Food Waste Energy Analysis:

Characterizing Energy Content as a Function of Proximate Analysis Factors

Yoo Shin Tanai

Abstract

One-third of all edible food produced in the world is discarded (1.3 billion tons), equivalent to one trillion dollars lost annually. Household food waste has not been thoroughly investigated as an energy source, necessitating its characterization to better understand this abundant and varied feedstock and its potential for energy production. Calorimetry and thermogravimetric analyses were conducted in triplicate for sixteen representative food waste samples covering four food categories to determine the proximate analysis factors of common food wastes. On average, meat samples released 18 MJ/kg, the highest of the food groups, and the average energy output for all foods was 14.31 MJ/kg. The mean energy content of the fruit samples was 13.75 MJ/kg and 12.83 MJ/kg for the vegetable samples. The carbohydrate samples contained the least energy with 12.63 MJ/kg. Fruit and vegetable samples contained the highest amounts of moisture, near 39%, while carbohydrate samples contained the least at 18%. Carbohydrates also contained the highest ash content (14.67%). All samples had a volatile content above 50% and carbohydrate samples contained the highest amount (59%). No correlations were found between energy content and fixed carbon ($r = -0.29$, $p = 0.30$) or ash ($r = 0.087$, $p = 0.77$) or volatile content ($r = 0.366$, $p = 0.198$). Estimates of the energy potential of food wastes determined that 11.5% of average household energy consumption could be offset by converting food waste to energy. Overall, these findings provide valuable insight into enabling technologies that can convert food waste into a reusable energy resource.

1.0 Introduction:

Approximately 1.3 billion tons of municipal solid waste is generated annually in urban areas worldwide, an amount expected to increase to 2.2 billion tons by 2025 (World Bank, 2012). Waste in landfills has the potential to be utilized as a source of energy, converting a negatively valued product into a resource. Because municipal solid waste is extremely heterogenous, identifying potential sources of energy through analysis of its components is necessary to develop efficient waste to energy infrastructure. Biomass, including food waste, wood, and paper products comprises about one-third of all wastes produced globally and has untapped energy potential. As the demand for energy is expected to increase by one-third by 2040 (International Energy Agency, 2015), the need to characterize biomass as an energy feedstock becomes critical.

Biomass is becoming increasingly attractive and feasible as a sustainable energy resource due to its abundance. Currently, biomass provides approximately 14 percent of the world's energy needs (Shen et al. 2009). Biomass is widely defined as renewable organic materials, including feedstocks used for energy production, such as switch grass, waste wood, and corn stover (McKendry, 2002), which are produced by the ever-expanding agricultural industry but are often wasted. In addition, unused biomass in landfills decomposes into methane which contributes greatly to worldwide greenhouse gas emissions if not captured and used for energy. Methane is particularly problematic as it is 25 times more potent as a greenhouse gas than carbon dioxide over a 100-year period (Environmental Protection Agency, 2015). Although many landfills capture these gases for energy production, the capture rates are normally less than 50% (Lou and Nair, 2009). Previous investigations on the use of biomass for energy have generally focused on industrial and agricultural wastes, yet, few have focused on reusing household food waste (Garcia et al. 2012) as a viable energy source.

Food waste remains a relatively untapped biomass resource that is ubiquitous in both developed and developing countries. Figure 1 provides a breakdown of the major food categories produced worldwide, showing that cereals, fruits, and vegetables are the largest. It is estimated that 32 percent of all foods produced globally in 2009 were wasted or lost during processing or transportation (World Resources Institute, 2014). It was determined that food waste amounted to a total of 2141.76 petajoules of discarded energy, equating to approximately eight percent of the energy consumed annually (Webber and Cuellar, 2010). This makes it promising to capitalize on food wastes as a possible source of renewable energy production rather than consumption. Additionally, the extraction of energy from food waste leaves behind a residual in the form of ash that is comprised of the minerals present in the food. This ash can be land-applied as a fertilizer, thus returning the nutrients needed for continued crop growth (James et al. 2012; Rajamma et al. 2009).

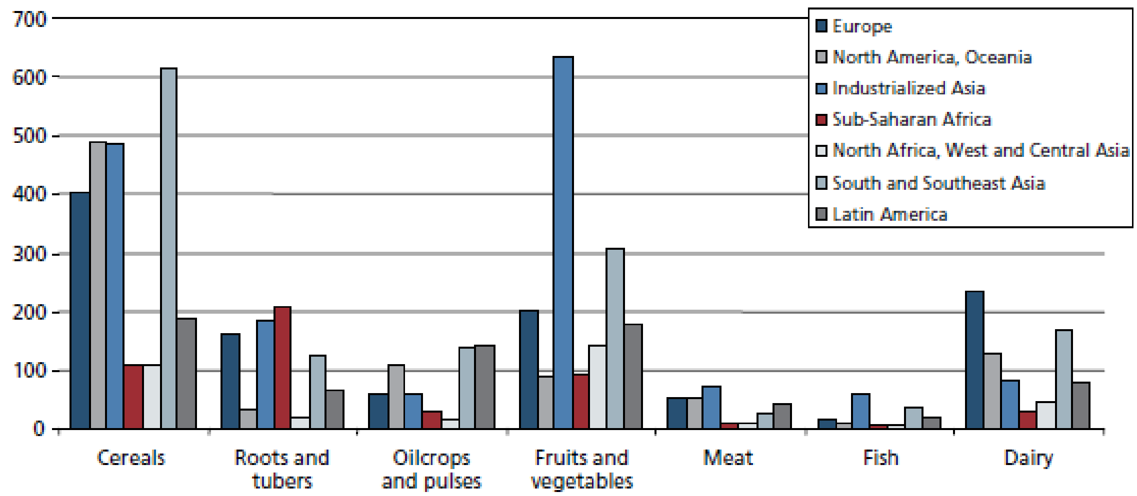

Figure 1: The worldwide production volumes (million tonnes) of different food commodity groups in 2007 are represented, along with their respective countries of origin (Food and Agriculture Organization, 2011). Some of the most commonly produced foods include cereals and fruits /vegetables.

Despite its abundance, food waste has not been thoroughly investigated as a potential energy source due to its diverse and somewhat unpredictable composition in comparison to traditional biomass feedstocks such as sugarcane or willow. The varied composition of food waste can influence the overall energy content, making it important to individually characterize common food wastes constituents. Previous research has studied industrial wastes, agricultural wastes, energy crops, and a variety of biomass feedstocks as energy sources (Garcia et al. 2012; Kok and Emre, 2013; Saldarriaga et al. 2015; Braz and Crnkovic, 2014) however, this study is novel in its efforts to characterize common household food wastes discarded into waste streams including fruits, vegetables, carbohydrates, and meats.

The characterization of food waste can lead to the optimization of energy production through existing waste-to-energy conversion processes, such as gasification and pyrolysis (Andre, 2006; Pereira et al. 2012). Previous research has investigated the use of food waste for anaerobic digestion, but this process faces numerous drawbacks. Anaerobic digestion is limited in scope because contamination by other sources of waste such as plastics and metals, may disrupt the biochemical process, necessitating pre-treatment (Mao et al. 2014). In addition, imbalances in reaction elements make it necessary for other feedstocks to be used in tandem with the food waste, limiting the types of food waste that can be used. In contrast, thermochemical conversion systems such as gasification or pyrolysis are attractive means of converting biomass into energy as they are versatile, and can convert undesirable contaminants in a short span of time (Andre, 2006). Thus, this study focused on characterizing common food wastes to support the development of these thermochemical processes for the waste to energy industry.

