

THERMAL DECOMPOSITION AND GASIFICATION  
OF CARBOHYDRATES, LIPIDS, PROTEINS  
AND FOOD WASTE

By

JACOB CODY COLLINS

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Stillwater, Oklahoma

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AND FOOD WASTE

Thesis Approved:

Dr. Ajay Kumar

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Thesis Adviser

Dr. Tim Bowser

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Dr. Danielle Bellmar

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**Abstract:**

The overall goal of this research was to investigate thermal decomposition of components of food and how food composition affects gasification performance. The specific objectives were to (1) investigate the thermal devolatilization properties of different types of the main components of food (carbohydrates, proteins, and fats), (2) investigate the products of pyrolysis from the components of food (carbohydrates, proteins, and fats), and (3) investigate the effect of food composition on gasification performance. The reaction kinetics of thermal devolatilization of the three types of each food component was investigated in a thermogravimetric analyzer and pyrolysis products were investigated using a pyroprobe connected to a gas chromatograph. The devolatilization kinetics parameters were evaluated based on the Arrhenius equation. All types of carbohydrates and proteins devolatilized and had 90 % conversion into pyrolysis products at 600 °C, however, the lipids primarily converted into vapor form and did not decompose. Pyrolysis products of carbohydrates were largely composed of furan and sugar based compounds, whereas those of protein varied depending on the type of protein. Since lipids mainly vaporized, only slight conversion (less than 1 %) into different lipid types and hydrocarbons was observed. One model compound of each type of the food component (dextrose, phenylalanine, and palmitic acid for carbohydrate, protein, and fat) and three food samples with one dominant component were gasified in an updraft gasifier at a gasification temperature of 800°C. The effect of the three main components (carbohydrates, proteins, and fats) in food on gasification performance of syngas yield, composition, carbon conversion efficiency, and cold gas efficiency was evaluated. . Carbon conversion efficiency (CCE) was the highest for carbohydrates, followed by fats, and the lowest conversion for proteins. Cold gas efficiency (CGE) was the highest for fats, followed by proteins, and the lowest efficiency for carbohydrates. No significant effects of food component were observed for the production of H<sub>2</sub>, CO, and CO<sub>2</sub>.

## TABLE OF CONTENTS

Chapter	Page
I. INTRODUCTION .....	1
II. BIOFUELS FROM FOOD WASTES: THERMAL DECOMPOSITION OF CARBOHYDRATES, LIPIDS, AND PROTIENS .....	3
Abstract .....	3
1 Introduction .....	4
2 Materials and methods.....	6
2.1. Experimental Design and Materials.....	6
2.2. Thermogravometric Analysis.....	7
2.3. Reaction Kinetics .....	7
2.4. Pyroprobe and Gas Chromatograph.....	8
3 Results and discussion.....	9
3.1. Weight loss profile .....	9
3.2. Devolatilization reaction kinetics .....	13
3.3. Devolatilization products .....	15
4 Conclusions .....	18
Acknowledgments.....	18
References.....	19
III. EFFECT OF COMPOSITION ON THE GASIFICATION OF FOOD WASTE .	21
Abstract.....	21
1 Introduction .....	22
2 Materials and methods.....	24
2.1. Experimental Design and Materials.....	24
2.2. Proximate Analysis .....	24
2.3. Gasification setup.....	25
2.4. Sample Preparation .....	26

2.5. Experimental analysis .....	27
3 Results and discussion.....	29
3.1. Hydrogen, carbon monoxide, and carbon dioxide analysis .....	29
3.2. Carbon conversion (CCE) and cold gas efficiencies (CGE).....	30
3.3. Mass balance.....	31
4 Conclusions .....	32
Acknowledgments.....	33
References.....	34

## LIST OF TABLES

### Chapter II

Table	Page
1. Devolatilization reaction kinetics of carbohydrates, proteins, switchgrass, lignocellulosic components.....	15
2. Products from pyrolysis of carbohydrate types .....	16
3. Products from pyrolysis of protein types .....	17
4. Products from pyrolysis of lipid types .....	18

### Chapter III

Table	Page
1. Composition of model and food samples.....	24
2. Proximate and ultimate analysis of model and food samples .....	25
3. Analysis of syngas constituents .....	30
4. Carbon conversion and cold gas efficiencies of syngas.....	31
5. Mass balance of model and food samples.....	32

## LIST OF FIGURES

### Chapter II

Figure	Page
1. Rate of weight loss with temperature of carbohydrates.....	10
2. Rate of weight loss with temperature of proteins .....	12
3. Rate of weight loss with temperature of lipids .....	13

### Chapter III

Figure	Page
1. Gasifier.....	26
2. Hopper setup for holding sample and sand.....	27



## CHAPTER I

### INTRODUCTION

Thermochemical conversion (TC) methods use heat to break down carbon based feedstocks into fuels and chemicals. Gasification is the method of partial combustion to create the energy needed to break down the remaining feedstock into fuels and chemicals. Pyrolysis is the method for converting biomass in an inert atmosphere to a desired liquid fuel, known as bio-oil, utilizing an external heat source. Feedstocks for TC are composed mainly of carbon, hydrogen, and oxygen, with ash being a minor constituent and not converted. The main focus for TC feedstocks have been hemicellulosic biomass sources such as fast growing trees and perennial grasses. High growth rate and yield make these feedstocks ideal for TC.

Another feedstock source that has been investigated, in limited scope, is food wastes. Food wastes are byproducts of the food industry and leftovers from municipalities, such as homes and restaurants. Food wastes are composed of mainly carbon, hydrogen, and oxygen. However, with high moisture and ash content, food wastes have not received the amount of consideration as other feedstocks. Food wastes composition can be broken into three components: carbohydrates, proteins, and fats. Food waste from the food industry has received the most attention due to its consistent yield, composition, and locality. Food waste from municipalities is from different sources and varies in composition and yield.

However, the characteristics and properties of different types of the main components have not been fully investigated. Characteristics of thermal decomposition and products from gasification and pyrolysis need to be known to have a more efficient conversion. The thermal decomposition with respect to temperature is needed to better understand the reaction kinetics and how quickly the sample decomposes. There is also limited knowledge on whether or not different types of the main components produce similar products from conversion. The thermal decomposition and reaction kinetics of three types of each component were investigated in a thermogravimetric analyzer and pyrolysis products were investigated using a pyroprobe connected to a gas chromatograph (Chapter II). The weight loss and rate of weight loss was evaluated for each type of component. The devolatilization kinetic parameters, found based on the Arrhenius equation, of, pre-exponential factor (A), activation energy (E), rate constant (k), and the order of reaction were evaluated. Gasification in an updraft gasifier for one model compound of each type of component along with three food samples with one dominate component was investigated in Chapter III. Gasification performance of syngas yield, composition, carbon conversion efficiency, and cold gas efficiency were evaluated

The overall goal of this research was to investigate the components of food and how food composition affects gasification performance. The specific objectives of this research were to: (1) Investigate the thermal devolatilization properties of different types of carbohydrates, proteins, and fats, (2) Investigate the products of pyrolysis from different types of carbohydrates, proteins, and fats, and (3) Investigate the effect of food composition on gasification performance.

## CHAPTER II

### BIOFUELS FROM FOOD WASTES: THERMAL DECOMPOSITION OF CARBOHYDRATES, LIPIDS, AND PROTIENS

Jacob Collins<sup>a</sup>, Ajay Kumar<sup>a\*</sup>, Tim Bowser<sup>a</sup>, Danielle Bellmer<sup>a</sup>

<sup>a</sup>Department of Biosystems and Agricultural Engineering, Oklahoma State University,  
111 Agricultural Hall, Stillwater, OK 74078-6016, United States

\*Corresponding author: 228 Agricultural Hall, Stillwater, OK – 74078. USA.

Tel.: +1 405 744 8396; fax: +1 405 744 6059. E-mail address: ajay.kumar@okstate.edu

#### **Abstract**

Food wastes differ in composition based on their sources, hence are difficult to use in gasification and pyrolysis technologies. The specific objectives of this study were to investigate the thermal devolatilization properties and products of different types of lipid, carbohydrate, and protein (food waste components) and to relate the properties to thermochemical conversion processes. All types of carbohydrates and proteins devolatilized and had 90% conversion before 600°C, however, the lipids primarily converted into vapor form and did not decompose. Pyrolysis products of carbohydrates were largely composed of furan and sugar based compounds, whereas those of protein varied depending on the type of protein. Since lipids mainly vaporized, only slight conversion (less than 1%) into different lipid types and hydrocarbons were observed.

