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Energy recovery from waste food by combustion or gasification with the potential for regenerative dehydration: A case study

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ABSTRACT

Energy recovery from food waste was studied using the food service at the US Naval Academy as a case study. Post-consumer food waste was captured over a period of ten days to estimate individual waste per meal and total waste per month. The food waste was analyzed for chemical composition and water content using ultimate and proximate analysis, and for energy content, and compared with the same analyses of wood (a more typical biomass fuel). Three different samples of food waste showed relative uniformity of properties despite being sampled on different days, with different menus. Food waste had lower oxygen content, higher nitrogen and ash content, and higher energy content than wood. The food waste in this study had approximately 70% water content. Temperatures and emissions from combustion of wood pellets, dried pelletized food waste, and dried non-pelletized food waste were measured and compared using a modified residential pellet stove. Temperatures were higher for food waste due to the higher energy content. Emissions of NO, HC, and soot were slightly higher for food waste. Despite the large water content, thermodynamic analysis showed that regenerative dehydration, in which waste energy from the combustion system is used to remove water from the incoming wet fuel, is possible. An excess enthalpy ratio is defined to formalize the comparison of waste sensible enthalpy with the energy required for dehydration. Analysis of fuel-lean combustion and fuel-rich gasification shows that little, if any, external energy would necessarily be required to remove the water from the incoming fuel. An equilibrium model was used to simulate waste food gasification by extending the simulation to high water content levels. Probable ranges for successful food waste gasification are identified. Energy recovery of waste food could result in cost savings by offsetting traditional fuel-use (e.g. natural gas for heating) and by reducing disposal costs.

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1. Introduction

Sharply rising food prices in the winter of 2008 triggered foot riots around the world. The rising cost of basic food grains during this period at least suggested a competition between food-use and fuel-use for these grains [1]. While the economics of this crisis may not be completely clear, the literature suggests there is grossly insufficient cropland to produce both food and sufficient fuel to satisfy future energy demand [2].

Still, the benefits of using food crops for fuels, such as corn for ethanol production in the US, are several. Because of the short time scale over which crops fix carbon from the atmosphere, the net greenhouse gas emissions from biofuels can be substantially less than fossil fuels [2]. Furthermore, biofuel crops can be produced domestically, ensuring a more stable supply and price, and allowing the development of domestic economies and infrastructure. If using food crops as fuel feedstocks can produce a harmful competition with food supplies for people, using food *wastes* could allow the same benefits without the potentially harmful consequences on the food supply.

Typically, food waste is discarded into the general flow of municipal solid waste (MSW). Waste products have long been utilized for energy extraction via combustion [3]. Demirbaş et al. provide historical context for modern biomass- and waste-to-energy processes in Ref. [4]. Extracting usable energy from waste offsets traditional fuel usage, allowing greater diversification of energy supply, and enhancing energy security, while reducing disposal costs. Recently, waste-to-energy technology was employed in a combat environment in Iraq. The technology aimed to reduce diesel fuel use (thereby reducing the supply chain burden for diesel fuel) and to reduce the logistic and security challenges of garbage disposal in that combat environment [5].

When food waste is sequestered for reuse, the usual method of reclamation is composting. Composting converts the food waste into nutrient-rich fertilizer, which is then utilized to enhance further food production. Composting operations are increasing in popularity. Ref. [6] provides an example of recent efforts to survey

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Nomenclature

ASTM	American Society of Testing and Materials	Φ	fuel–air equivalence ratio
CPC	condensation particle counter	η_{cg}	cold-gas efficiency
HC	unburned hydrocarbons	ε_i	enthalpy fraction passing through location i
HFID	heated flame ionization detector	Δh_f	enthalpy of formation
HHV	higher heating value	y_i	mass fraction of component i
LHV	lower heating value	MW_i	molecular weight of species i
MSW	municipal solid waste	h_i	enthalpy (chemical and sensible) of species i
NO	nitric oxide	h_{fg}	enthalpy of vaporization
SCFM	standard cubic feet per minute	h_{dry}	enthalpy required to dehydrate a sample to a specified extent
SLPM	standard liters per minute	r_{excess}	excess enthalpy ratio
SMPS	scanning mobility particle sizer	c_p	specific heat at constant pressure
v_i	stoichiometric coefficient of reactant species i	T	temperature
v_i'	stoichiometric coefficient of product species i		
α	stoichiometric coefficient of air		

