8	chicken	184.9
Other	49.8	Pizza	105.8	bacon	9.4
		Broccoli, lettuce, pickle	101	pineapple rinds	337.2
		Pineapple/others	104.3	orange peels	66.4
				banana peels	92.1
				apples	290.6
				burger patties	137.8
				Other	30.3

Table A2.3. Composition of food waste collected from multiple sources

Batches	**Place of collection**	**Type of food components**
Batch 1	DH1	Tomatoes, tortillas, bread, noodles, pizza, chicken nuggets, salad, broccoli, potato fries, burger patties
Batch 2	DH1 and DH2	Strawberries, lettuce, celery stalks, pineapple rinds and croens, cauliflower florets, mushrooms, ground beef, canned tuna, lime rinds, bell peppers
Batch 3a	DH1 and DH2	vegetables, celery, pineapple rinds, bread, water melon rinds
Batch 3b	Anaerobic digester	Pineapple crowns, water melon rinds, bell peppers, bread, green peas, pasta, bananas, collad greens
Batch 4	DH1	Fries, water melon rinds, melon rinds, pineapple rinds and crowns, pizza (~40% weight), strawberries
Batch 5a	DH1 and DH2	Mostly pasta and corn, some pineapple rinds and fruits
Batch 5b	Restaurant	lemon and lime rinds (lots), garlic and onion peels, ground beef, chicken wings (fried), green pea shells, soy bean shells, dough, asparagus, egg plant peels, some fish
Batch 6	Farmers market	Bread (~40-50%), bell peppers, cucumbers, mangoes, herbs, citru fruits
Batch 7	DH1	Pineapple crowns, water melon rinds, bell peppers, bread, green peas, pasta, bananas, collad greens and bread(~50%)
Batch 8	DH2	similar to batch 7
Batch 9	Grocery store	Melon rinds and straberries
Batch 10	DH1	Lots of deli meat, water melon rinds, pineapple rinds

DH: University's Dining Halls

APPENDIX 3

Table A3.1. Components food scraps (n=4)

Components	**Fraction, %**
Fruits and vegetables	59.4 ± 3.2
Meat	14.3 ± 3.8
Grains and cereals	23.0 ± 3.5

Table A3.2. Pre-optimization study to choose the ratio of CFW to co-substrates

Before the Effect of OLR was studied, a pre optimization study was carried out at OLR of 1.4 $gVSL^{-1}d^{-1}$ by varying the weight percent of various substrates for 45 days. The results from this experiment are given in the table below

Experiment	**OLR, gVS/L d**	**% CFW**	**% Co-Substrate**	**Methane FW/ Methane Co-Digestion**
CFW+Manure	1.4	30	70	0.78
	1.4	50	50	0.76
	1.2	20	80	0.77
	1.4	70	30	1.35
CFW+Bread	1.4	90	10	1.30
	1.4	80	20	1.06
	1.4	70	30	1.15
CFW+paper	1.4	92	8	0.74
	1.4	85	15	0.64
	1.4	95	5	1.34

Table A3.3. Experimental design for feeding CFW and cosubstrates at different OLRs. The mass of CFW and cosubstrates are in grams. If the weights of substrate and cosubstrates do not sum to 60g, the remaining amount comes from water. **OLR reduced to 3.5 $gVSL^{-1}d^{-1}$ due to the reactor failure at 4.4 $gVSL^{-1}d^{-1}$

	R1	R2		R3		R4		R5		R6		Test duration (d)
OLR, $gVSL^{-1}d^{-1}$	**CFW (g)**	**CFW**	**AW**	**CFW**	**ED**	**CFW**	**WB**	**CFW**	**PN**	**CFW**	**CM**	
1.4±0.2	11.6±0.3	9.2±0.4	30.6±0.8	11.5±0.1	48.3±6.1	8.4±0.23	1.5±0.1	9.6±0.1	0.5±0.0	10.1±0.0	4.1±0.4	25
2.8±0.1	23.2±0.1	19.2±0.2	42.1±1.4	23.1±0.2	37.6±0.7	15.1±0.1	2.4±0.2	11.3±0.3	1.1±0.0	19.6±0.2	8.2±0.1	21
4.4±0.1	36±0.1	34.4±0.7	26.1±0.9	36±0.0	24.1±0.1	23±0.2	3.8±0.0	17±0.3	1.7±0.0	29.8±0.8	13.6±0.8	14
5.5±0.1	**	45.2±0.2	15.6±0.4	46.2±0.2	14.5±0.5	29.8±0.4	5.0±0.0	21.6±0.4	2.0±0.0	38.2±0.1	18.3±0.3	10*

Table A3.4. Observed hydraulic retention times at different OLRs. Small variations in HRT are attributed to sample preparation error and volume losses during feeding and withdrawal.

	HRT (d)					
OLR, $gVSL^{-1}d^{-1}$	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**
1.4±0.2	31.7±0.4	31.3±0.4	31.5±0.4	32.8±0.5	32.4±1.2	32.1±0.7
2.8±0.1	33.4±0.4	33.3±0.7	33.2±0.4	32.7±0.7	32.2±0.8	33.5±0.3
4.4±0.1	29.7±0.3	29.5±1.0	29.9±0.1	29.6±0.4	30.9±0.4	29.5±1.2
5.5±0.1	NA	29.8±0.2	29.5±0.2	30.1±2.1	30.9±0.7	29.5±0.2

Table A3.5 - Digestate characteristics at OLR of 2.8 $gVSL^{-1}d^{-1}$; the digestate collected from 3 different time intervals as an effluent from each reactor was pooled into a single sample and was analyzed for soil properties by a third party laboratory. This is only for information purposes as there are no replicates and hence does not guarantee reproducibility.

	R1	R2	R3	R4	R5	R6
TS, %	1.1	1.2	1.5	2.0	0.9	1.4
C:N ratio	6.2	3.0	4.0	4.5	8.0	5.2
Carbon, %	41	24.8	41.6	35.2	61.7	36.5
Nitrogen, %	7.6	8.3	10.4	7.8	7.7	7.0
Phosphorus, %	1.53	0.7	1.5	1.4	0.9	1.3
Potassium, %	3.44	6.7	4.0	2.1	2.5	3.1
Magnesium, %	0.6	0.6	0.9	0.6	0.4	0.8
Calcium, %	2.9	4.5	3.0	3.0	1.4	2.8
Sodium, %	2	3.3	3.3	2.1	1.2	1.7
Sulfur, %	1.1	0.6	1.6	0.9	0.5	0.7
Iron, %	1.8	0.6	1.2	1.1	0.4	0.5

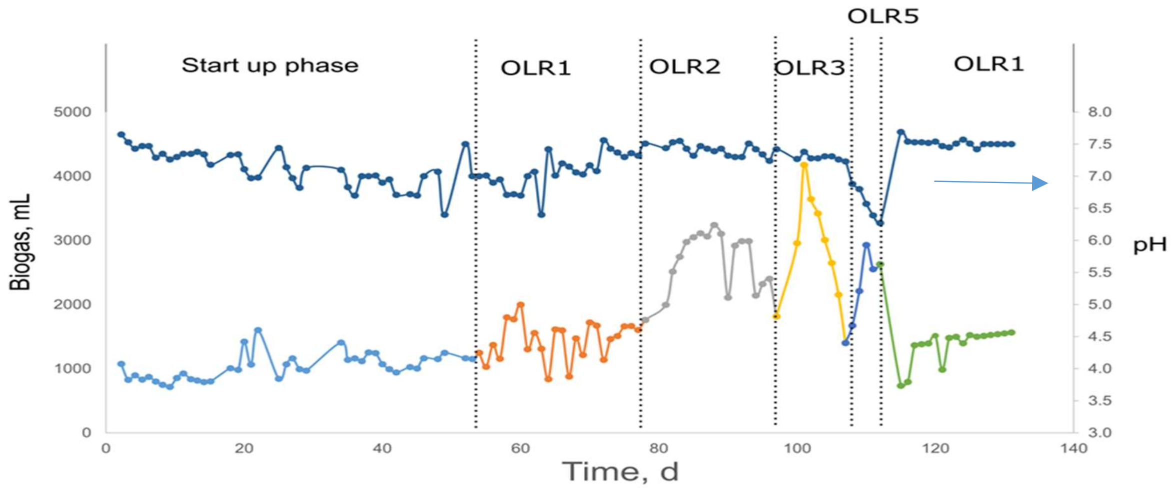

Figure A3.1. Sample kinetics of cafeteria food waste (CFW) digestion: the figures shows a sample kinetics for one of the digesters observed for 140 days. The region OLR5 indicates a reactor failure

A3.1. Anaerobic digestion of food scraps with continuous mixing:

The start-up procedure for CSTRs was the same as for AMPTSII reactors. The CSTRs were continuously mixed at 60 rpm, and the temperature was maintained at 37^0C using an embedded thermocouple. The FS showed a 20% and 27% lower average daily methane at 1.4 and 2.8 $gVSL^{-1}d^{-1}$, respectively, when compared with R1. The alkalinity, volatile acids and total ammoniacal nitrogen were also significantly higher compared to R1. The average hydrogen sulfide levels were nine times lower than R1 with intermittent mixing. There is literature on the effect of mixing on the composition of biogas. However, the mechanism by which mixing would reduce the H_2S concentration is not clear. Continuous mixing is not recommended since it reduces biogas production. However, In the case of excessive H_2S in the biogas, mixing continuously for a fixed time could help reducing H_2S levels.