Furthermore, a comprehensive understanding of the properties of biomass is generally found through ultimate and proximate analyses. This study focused on the characterization of specific food wastes through proximate analysis, in order provide a quantitative makeup of moisture, volatile matter, and fixed carbon, since it best represents the usable components in the food that impact technology design. However, the current method of proximate analysis outlined by the American Society for Testing and Materials (ASTM 2010) can take several hours and requires large quantities of each sample. Thus, other studies have introduced the use of a Thermogravimetric Analyzer (TGA) as a more efficient method to determine the proximate analysis of carbon based materials such as coal and biomass which can reduce the time required to less than one hour and be just as accurate (Garcia et al. 2013; Vhathvarothai et al. 2013; Mayoral et al. 2001). While previous research has focused on understanding coal and biomass as a whole, the use of a TGA to characterize other feedstocks, like food waste, is novel to this study. Therefore, this research sought out a better understanding of the characteristics of food waste and the relationship between energy content and proximate analysis factors using a TGA.

2.0 Research Goals:

The primary goal of this research was to characterize the energy content of common food wastes as a function of proximate analysis factors to develop a food waste energy model that would establish a relationship between the two. In addition, this study aimed to use a thermogravimetric analyzer combined with a bomb calorimeter to more accurately determine proximate analysis and total energy content of common food wastes.

3.0 Methods:

3.1 Food waste sample collection

Household food scraps were collected and stored in 20 mL glass vials (Figure 2). Food wastes were selected based upon how abundantly they are produced in the United States according to data from the United States Department of Agriculture (USDA 2014, 2016), and were divided into four different food groups (Table 1). Grains (including bread and rice) are some of the most wasted foods in the US and UK and have the potential for energy production because of their abundance (Ventour, 2008). Another study found that fresh fruits and vegetables are among the most-wasted items throughout the world (Parfitt et al. 2010), thus easily perishable items were analyzed including fruits, vegetables, carbohydrates (grains), and meats. The mass of all samples was determined using an electronic balance and recorded in grams (Mettler Toledo New Classic MT MS104S).

Table 1: Food groups- Food waste samples were chosen based upon how commonly they are wasted within the United States, and were divided into four general food groups, with four samples for each group.

Fruits	Vegetables	Carbohydrates	Meats
Apple flesh	Tomato	Uncooked white rice	Cooked pork
Orange peel	Lettuce	Whole grain bread	Raw chicken thigh
Banana peel	Potato	White bread	Cooked beef
Red grape	Carrot	Pasta noodle	Turkey breast

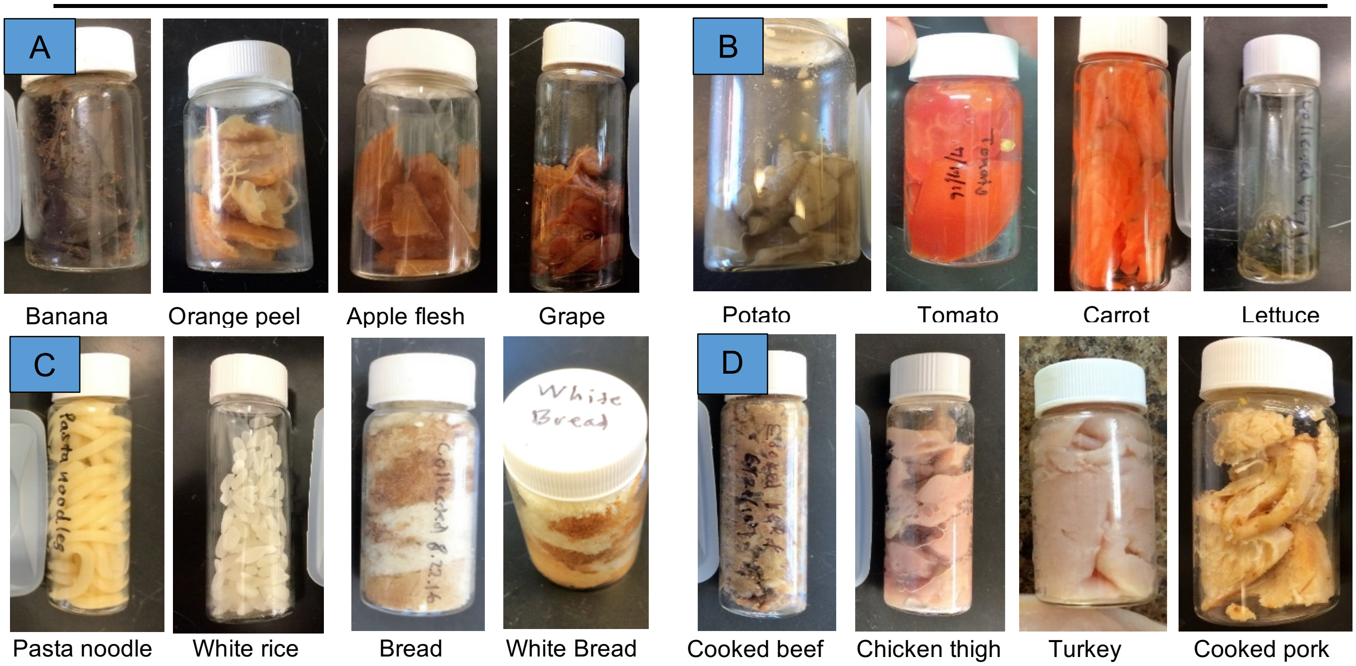

Figure 2: The food waste samples were divided into four groups: A) Fruits, B) Vegetables, C) Carbohydrates, and D) Meats, and were collected in glass vials to be tested.

3.2 Oxygen bomb calorimetry

An oxygen bomb calorimeter (Parr instrument company Model 1341) was used to determine the energy content of the food wastes in units megajoules per kilogram (MJ/kg). Samples placed in the calorimeter were cut to a size of less than one gram and were connected to a piece of wire to start the combustion. Before each testing, there was a five-minute stirring period to account for any potential energy changes from the stirrer. Calorimetry was run in triplicate for each food waste and means were calculated for each sample to determine the energy content. Certain samples were pre-dried at room temperature overnight because they did not ignite in the calorimeter after numerous tests (data not shown); this was attributed to the high amount of inherent moisture. Samples that required pre-drying included the vegetables, fruits, and some meat samples.

The caloric value of each sample was calculated with the following equation:

$$Q\ combustion = \Delta T * C_{bomb\ eff} - L_{wire} * C_{wire}/m_{fuel} \qquad (1)$$

where *Q combustion* is the heat of combustion of the biomass (MJ/kg), ΔT is the corrected temperature difference (°C), *C bomb eff* is the effective heat capacity of the calorimeter (MJ/kg), L_{wire} is the length of combusted wire (cm), C_{wire} is the heat capacity of wire (J/cm), and m_{fuel} is the mass of fuel samples (grams).

3.3 Thermogravimetric Analysis

A thermogravimetric analyzer (DuPont TGA 951) was used to determine the proximate analysis factors of the food waste samples. Thermogravimetric analysis (TGA) detects a change in the mass of the sample as a function of increases in temperature. Proximate analysis factors used to characterize food waste samples were moisture content, volatile content, fixed carbon, and ash. High moisture content influences biomass feedstocks as it compromises energy output, requiring additional energy to dry samples. The moisture content is influenced by the bound water contained in the food sample and moisture from external factors, including ambient humidity (Garcia et al. 2012). Volatiles are compounds within the sample which are reactive and are easily released at moderate temperatures in the absence of oxygen. Biomass generally contains high amounts of volatile matter, enabling combustion at lower temperatures. TGA was run in triplicate per sample to ensure precise values for proximate analysis factors, and means were calculated.