**Keywords:** Food waste; Devolatilization; Decomposition; Reaction kinetics; Pyrolysis; Py-GC/MS; TGA

## 1. Introduction

In 2012 the United States produced 251 millions of tons of municipal solid wastes (MSW) with food wastes comprising 14.5% of the MSW. However, only 4.8% of the food waste was used, mainly for composting, with the remaining being landfilled (www.epa.gov, 2012). This leaves 35 million tons of food waste that can potentially be converted into fuels and chemicals. Alternative technologies are needed to landfilling food wastes as landfills are quickly rising to capacity, use valuable land, have unwanted odors, and produce greenhouse gas emissions. Food wastes are composed primarily of carbon, hydrogen, and oxygen that can be converted into renewable fuels, chemicals, and power. Hence, it is critical to investigate and develop technologies for management and utilization of this food waste so that the waste can be converted into a valuable resource. Digman and Kim (2008) reviewed incineration, pyrolysis, and gasification as methods of conversion of food waste and concluded that food wastes have promise for thermochemical conversion into fuels and chemicals, however, the composition of food waste needs to be analyzed for efficient conversion.

Although there has been research into thermochemical conversion of food waste, the research has been limited to a single source with fixed composition. Ko et al. (2001) conducted an analysis on food waste from a mess hall in Korea that was first carbonized then gasified and found that carbonization at 200°C gave the highest conversion rate to carbonized solids at 25% to 32%. It was also found that the increase in reactor temperature (from 800°C to 900°C) increased gas yield (from 60% to 75%). The highest hydrogen yield, 700 mmol, at 800°C was obtained with a 1 to 2 steam input to carbon ratio, compared to 500 mmol and 450 mmol with 1 to 3 and 7 to 10 steam input to carbon

ratio, respectively. Ahmed and Gupta (2010) gasified and pyrolyzed food waste, represented by 35 g of dog food, at 800°C and 900°C and found that gas and H<sub>2</sub> yields at 900°C (29 g and 1.59 g of syngas and H<sub>2</sub> yield, respectively) were lower than those at 800°C (31 g and 1.63 g of syngas and H<sub>2</sub> yield, respectively). A small updraft batch scale gasifier was able to gasify pork waste and wood pellets producing syngas containing 3.4% v v<sup>-1</sup> H<sub>2</sub>, 13.3% v v<sup>-1</sup> CO and 11.8 % v v<sup>-1</sup> CO<sub>2</sub>, from pork waste and 2.1 % v v<sup>-1</sup> H<sub>2</sub>, 11.9 % v v<sup>-1</sup> CO and 7.2 % v v<sup>-1</sup> CO<sub>2</sub> from wood pellets (Bowser et al., 2005). To utilize food waste in a residential pellet stove, Caton et al. (2010) investigated devolatilization of ground food waste obtained from US Naval Academy. They found that, as compared to wood, the food waste contained lower oxygen, but higher nitrogen, ash, and energy and emitted higher nitrous oxide and unburned hydrocarbons during combustion.

Thermogravimetric analysis (TGA) is a routinely used method to obtain weight loss of materials undergoing pyrolysis with respect to temperature, with the results used to evaluate reaction kinetics of thermal decomposition. A pyroprobe connected to a gas chromatograph (Py-GC) is used for determination of pyrolysis products (Xu et al., 2013). This study used TGA and Py-GC to calculate reaction kinetics and identify products of thermal decomposition of food waste components. Similar studies have been reported on biomass components, such as cellulose, hemicellulose and lignin (Guidicianni et al., 2013; Pasangulapati et al., 2012; Yang et al., 2007).

Thangalazhy-Gopkumar et al. (2011) used Py-GC to investigate how changes in the pyrolysis temperature and heating rate affected the composition and yield of volatiles obtained from pine wood and switchgrass. They found that phenols and toluene increased with increased reactor temperature regardless of biomass type, whereas

ketones, furans, and guaiacols varied depending on biomass type. Du et al. (2013) studied the effects of temperature (450°C and 600°C) on pyrolysis of microalgae and its carbohydrate, protein and lipid samples, represented by cellulose, egg white powder and canola oil, respectively, at a heating rate of 1000°C s<sup>-1</sup>. The results showed that proteins had low aromatic products when used with HZSM-5 catalyst. Lipids were precursors of 40% of the total aromatic products obtained from microalgae. The percentage of aromatic compounds from all samples more than doubled with an increase in catalyst to microalgae ratio from 1:1 to 5:1.

The specific objectives of this study were to investigate the thermal devolatilization properties and products of different types of lipids, carbohydrates, and proteins and to relate the properties to thermochemical conversion processes commonly used to produce fuels and chemicals.

## **2. Materials and Methods**

### **2.1 Experimental Design and Materials**

A full factorial experimental design was used with three factors (carbohydrate, lipid, and protein) and three levels (component type) of each factor. The levels of food waste component type for carbohydrates were starch (amyloextrin), dextrose anhydrous, and sucrose, for lipids were linoleic acid, stearic acid, and palmitic acid, and for proteins were phenylalanine, histidine, and valine. All compounds (purchased from Fischer Scientific, U.S.A.) were chosen for their availability in different food types and their representation of each component. The 3 types of each component were chosen based on their relative availability in food.

## 2.2 Thermogravometric Analysis

Thermogravometric analysis (TGA, model: Thermo Scientific: Versa Therm TGA machine, U.S.A.) was used to determine weight loss with respect to temperature. Samples, 20 mg each, were heated at a rate of  $50^{\circ}\text{C min}^{-1}$  in an inert atmosphere of nitrogen with temperature increasing from  $50^{\circ}\text{C}$  to  $950^{\circ}\text{C}$ . Using the resulting  $dw dt^{-1}$  plot from the TGA analysis, the reaction kinetics for the devolatilization peaks were determined using OriginLab™ Data Analysis and Graphing Software (Northampton, MA). Parameters of devolatilization reaction kinetics were determined using a procedure similar to the one reported by Pasangulapati et al. (2012), Kumar et al. (2008), and Skreiberg et al. (2011).

## 2.3 Reaction Kinetics

Global kinetics of devolatilization is represented by:

$$-\left(\frac{dw}{dt}\right) = kw^n \quad (1)$$

where,

t = time (min),

k = rate constant ( $\text{min}^{-1}$ ),

w = sample weight (mg) and

n = order of reaction.

Using the Arrhenius equation, the rate constant can be written as:

$$k = Aexp(-E/RT) \quad (2)$$

where,

A = pre-exponential factor( $\text{s}^{-1}$ ),

E = activation energy ( $\text{KJ mol}^{-1}$ ),

R = universal gas constant (KJ K<sup>-1</sup> mol<sup>-1</sup>) and

T = temperature (K).

Equation (3) is obtained by simplifying equations (1) and (2) into a linear form.

$$\ln\left(\frac{-\left[\frac{dw}{dt}\right]}{w_f - w_i}\right) = \ln(A) - \frac{E}{RT} + n \cdot \ln\left(\frac{w - w_f}{w_i - w_f}\right) \quad (3)$$

where,

w = weight of sample (mg) at time t,

w<sub>f</sub> = final weight of sample in the specific weight loss stage (mg),

w<sub>i</sub> = initial weight of the sample in the specific weight loss stage (mg) and

dw dt<sup>-1</sup> = ratio of change in weight to change in time.

Equation (3) can be expressed by the linear equation as follows.

$$y = B + Cx + Dz \quad (4)$$

where,

$$B = \ln(A), C = -\frac{E}{R}, \text{ and } D = n.$$

$$x = \frac{1}{T}, y = \ln\left(\frac{\frac{dw}{dt}}{w_f - w_i}\right), \text{ and } z = \ln\left(\frac{w - w_f}{w_i - w_f}\right)$$

The multi-regression method in Excel™ was used to calculate the variables μB, C, and D, which were then used to find the kinetic parameters of the devolatilization.