composting operations due to increasing demand for services. Examples of successful composting operations at schools, universities, and large industrial manufacturing sites are given in Refs. [7–9], respectively. On an even larger scale, Ref. [10] cites a study on the feasibility of city-wide composting the metro Atlanta area. Food waste may also be captured for conversion in anaerobic digesters, in which anaerobic bacteria convert the food wastes into methane (biogas) and carbon dioxide, leaving organic solids behind that may also be used as fertilizer [11]. While the biogas does not meet standards for pipeline natural gas without further processing, it can be used to generate electricity locally. Refs. [12,13] illustrate examples of energy production from waste-to-biogas from a food manufacturer and the airline industry, respectively.

There are no known studies that focus on direct energy recovery from food waste by combustion. The large majority of biomass-to-energy conversion takes place via combustion [4], and food has significant chemical energy that could be released directly by combustion [14]. However, food waste seems ill-suited for direct combustion due to high water content. Dehydration of wet food waste could be too costly, relative to the energy released during combustion, due to the relatively high enthalpy of vaporization of water. In addition, high water content lowers gravimetric energy density, making transportation expensive, and necessitating local use.

Although high water content poses challenges for food waste combustion, dehydration may be facilitated by using waste thermal energy from a combustion system. Typical combustion systems inevitably suffer from a large amount of thermal losses, either through the housing of the system or expelled through the exhaust. These losses are difficult to recover due to the relatively low temperatures in these flows. However, they could be utilized to help dehydrate a wet fuel like food waste, since dehydration would be best conducted at relatively low temperatures (near the boiling point of water). Could the waste energy, inherent in any combustion system, offset the energy required to dehydrate waste food used as a fuel?

Another important question surrounding food waste energy recovery is that of quantity: How much food waste is available for energy recovery? There are many and varied estimates of food waste in the literature. Table 1 shows ten different published estimates of food waste since 1991. The estimates are placed into three categories: total estimates of food waste by weight; food waste as a percentage of MSW; and food waste on a per person, per meal basis. The estimates reflect the variable nature of waste and the difficulty in measurement. Often, these estimates lack rigorous explanations and raise questions: Was non-food trash (e.g. napkins, wrappers) included? Was non-edible food (e.g. pits, peels) included? Despite the variability and questions that result, these data show that food waste is extensive from homes, convenience stores, restaurants, industries, and schools. One recent estimate puts food waste as 12–14% of MSW in the US [17]. Two different estimates of post-consumer "plate" waste suggest approximately 5 oz of food is wasted per person, per meal [8,21].

This study explores the possible utilization of food waste for energy recovery by direct combustion. Given the variability of food waste estimates in the literature, this study first aims to quantify waste from a particular commercial food service as a case study. Chemical and energy content analysis of actual food waste are compared with wood, a typical biomass fuel, and with other typical fossil fuels. The combustion of waste food is studied and compared with the combustion of wood. The resulting combustion data are used to determine how well waste energy from the combustion process could be utilized to dehydrate the incoming fuel (a regenerative process). As an alternative to combustion, this study also explores the potential for gasification of food waste into a producer gas using computer simulation.

2. Experiment

2.1. Sampling methods and case study of commercial food service

Food waste was sampled from the commercial food service at the US Naval Academy, which serves up to 4400 students simultaneously at each meal. Meals are served in one large hall where most students sit at 12-seat tables. Waste food was collected for ten days from each meal from four tables. Over the course of these ten sample days, approximately 1000 students were served meals at the sampled tables. The collected food waste was weighed after each meal on a scale accurate to the nearest ounce (±28 g) so that the maximum weighing error was ∼1% (for meals with the least waste) and much less for most meals. All food waste was recovered, including all plate waste and extra food remaining in the serving bins at each table. Bulk liquids were not collected, such as water, milk, or liquid remaining in a cup. Food-related trash was also not collected, such as napkins, popsicle sticks, wrappers, cartons, or straws. However, non-edible food waste was included, such as peels, pits, and bones. Note that this sampling method captures all of the food-based post-consumer waste, but does not capture any pre-consumer waste that inevitably occurs during the food preparation process (Fig. 1). Thus, the measured waste in this study represents a lower bound on the actual waste that is produced during the food service process.

For three of the ten sample days, the waste food collected from each meal was processed for chemical analysis and combustion