The heating method used herein modeled procedures outlined in Garcia et al. in 2012, which compared multiple methodologies for the determination of proximate analysis factors. After comparisons were made, average experimental error values, bias error, and absolute deviation were found to be lowest in the method developed by Karatepe and Kucukbayrak in 1993. The drying process operated from room temperature (25ºC) to 120ºC and was held for three minutes. Subsequently, the temperature was raised to 950ºC for seven minutes to release volatiles, and quickly decreased to 450ºC. Finally, the temperature was increased to 850ºC and was held for three minutes. Residuals such as ash from the tests (Figure 3) were stored in 10 mL glass vials, and weighing boats were cleaned afterward. Figure 4 represents the resulting heating method that was optimized for use on biomass, and was adopted for this study.

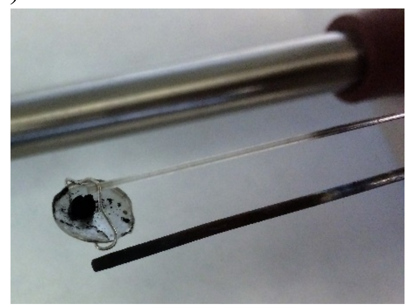

Figure 3: Potato TGA Residual
Residuals from a potato sample may include leftover carbon and ash.

Based upon the curves in the TGA graph and the calculated derivative, proximate analysis factors were determined. Figure 5 shows how data were obtained during the heating method used for each test sample. The first large mass decrease until minute six indicates a loss in moisture content during the drying process. The second mass loss is the release of volatile matter during the devolatilization process from minutes six to ten. Fixed carbon is oxidized from minutes ten to fourteen, and the remaining

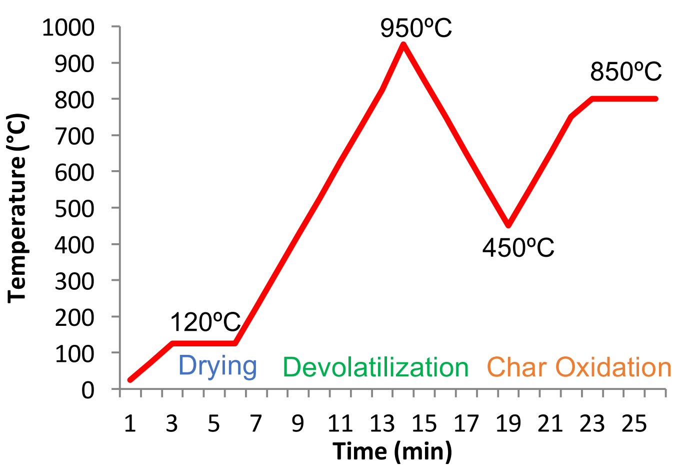

Figure 4: Thermogravimetric Analysis Heating Method
The heating method developed by Garcia et al. 2012 compared multiple proximate analysis methodologies, and was optimized for biomass. N_2 gas is flown through at a rate of 40 SCCM.

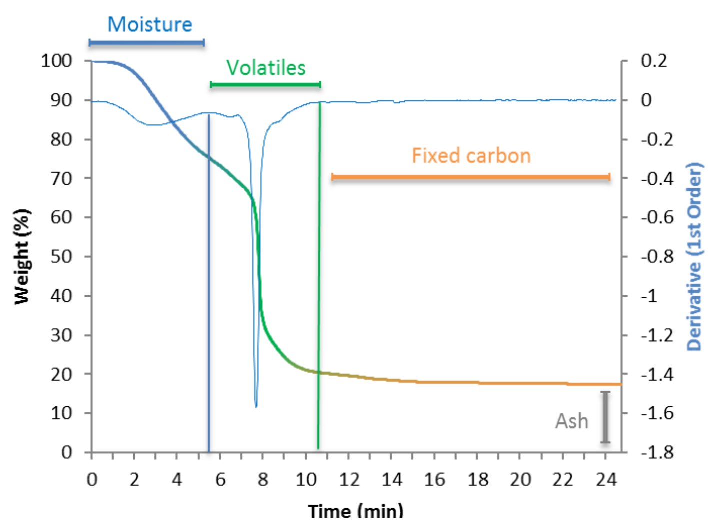

Figure 5: Proximate Analysis Determination
Thermogravimetric analysis steps involved are drying, devolatilization and char oxidation. Differentiating steps by looking at mass plateaus and derivatives allows for the determination of proximate analysis factors.

uncombusted mass is the ash. First order derivatives of the loss in mass as a function of time were also used to calculate proximate analysis factors. The stabilization of the mass slope (where the calculated derivative is closest to zero) indicated the distinctions between the different proximate analysis factors.

3.4 Food waste energy estimates calculation

The loss-adjusted food availability reported by the United States Department of Agriculture Economic Research Service (USDA ERS 2016) data were used to determine how much of each food samples is wasted by weight (kg) per capita per year. These values of food loss were used to estimate how much energy could be produced by each of the sixteen food samples (Eq. 2). Average annual electricity consumption by American households was found to be 38,923.2 MJ (U.S. EIA 2015). The energy produced by food waste samples was multiplied by 2.54 to account for how many individuals are in an average American household.

*Food waste energy potential = kg/capita/year wasted * MJ/kg* (2)

The energy values calculated by Eq. 2 for each of the sixteen food waste samples were added and then this value was divided by the average annual electricity use of households.

3.5 Data analysis

Standard deviations among sample repetitions and confidence levels were calculated using Microsoft Excel 2016. The standard errors for the calorimetry values were also calculated to assess the variability. One-way Analysis of Variance (ANOVA) was run on Graphpad (Version 6.07) between food waste samples and between food groups to determine if differences in calculated energy content were statistically significant. Pearson's correlations were run between energy content and proximate analysis factors, namely moisture and volatile content because they primarily comprise biomass samples and may influence the energy contained in samples. The correlations were used to characterize how the proximate analysis factors influence energy content of food waste samples in order to create a model.

4.0 Results:

4.1 Calorimetry: Meat samples contained the highest average energy content

The energy content of food wastes was determined through oxygen bomb calorimetry, and the comparisons between the food groups are represented in Figure 6. Average caloric values of individual samples run in triplicate are compared in Figure 7. The mean energy content across all sample types was 14.31 MJ/kg. The meat group had the highest average of 18.02 ± 3.65 MJ/kg. The fruits contained an average energy content of 13.75 ± 0.60 MJ/kg. The vegetables had an average of 12.83 ± 2.12 MJ/kg, and the carbohydrates had an average of 12.63 ± 0.65 MJ/kg. Out of the vegetable samples, carrot contained a noticeably high energy content (18.48 MJ/kg). Cooked pork contained the lowest amount of energy overall (7.9 MJ/kg), which was a large variance from the other meat samples.

Error values for the energy are also represented. The high error value found in the apple and cooked beef samples (Fig. 6) are a result of an abnormally low energy value found in one of the three tests. In addition, caloric values supplied by the US Department of Energy (2011) for feedstocks such as coal, gasoline, and types of biomass were included in the purple bars to provide a reference for comparison. A one sample T-test was run comparing the highest energy group, meat samples to the herbaceous biomass, revealing that there was no significant difference between the energy of the samples ($t = 0.41$, $p = 0.69$). This indicates that the meat samples had a comparable energy content to the biomass and corn stover; the other food groups analyzed contained lower average energy content.