Table A3.6. Process monitoring during digestion of mixed FS and vegetable waste with continuous mixing

	Food scraps		Vegetable waste	
Parameters	**OLR1**	**OLR2**	**OLR1**	**OLR2**
pH	7.6±0.1	7.5±0.1	7.5±0.1	7.3±0.2
Avg. daily biogas, mL	1261±406	2241±384	1021±241	1402±296
Biogas methane, %	60±4	60±1	56±4	50±5
Biogas H_2S, ppm	18±7	101±32	33±37	381±175
Avg. daily methane, mL	746±193	1354±240	562±133	686±239
SMY, mL CH_4 gVS^{-1} d^{-1}	260±58	253±22	198±48	125±45
Total volatile acids, mg CH_3COOH L^{-1}	1089±514	886±168	1271±572	2197±1070
Total alkalinity, mg $CaCO_3$ L^{-1}	7300±1256	7410±1489	7471±1294	6230±356
Total ammoniacal nitrogen, mg NH_3-N L^{-1}	1840±56	1546±32	1624±29	1518±110

Table A3.7. Volatile acid profile for a selected OLR using GC analysis; the profile of various VFAs in during the AD experiment measured for two data points within a single OLR period

	Acetic acid	**Propionic acid**	**Butyric acid**	**Isobutyric acid**	**Valeric acid**	**Isovaleric acid**
OLR=1.4 gVS/L.d; Avg of 2 data points (day 7 and day 8)						
R1	1461.3	114.5	31.8	40.8	30.2	5.7

R2	1339.2	198.1	43.4	71.8	17.7	17.9
R3	615.9	52.7	18.6	25.4	4.8	11.3
R4	476.9	55.4	41.6	23.2	31.4	55.5
R5	278.1	148.1	84.5	61.0	48.6	38.0
R6	413.8	48.7	59.0	36.0	29.0	54.4

Section A3.2. Different measures of percent degradation: The degradibity is a measure of the waste management efficiency and can be calculated using initial and final COD or volatile solids or by using a ratio of observed to theoretical biomethane potential as shown in figure A3.2 through A3.5. Any method can be used as long as the same method is used consistently.

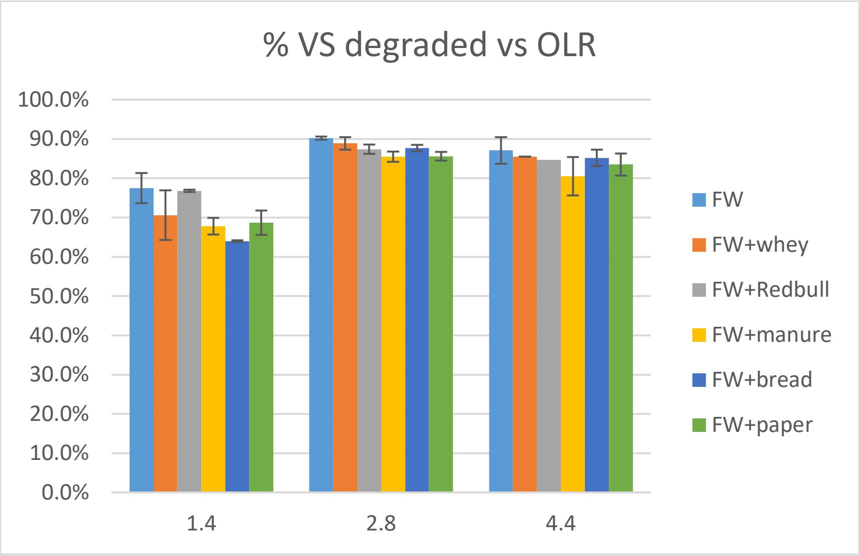

Figure A3.2. Percent degradation based on initial and final VS

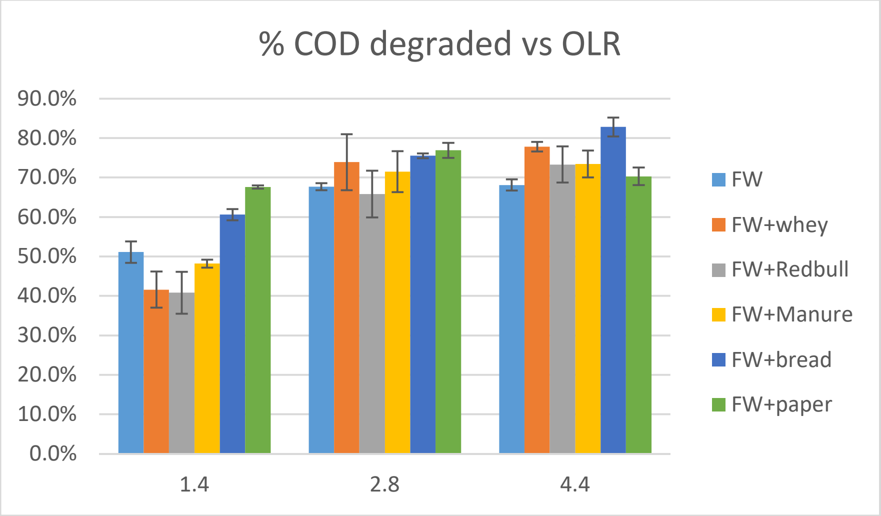

Figure A3.3. Percent degradation based on initial and final COD

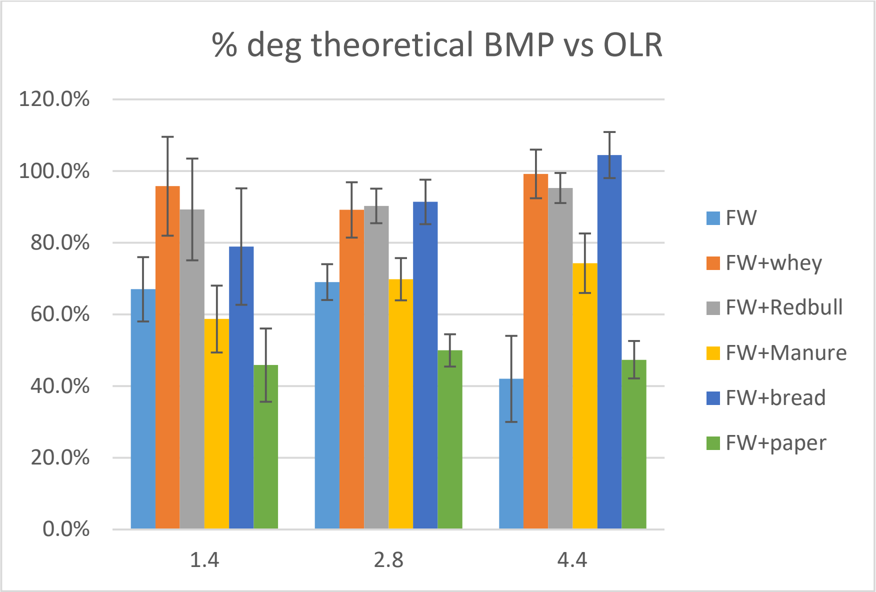

Figure A3.5. Percent degradation as a ratio of observed to theoretical biomethane potential