#### 2.4 Pyroprobe and Gas Chromatograph

Pyroprobe (Pyroprobe 5200 with Thermal Desorption and Reactant Gas Operation with Heated Tubular Reactor, CDS Analytical, Oxford, PA) was used to convert the samples into pyrolysis products. A sample of 2 mg was used in a helium atmosphere with a heating rate of 1000°C s<sup>-1</sup> from 25°C to 600°C. The sample was



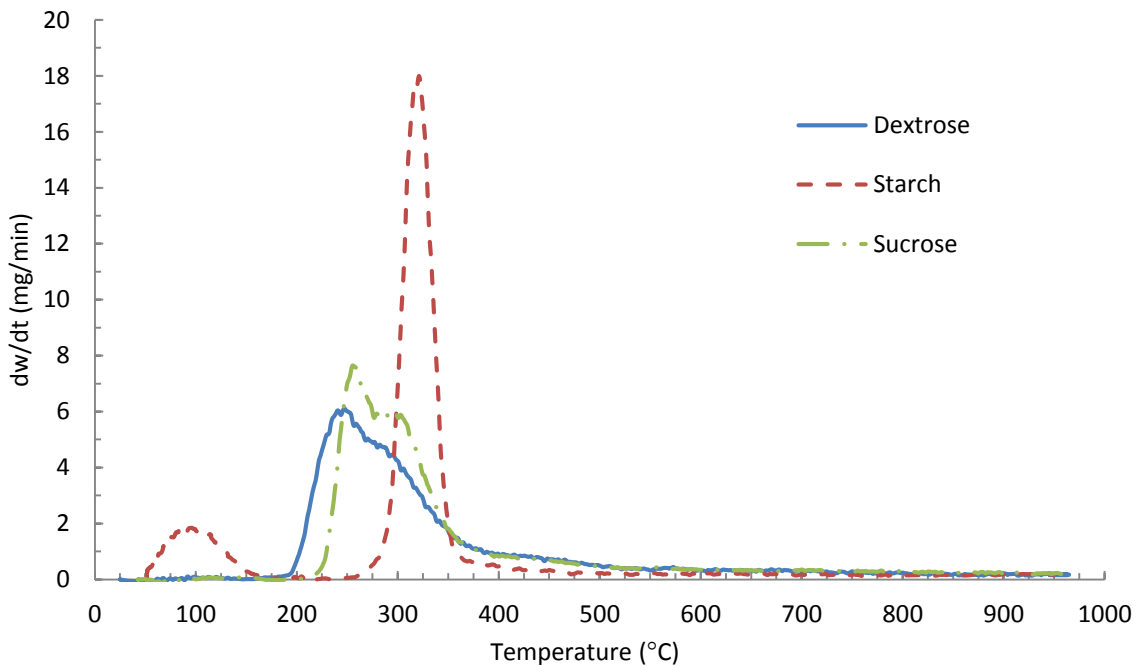
loaded into a quartz tube (No. 10A1-3008, CDS Analytical, Oxford, PA) with quartz wool (No. 1001-0345 CDS Analytical, Oxford, PA) on both sides to hold sample in the middle of the tube lengthwise so that the sample is placed in the middle of the probe filament for optimal heating. Helium atmosphere was used in pyroprobe due to the use of helium as a carrier gas in the gas chromatograph. The pyroprobe was connected to a Gas Chromatograph, GC, (model 7890A, Agilent Technologies) equipped with a DB-5 capillary column (30 mL×0.32mm I.D., 0.25 µm film thickness). The GC oven temperature was set to maintain at 40°C for 4 min, and then the temperature was programmed at a rate of 5°C min<sup>-1</sup> to 280°C and maintained for 20 min. The injector temperature was 250°C, and the split ratio was set to 30:1. Helium (purity: 99.99%) was used as the carrier gas at a flow rate of 1mL/min. The GC was connected to a Mass Spectrometer (model 5975 C inert XL MSD, Santa Clara, CA) with triple axis detector to determine the composition of volatiles.

### **3. Results and Discussion**

#### **3.1 Weight loss profile**

Figures 1, 2, and 3 show the rates of weight loss with respect to time ( $\frac{dw}{dt}$ ) and temperature for the different types of carbohydrate, protein, and lipid, respectively. Each food component (carbohydrate, protein, and lipid) shows three regions of weight loss; (1) moisture loss with light devolatilization, (2) main devolatilization (also called active pyrolysis), and (3) secondary devolatilization. Three similar weight loss regions were observed with analysis of wood, coffee waste, and glossy paper (Skreiberg et al., 2011), and with analysis of corn and sugar cane bagasse (Aboyade et al., 2011).

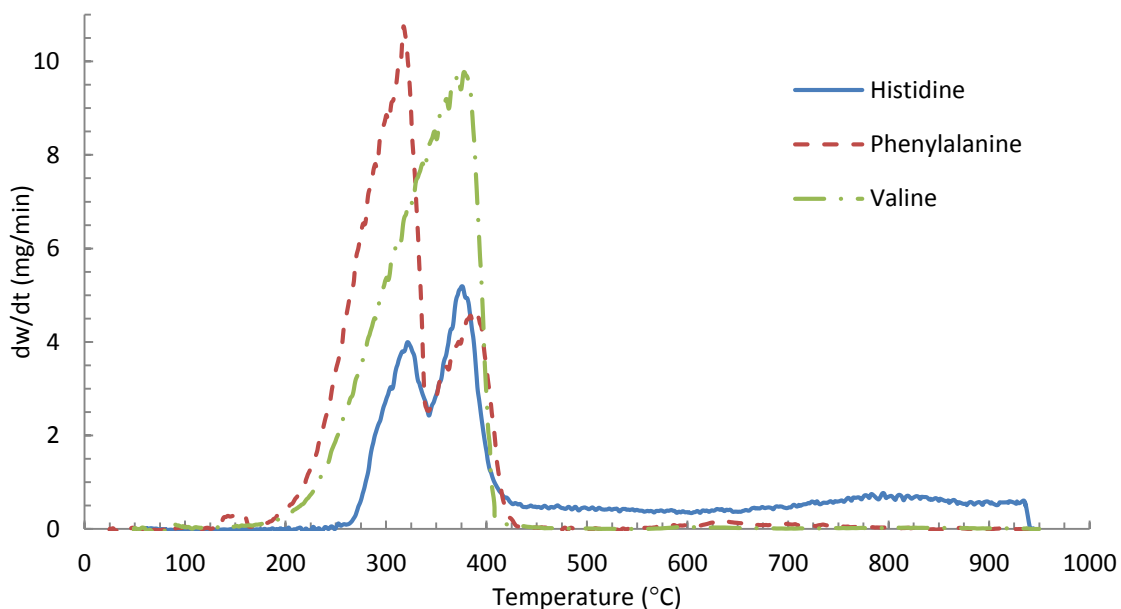
As shown in Figure 1, regions 1, 2 and 3 for all types of carbohydrate occur from 50°C to 175°C, 175°C to 450°C, and 450°C to 950°C, respectively. Main devolatilization peaks of dextrose and sucrose had a similar shape and appeared at a lower temperature and with larger width than that of starch. Sucrose and dextrose devolatilization occurred with three peaks but only one peak appeared in starch devolatilization. Peak heights of dextrose and sucrose were less than half of that of starch, showing lower reactivity for dextrose and sucrose. Maximum devolatilization rates for dextrose, sucrose, and starch were 6.1, 7.6, and 18.0 mg min<sup>-1</sup> at 247, 256, and 321 °C, respectively, compared to switchgrass at 4.9 mg min<sup>-1</sup> and 380 °C at a heating rate of 50 °C min<sup>-1</sup> (Pasangulapati et al., 2012). The data show that all food waste samples have over 80% devolatilization before 450°C and are compatible with thermochemical conversion processes.