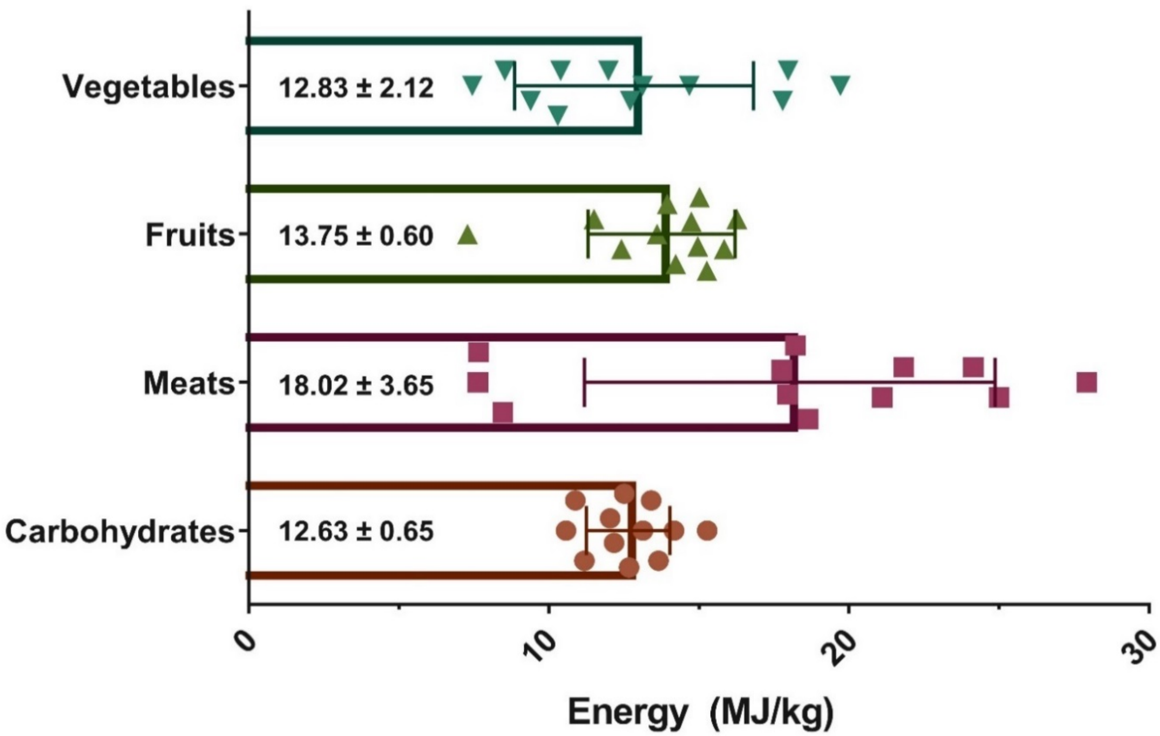

Figure 6: Food Waste Groups Comparison: Oxygen bomb calorimetry results divided into the food groups are represented. All three tests for each food sample are shown (n=12 / group). On average the meat samples contained the most energy (18.02 MJ/kg). Fruits had 13.75 MJ/kg with one apple sample being an outlier. Vegetable and carbohydrates had a similar average energy content with 12.83 MJ/kg and 12.63 MJ/kg respectively.

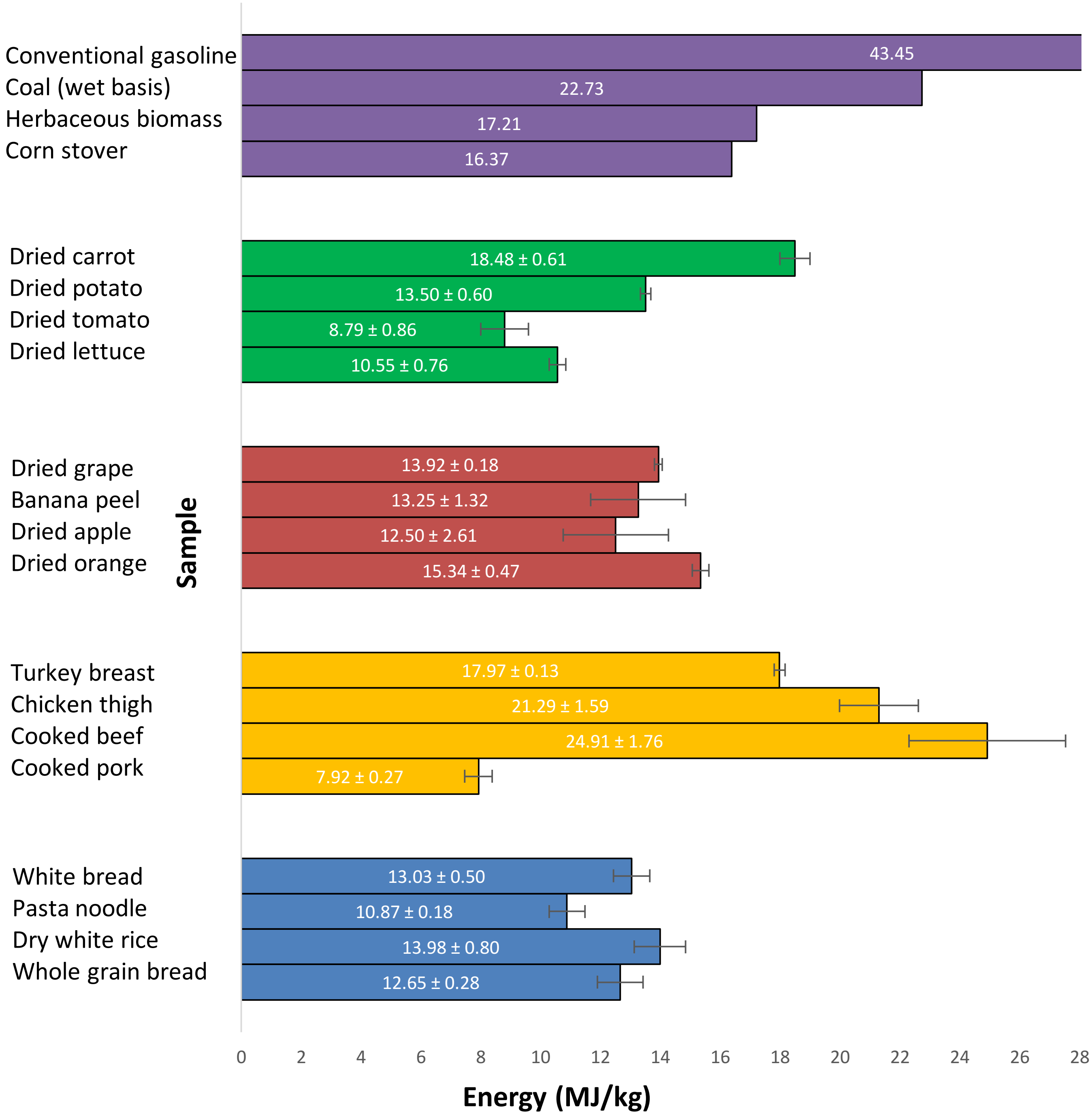

Figure 7: Food Waste Calorimetry: Mean oxygen bomb calorimetry results for various food waste samples (n=3/sample). The cooked beef contained the most energy (24.9 MJ/kg), and on average the meat samples contained the most energy. Cooked pork contained the least energy (8 MJ/kg). Average caloric value for all samples was 14.31 MJ/kg. Standard experimental error bars are shown. Samples in purple are included to provide context for the energy values of the food wastes. Energy values for samples in purple were provided by the USDE. ANOVA's were run, showing that the differences in energy values were statistically significant. Differences between food groups were statistically significant ($p = 0.0093$). Differences between individual foods were also statistically significant ($p < 0.0001$).