Table A 3.8. Sample analysis of real time digester data for choosing a base OLR

	Waste input, gallon					Waste input, kg					VS loading	**OLR**
	Dairy waste	Grease trap	Syrups/dressing	Fruits/Vegetable waste	Manure, gallon	kg, manure	kg, dairy waste	kg, grease trap	kg, Syrups	kg Fruit/Vegetable waste	kgVS/d	**kg VS/m3 d (or) gVS/L d**
1	51831.00	0.00	4180.00	0.00	43913.00	65869.50	197670.48	0.00	23512.50	0.00	16328.71	**2.18**
2	33210.00	11766.00	3850.00	1638.00	44220.00	66330.00	126654.64	39710.25	21656.25	2457.00	15191.42	**2.03**
3	12726.00	0.00	0.00	0.00	74398.00	111597.00	48533.78	0.00	0.00	0.00	11354.45	**1.51**
4	8000.00	0.00	0.00	0.00	83084.00	124626.00	30510.00	0.00	0.00	0.00	11495.58	**1.53**
5	21500.00	15095.00	0.00	0.00	36707.00	55060.50	81995.63	50945.63	0.00	0.00	11357.58	**1.51**
6	36065.00	9095.00	0.00	0.00	45693.00	68539.50	137542.89	30695.63	0.00	0.00	14079.26	**1.88**
7	40136.00	21892.00	0.00	0.00	46257.00	69385.50	153068.67	73885.50	0.00	0.00	17341.86	**2.31**
8	19657.00	15044.00	4015.00	0.00	67530.00	101295.00	74966.88	50773.50	22584.38	0.00	15824.48	**2.11**
9	36592.00	3500.00	0.00	0.00	49954.00	74931.00	139552.74	11812.50	0.00	0.00	13633.62	**1.82**
10	12820.00	0.00	0.00	0.00	76968.00	115452.00	48892.28	0.00	0.00	0.00	11680.77	**1.56**
11	0.00	0.00	0.00	0.00	87079.00	130618.50	0.00	0.00	0.00	0.00	10449.48	**1.39**
12	30996.00	15272.00	0.00	0.00	35412.00	53118.00	118211.00	51543.00	0.00	0.00	13046.40	**1.74**
13	21866.00	0.00	0.00	0.00	59312.00	88968.00	83391.46	0.00	0.00	0.00	11287.01	**1.50**
14	27846.00	21054.00		0.00	37583.00	56374.50	106197.68	71057.25	0.00	0.00	13799.05	**1.84**
15	30953.00	6939.00	0.00	0.00	46154.00	69231.00	118047.00	23419.13	0.00	0.00	12752.30	**1.70**
16	39800.00	10476.00	3500.00	0.00	33276.00	49914.00	151787.25	35356.50	19687.50	0.00	14546.82	**1.94**
17	8000.00	4000.00	0.00	0.00	75087.00	112630.50	30510.00	13500.00	0.00	0.00	11291.94	**1.51**
18	0.00	0.00	0.00	0.00	93058.00	139587.00	0.00	0.00	0.00	0.00	11166.96	**1.49**
19	26773.00	15288.00	0.00	0.00	48031.00	72046.50	102105.53	51597.00	0.00	0.00	13758.43	**1.83**
20	28734.00	9100.00	4345.00	0.00	40903.00	61354.50	109584.29	30712.50	24440.63	0.00	13329.51	**1.78**
21	33144.00	14546.00	0.00	0.00	42392.00	63588.00	126402.93	49092.75	0.00	0.00	14156.38	**1.89**
22	13597.00	8193.00	0.00	0.00	76249.00	114373.50	51855.56	27651.38	0.00	0.00	13291.13	**1.77**
23	38393.00	21572.00	0.00	1342.00	26221.00	39331.50	146421.30	72805.50	0.00	2013.00	14745.99	**1.97**
24	8000.00	0.00	0.00	0.00	82828.00	124242.00	30510.00	0.00	0.00	0.00	11464.86	**1.53**
25	0.00	0.00	0.00	0.00	90075.00	135112.50	0.00	0.00	0.00	0.00	10809.00	**1.44**
26	34585.00	7625.00	0.00	0.00	43873.00	65809.50	131898.54	25734.38	0.00	0.00	13300.81	**1.77**
27	6000.00	0.00	0.00	0.00	36485.00	54727.50	22882.50	0.00	0.00	0.00	5522.33	**0.74**
28	6000.00	10492.00	0.00	0.00	65913.00	98869.50	22882.50	35410.50	0.00	0.00	11036.67	**1.47**
29	24157.00	8690.00	0.00	0.00	57232.00	85848.00	92128.76	29328.75	0.00	0.00	13116.69	**1.75**
30	34004.00	12993.00	0.00	0.00	32825.00	49237.50	129682.76	43851.38	0.00	0.00	12878.81	**1.72**
31	27593.00	0.00	0.00	0.00	63942.00	95913.00	105232.80	0.00	0.00	0.00	12934.68	**1.72**
32	8000.00	0.00	0.00	0.00	86557.00	129835.50	30510.00	0.00	0.00	0.00	11912.34	**1.59**
33	29625.00	7018.00	0.00	0.00	57914.00	86871.00	112982.34	23685.75	0.00	0.00	13925.20	**1.86**
34	33619.00	6688.00	0.00	1000.00	51238.00	76857.00	128214.46	22572.00	0.00	1500.00	13973.32	**1.86**
35	45468.00	7960.00	0.00	0.00	23619.00	35428.50	173403.59	26865.00	0.00	0.00	13008.90	**1.73**
36	41737.00	8000.00	4400.00	2500.00	25400.00	38100.00	159174.48	27000.00	24750.00	3750.00	14131.22	**1.88**
37	40865.00	6500.00	0.00	0.00	35686.00	53529.00	155848.89	21937.50	0.00	0.00	13303.26	**1.77**
38	21500.00	0.00	0.00	0.00	65549.00	98323.50	81995.63	0.00	0.00	0.00	11965.66	**1.60**
39	5093.00	0.00	0.00	0.00	81968.00	122952.00	19423.43	0.00	0.00	0.00	10807.33	**1.44**
40	8000.00	13485.00	0.00	0.00	65536.00	98304.00	30510.00	45511.88	0.00	0.00	11938.49	**1.59**
41	28800.00	6904.00	0.00	1500.00	37908.00	56862.00	109836.00	23301.00	0.00	2250.00	11570.62	**1.54**
42	19000.00	3500.00	0.00	0.00	35829.00	53743.50	72461.25	11812.50	0.00	0.00	8584.04	**1.14**
43	31642.00	7176.00	37535.00	1317.00	10698.00	16047.00	120674.68	24219.00	211134.38	1975.50	19428.03	**2.59**
44	28033.00	5544.00	0.00	0.00	54993.00	82489.50	106910.85	18711.00	0.00	0.00	12992.52	**1.73**
45	13500.00	0.00	0.00	0.00	64804.00	97206.00	51485.63	0.00	0.00	0.00	10350.76	**1.38**
46	11088.00	0.00	0.00	0.00	67216.00	100824.00	42286.86	0.00	0.00	0.00	10180.26	**1.36**
47	37303.00	8061.00	0.00	5200.00	38667.00	58000.50	142264.32	27205.88	0.00	7800.00	14056.78	**1.87**
48	27000.00	6773.00	4400.00	0.00	31221.00	46831.50	102971.25	22858.88	24750.00	0.00	11412.68	**1.52**
49	25707.00	13626.00	0.00	4000.00	44190.00	66285.00	98040.07	45987.75	0.00	6000.00	13380.12	**1.78**
50	25433.00	7506.00	0.00	900.00	65852.00	98778.00	96995.10	25332.75	0.00	1350.00	14305.63	**1.91**
51	42015.00	9657.00	0.00	0.00	50367.00	75550.50	160234.71	32592.38	0.00	0.00	15880.95	**2.12**
52	35000.00	0.00	0.00	0.00	60867.00	91300.50	133481.25	0.00	0.00	0.00	13978.10	**1.86**
53	12422.00	0.00	0.00	0.00	77615.00	116422.50	47374.40	0.00	0.00	0.00	11682.52	**1.56**
54	35000.00	5893.00	0.00	0.00	26049.00	39073.50	133481.25	19888.88	0.00	0.00	10913.72	**1.46**
55	27562.00	0.00	4180.00	0.00	28636.00	42954.00	105114.58	0.00	23512.50	0.00	9867.67	**1.32**
56	23624.00	11716.00	0.00	0.00	45498.00	68247.00	90096.03	39541.50	0.00	0.00	12178.89	**1.62**
57	0.00	7514.00	0.00	0.00	80517.00	120775.50	0.00	25359.75	0.00	0.00	11082.19	**1.48**
58	4776.00	11586.00	0.00	0.00	67662.00	101493.00	18214.47	39102.75	0.00	0.00	11219.92	**1.50**
59	8000.00	0.00	0.00	0.00	79679.00	119518.50	30510.00	0.00	0.00	0.00	11086.98	**1.48**
60	8000.00	0.00	0.00	0.00	81374.00	122061.00	30510.00	0.00	0.00	0.00	11290.38	**1.51**

APPENDIX 4

Table A4.1. Review of literature on ethanol production via fermentation of food waste

Food waste type	Organism	Pretreatment method	Process conditions	Fermentation time [h]	Ethanol output		Reference
					Concentration [g/L]	g/g wet FW	
Kitchen waste	*S cerevisiae*	Enzymatic hydrolysis	Batch fermentation 100mL, 30^{0}C, 150 rpm	58.8	32.2	0.58	[143]
Kitchen garbage	*Zymomonas mobilis*	Enzymatic hydrolysis using protease and amylase	Batch fermentation, 150 mL, 30^{0}C	40	53.4		[37]
Household food waste	Baker's yeast	Enzymatic and microwave heat treatment	Batch fermentation, 100 mL, 30^{0}C, 100 rpm	15	42.8	0.14	[61]
Cafeteria food waste (Korea)	*S cerevisiae*	Grinding and enzymatic hydrolysis	Batch fermentation in 5L fermenter with 3L working volume, 35^{0}C, pH 4.5	24	28.32	0.16	[383]
Retail store waste (mainly containing mashed potatoes, sweet corn and bread)	NR	Enzymatic hydrolysis with stargen (starch hydrolyzing enzyme) and protease	3L fermenter, 32^{0}C, 30 rpm	72	144	0.33	[293]
Dining hall food waste (China)	*S cerevisiae*	Enzymatic	1000 L fermenter with 700L working volume	60	94	0.10	[279]
Bread waste	Yeast (sp not mentioned)	Amylase and protease	Batch fermentation, 300 mL, 35^{0}C, 150 rpm	72	279.6*	0.35	[384]
Bread crust	Commercial yeast “Super Camellia”	Enzymatic hydrolysis with α-amylase and glucoamylase	Fed-batch fermentation rotating drum reactor with a humidifier and condenser, 32^{0}C, 5rpm	30	NR	0.27	[102]
Bakery wastes (bread, biscuits, buns, cakes, donuts,potato chips and flour) and cheese whey	*S cerevisiae* (distiller's yeast)	Enzymatic hydrolysis using termamyl/AMG at 70C and pH 5.0	Batch fermentation in 14 L Microferm benchtop fermenter, 30^{0}C, pH 5.0	14	255.9*	0.25	[292]

Potato chips	Commercial yeast “Super Camellia”	Enzymatic hydrolysis with α-amylase and glucoamylase	Continuous fermentation in a rotating drum reactor, 32^0C, 5rpm	NR	32	0.24	[102]
Waste potato mash	*S cerevisiae*	Liquefaction and saccharification using amylase and amyloglucosidase	Batch fermentation in 2.5L fermenter at 30^0C, pH 5.5 and 400 rpm.	18	31	0.21	[299]
Potato peel waste	*S cerevisiae var. bayanus*	Enzymatic hydrolysis with a combination of three enzymes	Batch fermentation in 250ml Erlenmeyer flask at 30^0C, 100 rpm and pH 5.0	48	7.6	<0.1	[299]
Sweet potato waste	S cerevisiae	Enzymatic hydrolysis using cellulase and pectinase.	Batch fermentation, 30^0C	72	79	0.23	[385]
Apple pomace	*S cerevasiae*	Dilute acid hydrolysis and laccase enzyme	Batch fermentation with 5L working volume fermentation bucket, 25^0C	168	149.9*	0.4	[44]
Apple pomace	*Saccharomyces cerevisiae Montrachet strain 522 w*	None	Solid-state fermentation in 3.8L mason jars fitted with a CO_2 exhuast tube at 30^0C.		43		[111]
Apple pomace amended with molasses	*S cerevisiae*	Enzymatic hydrolysis of apple pomace with α-amylase and then amended with molasses	Batch fermentation, 2L, 30^0C and 40 rpm.	62.1	72		[295]
Grape pomace	*S cerevisiae*	None	Solid-state fermentation (SSF), 28^0C	48	39.9*	0.05	[386]
Grape pomace	*Pichia rhodanensis*	Enzymatic hydrolysis using cellulase and pectinase.	Batch fermentation at 30^0C	48	18.1		[300]