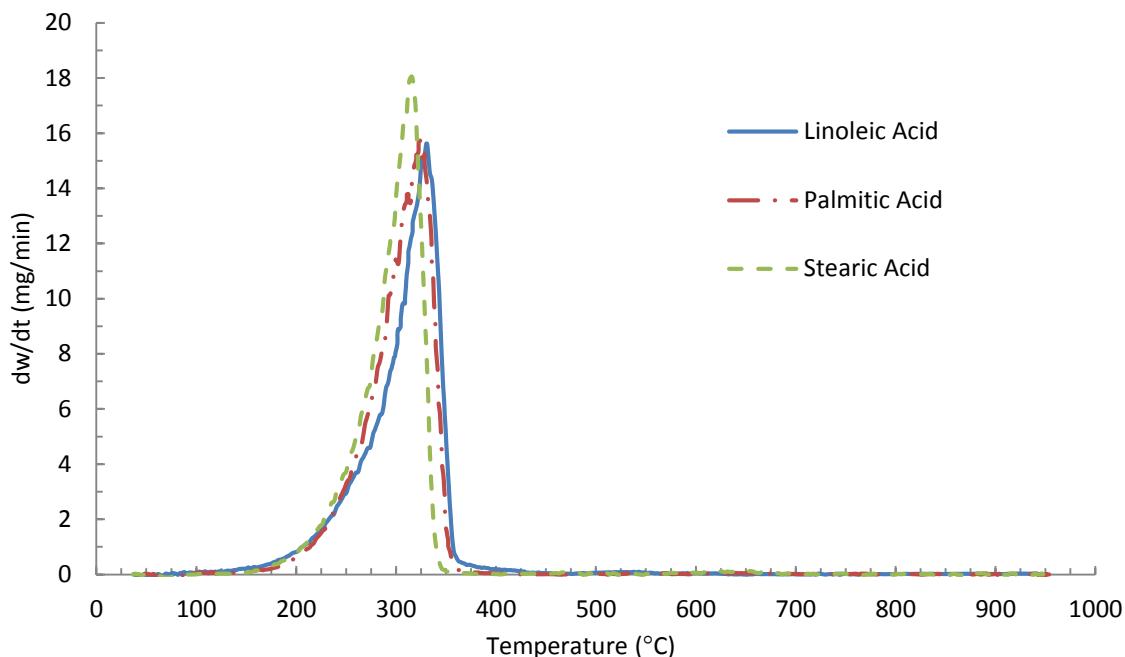
**Figure 1. Rate of weight loss with temperature of carbohydrates**

In Figure 2, regions 1, 2, and 3 occur from 50°C to 175 °C, 175°C to 450 °C, and 450°C to 950 °C, respectively. Peaks of phenylalanine and valine appeared at lower temperatures and over a larger temperature range than the peak of histidine, with valine having only one peak having a width comparable to phenylalanine. Phenylalanine and histidine had multiple peaks with the first peak, 10.4 mg min<sup>-1</sup>, for phenylalanine being over twice that for the first and second peaks for histidine at 4.0 and 5.2 mg min<sup>-1</sup>, with the last peak for both being similar at around 5 mg/min. Maximum devolatilization rates of phenylalanine, histidine and valine were found to be 10.7, 5.2 and 9.8 mg min<sup>-1</sup> at 317, 378, and 376 °C, respectively, compared to 6.3 mg min<sup>-1</sup> maximum devolatilization of cellulose at 345 °C (Pasangulapati et al., 2012). The first peak of phenylalanine found in this study (58% weight loss/min) was twice the first peak (30% weight loss min<sup>-1</sup>) found by Jie et al. (2008). However, the second phenylalanine peaks were similar (22% and 23% weight loss min<sup>-1</sup>). The difference in the first peak can be attributed to comparatively lower heating rate of 20°C min<sup>-1</sup> and smaller sample weight of 10 mg used by Jie et al. (2008). The results show that all samples have over 90% devolatilization before 450°C and are compatible with thermochemical conversion processes.

Figure 2. Rate of weight loss with temperature of proteins



As shown in figure 3, all three types of lipid have similar peaks that start and end at roughly the same temperatures of 150°C and 375°C, with stearic acid having a slightly taller peak. Maximum weight loss rates for stearic acid, palmitic acid and linoleic acid were 18.1, 15.7 and 15.6 mg min<sup>-1</sup> at 315.6, 324.3, and 330.3 °C, respectively. Results also show that all samples have over 90% weight loss before 400°C and are compatible with thermochemical conversion processes. With a lower heating rate (10°C min<sup>-1</sup> as compared to 50°C used in this study) and smaller sample weight (7 mg as compared to 20 mg used in this study) for stearic acid, Lerdkanchanaporn & Dollimore (1998) found a devolatilization peak of 2.0 mg min<sup>-1</sup> that is 9 times lower than that found in this study. Analysis of products and kinetics parameters of the devolatilization reactions are discussed below.



**Figure 3. Rate of weight loss with temperature of lipids**

### 3.2 Devolatilization reaction kinetics

All lipids (palmitic, stearic and linoleic acid) had only one peak with all samples devolatilized at temperature below 400°C. However, palmitic acid, with a high boiling point of 350°C (NCBI, 985), did not convert into other pyrolysis products, but rather vaporizes with over 97% of the products being palmitic acid. Pyrolysis products are discussed further in section 3.3. Stearic acid, with a high boiling point of 360°C (NCBI, 5281), had a similar trend with stearic acid representing 57% of the products. This means that only 43% of stearic acid decomposed. Linoleic acid has a slightly lower boiling point at 230°C (NCBI, 5280450), but behaved similar to palmitic acid with over 99% of the products being linoleic acid. Since weight losses of lipids were not completely a decomposition reaction, reaction kinetics were not analyzed.

Protein types (phenylalanine, histidine, and valine in Table 1) had different numbers of peaks with phenylalanine, histidine, and valine having 3, 2, and 1 peaks,

respectively, signifying that the protein types decomposed differently. Phenylalanine had two smaller and narrower second and third peaks with over twice the activation energy as compared to the tall and wide first peak. Both phenylalanine and histidine had high activation energies ranging from 180 to 350 kJ mol<sup>-1</sup> compared to 75 and 103 kJ mol<sup>-1</sup> for valine and switchgrass (Pasangulapati et al., 2012) respectively, indicating harder devolatilization. All regression results for the types of protein yielded a coefficient of determination of over 0.90, indicating a close relationship between the data and regression model. The order of reaction ranged from 0.87 to 1.43, with most being first order. The pre-exponential numbers ranged from 8.7E+05 to 5.2E+43 s<sup>-1</sup> compared to switchgrass with a range from 1.4E+03 to 5.4E+11 indicating a larger variation in rate constants for different carbohydrates.

Dextrose and sucrose (carbohydrates in table 1) had three peaks indicating a more complex devolatilization than starch's one peak with dextrose having the highest activation energies ranging from 58 to 227 kJ mol<sup>-1</sup>. Carbohydrates can be compared with cellulose in switchgrass with an activation energy of 119 kJ mol<sup>-1</sup> (Pasangulapati et al., 2012). Regression results for the carbohydrates yielded a coefficient of determination of over 0.90, indicating a close relationship between the data and regression model. The order of reactions had a large range from 0.44 to 1.75 indicating the presence of rate limiting steps. With a pre-exponential numbers ranging from 1.5E+00 to 7.1E+27 s<sup>-1</sup>, protein had a smaller range for rate constants than carbohydrates, but was larger than switchgrass.