4.2 Food waste energy estimates

Estimates of the energy potential of the food waste samples tested in this study were calculated using data on food loss and average American household electricity consumption. Calculations using Eq. 2 determined that the sixteen food wastes tested in this study can provide nearly 11.5% of the energy consumed by the average American household in 2015, equivalent to 4462.8 MJ/kg (EIA 2016). The meat samples were shown to provide the most energy (61.2% of the total), as they are wasted in higher volumes and have relatively high energy values.

4.3 Proximate analysis: Fruit and vegetable samples contained the highest moisture

Proximate analysis factors of the different food wastes were discerned using distinct mass plateaus, indicating the loss of various compounds. In addition, derivatives were calculated to confirm changes in slope which correlate to the four primary steps involved in pyrolysis. A representative sample of the mean of three grape samples is shown in Figure 8. Standard error between the three repetitions are represented, which indicated higher error near the drying process (minutes 3 to 8) and near the end at minutes 20 to 25 (see inset).

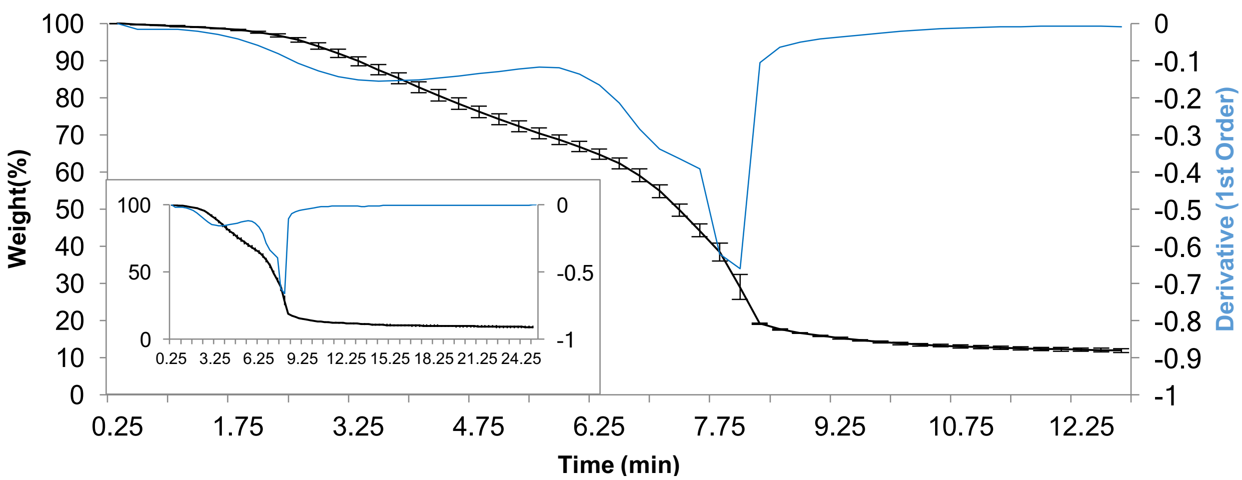

Figure 8: Grape average with standard error: Dried grapes were pyrolyzed with a flow gas of nitrogen to determinate proximate analysis factors. The first order derivative was calculated in excel and is represented. Standard error bars are shown, which indicate higher error potential during the loss of moisture from minutes 3 to 8.

In Figure 9, the proximate analysis factors for each of the four food groups is summarized. The high amount of moisture (on average 39%) in the fruits and vegetables was expected due to inherent moisture from growth. On average, the carbohydrate samples contained the highest ash content. Average volatile content for the food groups were: 59.86% for carbohydrates, 58.62% for meats, 54.04% for vegetables, and 53.47% for fruits. In Figure 10, the proximate analysis data for all food samples is represented. Potato contained the most moisture

(58.26%) and the lowest amount of volatiles (30.14%), while white rice contained the most volatiles (80.54%) and the least moisture (4.95%).

In Table 2, the results of multiple one-way ANOVA analyses for energy content and the proximate analysis factors are represented. The differences in energy content between food waste samples were found to be statistically significant ($p < 0.01$), indicating that the means between samples were not different due to chance or random sampling. In addition, differences in the moisture content and volatile content were found to be statistically significant ($p < 0.0001$). Tukey HSD Post-hoc tests were run to determine specifically where the differences between groups were. For energy values, the following groups were found to be statistically different ($p < 0.05$): meats vs. vegetables, and meats vs. carbohydrates, with meats containing significantly higher energy values than vegetables or carbohydrates. For moisture content, there were significant differences ($P < 0.01$) between carbohydrates vs. meats, carbohydrates vs. fruits, and carbohydrates vs. vegetables. Differences between volatile content were not found to be statistically significant. Differences between fixed carbon content of the food groups were also not statistically significant. For ash content, there were significant differences ($p < 0.01$) between carbohydrates and the other food groups with carbohydrates containing significantly more ash than all other food groups.

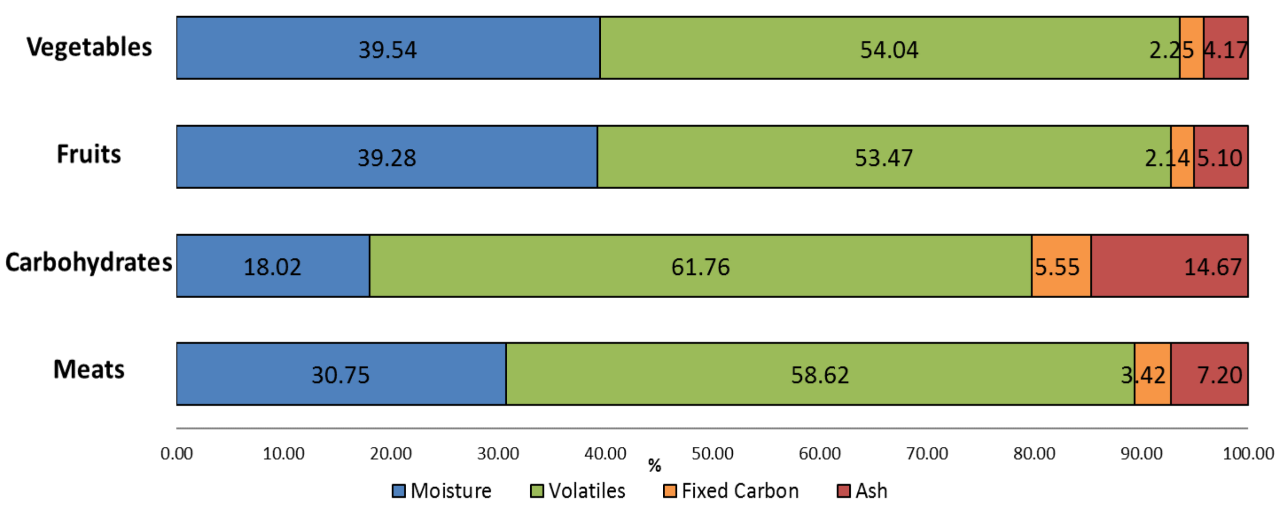

Figure 9: Food groups proximate analysis means: The vegetable and fruit samples contained similar amounts of moisture, volatiles, fixed carbon, and ash at around 39%, 54%, 2%, and 4.5% respectively. The carbohydrates contained the least amount of moisture which was expected, and the highest number of volatiles (62%) and ash (15%).