Carrot pomace	thermo-tolerant *Kluyveromyces marxianus*	Enzymatic hydrolysis with Accellerase 1000 and pectinase	Solid state fermentation in 1L custom made jar fermenters at 42^0C, 680 rpm and initial pH of 5.0	37	42	0.18	[298]
Cola based sweet beverage	*Saccharomyces cerevisiae var. Windsor*	The sweet beverage medium was degassed before use.	Batch fermentation, 500ml, 30^0C.	8	55	0.51	[172]
Tomato serum left after sauce production	Immobilized *S cerevisiae*	Enzymatic hydrolysis using Driselase	Batch fermentation	10	23.7		[296]
Whey permeate	*K marxianus*	Whey was de-proteinated by boiling and filtration and concentrated using vacuum evaporation	Batch fermentation at 30^0C, pH 4.6	60	46		[294]
Cheese whey	*K marxianus*	Cheese whey supplemented with yeast extract	Fed batch fermentation	4	8	0.21	[387]
Lipid extracted coffee grounds	*S cerevisiae*	Dilute sulfuric acid hydrolysis and autoclaving	Batch fermentation, 250mL, 30^0C	10	17.2		[388]
Pineapple and banana peels	Co-culture of *A niger* and *S cerevisiae*	Oven dried and ground before fermentation. *A niger* assisted hydrolysis	Batch fermentation, 28^0C, pH 5.5	96	32-49.34		[389]
Banana peels from a processing plant	*S cerevisiae*	Drying, grinding, steam treatment, and acid hydrolysis	Batch fermentation, 250mL, 30^0C, 200 rpm, pH 5-5.5	NR	NR	0.45	[297]

Table A4.2 Review of literature on butanol production via fermentation of food waste

Food waste	**Product**	**Yield (g/L)**	**Reference**
Retail waste	ABE	20.9	[38]
Apple and pear peels	ABE	20	[390]
Household organic waste	ABE	$75^{\$}$	[108]
Milk dust powder	1-butanol	7.3	[39]
Bakery waste (inedible dough, batter liquid and waste breading)	1-butanol	14.4-15.1	[66]
Apple droppings and waste corn	1-butanol	9.8	[107]
Waste potatoes	1-butanol	4.7	[310]
Beverage waste	1-butanol	12.8-14	[309]
Waste potato starch	1-butanol	15.3	[308]
wastewater from palm oil processing	1-butanol	10.4	[391]
Cheese whey	1-butanol	5	[307]
Apple pomace	1-butanol	17.6*	[109]
Acid whey	1-butanol	12.2	[16]

Table A4.3. Concentration of different products during ABE fermentation for selected experiments; CW: Cheese whey; YW: Yogurt whey; TWW: Tofu wastewater; AP: Apple pomace; TP: Tomato pomace; YE: Yeast extract

Organism	**Products**	**CW**	**YW**	**TWW**	**AP+TWW**	**AP+YE**	**AP hydrolysate**	**TP+TWW**	**TP hydrolysate**	**TCR hydrolysate**
C acetobutylicum **ATCC 4259**	Butanol, g/l	6.06±0.22 (220h)	6.85±0.06 (145 h)	1.99±0.03 (192 h)	1.18 (145 h)					
	Acetone+EtOH, g/l	0.5±0.06	11.56±0.13							
	Acetic acid, g/l	5.9±0.6 (91 h)	5.8±0.27 (145 h)	2.2±0.09 (145 h)	1.64±0.05					
	Butyric acid, g/l	1.00	1.12±0.005 (145h)	1.57±0.04 (95 h)	1.2					
	propanol, g/l	ND	ND	ND	ND					
	Lactic acid, g/l	0.22	1.47±0.05 (145 h)	ND	ND					
C acetobutylicum **NRRL B-527**	Butanol, g/l	0.07±0.0	ND		ND	0.17±0.04 (180 h)	3.33±0.2 (120h)	ND	0.8, 5d	0.18
	Acetone+EtOH, g/l	0.08±0.02	ND		1.46±0.0	1.13±0.12		0.94±0.19 (12d)	0.13, 7d	0.03
	Acetic acid, g/l	0.46±0.03	1.32±0.42 (5d)		1.9	3.94±1.14 (10d)	2.28±0.23 (120 h)	1.02±0.13 (94 h)	1.94±0.18	3.35±0.05
	Butyric acid, g/l	0.37±0.1	0.08±0.01		0.11	1.43±0.16	0.02±0.0	0.16	ND	0.17±0.01
	propanol, g/l	ND	ND		ND	ND	ND		ND	ND
	Lactic acid, g/l	1.74±0.05	2.6±0.06		ND	NA	ND		ND	ND
C beijerinckii **NRRL B -598**	Butanol, g/l,	0.07±0.0, 7d	0.06±0.003, 7d		ND	0.13±0.008	0.06±0.00	ND	0.06	0.1
	Acetone+EtOH, g/l	0.03±0.00, 7d	0.02±0.00, 7d		2.5±0.04, 72h	1.5, 180h	0.1	1.51±0.09, 72h	0.6	0.04±0.0
	Acetic acid, g/l	0.37±0.004, 5d	1.53±0.02, 5d		2.06±0.04	0.37±0.1	3.24±0.23	0.57±0.009	1.94±0.08, 5d	1.82±0.01, 5d
	Butyric acid, g/l	0.37±0.1, 5d	0.04±0.002		0.11±0.00	0.32, 280d	0.02	0.13±0.00, 94h	0.01	0.14±0.006
	propanol, g/l	0.02±0.00, 7d	0.02		2.38±0.007	0.13	3.31±0.06, 5d	ND	0.61	0.2±0.0
	Lactic acid, g/l	1.68±0.05, 7d	2.69±0.005		ND	ND	ND	ND	ND	ND

Table A4.4. The data inventory used to develop feasibility metric for fermentation

	Ethanol, g/L	**Ref**	**Butanol, g/L**	**Ref**	**Lactic acid, g/L**	**Ref**	**Succinic acid, g/L**	**Ref**
Food scraps								
Food scraps unclassified	32.2	[143]					43.1	[392]
Food scraps (rich in vegetables and fruits)					20	[393]	56.7	[70]
Food scraps (rich in starch)	144	[38]			67.5	[394]		
Food scraps (mixed meat and vegetables)	42.8	[61]			58	[395]	29.9	[396]
Fruit and veg processing								
Apple pomace/waste								
Tomato pomace/serum	43.2	[295]	9.8	[107]	32.5	[41]		
Grape pomace	23.7	[296]						
Carrot pomace	39.9	[298]						
Waste potato mash	42	[299]	12.9	[310]				
Waste potato starch	31	[299]	4.7	[310]				
Potato peel waste	18.5	[301]	15.3	[308]	25	[397]		
Potato wash water	7.6	[299]			33.8	[398]		
Sweet potato waste	49.1	[399]						
Waste fruits	79	[142]					23.5	[400]
Waste banana peels	16	[401]			92	[402]		
Waste orange peels	65.052	[389]	19.5	[106]			2	[403]
Mango peels	58.11	[389]			116	[404]		
Tofu processing water	12.9	This study	2		63.3	[398]		
Bakery wastes								
Waste liquid batter			15	[66]				
Inedible dough			9.3	[66]				

Bakery wash water	279.6	[292]			78.5	[405]		
Waste bread	255.9	[384]					47.3	[230]
Bakery sweets							31.7	[71]
Dairy wastes								
Cheese whey	26.5	This study	6.1	This study	53	[406]	29	[70]
Yogurt whey	29	This study	6.9	This study				
Whey permeate	46	[294]			55	[284]		
Milk dust powder								
Beverage industry								
Left over beverages	55	[172]	7.3	[39]				
Waste fruit juice	94	[407]						
Waste fruit syrup			19.2	[309]				
Brewery stillage					50	[408]		
Coffee grounds (lipid extracted)	17.2	[388]						

APPENDIX 5

A5.1. Calculation of stoichiometric air to fuel ratio of food waste

The food waste mass formula can be written as, $C_{4.7}H_{0.64}N_{0.3}O_{2.3}$, Therefore the molecular formula of food waste is $CH_{0.64}N_{0.07}O_{0.48}$

The reaction stoichiometry for complete combustion/oxidation of food waste is,

$CH_{0.64}N_{0.07}O_{0.48} + aO_2 \rightarrow bCO_2 + c\ H_2O$

Solving the equation using elemental balance gives,

$CH_{0.64}N_{0.07}O_{0.48} + 0.92\ O_2 \rightarrow CO2 + 0.32\ H_2O + 0.035\ N_2$