**Table 1. Devolatilization reaction kinetics of carbohydrates, proteins, switchgrass, and lignocellulosic components**

Component	Type of Component	Peak #	Peak	A (s <sup>-1</sup> )	E	n	R <sup>2</sup>
			Temperature range, °C		(kJ mol <sup>-1</sup> )		
Carbohydrate	Dextrose	1	167 - 295	5.29E+15	151.7	1.17	0.90
		2	156 - 377	2.78E+08	88.6	0.76	0.91
		3	155 - 566	8.52E+00	24.5	0.44	0.90
	Sucrose	1	197 - 337	1.05E+14	145.2	0.92	0.90
		2	210 - 286	7.05E+27	275.9	1.24	0.95
		3	235 - 557	1.45E+00	33.9	0.59	0.91
	Starch	1	250 - 380	4.29E+24	272.5	1.75	0.93
Protein	Phenylalanine	1	180 - 384	5.10E+15	158.9	0.87	0.90
		2	282 - 345	5.23E+43	489.5	1.43	0.97
		3	316 - 435	2.38E+26	326.8	1.27	0.97
	Histidine	1	270 - 384	6.97E+19	281.8	1.00	0.90
		2	341 - 431	2.43E+27	336.7	1.13	0.91
		Valine	1	160 - 450	8.70E+05	70.2	0.91
	Switchgrass*	1	220–400	2.16E+07	103.7	0.67	0.95
	Cellulose*	1	270–390	6.86E+09	119.21	0.77	0.94
	Xylan*	1	200–260	5.40E+11	116.84	0.44	0.95
		2	260–315	1.66E+05	58.48	0.40	0.94
	Lignin*	1	200–400	1.40E+03	43.29	0.54	0.92
		2	680–740	5.50E+04	98.06	0.07	0.92

\*Adapted from Pasangulapati et al. (2012)

### 3.3 Devolatilization products

As shown in Table 2, the products of carbohydrates were made up of furan and sugar based compounds with 5-methyl-2-Furancarboxaldehyde, being in all carbohydrate types in the similar amounts of 6.7, 6.1, and 5.1% for sucrose, dextrose and starch, respectively. Furfural found in dextrose and sucrose, at 12.9 and 7.5%, respectively, was also found in pyrolysis products of cellulose, but at only 1.04% (Du et al., 2013). Patwardhan et al. (2009) found furan based products from fast pyrolysis of glucose-based carbohydrates (glucose, cellobiose, maltose, maltohexaose, cellulose, waxy maize starch, curdlan, and dextran) indicating that all types of carbohydrate produce similar pyrolysis products.

**Table 2. Pyrolysis products from carbohydrates**

Family	Total Area %		
	Dextrose	Sucrose	Starch
Acid	1.38	1.29	4.35
Alcohol	1.13	0.92	-
Alkane	-	2.52	6.89
Furan	26.36	15.94	13.79
Ketone	1.16	2.02	4.93
Lactone	1.92	-	-
Phenol	3.00	2.53	3.17
Pyran	0.60	0.58	1.17
Sugar	8.57	4.36	8.23
Other aromatics	3.18	23.03	-

Table 3 shows that the pyrolysis products of proteins were mainly hydrocarbons but in different families. Two products (benzocyclobutane and ethylbenzene) were common in volatiles of phenylalanine and valine. By pyrolyzing three green algae strains (*Chlamydomonas reinhardtii* wild type, its cell wall deficient mutant *C. reinhardtii*<sup>+</sup>, and *Chlorella vulgaris*) and their extracted protein and lipid components, Kebelmann et al. (2013) found that the main pyrolysis products of the proteins were toluene, phenol, 4-methylphenol, 1H-indole, 1H-indole-3methyl, and diterpenes in the average amounts of 7.5, 2.5, 5, 7.5, and 1%, respectively, indicating the algae strains were composed of similar proteins. Toluene from the Kebelmann study was the only compound found in products of proteins (phenylalanine at 35.4 %), indicating that different types of protein produce different products. Knowing that all proteins result in different pyrolysis products, the proteins in food wastes must be identified to improve the prediction of pyrolysis products.



**Table 3. Pyrolysis products from proteins**

Family	Total area %		
	Histidine	Phenylalanine	Valine
Acid	1.95	0.23	1.73
Alkane	1.51	0.57	2.77
Alkene	-	-	42.36
Amino acid	5.58	-	-
Diarylethene	-	2.04	-
Diazole	71.55	-	-
Nitrile	-	-	2.37
Aromatics	0.65	91.37	21.77

As shown in Table 4, the three fat types (palmitic, stearic, and linoleic acid) generated mainly acid based compounds with the majority being the sample compound, showing that fats did not fully decompose, but rather vaporized or converted into other acids. By studying the pyrolysis products of three different animal fatty wastes (lamb, poultry and swine), Ben Hassen-Trabelsi et al. (2014) found that the products of the different lipids were similar and showed high amounts of fatty acids in the products with varying amounts. In this study, pyrolysis products of palmitic acid at 600°C consisted of 98% palmitic acid. Since palmitic acid has a high boiling point of 350°C it can be concluded that palmitic acid does not breakdown and convert at typical pyrolysis reactor temperature, however, with a pyrolysis temperature of 750°C the palmitic acid concentration in the product dropped to 89 % indicating a need for higher temperatures for decomposition. Similar observations were made with stearic acid. Pyrolysis of stearic acid at 600°C yielded 57% stearic acid, 10% palmitic acid and 4% myristic acid indicating that although there was breakdown of stearic acid, over 70% of the products were fatty acids. Linoleic acid also had a high 99.3% percent of linoleic acid in its pyrolysis products.

**Table 4. Pyrolysis products from lipids**

Family	Total area %		
	Palmitic acid	Stearic Acid	Linoleic acid
Acid	99.83	71.26	99.83
Alicyclic	-	1.41	-
Alkane	0.05	0.56	0.05
Alkene	-	19.76	-
Ketone	-	0.10	-
Phenol	-	0.06	-
Other	0.12	1.41	0.12
Aromatic			

#### 4. Conclusions

Thermal devolatilization of different types of carbohydrate, protein, and lipid were conducted. All carbohydrate and protein samples showed three primary regions of devolatilization with lipid samples mainly vaporizing and not fully devolatilizing, however, the conversions appear to be complete by 600°C suggesting that this reactor temperature will be sufficient for pyrolysis of food wastes. The pyrolysis of carbohydrates produced furan and sugar based products. Pyrolysis of proteins produced mainly hydrocarbon based products but in different families. Pyrolysis of lipids produced high amounts of acids in their products indicating a low decomposition, but low concentration of hydrocarbon and alkene products were also found.

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## CHAPTER III

### EFFECT OF COMPOSITION ON THE GASIFICATION OF FOOD WASTE

Jacob Collins<sup>a</sup>, Ajay Kumar<sup>a\*</sup>, Tim Bowser<sup>a</sup>, Danielle Bellmer<sup>a</sup>

<sup>a</sup>Department of Biosystems and Agricultural Engineering, Oklahoma State University, 111 Agricultural Hall, Stillwater, OK 74078-6016, United States

\*Corresponding author: 228 Agricultural Hall, Stillwater, OK – 74078. USA.

Tel.: +1 405 744 8396; fax: +1 405 744 6059. E-mail address: ajay.kumar@okstate.edu

#### **Abstract**

Less than 5% of the 37 million tons of food waste produced in the U.S. in 2012 was utilized, with the remainder going into landfills. Food wastes have the potential for conversion into renewable fuels and chemicals. The objective for this study was to investigate the effect of food composition on gasification performance. Gasification was conducted in an updraft batch gasifier with air as the gasifying agent. No significant relationship was observed for the production of H<sub>2</sub>, CO, and CO<sub>2</sub> with food composition. No significant correlation was identified between food composition and H<sub>2</sub>, CO, and CO<sub>2</sub> production. However, food composition and carbon conversion efficiency was found to be correlated, with the highest conversion of carbon to carbon-based gases from carbohydrates, followed by fats, and the lowest conversion from proteins. Food composition and cold gas efficiency was also found to be correlated, with the highest gas efficiency from fats, followed by proteins, and the lowest efficiency from carbohydrates.

**Keywords:** Food waste, updraft gasification, syngas, biofuels

## **1. Introduction**

In 2012 the United States produced 36.4 million tons of food waste. Only 4.7% of the food waste was utilized, primarily for composting (www.epa.gov, 2012), with the remainder discarded in landfills. Food waste is comprised of three main components (carbohydrates, lipids, and protein) and comes from two sources, food industry and municipalities. Food industry sources produce food waste with consistent composition of the main components. Municipalities produce food waste from multiple sources with compositions of the main components varying from source to source.

Food waste can be converted into useful fuels and chemicals. Conversion methods for food waste include biochemical and thermochemical. Biochemical conversion uses micro-organisms, chemicals or enzymes for conversion into primarily liquid fuels (Digman and Kim 2008). Thermochemical conversion utilizes heat for conversion into gaseous, solid, and liquid fuels (Pham et al. 2015). This study focused on the thermochemical conversion of food waste.