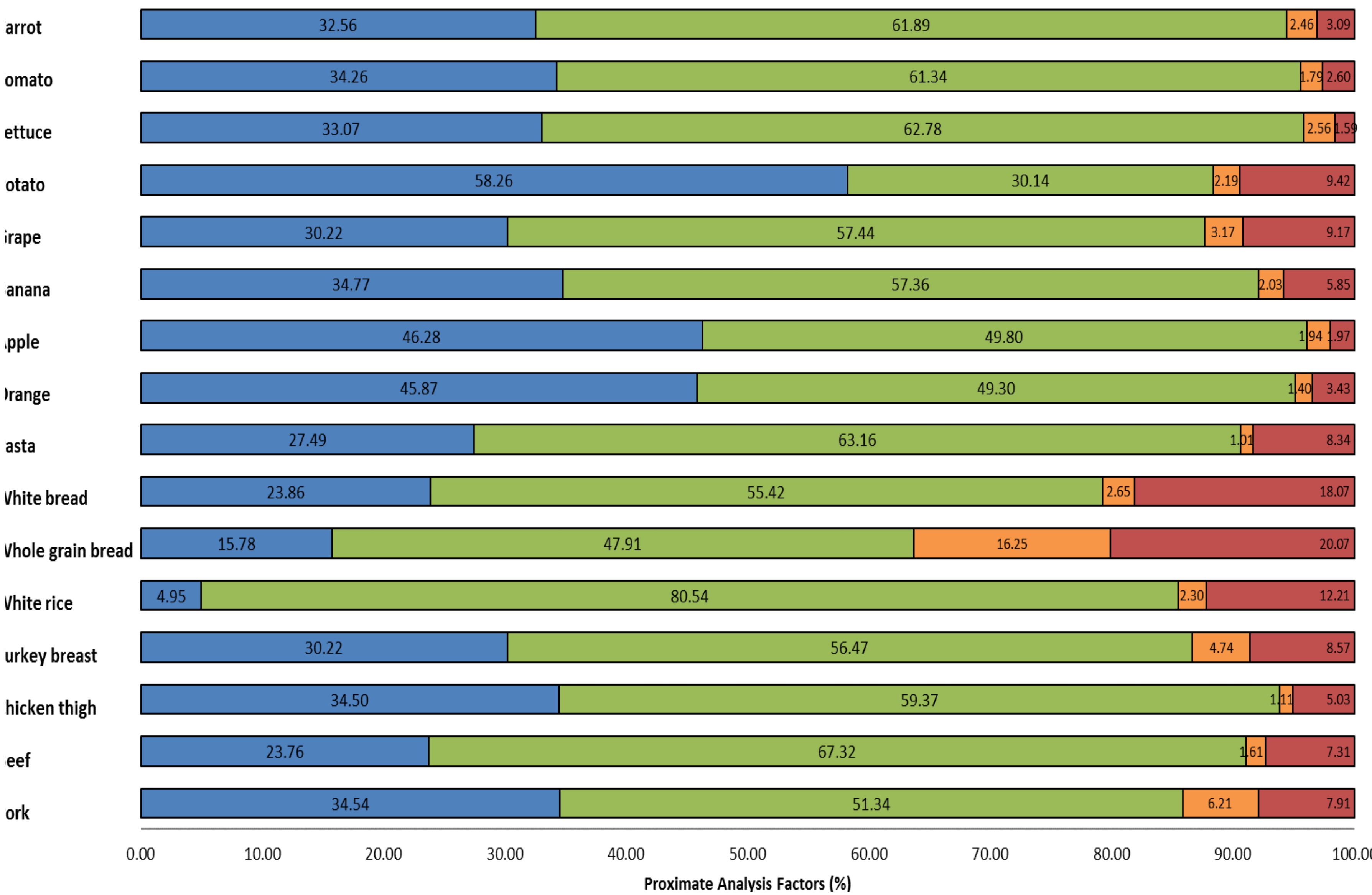

Figure 10: Proximate Analysis of Food Waste Samples determined through Thermogravimetric Analysis

Characteristics of the food waste samples are represented (in %). Potato samples contained the highest amount of moisture, along with apple samples and orange peels, as expected of the fruits and vegetables. Carbohydrate samples contained the highest average volatile content (61.76%), with meats only having the second highest volatiles (58.62%). Carbohydrates also contained the highest ash concentrations, indicating a higher amount of incombustible metals (n=16).

Table 2: One-way ANOVA of thermochemical properties of food waste samples: Differences between and within columns for all three factors were found to be statistically significant.

		Sum of squares	Degree of freedom	Mean square	F (DFn, DFd)	Significance (P)
Energy	Between	899.4	15	59.96	$F\ (15, 32) = 18.21$	$p < 0.0001$
	Within	105.3	32	3.292		
Moisture	Between	6062	15	404.2	$F\ (15, 31) = 30.76$	$p < 0.0001$
	Within	407.2	31	13.14		
Volatiles	Between	11331	15	755.4	$F\ (15, 31) = 50.58$	$p < 0.0001$
	Within	463	31	14.93		
Fixed Carbon	Between	611.9	15	40.79	$F\ (15, 31) = 5.869$	$P < 0.0001$
	Within	215.4	31	6.95		
Ash	Between	1280	15	85.34	$F\ (15, 31) = 7.376$	$P < 0.0001$
	Within	358.6	31	11.57		

4.4 Food waste model: Correlations between fixed carbon / volatiles / ash and energy

No clear correlations emerged between the energy values of all sixteen samples and the proximate analysis factors. For energy plotted against fixed carbon content shown in Figure 11, the R value was -0.29, $n = 15$, $p = 0.30$ which would indicate a weak negative relationship if statistical significance was reached. An outlier in this correlation was whole grain bread which had an excessively high fixed carbon content. The correlation between energy and volatile content (Fig. 12) revealed a weak trend-level positive relationship, when the outliers of potato and rice were removed ($r = 0.366$, $n = 14$, $p = 0.198$). Figure 13 shows that energy and ash content also revealed a weak positive trend ($r = 0.087$, $n = 14$, $p = 0.77$). However, neither of the correlations of fixed carbon nor ash were found to be statistically significant, and energy versus volatiles was marginally approaching significance, indicating a need for more food waste samples to be tested to develop an accurate food waste characterization model.

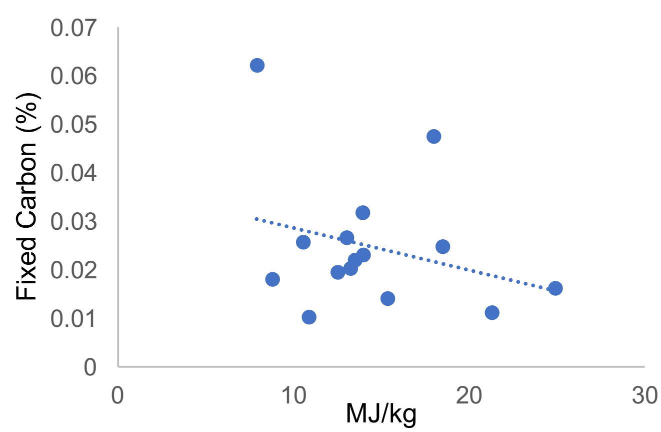

Figure 11: Correlations between energy and fixed carbon: There was a slight negative correlation between energy and moisture, with an R-value of -0.29 ($p = 0.30$) without the outlier of whole grain bread.