1 kmole of food waste = (12) + (0.64*1) + (0.07*14) + (0.48*16) = 21.3 kg

1 kmole of O_2 = 32 kg

$(Oxy/fue)_{stoi}$ = (0.92*32)/21.3 = 1.38 kg O2/kg FW

Or $(Air/fuel)_{stoi}$ = (1.38*100/21) = 6.57 kg air/kg FW

A 5.2. Estimation of the energy content of the food waste and products

Several correlations are available to calculate higher heating value (HHV) of biomass fuels [84], [329], [339], [369]. Equations 5.1 through 5.4 were used to calculate the HHV, lower heating value (LHV) and chemical exergy of food waste and biochar using ultimate analysis data (Table 5.2). The HHV of feedstock was calculated using Equation 5.1[84]:

$$\mathrm{HHV_{dry}} = 0.35\mathrm{X_c} + 1.18\mathrm{X_H} + 0.1\mathrm{X_s} + 0.02\mathrm{X_N} + 0.1\mathrm{X_O} \qquad \textbf{Eq. A5.1}$$

where, $\mathrm{HHV_{dry}}$ is the higher heating value of bone-dry feedstock in $MJkg^{-1}$, X represents the mass fractions of carbon (C), hydrogen (H), sulfur (S), nitrogen (N), oxygen (O) and ash. HHV represents the energy value of a fuel. However, the energy available to derive useful work is represented by LHV. LHV calculations assume that one of the final products of combustion water is in vapor state, as opposed to the higher heating value (HHV; a.k.a. gross calorific value) which assumes that all of the water in a combustion process is in a liquid state after a combustion process [409], [410]. LHV is useful in comparing fuels where condensation of the combustion products is impractical, or heat at a temperature below 150 °C cannot be put to use [410]. In summary, LHV is determined by subtracting the heat of vaporization of the water from the higher heating value. This treats any water formed as a vapor and the energy required to vaporize the water therefore is not released as heat. LHV is a more accurate measure of exergy contained in the feedstock, while HHV determines the energy value. An estimate of lower heating value is then obtained using Equation 5.2[84]:

$$\mathrm{LHV} = \mathrm{HHV}_{\mathrm{dry}}\,(1 - \mathrm{M}) - 2.447\mathrm{M} - 0.02\mathrm{X}_{\mathrm{ash}} \qquad \textbf{Eq. A5.2}$$

where M is the moisture content of the feedstock or products in percentage and 2.447 is latent heat of evaporation of water in $\mathrm{MJkg^{-1}}$ at 25^{0}C. The available chemical exergy, E_x^{chem} of food waste and biochar was calculated from LHV using an exergy coefficient (β):

$$E_x^{chem} = \beta * (LHV) \qquad \textbf{Eq. A5.3}$$

where β is a coefficient used to calculate exergy and its value is derived from the elemental composition. Equation 5.4 was used to estimate β and hence E_x^{chem} [329]: Equation 5.4 was used to calculate β for both feedstock and products.

$$\beta = \frac{1.0412 + \ .2160\frac{\mathrm{X_H}}{\mathrm{X_c}} - 0.2499\frac{\mathrm{X_O}}{\mathrm{X_c}}\left[1 + 0.7884\frac{\mathrm{X_H}}{\mathrm{X_c}}\right] + 0.0450\frac{\mathrm{X}_N}{\mathrm{X_c}}}{1 - 0.3035\frac{\mathrm{X_O}}{\mathrm{X_c}}} \qquad \textbf{Eq. A5.4}$$

A5.3. Input energy requirement of feedstock drying

The drying energy was calculated as the energy required to evaporate water and bring the moisture levels of the food waste feedstock down from 60-80% to a final moisture content, using a perforated plate conveyor type dryer. The drying energy was calculated using the following equation as the energy required to evaporate known amount of water from food waste using a single stage drying process [411].

$$\text{Heat input required to dry 1kg of food waste} = \\ \text{Heat energy to raise the temperature of the solids} + \text{latent heat to remove water}$$

$$= (T_{drying} - T_{amb}) \times Sp.heat\ capacity\ of\ food\ waste + (Quantity\ of\ water\ to\ be\ evaporated\ \times latent\ heat\ of\ evaporation\ of\ water)$$

Eq. A5.5

where, T_{drying} is 150^{0}C, the T_{amb} is ambient temperature and assumed as 25^{0}C;

Calculation of specific heat capacity of food waste

The specific heat capacity of food waste was measured using carbohydrate, protein, lipid, fiber and ash content of the food waste. The composition of food waste given in Table 2.x. was used in the calculations. Following equations were used which were adapted from ASHRAE handbook [244].

Proteins: $C_{p,prot}$=2.0082+(1.2089*10^{-3}T)-(1.3129*10^{-6}*T^2)

Fats: $C_{p,fat}$= 1.9842+(1.4733*10^{-3}*T)-(4.8008*10^{-6}*T^2)

Carb: $C_{p,carb}$ = 1.5488+(1.9625*10^{-3}*T)-(5.9399*10^{-6}*T2)

Fibers: $C_{p, fib}$=1.8459 + (1.8306*10^{-3}*T)-(4.6509*10^{-6}*T^2)

Ash: $C_{p, ash}$=1.0926 + (1.8896*10^{-3}*T)-(3.6817*10^{-6}*T^2)

After calculating individual Cp values, the weight fraction of the individual components was used to calculate Cp of food waste.

The specific heat capacity of 1.5 KJ kg^{-1}C$^{0-1}$ for food waste was derived from an average from various literature sources for olive pomace [412], banana waste [413] and certain fruits[414] and verified by back calculating it for the measured nutrient composition.. The latent heat of evaporation of 2107 KJ/kg at 150^{0}C[32] for water was used in the calculation. The efficiency of drying was estimated as 51% by using estimated values for biowaste (using specific heat capacity of 5 KJ kg^{-1}C$^{0-1}$;)[355] and empirical data for the energy requirement of the specified dryer to dry biowaste from an initial moisture of 77% to a final moisture of 35% [356]. The following assumptions were used in calculation of input energy:

- The heat losses from the dryer body, which are typically 5-10% for convective dryers [357], was assumed to be included within the efficiency.
- It is important to note that parameters like drying bed thickness, particle size and air velocities have a major role in determining drying energy. Here, a constant bed thickness of 100 mm was assumed for which Hallowell et al. [358] measured the drying energy requirement.
- No air recycling was considered, as the feedstock contained very high moisture that saturated and cooled the outlet air, requiring further energy input to recycle heated air.

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[32] Steam characteristic; ThermExcel, https://www.thermexcel.com/english/tables/vap_eau.htm

Other than the energy required to remove water from the feedstock, the drying process needed additional input in the form of electricity to run the machinery. For example, the exergy input to dry the food waste from 75% moisture to 10% was 2540 $\mathrm{MJton_{wet}^{-1}}$ and the electric requirement was 525 $\mathrm{MJton_{wet}^{-1}}$, accounting for a total exergy input of 3065 $\mathrm{MJton_{wet}^{-1}}$. The electrical energy requirement was calculated based on the power rating of the dryer and the time required to dry 1 ton of wet food waste at the rate of 96 kg/h[356]. The output mass flow rates varied depending on the final moisture. An overall mass balance on solids and water was used to calculate input and output mass flows. One should note that the chemical exergy of the feedstock per unit mass increases as the water is evaporated, therefore the chemical exergy of the feedstock must also be considered in calculating the overall exergy of inlet and exiting streams through the dryer. The mass flows in and out of the dryer must be carefully considered to calculate chemical exergy of wet and dry feed streams. Therefore, the exergy balance on the dryer yields Equation 5.15.

$$E_{x,net}^{dryer} = E_{x,chem}^{dry\,feed} - E_{x,chem}^{wet\,feed} - E_{x,electric}^{dryer} - E_{x,hea} \qquad \textbf{Eq. A5.6}$$

where $E_{x,net}^{dryer}$ is the net exergy flow through the dryer.

A5.4. Input energy requirement of size reduction

Grinding or homogenization is necessary before the feedstock is sent through the dryer and the associated grinding energy requirement depends on moisture content, initial and final particle size and other rheological properties [359], [360]. However, grinding food waste to extremely small particle size is not beneficial in biochar production, as smaller particle size does not favor the secondary biochar formation reactions, thus decreasing the biochar yield[361]. The grinding process is staged after the drying stage, as dry feedstock requires significantly lower energy to grind than wet feedstock [360] . Grinding energy requirements were calculated for a rotary hammer mill of 5 hp (3.7kW) capacity [356] capable of grinding the feedstock to a predefined mesh size (10mm-25mm required by the feed hopper in main TCP unit) and a flow rate of 27 $\mathrm{kgh^{-1}}$. The overall energy input was calculated based on the time required to process the dried feedstock (dryer output mass flow rate).

A5.5. Input energy requirement of thermochemical processing

The heat energy (Q_{prehe}) required to preheat the feedstock to desired temperature was calculated by integrating the specific heat capacities of food waste solids and water from ambient temperature to process temperature using Equation 5.16 [84].

$$Q_{preheat} = m_{feed} * \int_{298K}^{T_p} C_{p,feed}dT + m_{water} * \int_{298K}^{T_p} C_{p,water}dT \qquad \textbf{Eq. A5.7}$$

Equation 5.16 reduces to Eq. 5.17 after integrating between temperature limits,

$$Q_{preheat} = m_{feed} * 1.5 * (T_p - 298) + m_{water} * 4.2 * (T_p - 298) \qquad \textbf{Eq. A5.8}$$

The quantity of energy required to maintain the equipment at constant temperature was calculated using a maximum steady state energy requirement of 65 $\mathrm{MJh^{-1}}$[356],however the actual measured energy requirement of the system was less than 4 MJh^{-1}. Therefore any derivations associated with this, for example exergy destruction may be slightly overestimated. Since the time required to process feedstocks at different moisture levels vary, the overall energy required to maintain the process at steady-state varied. Therefore, total chemical exergy destruction (or irreversibility) of the fuel (food waste) during thermochemical processing could be calculated as a sum of the energy required to preheat the feedstock, energy required to maintain the system at steady-state, and energy lost during catalytic combustion.