Similar to biomass, food waste is composed of carbon, hydrogen, and oxygen that are consumed in thermochemical conversion methods of combustion, pyrolysis, and gasification to produce electrical and heat energy, fuels, and chemicals (Digman and Kim 2008, Saxena et al. 2009). Gasification is a thermochemical conversion method that can convert a wide range of feedstocks into syngas (hydrogen, carbon monoxide, carbon dioxide, and methane) under partial oxidation (Heidenreich and Foscolo, 2015). The feedstock enters the reactor with an amount of oxygen specified by the equivalence ratio (ER), or the ratio of oxygen supplied to the oxygen needed for full combustion, with a typical range of 0.2 to 0.4 (Tilay et al., 2014). Temperature, typically ranging from 750

to 900°C, is an important factor and has significant effects on the composition of syngas (Emami Taba et al. 2012 and Pinto et al. 2003). Effective conversion of food waste also requires knowledge of how its main components interact during thermochemical conversion processes.

Previous research on the thermochemical conversion of food waste into renewable fuels and chemicals is limited to a single food source with consistent composition. Canton et al. (2010) investigated the use of food waste in a residential pellet stove. Ash, nitrogen, and energy contents of food waste from the US Naval Academy were 1.8, 2.9, and 3.0 wt.% (dry), respectively, higher than those of wood pellets. However, oxygen content of the food waste was 13.12 wt.% (dry) lower than that of wood pellets. Ahmed and Gupta (2010) pyrolyzed and gasified dog food, as a representative food waste, in a bench scale reactor at 800 and 900°C. Gasification at 900°C produced syngas with a lower gas and H<sub>2</sub> yields (31 and 1.63 g compared to 29 and 1.59 g of gas and H<sub>2</sub> yield, respectively, at 800°C). Ko e al. (2001) carbonized then gasified food waste and found the highest conversion rate to carbonized solids at 25% to 32% with a carbonization temperature of 200°C. Hydrogen yields were the highest, 700 mmol, at a reactor temperature of 800°C and a 1 to 2 steam input to carbon ratio, as compared to 1 to 3 and 7 to 10 steam input to carbon ratio with 500 and 450 mmol respectively. Bowser et al. (2005) gasified pork processing byproduct and wood pellets in a small updraft batch scale gasifier and produced H<sub>2</sub>, CO and CO<sub>2</sub> in amounts of 3.4, 13.3 and 11.8% v v<sup>-1</sup>, respectively, from pork waste and 2.1, 11.9 and 7.2% v v<sup>-1</sup>, respectively, from wood pellets.

The above studies investigated only one food source with consistent composition. This study expands on previous research by investigating the effect of the varying food composition on syngas yield and composition. The food wastes can be more efficiently used if the effect of carbohydrates, proteins, and fats can be predicted. The objective for this study was to investigate the effect of food composition on gasification performance.

## 2. Materials and Methods

### 2.1 Experimental Design and Materials

A full factorial experimental design was used with one factor (food composition) and six levels (food samples with varying composition). The levels were three pure compounds (carbohydrate, fat and protein) and three samples of varying composition. The samples were gasified at 800°C and with one replication. Pure compounds were dextrose, palmitic acid, and phenylalanine to represent carbohydrates, fats and proteins, respectively. Pure compounds (purchased from Fischer Scientific, U.S.A.) were chosen for their availability in food and their representation of each component. Potato, peanuts, and beef stew meat (purchased from Walmart, U.S.A.) were chosen to represent food with very different compositions. Carbohydrate, protein, and fat compositions of the three food samples, Table 1, were obtained from the USDA National Nutrient Database for Standard Reference ([ndb.nal.usda.gov](http://ndb.nal.usda.gov)) for the three food samples.

**Table 1. Composition of model and food samples**

	Carbohydrate (%)	Protein (%)	Fat (%)
Dextrose	0.99	0.00	0.00
Phenylalanine	0.00	0.98	0.00
Palmitic Acid	0.00	0.00	0.99
Potato <sup>a</sup>	0.84	0.09	0.01
Beef <sup>a</sup>	0.01	0.73	0.15
Peanut <sup>a</sup>	0.24	0.21	0.50

<sup>a</sup> Adapted from [ndb.nal.usda.gov/](http://ndb.nal.usda.gov/)



## 2.2 Proximate and Ultimate Analysis

Proximate analysis (shown in Table 2) was conducted in a muffle furnace (model 3-550A, Dentsply Prosthetics, PA) to determine contents of moisture, ash, and volatile matter of sample used for experimentation. Moisture, ash, and volatile matter contents were determined following ASAE S358.2 standard of moisture measurement in forages, ASTM E1755 – 01 standard test method for ash in biomass, and ASTM D3175 standard test method for volatiles, respectively. Carbon (C), nitrogen (N), and hydrogen (H) contents (ultimate analysis shown in Table 2) of food samples was determined by Midwest Microlab (Indiana, U.S.A.). Oxygen (O) was calculated by difference. Ultimate analysis for the model compounds was determined from their chemical formula.

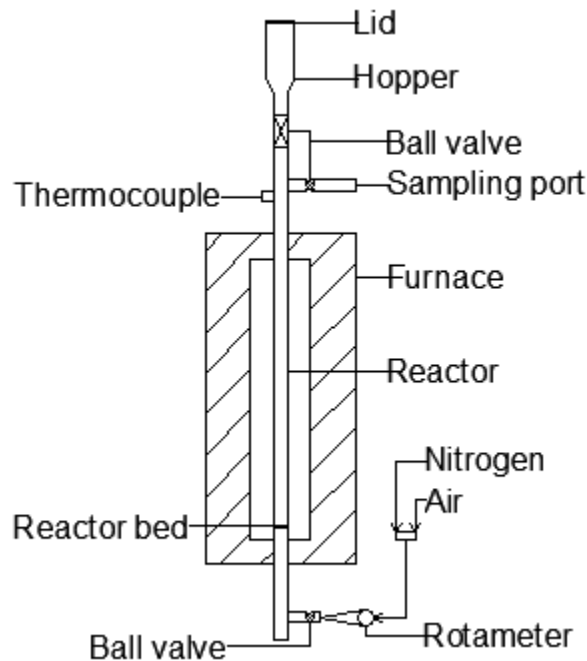
**Table 2. Proximate and ultimate analysis of model and food samples**

	Proximate analysis				Ultimate Analysis			
	Moisture (%)	Fixed Carbon (%)	Volatiles (%)	Ash (%)	C (%)	H (%)	O (%)	N (%)
Dextrose	0.01	0.07	0.93	0.00	0.40	0.07	0.53	0.00
Phenylalanine	0.00	0.00	1.00	0.00	0.65	0.07	0.19	0.08
Palmitic Acid	0.01	0.00	1.00	0.00	0.75	0.13	0.12	0.00
Potato	0.05	0.22	0.72	0.06	0.45	0.06	0.47	0.02
Beef	0.11	0.13	0.80	0.07	0.56	0.08	0.21	0.14
Peanut	0.02	0.09	0.83	0.08	0.68	0.10	0.15	0.05

## 2.3 Gasification Setup

Gasification was performed in a fixed bed updraft gasifier that is modified from gasifier used by Sarkar et al. (2014). The gasifier (Figure 1) has a reactor tube length of 0.933 m, from gas input to gas sampling port, and inside diameter of 0.025 m. A one inch ball valve, at 1.01 m above gas input, was used to release sample from hopper to reactor. The stainless steel reactor was heated using a vertical split-hinge tube furnace (model TVS 12/600, Carbolite Inc., WI, USA). The reactor bed consisted of ten mg of

quartz wool (CE Elantech, U.S.A.) placed on metal bars welded at 0.195 m above the gas input to hold the sample within the heated section of reactor. Nitrogen and air were used with a flow rate of  $2 \text{ l min}^{-1}$  regulated by a rotameter (model PMR1, Aalborg, NY, U.S.A.). Nitrogen was used to purge oxygen from the reactor prior to the experiment. Air was used as gasifying agent. Two g of sample and 25 g of silica sand was placed in the hopper for gasification. The silica sand was placed to ensure that samples did not attach to the sides of the hopper.