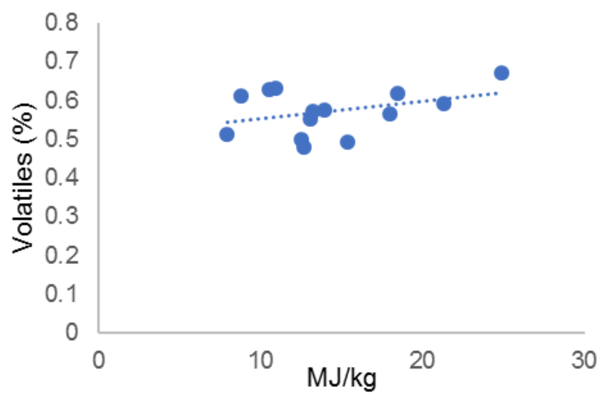

Figure 12: Correlations between energy and volatiles: There was a slight positive correlation between energy and volatiles, with an R-value of 0.366 (p = 0.198) without the outliers, potato and rice.

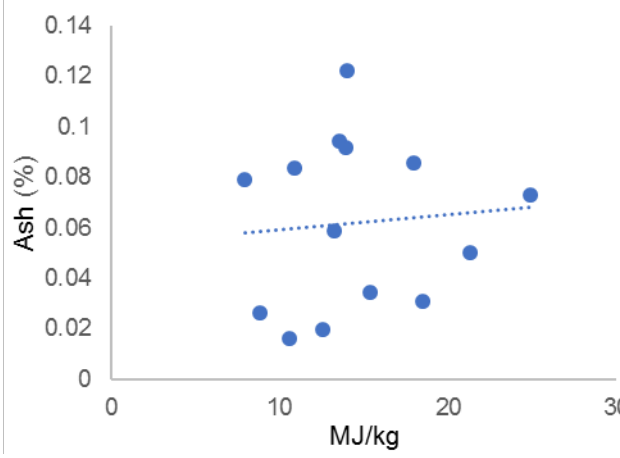

Figure 13: Correlations between energy and ash: There was a weak negative correlation between energy and ash, with an R-value of 0.087 (p = 0.77) without the outliers of whole grain bread and white bread.

5.0 Discussion:

This research aimed to characterize food waste samples abundant in the United States using calorimetry and thermogravimetric analysis. The food waste energy model developed from the correlations revealed a weak trend between the energy content and the volatile content. Calorimetry indicated that cooked beef and chicken thigh contained the most energy and thus are highly desirable resources for biomass energy production. On average, the fruits and vegetables had similar proximate analysis factors: they had the highest moisture content and the lowest volatile content reducing their potential as an energy feedstock. Carbohydrate samples contained the highest average ash content indicating potential for the recovery of the ash as use for landfill fly ash and cement (Adrian et al. 2010). The high energy content found in fruits and meats is most likely attributable to higher ratios of hydrogen and carbon. These elements can thus produce compounds like methane which are highly exothermic when combusted, resulting in greater amounts of energy. Food waste energy estimates determined that over one-tenth of average household energy consumption in America could be supplied by converting food wastes into energy. This study was the first of its kind to characterize household food wastes as opposed to biomass from industrial or agricultural sources.

Compared to standard biomass feedstocks like switch grass, which has 18.0 MJ/kg (Phyllis database), the food wastes examined herein had an average energy content of 14.31 MJ/kg. However, the meat samples outperformed USDE standards for herbaceous biomass and corn stover. In addition, according to the USDA Economic Research Service (2014), meat wastes were the largest source of food loss in terms of value being lost (30%) making it important to recover this loss. Traditional fossil fuels like coal (about 30 MJ/kg) and gasoline (44.4 MJ/kg) have significantly higher energy contents. Although the overall energy value is not high, the large quantity of food produced may justify the use of food waste for energy production. Samples with the lowest energy values were cooked pork and tomato, which had a similar moisture content (34%). These results support the low energy content associated with samples that have large amounts of inherent moisture.

Previous research has studied a variety of energy feedstocks ranging from firewood and coal to industrial wastes (Garcia et al. 2013; Saldarriaga et al. 2015). Many similar studies were conducted in European countries, which produce different types of biomass. Samples included energy crops such as Miscanthus or switch grass, agricultural wastes including peanut shell or rice husk, and commercial wastes such as sawdust and wood chips. Garcia et al. in 2012 found that the energy crop Miscanthus had about 7.53% moisture, 79% volatile matter, 11.4% fixed carbon, and 9.6% ash. The high number of volatiles and low moisture correlate with the high amount of energy of 18.57 MJ/kg found in Miscanthus. The only sample that had comparable values was the white rice sample with 80.54% volatiles and 12.21% ash. On the contrary, pepper plant waste contained higher amounts of ash (23%) which may have lowered heating values (13 MJ/kg). All but one food waste sample within this study contained a volatile matter percentage below 70%. This data contrasted with Saldarriaga's study in that many samples tested contained moisture contents higher than 10%.

Limitations of this study included a relatively small sample size of foods, and the discrepancies that may be found in the food types and their quality. A larger quantity of food samples should be tested, with a higher number of repetitions to increase the statistical significance of the correlations to develop a stronger food waste energy model. In the case of the meat samples, some were cooked (pork and beef) while others were raw (chicken and turkey). In addition, certain samples were dried before being combusted in the bomb calorimeter, which may influence the energy content of the samples. Primarily, the fruit and vegetable samples were air-dried to ensure that they would ignite in the bomb. However, this would most likely represent a more accurate assessment of the heating values of the foods because pre-drying may be necessary when the samples are used in waste to energy facilities.

Future research should characterize a variety of food waste samples from other food groups. Additional food waste samples could include other protein sources such as fish or other meats, bones, other commonly wasted fruits like watermelon, and nuts. Variances in the preparation of food wastes could also be examined, comparing differences in cooked versus uncooked samples which may influence the energy content and the characteristics of the foods. Characterization involving ultimate analysis should also be studied to determine the elemental composition of food wastes and their reaction kinetics, and comparisons to other types of biomass should be made. The ash component of the food wastes should also be studied through techniques such as X-ray diffraction in order to determine the elemental breakdown of the ash in order to determine the potential applications of the uncombusted ash. Food wastes could also be tested in pilot scale gasification systems to understand which compounds are released which have the greatest potential for energy production. This would also provide industries with more knowledge to determine what type of technology is optimal for conversion of food wastes to energy.

6.0 Conclusion:

Energy content of food wastes were determined, with meats generally having higher energy values on average (18.02 MJ/kg). The average caloric values in MJ/kg for food groups were: 13.75 for fruit samples, 12.83 for vegetables, and 12.63 for carbohydrates. The cooked beef sample contained the highest amount of energy, indicating its potential for energy production (24.91 MJ/kg), while being characterized by a high percentage of volatile compounds. The average caloric value for all food waste samples was 14.31 MJ/kg. No strong trends were found between energy and fixed carbon content ($r = -0.29$, $p = 0.30$), as well as between energy and ash content ($r = 0.087$, $p = 0.77$), while the relationship between energy and volatile content was approaching significance ($r = 0.366$, $p = 0.198$). Food waste energy estimates based upon the values obtained from the samples analyzed by this study revealed that 11.5% of average American household energy consumption could be offset through the conversion of food wastes into energy. This research advances the understanding of sixteen food wastes and their potential for energy production in thermochemical reaction systems.