A5.6. Estimation of stack emissions

CO_2 from the stack was measured using a portable measuring device (Wohler) during each run in two distinct intervals of 15 minutes each. The sampling was done post catalytic combustion of gaseous products. During each time interval, the instrument recorded 9900 data points and the average value was used to calculate stack emissions. The emissions of CO and particulates were measured using a second portable device (Testo 300), also averaged over two distinct 15 minutes interval during each run, with 190 discrete measurements. Stack gas flow rates were estimated using the measured composition of stack gas. CO_2, CO, oxygen and water vapor were measured during a run and the remaining component in the gas was assumed to be nitrogen. The stack gas flow rate, and hence the individual gas flow rates, were calculated using the measured composition by using the following equation [415]:

$$v = 34.97 * C * \sqrt{\Delta P} * \frac{\sqrt{}T_{stack}+273}{\sqrt{}M_{wet}*P_{abs}} \qquad \textbf{Eq. A5.9}$$

where v is the stack gas velocity in m/s; C is a dimensionless constant called velocity pressure coefficient and should be set to 0.9 when unknown; ΔP is the draft pressure in mm Hg and indicates a difference between the stack pressure and atmospheric pressure, which was recorded by the instrument during stack measurement; M_{wet} is the combined molecular weight of the stack gas components on a wet basis, calculated as 28.9 g/gmole; P_{abs} is the absolute pressure in mm Hg of the stack, estimated from ΔP by assuming that the surrounding was at atmospheric pressure; T_{stack}, stack temperature is the exhaust temperature of the stack after heat exchange and was also measured using the user interface for the online data acquisition system. The average value of stack temperature throughout the run was used. For the final estimation of greenhouse gas emissions per unit mass of food waste, the stack flow rates of individual components were calculated assuming a moisture-free basis at reference conditions (1atm pressure and 25^0C).

Table A5.1. Additional biochar properties

	Feedstock	Biochar				
Properties	FW	FW800-1	FW800-2	FW800-3	FW500-1	FW500-2
Moisture, %	10.8	3.2	4.15	1.2	2.97	1.9
Ash, %	4.8	23.2	22.45	23.3	20.99	21.4
Volatile matter, %	75.9	10.3	15.15	11.6	17.47	14.6
Organic C, %	47.9	68.7	65.41	60.4	65.22	64.8
Fixed Carbon(by weight, calculated), %	8.5	63.3	58.25	63.9	58.57	62.1
Fixed carbon as a % of total carbon	0.18	92	89	1	90	96
Total N, %	2.9	3.0	3.59	3.31	3.59	3.82
H, %	NM	NM	1.17	NM	1.55	NM
O, %	NM	NM	7.12	NM	8.37	NM
H:C	1.48	0.29	NM	0.5	NM	0.45
P, %	0.266	1.4	1.62	1.41	1.41	1.22
K, %	1	3.9	5.34	4.45	4.79	4.23
Ca, %	0.5186	2.8	3.08	3.11	2.63	1.65
Mg, %	0.11	0.49	0.71	0.5	0.62	0.5

A5.7. Effect of final moisture on exergy efficiency and energy input

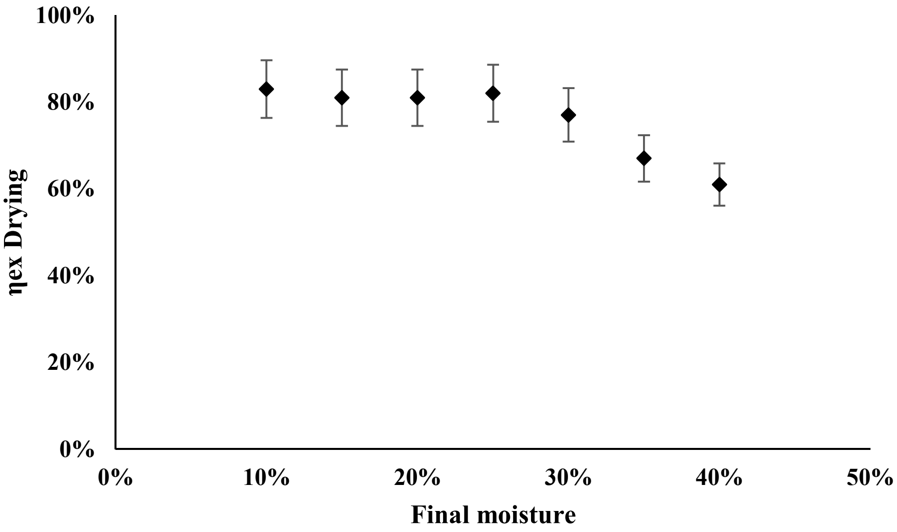

Figure A5.1. Effect of final moisture on exergy efficiency of drying process; the error bars correspond to 8% variation in exergy efficiency resulting from up to 10% variation in mass flow during the process

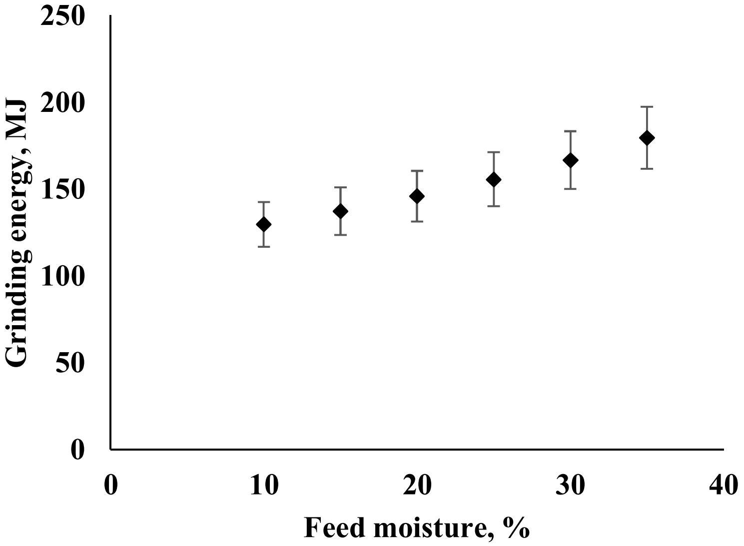

Figure A5.2. Estimated energy input of size reduction at various moisture levels; the error bars correspond to 10% variation in energy requirement due to varying particle size of input

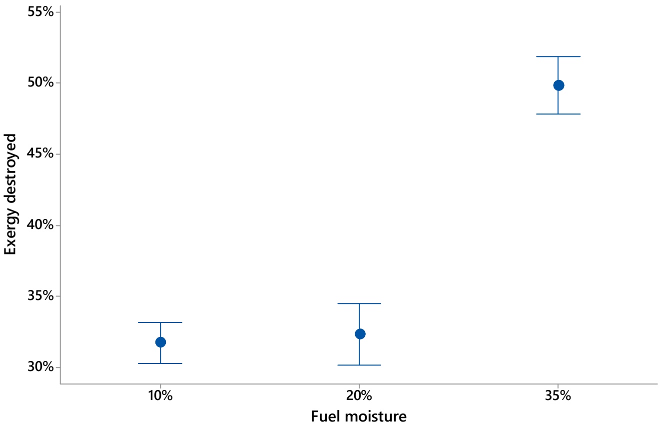

Figure A5.3- Effect of moisture on total chemical exergy destruction from food waste

Table A5.2. Sample calculation for a general exergy analysis for 35% fuel moisture with 20% assumed biochar yield

Unit operations and parameters	Temperature, C			
	800	**700**	**600**	**500**
Drying				
Mass flow rate of wet food waste, kg/h	96.0	96.0	96.0	96.0
Assumed initial moisture	0.75	0.75	0.75	0.75
Assumed final moisture	0.35	0.35	0.35	0.35
Mass flow rate of dry food waste, kg/h	384.6	384.6	384.6	384.6
Exergy input required to dry 1 ton of wet food waste	2211	2211	2211	2211
Total time to process 1 ton of wet FW	10.4	10.4	10.4	10.4
Total electric draw of the specified equipment, kW	14	14	14	14
Total electric draw per ton of wet FW processed, MJ	525	525	525	525
The LHV of wet feedstock , MJ	3000	3000	3000	3000
Total exergy input per ton wet FW	6072.0	6073.0	6074.0	6075.0
Exergy output as feedstock LHV, MJ	4805.6	4805.6	4805.6	4805.6
Exergy of output utilities	0.0	0.0	0.0	0.0
Energy losses in the dryer	0.0	0.0	0.0	0.0
Net energy of drying per wet ton	-1266.4	-1267.4	-1268.4	-1269.4
Exergy efficiency	79%	79%	79%	79%
Grinding				
Input exergy of dry fuel, MJ	4805.6	4805.6	4805.6	4805.6
Grinder flow rate, kg/h	27	27	27	27
time to process dry feedstock, h	14.2	14.2	14.2	14.2
Power rating of the grinder (5hp), kW	3.7	3.7	3.7	3.7
Total electric energy input, MJ	190	190	190	190
Mass Losses	0	0	0	0
Output exergy of fuel	4805.6	4805.6	4805.6	4805.6
Total exergy input	4995.3	4995.3	4995.3	4995.3
total exergy output	4805.6	4805.6	4805.6	4805.6
Net energy	-189.7	-189.7	-189.7	-189.7
Exergy efficiency	96%	96%	96%	96%
Biochar				
Thermochemical processor feed flow rate, kg/h	27	27	27	27
Input exergy	4805.6	4805.6	4805.6	4805.6
Char yield, %	20%	20%	20%	20%
Char flow , kg	61.3	62.0	62.8	63.6
Predicted BC yield	15.9%	16.1%	16.3%	16.5%
Input exergy from fuel during start up	379	330	281	232
Input exergy from fuel during steady state	600	600	600	600
Overall input exergy from fuel	979	930	881	832
preheat	8%	7%	6%	5%
steady state	12%	12%	12%	12%