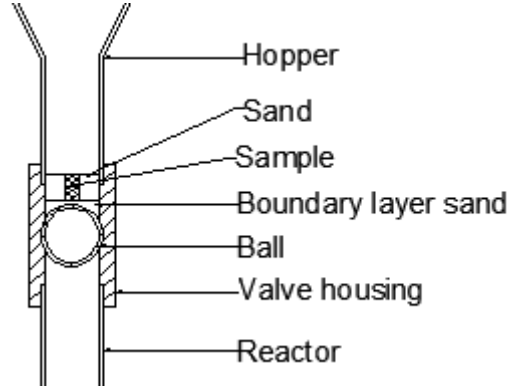


**Figure 1. Gasifier**

#### 2.4 Sample Preparation

50 g of potato and beef with high moisture content of 75 and 81 %, respectively, were dried for 6 hours to reduce the moisture contents to 5 and 11 %. The peanut sample obtained was roasted during production and had low moisture content of 2 % and was not dried. The samples were ground using a mortar and pestle and pressed through a 2 mm screen. As shown in Figure 2, a boundary layer of sand was placed on the ball of the valve. A plastic sample loading tube was placed in the middle of the

hopper, with additional sand placed around the tube. The sample was poured in the loading tube. A probe was inserted in the loading tube and the tube was removed leaving the non-compacted sample within the sand.



**Figure 2. Hopper setup for holding sample and sand**

## 2.5 Experimental Analysis

Syngas was collected in 1 liter gas sample bags (model 232-01, SKC, PA, U.S.A.) during gasification and analyzed in a gas chromatograph (GC, model CP3800, Varian Inc., CA) with a packed column (model HayeSep DB-100/120, Alltech Associates, Inc., Deefield, Ill.) and a thermal conductivity detector (TCD). Analysis was conducted to determine the % V V<sup>-1</sup> of syngas components with focus on main components of H<sub>2</sub>, CO, CO<sub>2</sub>, with other components being CH<sub>4</sub>, C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, and C<sub>2</sub>H<sub>6</sub>.

Nitrogen balance on the collected samples was performed to determine the total yield of syngas using equation 2 (Guangul et al., 2012, Ju et al., 2010).

$$Y_{syngas} = (Q_{air} * 79) / (N_2 * m_b) \quad (1)$$

where,  $Y_{syngas}$  is the yield of syngas per kg of biomass (Nm<sup>3</sup> kg<sup>-1</sup>, d.b.),  $Q_{air}$  is the flow rate of air (Nm<sup>3</sup> hr<sup>-1</sup>),  $N_2$  is the concentration of nitrogen in the syngas (% V/V), and  $m_b$  is biomass used per unit time (kg h<sup>-1</sup>).

The lower heating value, LHV, of the syngas was calculated using equation 3 (He et al., 2010).

$$LHV_{syngas} = ((107.98 * H_2) + (126.36 * CO) + (358.18 * CH_4) + (56.00 * C_2H_2) + (59.04 * C_2H_4) + (63.77 * C_2H_6))/1000 \quad (2)$$

where,  $LHV_{syngas}$  is the lower heating value of syngas ( $MJ Nm^{-3}$ ), and  $H_2$ ,  $CO$ ,  $CH_4$ ,  $C_2H_2$ ,  $C_2H_4$  and  $C_2H_6$  are the volume percentages of components of syngas, respectively.

Carbon conversion efficiency is the ratio of amount of carbon present in the syngas and the carbon in biomass and was calculated using equation 4 (He et al., 2010).

$$CCE = 12 * Y_{syngas} * (CO + CO_2 + CH_4 + 2 * C_2H_2 + 2 * C_2H_4 + 2 * C_2H_6) / (22.4 * C_{sample}) \quad (3)$$

where,  $CCE$  is the carbon conversion efficiency (%) and  $C_{sample}$  is the mass percentage of carbon in the sample.

Cold gas efficiency (CGE) was calculated using equation 5 (Guangul et al., 2012).

$$CGE = (LHV_{syngas} * Y_{syngas} * 100) \quad (4)$$

where,  $LHV_{syngas}$  is the lower heating value of biomass ( $MJ kg^{-1}$ ).

The mass of water was calculated using the unaccounted oxygen, as the limiting reactant, in equation 6.

$$H_2O = (O_{input} - O_{exp.syngas}) (18.02 g H_2O / 16.00 g O) \quad (5)$$

Statistical analysis was conducted with SAS 9.4 (SAS Institute Inc., Cary, NC, U.S.A.). A one-way ANOVA with Duncan's Multiple Range Test was performed on Carbon Conversion Efficiency (CCE) and yields of the primary syngas components ( $H_2$ ,  $CO$ , and  $CO_2$ ).

### 3. Results and Discussion

#### 3.1 Hydrogen, Carbon Monoxide, and Carbon Dioxide Analysis

H<sub>2</sub> and CO yields (Table 3) from the pure samples were the highest from palmitic acid, followed by phenylalanine, and the least from dextrose. H<sub>2</sub> and CO yields (Table 3) from food samples were the highest from beef, followed by peanut, and the least from potato. CO<sub>2</sub> yield (Table 3) from pure samples was the highest from dextrose, followed by phenylalanine, and the least from palmitic acid. CO<sub>2</sub> production (Table 3) from food samples was the highest from potato, followed by beef, and the least from peanut. All pure samples produced significantly different yields of H<sub>2</sub>, CO, and CO<sub>2</sub>. However, food samples did not produce significantly different yields of CO and CO<sub>2</sub>. H<sub>2</sub> production from potato and beef are significantly different. H<sub>2</sub> production from peanut is not significantly different from that of potato or beef. Production of H<sub>2</sub>, CO, and CO<sub>2</sub> from switchgrass is not significantly different from those from dextrose. Switchgrass is not significantly different from beef for H<sub>2</sub> production and phenylalanine for CO<sub>2</sub> production. Ahmed et al. (2010) gasified dog food as representation of food waste and found H<sub>2</sub> production of 0.045 g/g food waste which is consistent with a composition high in protein and fat. Ahmed et al. (2010) found the inorganic elements of food waste have a catalytic effect on syngas properties. This catalytic effect could be the reason no trend for production of H<sub>2</sub>, CO, and CO<sub>2</sub> with food composition was found.

**Table 3. Analysis of syngas constituents**

	H2 (g/g sample)	CO (g/g sample)	CO2 (g/g sample)
Dextrose	0.016 <sup>C#</sup> (0.001) <sup>b</sup>	0.347 <sup>C</sup> (0.095)	0.678 <sup>A</sup> (0.113)
Phenylalanine	0.039 <sup>B</sup> (0.001)	0.729 <sup>B</sup> (0.025)	0.492 <sup>B</sup> (0.086)
Palmitic Acid	0.067 <sup>A</sup> (0.005)	1.029 <sup>A</sup> (0.033)	0.220 <sup>C</sup> (0.011)
Potato	0.002 <sup>F</sup> (0.000)	0.148 <sup>D</sup> (0.022)	0.630 <sup>AB</sup> (0.003)
Beef	0.011 <sup>DE</sup> (0.005)	0.227 <sup>D</sup> (0.026)	0.619 <sup>AB</sup> (0.055)
Peanut	0.007 <sup>EF</sup> (0.000)	0.209 <sup>D</sup> (0.012)	0.583 <sup>AB</sup> (0.003)
Switchgrass <sup>a</sup>	0.140 <sup>CD</sup> (.002)	0.377 <sup>C</sup> (0.017)	0.608 <sup>AB</sup> (0.017)

<sup>a</sup> Adapted from Sarkar et al. (2014)

<sup>b</sup> Numbers in parentheses are standard deviation (n=2)

# Means with the same letters under the same column are not significantly different at 5% level

### 3.2 Carbon conversion efficiency (CCE) and cold gas efficiency (CGE)

CCE for model compounds was the highest for carbohydrates (Table 4) followed by fats, and the lowest for proteins. This is due to the difference in structure of the components. Carbohydrates with the highest oxygen content decompose more than fats and proteins. Proteins having a more stable structure had the least decomposition and the lowest CCE. Similar trend follows for the food samples with CCE being the highest for potato (high in carbohydrates), followed by peanut (high in fats), and the lowest for beef (high in proteins). As expected, with dextrose being similar to switchgrass in chemical structure, CCE and carbon conversion to CO differed by only 1.7 and 3.3%, respectively (Sarkar et al., 2014). However, carbon conversion to CO<sub>2</sub> were significantly different for dextrose and switchgrass. CCE and carbon conversion to CO and CO<sub>2</sub> of switchgrass were significantly different from those of the pure compounds (dextrose, phenylalanine, and palmitic acid). However, CCE of switchgrass was not significantly different from those of dextrose and palmitic acid. CGE was the highest for fats, followed by proteins, and the lowest for carbohydrates. CGE of switchgrass was not significantly different from that of dextrose as expected. Switchgrass was not significantly different from

phenylalanine, and palmitic acid. CGE for food samples were less than half of the CGE for model compounds due to lower H<sub>2</sub> and CO yields.