7.0 Acknowledgements:

Throughout the research process, I have been aided by Professor Castaldi and Mike Lugo from the City College of New York, who have allowed me to use their facilities and equipment. I would also like to thank my science research teachers, Angelo Piccirillo and Valerie Holmes for their consistent ability to push me beyond my limits. Lastly, I want to thank my family and friends for their endless support without which this research would not have been possible.

8.0 References:

1. Hoornweg, Daniel, and Perinaz Bhada-Tata. *What A Waste: A Global Review of Solid Waste Management*. Rep. The World Bank, Mar. **2012**. Web.

2. *World Energy Outlook 2015 Factsheet*. Rep. International Energy Agency, 10 Nov. **2015**. Web.

3. D.K. Shen, S. Gu, K.H. Luo, A.V. Bridgwater, M.X. Fang, Kinetic study on thermal decomposition of woods in oxidative environment, Fuel, Volume 88, Issue 6, June **2009**, Pages 1024-1030, ISSN 0016- 2361.

4. Peter McKendry, Energy production from biomass (part 1): overview of biomass, Bioresource Technology, Volume 83, Issue 1, May **2002**, Pages 37-46, ISSN 0960-8524.

5. "Methane Emissions." *EPA*. Environmental Protection Agency, n.d. Web. June **2015**. <http://epa.gov/climatechange/ghgemissions/gases/ch4.html>.

6. X.F. Lou, J. Nair, The impact of landfilling and composting on greenhouse gas emissions – A review, Bioresource Technology, Volume 100, Issue 16, August **2009**, Pages 3792-3798, ISSN 0960-8524

7. Roberto García, Consuelo Pizarro, Antonio G. Lavín, Julio L. Bueno, Characterization of Spanish biomass wastes for energy use, Bioresource Technology, Volume 103, Issue 1, January **2012**, Pages 249-258, ISSN 0960-8524.

8. Lipinski, Brian, Craig Hanson, James Lomax, Lisa Kitinoja, Richard Waite, and Tim Searchinger. *Reducing Food Loss and Waste*. Rep. World Resources Institute; UN Environment Programme, June **2014**.

9. Cuéllar, Amanda D., and Michael E. Webber. “Wasted Food, Wasted Energy: The Embedded Energy in Food Waste in the United States.” *Environmental Science & Technology* 44.16 (**2010**): 6464–6469. *PMC*.

10. James, A.K.; Thring, R.W.; Helle, S.; Ghuman, H.S. Ash Management Review—Applications of Biomass Bottom Ash. *Energies* **2012**, *5*, 3856-3873.

11. Rajamma, Rejini, Richard J. Ball, Luís AC Tarelho, Geoff C. Allen, João A. Labrincha, and Victor M. Ferreira. "Characterisation and use of biomass fly ash in cement-based materials." *Journal of hazardous materials* 172.2 (**2009**): 1049-1060.

12. Food and Agriculture Organization. **2011**. Global food losses and food waste – Extent, causes and prevention. Rome.

13. Kok, Mustafa Versan, and Emre Özgür. "Thermal analysis and kinetics of biomass samples." *Fuel Processing Technology* 106 (**2013**): 739-743.

14. Juan F. Saldarriaga, Roberto Aguado, Aitor Pablos, Maider Amutio, Martin Olazar, Javier Bilbao, Fast characterization of biomass fuels by thermogravimetric analysis, Fuel, Volume 140, 15 January **2015**, Pages 744-751, ISSN 0016-2361.

15. Braz, Carlos Eduardo Mendes, and Paula Cristina Garcia Manoel Crnkovic. "Physical-chemical characterization of biomass samples for application iin pyrolysis process." *Chemical Engineering Transactions* (**2014**): 523-528.

16. Faaij, André. "Modern biomass conversion technologies." *Mitigation and adaptation strategies for global change* 11.2 (**2006**): 335-367.

17. Emanuele Graciosa Pereira, Jadir Nogueira da Silva, Jofran L. de Oliveira, Cássio S. Machado, Sustainable energy: A review of gasification technologies, Renewable and Sustainable Energy Reviews, Volume 16, Issue 7, September **2012**, Pages 4753-4762.

18. Mao, Chunlan, Yongzhong Feng, Xiaojiao Wang, and Guangxin Ren, "Review on research achievements of biogas from anaerobic digestion." *Renewable and Sustainable Energy Reviews* 45 (**2015**): 540-555.

19. Standard, A. S. T. M. "Annual book of ASTM standards." *American Society for Testing and Materials Annual, Philadelphia, PA, USA* (**2010**): D3172, E870.

20. Roberto García, Consuelo Pizarro, Antonio G. Lavín, Julio L. Bueno, Biomass proximate analysis using thermogravimetry, Bioresource Technology, Volume 139, July **2013**, Pages 1-4, ISSN 0960-8524.

21. Vhathvarothai, Navirin, James Ness, and Qiming J. Yu. "An investigation of thermal behaviour of biomass and coal during copyrolysis using thermogravimetric analysis." *International journal of energy research* 38.9 (**2014**): 1145-1154.

22. M.C. Mayoral, M.T. Izquierdo, J.M. Andrés, B. Rubio, Different approaches to proximate analysis by thermogravimetry analysis, Thermochimica Acta, Volume 370, 4 April **2001**, Pages 91-97, ISSN 0040-6031.

23. Buzby, Jean C., Hodan F. Wells, and Jeffrey Hyman. The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States, EIB-121, U.S. Department of Agriculture, Economic Research Service, February **2014**.

24. Bentley, Jeanine, and Linda Kantor. "Food Availability (Per Capita) Data System." United States Department of Agriculture Economic Research Service, 24 Aug. **2016**. Web.

25. Ventour, Lorrayne. The food we waste. Vol. 237. Banbury/Oxon: WRAP, **2008**.

26. Parfitt, Julian, Mark Barthel, and Sarah Macnaughton. "Food waste within food supply chains: quantification and potential for change to 2050."*Philosophical Transactions of the Royal Society B: Biological Sciences*365.1554 (**2010**): 3065-3081.

27. Nilgün Karatepe, Sadriye Küçükbayrak, Proximate analysis of some Turkish lignites by thermogravimetry, Thermochimica Acta, Volume 213, **1993**, Pages 147-150, ISSN 0040-6031.

28. "Food Availability (Per Capita) Data System." *USDA ERS* -. United States Department of Agriculture Economic Research Service, 12 Oct. **2016**. Web.

29. "How Much Electricity Does an American Home Use?" *U.S. Energy Information Administration - EIA - Independent Statistics and Analysis*. U.S. Energy Information Administration, 18 Oct. **2016**. Web.

29. U.S Department of Energy. **2011**. Biomass Energy Data Book. http://cta.ornl.gov/bedb/pdf/BEDB4_Appendices.pdf

30. Phyllis2, database for biomass and waste, https://www.ecn.nl/phyllis2 Energy research Centre of the Netherlands.

31. Hossen, Md Mosaddek, AHM Sazedur Rahman, Afsana Sara Kabir, MM Faruque Hasan, and Shoeb Ahmed. "Systematic assessment of the availability and utilization potential of biomass in Bangladesh." *Renewable and Sustainable Energy Reviews* 67 (**2016**): 94-105.

32. Buzby, Jean, Hodan Farah Wells, and Jaspreet Aulakh. "Food Loss-Questions About the Amount and Causes Still Remain." *USDA ERS*. United States Department of Agriculture Economic Research Service, 2 June **2014**. Web.