Mass Fraction of the fuel lost	20%	19%	18%	17%
Fraction of input LHV to process ton dry FW	20.4%	19.4%	18.3%	17.3%
Total electric draw of the control system and machinery, kW	1	1	1	1
Time required to process dry FW, h	14.2	14.2	14.2	14.2
Total electric draw, MJ	51	51	51	51
Biochar LHV	25.1	25.1	25.1	25.1
Total exergy of biochar output	1537	1557	1577	1596
Total exergy input	4857	4857	4857	4857
Exergy losses	979	930	881	832
Exergy efficiency	**31.7%**	**32.1%**	**32.5%**	**32.9%**
Net energy	-3319	-3300	-3280	-3260
Air pollution control (catalytic combustion)				
Remaining LHV of fuel	2289	2318	2348	2377
wet mass flow Vapor/gas yield	323.4	322.6	321.8	321.0
dry yield vap/gas	72.9%	72.7%	72.5%	72.3%
LHV of vap and gases	1668	1685	1701	1718
Fraction of moisture in gas (from mass balance)	11.2%	11.2%	11.2%	11.2%
Exergy loss in the process	621	634	646	659
Stack losses during cat combustion, measured	13%	13%	13%	13%
Stack losses during cat combustion, MJ	217	219	221	223
Total exergy input	2289	2318	2348	2377
Total exergy output	830.4	832.2	833.7	835.1
Net energy	-1458.7	-1486.3	-1513.9	-1542.0
Exergy efficiency (heat production)	36.3%	35.9%	35.5%	35.1%
TCP efficiency (biochar and heat)	48.8%	49.2%	49.6%	50.1%
Overall, exergy eff (drying, grinding and TCP)	64.5%	64.7%	64.9%	65.1%
Total input energy, MJ	2977	2977	2977	2977
Net energy if produced heat is utilized in drying at 70% HE efficiency	2396	2395	2393	2392
If char used as a fuel, remaining energy, MJ	858	837	817	796
Balance				
Fuel exergy	100%	100%	100%	100%
Energy to raise the temp (exergy loss preheat)	8%	7%	6%	5%
Energy steady state (exergy loss steady state)	12%	12%	12%	12%
Energy cat combustion (Exergy loss)	13%	13%	13%	13%
Total exergy destruction	**33%**	**32%**	**31%**	**30%**
Exergy conserved in Char product	32%	32%	33%	33%
Exergy conserved as useful heat	17%	17%	17%	17%
(exergy balance doesn't always close, 79-98% closure in various scenarios)	82.6%	82.1%	81.5%	80.9%

Table A 5.3. GWP estimation tables and sample calculations

			DRYING								
Moisture_BC yield_Temp	Temp	Predicted BC yield	Moisture content of dried o/p	Mass of dry o/p, kg per ton wet FW	Energy, MJ	NG use, m3	Electricity, MJ	Drying, NG, kgCO2e	Dry, Elec, kgCO2e	Total CO2e/ton dryer output	**Drying, CO2e kg/ton wet FW**
10_10_8	800	0.1	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
10_20_8	800	0.2	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
10_30_8	800	0.3	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
20_10_8	800	0.1	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
20_20_8	800	0.2	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
20_30_8	800	0.3	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
35_10_8	800	0.1	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
35_20_8	800	0.2	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
35_30_8	800	0.3	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
10_10_7	700	0.1	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
10_20_7	700	0.2	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
10_30_7	700	0.3	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
20_10_7	700	0.1	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
20_20_7	700	0.2	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
20_30_7	700	0.3	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
35_10_7	700	0.1	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
35_20_7	700	0.2	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
35_30_7	700	0.3	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
10_10_6	600	0.1	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
10_20_6	600	0.2	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
10_30_6	600	0.3	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
20_10_6	600	0.1	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
20_20_6	600	0.2	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
20_30_6	600	0.3	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
35_10_6	600	0.1	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
35_20_6	600	0.2	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
35_30_6	600	0.3	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
10_10_5	500	0.1	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
10_20_5	500	0.2	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
10_30_5	500	0.3	0.1	278	2547	66.2	525	85.3	92.8	178.1	**115.3**
20_10_5	500	0.1	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
20_20_5	500	0.2	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
20_30_5	500	0.3	0.2	313	2435	63.2	525	81.5	92.8	174.3	**89.1**
35_10_5	500	0.1	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
35_20_5	500	0.2	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**
35_30_5	500	0.3	0.35	385	2211	57.4	525	74	92.8	166.8	**56.3**

SLOW PYROLYSIS AND CAT COMBUSTION

Elect, MJ	BC yield, kg/wet ton FW	kgCO2e/kg BC	kgCO2e/kg dry output	kgCO2/ton wet FW	CO2 emissions, direct, kg CO2/ton wet FW	CO emission, kgCO/ton wet FW	Total CO2e emissions, kgCO2e/wet ton FW	**Total thermo process emissions, kgCO2/ton wet FW**
7	21.8	0.0568	0.004445	1.236	192	13	205.0	**206.2**
7	43.5	0.0285	0.00446	1.240	216	15	231.0	**232.2**
7	54.5	0.0227	0.00445	1.237	266	19	285.0	**286.2**
7.5	22.9	0.0579	0.004232	1.325	192	13	205.0	**206.3**
7.5	46.4	0.0286	0.00424	1.327	216	15	231.0	**232.3**
7.5	69.6	0.0191	0.004247	1.329	266	19	285.0	**286.3**
9.3	22.6	0.0728	0.004273	1.645	192	13	205.0	**206.6**
9.3	53.9	0.0323	0.004522	1.741	216	15	231.0	**232.7**
9.3	80.8	0.0204	0.004281	1.648	266	19	285.0	**286.6**
7	22.0	0.0563	0.004455	1.239	192	13	205.0	**206.2**
7	44.1	0.0285	0.004521	1.257	216	15	231.0	**232.3**
7	54.5	0.0285	0.005587	1.553	266	19	285.0	**286.6**
7.5	23.3	0.0285	0.002122	0.664	192	13	205.0	**205.7**
7.5	47.5	0.0285	0.004325	1.354	216	15	231.0	**232.4**
7.5	69.9	0.0285	0.006365	1.992	266	19	285.0	**287.0**
9.3	25.2	0.0285	0.001865	0.718	192	13	205.0	**205.7**
9.3	54.7	0.0285	0.004049	1.559	216	15	231.0	**232.6**
9.3	82.1	0.0285	0.006078	2.340	266	19	285.0	**287.3**
7	22.3	0.0285	0.002286	0.636	192	13	205.0	**205.6**
7	44.7	0.0285	0.004583	1.274	216	15	231.0	**232.3**
7	56.1	0.0285	0.005751	1.599	266	19	285.0	**286.6**
7.5	23.7	0.0285	0.002158	0.675	192	13	205.0	**205.7**
7.5	47.5	0.0285	0.004325	1.354	216	15	231.0	**232.4**
7.5	71.2	0.0285	0.006483	2.029	266	19	285.0	**287.0**
9.3	25.9	0.0285	0.001917	0.738	192	13	205.0	**205.7**
9.3	55.6	0.0285	0.004116	1.585	216	15	231.0	**232.6**
9.3	83.4	0.0285	0.006174	2.377	266	19	285.0	**287.4**
7	22.6	0.0285	0.002317	0.644	192	13	205.0	**205.6**
7	45.3	0.0285	0.004644	1.291	216	15	231.0	**232.3**
7	57.8	0.0285	0.005926	1.647	266	19	285.0	**286.6**
7.5	24.2	0.0285	0.002204	0.690	192	13	205.0	**205.7**
7.5	48.3	0.0285	0.004398	1.377	216	15	231.0	**232.4**
7.5	72.5	0.0285	0.006601	2.066	266	19	285.0	**287.1**
9.3	26.7	0.0285	0.001976	0.761	192	13	205.0	**205.8**
9.3	56.5	0.0285	0.004182	1.610	216	15	231.0	**232.6**
9.3	84.7	0.0285	0.00627	2.414	266	19	285.0	**287.4**