**Table 4. Carbon conversion and cold gas efficiencies of syngas**

	CCE (%)	CC-CO (%)	CC-CO <sub>2</sub> (%)	CGE (%)
Dextrose	89.4 <sup>A#</sup> (2.72) <sup>b</sup>	37.4 <sup>C</sup> (7.23)	46.6 <sup>A</sup> (5.48)	51.34 <sup>B</sup> (7.82)
Phenylalanine	73.0 <sup>C</sup> (2.51)	47.8 <sup>B</sup> (1.17)	20.5 <sup>C</sup> (2.55)	52.31 <sup>B</sup> (6.21)
Palmitic Acid	81.4 <sup>B</sup> (0.15)	59.4 <sup>A</sup> (1.34)	8.1 <sup>D</sup> (0.28)	67.59 <sup>A</sup> (0.55)
Potato	71.3 <sup>C</sup> (0.86)	18.0 <sup>D</sup> (1.88)	48.5 <sup>A</sup> (0.18)	21.24 <sup>D</sup> (0.77)
Beef	64.1 <sup>D</sup> (1.42)	20.6 <sup>D</sup> (1.66)	35.7 <sup>B</sup> (2.23)	24.03 <sup>D</sup> (0.60)
Peanut	66.8 <sup>DC</sup> (0.29)	16.4 <sup>D</sup> (0.67)	29.0 <sup>B</sup> (0.12)	37.60 <sup>C</sup> (0.18)
Switchgrass <sup>a</sup>	87.7 <sup>AB</sup> (3.33)	34.1 <sup>C</sup> (1.51)	35.0 <sup>B</sup> (1.00)	58.39 <sup>AB</sup> (2.83)

<sup>a</sup> Adapted from Sarkar et al. (2014)

<sup>b</sup> Numbers in parentheses are standard deviation

<sup>#</sup> Means with the same letters under the same column are not significantly different at 5% level

### 3.4 Mass balance

Table 5 shows the input (C, H, and O in the sample and supplied oxygen for the duration of gasification) along with the C, H, and O in the syngas. On average, there was 16.3% mass difference between the total weight of input and syngas in the experimental data. Carbon was balanced with 0% to 3% mass difference. Hydrogen and oxygen have average 59.6 and 19.1% mass differences, respectively, between input and output. The difference between hydrogen and oxygen in gasifier input and output could be because of unaccounted water in syngas. Water content of syngas could not be measured in the GC. To account for syngas water content, it was assumed that all unaccounted oxygen in the output was in the form of water. This correction lowered the average difference between total weight of input and syngas to less than 3.3 %. The mass difference of hydrogen in the input and syngas still ranged from 10% to 68% and could be the result of H<sub>2</sub> escaping during sample collection.

**Table 5. Mass balance of model and food samples**

		Input (g)	Experiment		With water calculated	
			Syngas (g)	Diff. (%)	Syngas (g)	Diff. (%)
Dextrose	Total	2.92 (0.04) <sup>a</sup>	2.21 (0.02)	-24.3 (0.4)	2.89 (0.03)	-0.2 (0.1)
	C	0.80 (0.00)	0.78 (0.01)	-1.6 (1.7)	0.78 (0.01)	-1.6 (1.7)
	H	0.13 (0.00)	0.04 (0.00)	-66.6 (3.1)	0.12 (0.00)	-10.0 (2.7)
	O	1.99 (0.04)	1.38 (0.04)	-30.5 (0.5)	1.99 (0.04)	0.0 (0.0)
Phenylalanine	Total	3.12 (0.09)	2.95 (0.05)	-5.5 (1.0)	3.09 (0.07)	-0.3 (0.1)
	C	1.31 (0.00)	1.31 (0.00)	-0.1 (0.3)	1.31 (0.00)	-0.1 (0.3)
	H	0.13 (0.00)	0.09 (0.01)	-30.7 (9.1)	0.11 (0.01)	-18.5 (7.2)
	O	1.68 (0.09)	1.55 (0.07)	-7.7 (.7)	1.68 (0.09)	0.0 (0.0)
Palmitic Acid	Total	3.23 (0.09)	3.13 (0.09)	-2.9 (5.3)	3.19 (0.02)	0.3 (0.8)
	C	1.49 (0.00)	1.44 (0.05)	-3.1 (3.2)	1.44 (0.05)	-3.1 (3.2)
	H	0.25 (0.00)	0.19 (0.00)	-23.7 (0.2)	0.20 (0.01)	-20.7 (2.8)
	O	1.49 (0.09)	1.50 (0.04)	1.0 (8.5)	1.55 (0.02)	4.7 (4.7)
Potato	Total	2.76 (0.04)	1.82 (0.03)	-34.3 (0.2)	2.67 (0.06)	-1.2 (0.0)
	C	0.79 (0.00)	0.72 (0.02)	-9.8 (2.2)	0.72 (0.02)	-9.8 (2.2)
	H	0.13 (0.00)	0.01 (0.00)	-88.4 (2.8)	0.11 (0.00)	-12.5 (0.5)
	O	1.84 (0.04)	1.09 (0.02)	-41.1 (0.3)	1.84 (0.04)	0.0 (0.0)
Beef	Total	2.95 (0.04)	2.46 (0.01)	-16.7 (1.7)	3.00 (0.08)	0.8 (0.3)
	C	0.92 (0.00)	1.03 (0.02)	11.4 (2.4)	1.03 (0.02)	11.4 (2.3)
	H	0.16 (0.00)	0.04 (0.00)	-71.4 (2.7)	0.11 (0.01)	-32.5 (9.3)
	O	1.87 (0.04)	1.38 (0.04)	-25.9 (3.9)	1.87 (0.04)	0.0 (0.0)
Peanut	Total	2.96 (0.09)	2.54 (0.00)	-14.0 (2.7)	2.69 (0.14)	-3.3 (0.7)
	C	1.24 (0.00)	1.11 (0.03)	-10.5 (2.5)	1.11 (0.03)	-10.5 (2.5)
	H	0.19 (0.00)	0.04 (0.00)	-76.8 (2.2)	0.06 (0.02)	-67.8 (10.4)
	O	1.52 (0.09)	1.38 (0.04)	-8.6 (7.9)	1.52 (0.09)	0.0 (0.0)

<sup>a</sup> Numbers in parentheses are standard deviation

#### 4. Conclusions

The effect of the three main components (carbohydrates, proteins, and fats) in food on gasification performance was evaluated. A correlation was observed between food composition and carbon conversion efficiency (CCE). CCE was the highest for carbohydrates, followed by fats, and the lowest conversion for proteins probably due to the carbohydrates having higher oxygen content and decompose the most, with proteins having a more stable structure and decompose the least. Food composition and cold gas efficiency (CGE) was found to be correlated. CGE was the highest for fats, followed by



proteins, and the lowest efficiency from carbohydrates, probably due to fats having the highest hydrogen content, followed by proteins, and carbohydrates having the lowest hydrogen content. No significant relationship was observed between the yields of H<sub>2</sub>, CO and CO<sub>2</sub>, and food composition.

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VITA

Jacob Cody Collins

Candidate for the Degree of

Master of Science

Thesis: THERMAL DECOMPOSITION OF CARBOHYDRATES, LIPIDS, AND  
PROTEINS AND FOOD WASTE GASIFICATION

Major Field: Biosystems and Agricultural Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Biosystems and Agricultural Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2015.

Completed the requirements for the Bachelor of Science in Mechanical Engineering Technology at Oklahoma State University, Stillwater, Oklahoma in December, 2010.

Experience:

Graduate Research Assistant, Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, Oklahoma. January 2013 to May 2015

Undergraduate Lab Assistant, Industrial Engineering and Management, Oklahoma State University, Stillwater, Oklahoma. August 2007 to August 2010

Undergraduate Lab Assistant, Industrial Engineering, Texas Tech University, Lubbock, Texas. January 2006 to May 2007