TRANSPOI		AVOIDED EMISSIONS									SCENARIOS							
CO2 emission during biochar transportation	Displaced natural gas from heat generation, MJ	Displaced natural gas, m3	Avoided emissions from heat kgCO2e/MJ	Avoided emissions from biochar land application	**Total avoided emissions, kgCO2/wet ton FW**	Net emissions from thermo_chem, kgCO2e/wet ton FW	Biogenic emission, kgCO2e/wet ton FW	**Net emissions, BC (soil, waste heat)**	MJavailable if all the biochar produced is used for heat generatio	Avoided emissions from using BC for heat gen, kgCO2/ton wet FW	Direct emissions from biochar combustion, kgCO2e	**Net emissions, BC (heat, waste heat) kgCO2e/ton wet FW**	**BC used for heat, Net emissions after subtracting biogenic**	**Exergy efficiency, BC (soil, waste heat)**	**Exergy efficiency BC (heat, waste heat)**	**Exergy Efficiency, BC (soil, no waste heat)**	**Emissions, BC (soil, no waste heat)**
6.025648	1645.5	42.2	-92.1	-2.1	**-94.2**	249.0	-205.0	**44.0**	2130	-119.3	-79.8	138.2	13.0	35	33	9	136.2
12.0495	1391.0	35.7	-77.9	-4.2	**-82.1**	293.2	-231.0	**62.2**	2362	-132.3	-159.5	71.5	0.0	38	34	16	140.1
15.09617	1411.3	36.2	-79.0	-5.2	**-84.3**	348.1	-285.0	**63.1**	2589	-145.0	-199.8	72.4	-12.8	41	37	26	142.1
6.336901	1446.8	37.1	-81.0	-2.2	**-83.2**	232.5	-205.0	**27.5**	1957	-109.6	-83.9	115.9	-5.2	33	31	9	108.5
12.8528	1171.2	30.0	-65.6	-4.5	**-70.0**	278.2	-231.0	**47.2**	2191	-122.7	-170.1	42.5	-18.3	36	32	18	112.8
19.2792	801.6	20.6	-44.9	-6.7	**-51.6**	357.1	-285.0	**72.1**	2331	-130.5	-255.2	3.6	-26.2	39	33	26	117.0
6.2602	1132.0	29.0	-63.4	-2.2	**-65.6**	215.0	-205.0	**10.0**	1675	-93.8	-82.9	97.6	-24.5	29	27	10	73.4
14.9303	895.6	23.0	-50.2	-5.2	**-55.3**	260.0	-231.0	**29.0**	2096	-117.4	-197.6	-14.6	-48.0	36	33	22	79.1
22.3816	501.8	12.9	-28.1	-7.8	**-35.9**	340.8	-285.0	**55.8**	2303	-129.0	-296.3	-70.9	-59.7	40	34	32	83.9
6.094	1662.5	42.6	-93.1	-2.1	**-95.2**	248.1	-205.0	**43.1**	2153	-120.6	-80.7	136.0	11.7	36	34	9	136.2
12.2157	1405.6	36.0	-78.7	-4.2	**-82.9**	292.5	-231.0	**61.5**	2389	-133.8	-161.7	67.8	-1.5	38	35	17	140.2
15.0965	1407.0	36.1	-78.8	-5.2	**-84.0**	348.6	-285.0	**63.6**	2621	-146.8	-199.8	70.9	-14.2	42	38	27	142.4
6.4541	1468.6	37.7	-82.2	-2.2	**-84.5**	230.7	-205.0	**25.7**	1988	-111.3	-85.4	111.9	-7.6	33	32	9	107.9
13.1575	1174.6	30.1	-65.8	-4.6	**-70.3**	278.2	-231.0	**47.2**	2228	-124.8	-174.2	36.5	-20.4	36	33	18	113.0
19.3623	812.0	20.8	-45.5	-6.7	**-52.2**	357.2	-285.0	**72.2**	2370	-132.7	-256.3	1.0	-27.7	39	34	27	117.7
6.9804	1263.5	32.4	-70.8	-2.4	**-73.2**	207.2	-205.0	**2.2**	1824	-102.1	-92.4	78.8	-33.8	32	30	11	72.9
15.1519	1072.4	27.5	-60.1	-5.3	**-65.3**	250.1	-231.0	**19.1**	2127	-119.1	-200.6	-19.5	-49.9	36	34	23	79.1
22.7417	717.0	18.4	-40.2	-7.9	**-48.0**	329.7	-285.0	**44.7**	2337	-130.9	-301.0	-76.9	-60.9	41	34	33	84.8
6.1771	2399	61.5	-134.3	-2.1	**-136.5**	206.3	-205.0	**1.3**	2176	-121.9	-81.8	133.0	9.8	37	35	9	135.7
12.3819	2029	52.0	-113.6	-4.3	**-117.9**	257.7	-231.0	**26.7**	2416	-135.3	-163.9	64.1	-3.0	45	42	20	140.4
15.5397	2004	51.4	-112.2	-5.4	**-117.6**	315.5	-285.0	**30.5**	2654	-148.6	-205.7	63.3	-16.0	42	39	30	142.7
6.5649	2129	54.6	-119.2	-2.3	**-121.5**	193.8	-205.0	**-11.2**	2019	-113.1	-86.9	108.7	-9.4	34	32	10	108.0
13.1575	1724	44.2	-96.5	-4.6	**-101.1**	247.4	-231.0	**16.4**	2265	-126.8	-174.2	34.4	-22.5	40	36	20	113.0
19.7224	1175	30.1	-65.8	-6.8	**-72.6**	337.2	-285.0	**52.2**	2409	-134.9	-261.1	-5.9	-29.8	43	37	30	118.0
7.1743	1855	47.6	-103.9	-2.5	**-106.4**	174.2	-205.0	**-30.8**	1876	-105.1	-95.0	73.4	-36.7	33	31	11	73.1
15.4012	1026	26.3	-57.5	-5.3	**-62.8**	252.8	-231.0	**21.8**	1957	-109.6	-203.9	-13.2	-40.4	40	35	26	79.3
23.1018	558	14.3	-31.2	-8.0	**-39.3**	338.9	-285.0	**53.9**	2249	-125.9	-305.8	-76.7	-55.9	47	39	40	85.1
6.2602	2422	62.1	-135.6	-2.2	**-137.8**	205.1	-205.0	**0.1**	2199	-123.1	-82.9	130.6	8.5	36	34	9	135.7
12.5481	2049	52.5	-114.7	-4.3	**-119.1**	256.7	-231.0	**25.7**	2433	-136.2	-166.1	60.9	-4.0	46	42	20	140.5
16.0106	1997	51.2	-111.8	-5.5	**-117.4**	316.3	-285.0	**31.3**	2686	-150.4	-211.9	55.3	-17.8	43	39	22	143.1
6.7034	2160	55.4	-121.0	-2.3	**-123.3**	192.1	-205.0	**-12.9**	2050	-114.8	-88.7	105.2	-11.1	34	32	10	108.1
13.3791	1750	44.9	-98.0	-4.6	**-102.6**	246.2	-231.0	**15.2**	2301	-128.9	-177.1	29.5	-24.4	41	37	20	113.2
20.0825	1190	30.5	-66.6	-7.0	**-73.6**	336.6	-285.0	**51.6**	2448	-137.1	-265.8	-12.8	-32.0	44	38	30	118.2
7.3959	1906	48.9	-106.7	-2.6	**-109.3**	171.5	-205.0	**-33.5**	1928	-108.0	-97.9	67.5	-39.6	34	32	11	73.2
15.6505	1038	26.6	-58.1	-5.4	**-63.6**	252.4	-231.0	**21.4**	1985	-111.2	-207.2	-18.1	-41.9	41	35	27	79.5
23.4619	563	14.4	-31.5	-8.1	**-39.7**	338.9	-285.0	**53.9**	2282	-127.8	-310.6	-83.3	-57.7	48	40	40	85.4

Table A5.4: Sample data inventory used in GWP estimation

Data inventory		moisture%, BC %, Temp																	
	Source	10%, 10%, 800C	10%, 20%, 800C	10%, 30%, 800C	20%, 10%, 800C	20%, 20%, 800C	20%, 30%, 800C	35%, 10%, 800C	35%, 20%, 800C	35%, 30%, 800C	10%, 10%, 700C	10%, 20%, 700C	10%, 30%, 700C	20%, 10%, 700C	20%, 20%, 700C	20%, 30%, 700C	35%, 10%, 700C	35%, 20%, 700C	35%, 30%, 700C
Fuel moisture, char yield	Basis	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Raw food waste, kg	Estimated	278	278	278	313	313	313	385	385	385	313	278	278	313	313	313	385	385	385
Dry food waste, kg	Estimated	21.8	43.5	54.5	22.8769	46.4	69.6	22.6	50.9	80.8	22	44.1	54.5	23.3	47.5	69.9	25.2	44.5	80.8
Char, kg	Estimated	225.5	182.9	140.8	255.3	207.9	153.3	318.9	260.6	191.6	256.1	182.4	140.8	254.9	207.1	153.2	316.6	265.6	237.3
VGPs, kg	Estimated	30.7	51.6	82.7	34.8	58.7	90.1	43.5	73.5	112.6	34.9	51.5	82.7	34.8	58.4	89.9	43.2	74.9	66.9
water, kg	Estimated	8%	16%	20%	7%	15%	22%	6%	13%	21%	7%	14%	17%	7%	15%	22%	8%	14%	26%
Char, %	Estimated	81%	66%	51%	82%	66%	49%	83%	68%	50%	82%	58%	45%	81%	66%	49%	101%	85%	76%
VPGs, %	Estimated	11%	19%	30%	11%	19%	29%	11%	19%	29%	11%	16%	26%	11%	19%	29%	14%	24%	21%
water,%	Estimated	2547	2547	2547	2435	2435	2435	2211	2211	2211	2547	2547	2547	2435	2435	2435	2211	2211	2211
Drying energy, heat, MJ	Fortis BC	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7
Natural gas LHV, MJ/m3	Estimated	65.8	65.8	65.8	62.9	62.9	62.9	57.1	57.1	57.1	65.8	65.8	65.8	62.9	62.9	62.9	57.1	57.1	57.1
Natural gas reqd in drying, m3	Estimated	1645.5	1391.0	1411.3	1446.8	1171.2	801.6	1132.0	895.6	501.8	1662.5	1405.6	1407	1468.6	1174.6	812	1263.5	1072.4	1072.4
Output heat after accounting f	Estimated	43	36	36	37	30	21	29	23	13	43	36	36	38	30	21	33	28	28
Displaced natural gas (produc	Estimated	137	137	137	154	154	154	190	190	190	137	137	137	154	154	154	190	190	191
Grinding energy, MJ	Estimated	532	532	532	686	686	686	722	722	722	533	533	533	686	686	686	722	722	722
Total elecric energy requireme	Estimated/mea	4833	4833	4833	4625	4625	4625	4346	4346	4346	4833	4833	4833	4625	4625	4625	4346	4346	4347
LHV of food waste, MJ	Ibarrola, 2012	0.0064	0.0128	0.0160	0.0067	0.0136	0.0205	0.0066	0.0150	0.0238	0.0065	0.0130	0.0160	0.0069	0.0140	0.0206	0.0074	0.0131	0.0238
ha of land covered at 3.4ton/h	Roberts 2010	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164
N fertilizer appl rate, kg/ha	Roberts 2010	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64
P fertilizer appl rate, kg/ha	Roberts 2010	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94
K fertilizer appl rate, kg/ha	Roberts 2010	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Reduced N fertilizer use from	Roberts 2010	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Reduced P fertilizer use from	Roberts 2010	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Reduced K fertilizer use from	Estimated	0.10	0.21	0.26	0.11	0.22	0.34	0.11	0.25	0.39	0.11	0.21	0.26	0.11	0.23	0.34	0.12	0.21	0.39
Avoided N fertilizer, kg	Estimated	0.02	0.04	0.05	0.02	0.04	0.07	0.02	0.05	0.08	0.02	0.04	0.05	0.02	0.04	0.07	0.02	0.04	0.08
Avoided P fertilizer, kg	Yeboah, 2016	0.03	0.06	0.08	0.03	0.06	0.10	0.03	0.07	0.11	0.03	0.06	0.08	0.03	0.07	0.10	0.03	0.06	0.11