Can Autocatalytic Pyrolysis of Wastewater Biosolids be Energy Neutral and Generate Value-Added Products?

Zhongzhe Liu¹, Simcha Singer², Daniel Zitomer¹, and Patrick McNamara¹*

1Department of Civil, Construction and Environmental Engineering, Marquette University, P.O. Box 1881, Milwaukee, Wisconsin 53201, USA
2Department of Mechanical Engineering, Marquette University, P.O. Box 1881, Milwaukee, Wisconsin 53201, USA
*Corresponding author email: patrick.mcnamara@marquette.edu

Abstract

Over eight million metric dry tons of wastewater biosolids are produced annually from water resource recovery facilities (WRRFs) in the United States. WRRFs are facing multiple challenges including energy generation, nutrient recovery, and pollutant removal requirements. Autocatalytic pyrolysis of wastewater biosolids is a promising process to improve energy generation and product recovery while removing pollutants. In particular, it can generate biochar (a valuable soil amendment) as well as high-yield pyrolysis gas, which is a renewable clean energy to complement the energy requirement at WRRFs. An energy analysis of autocatalytic pyrolysis was conducted with the assumption of 10% heat loss and using the highest catalyst loading. The results showed that the autocatalytic pyrolysis at 600°C was slightly exothermic but was endothermic at 700°C and 800°C. Therefore, some py-gas was used to supply the heat for 700°C and 800°C operation. However, the remaining fraction of py-gas still reduced the energy for biosolids drying by approximately 70%. At pyrolysis temperatures of 600°C, the remaining py-gas could cover 40% of the energy for biosolids drying. In summary, autocatalytic pyrolysis of wastewater biosolids can be energy neutral and generate the value-added product, biochar.

Keywords: Biochar; Energy content; Heat balance; Wastewater sludge; Catalyst; Bio-oil

Introduction

Over eight million metric dry tons of wastewater biosolids are produced annually from water resource recovery facilities (WRRFs) in the United States (Gude, 2015). WRRFs are facing multiple challenges including energy generation, nutrient recovery, and pollutant removal requirements (Eggen et al., 2014; Jhansi and Mishra, 2013; Mo and Zhang, 2013; Venkatesan et al., 2016). Pyrolysis could be a key technology to aid in energy generation and product recovery while removing pollutants.

Biosolids pyrolysis is a process that decomposes wastewater biosolids upon heating at elevated temperature under anoxic conditions. The process produces biochar, a valuable soil amendment, along with pyrolysis gas (py-gas), and bio-oil (pyrolysis condensate) (Bridle and Pritchard, 2004). Meanwhile, micropollutants such as triclosan and estrogens can be removed from biochar during pyrolysis (Hoffman et al., 2016; Ross et al., 2016). Moreover, pretreated biochar can be used as an adsorbent for nutrient and micropollutant removal from used water (Carey et al., 2015; Tong et al., 2016). A recent study concluded that biosolids pyrolysis could be a low waste solution to biosolids handling in Europe (Samolada and Zabaniotou, 2014). However, biosolids derived bio-
oil normally accounts for approximately 40% (by mass) of the total products of biosolids pyrolysis (Inguzano and Dominguez, 2002; McNamara et al., 2014), and the bio-oil requires costly upgrading before being used as a fuel due to its corrosive and unstable properties. Thus, autocatalytic biosolids pyrolysis (Figure 1) was developed by using biochar as the catalyst to convert the majority of bio-oil vapor to py-gas that needs no conditioning before use for energy recovery via combustion. Our previous work showed that using biochars such as biosolids derived biochar as a catalyst can significantly reduce bio-oil yield while increasing py-gas yield (Liu et al., 2016; Liu et al., 2016). Using our biosolids derived biochar catalyst, energy can shift from bio-oil to py-gas and the remaining condensate becomes cleaner with fewer high-molecular-weight hydrocarbons. The autocatalytic process has many potential benefits including maximizing energy generation, minimizing negative environmental impacts, and recovering nutrients.

To ensure that the autocatalytic process is sustainable, a complete energy balance analysis must be conducted. The main objective of this study was to evaluate the enthalpy of autocatalytic pyrolysis of dried biosolids. Also, the net energy in py-gas (i.e. the remaining energy after a portion of total energy in py-gas is used to heat the pyrolysis process) was compared to the heat required for biosolids drying in order to determine how much energy for drying can be saved by using the py-gas.

Methods

Dried biosolids (i.e., Milorganite®) were pyrolyzed with the introduction of biochar as a catalyst located downstream. The hot pyrolysis vapor exited the main pyrolysis reactor, passed through the hot catalyst, and was then separated by condensation. The biochar was obtained in the main reactor, and the bio-oil was collected in the condensers. The py-gas was collected in a Tedlar® bag for gas chromatography analysis. The pyrolysis temperature was varied from 600°C to 800°C. The catalyst temperature was maintained at the same value as the main pyrolysis reactor. The mass ratio of catalyst to feedstock ranged from 0.2 to 1. Control tests without catalyst addition were conducted with the downstream temperature fixed at 500°C. The energy content, higher heating value (HHV), of py-gas was calculated based on the gas composition and the corresponding component HHVs. The HHVs of biochar and bio-oil were determined by bomb calorimetry (Parr 1341, Parr Instrument Company, Moline, IL). The chemical energy (kJ) of the product per mass (kg) of biosolids pyrolyzed was calculated by multiplying the yield by the corresponding HHV.

The enthalpy of autocatalytic pyrolysis was calculated using a modified heat balance (Figure 2) based on our previous work (McNamara et al., 2016). The heat flow diagram shows that the input energy is the chemical energy of dried biosolids and the output energies are the chemical energies of biochar, bio-oil, py-gas, heat loss, and sensible and latent heat released when the products cooled down to the reference temperature of 25°C. 10% heat loss was assumed in this study. The sensible heat of py-gas was estimated based on the temperature-dependent heat capacity of each gas component. The sensible and latent heat of bio-oil was estimated according to the properties of petroleum with a similar specific gravity of 1. The enthalpy of autocatalytic pyrolysis was determined by the difference of output energy minus input energy. A negative difference meant exothermic and positive meant endothermic.
Results and Discussion

Autocatalytic biosolids pyrolysis increased the py-gas yield and decreased the bio-oil yield simultaneously (Liu et al., 2016). Meanwhile, the py-gas HHV increased and the bio-oil HHV decreased during autocatalysis compared to the control test without catalyst. In particular, when the catalyst to feedstock ratio increased to 1 at 800°C, the bio-oil energy content (HHV) decreased to its lowest value of 1,300 kJ/kg. Correspondingly, the energy contained in bio-oil decreased dramatically and more energy shifted from bio-oil to py-gas via autocatalysis. When 1 kg of biosolids was pyrolyzed at 800°C with the highest catalyst loading, the energy contained in the py-gas was 11,100 kJ while the energy in bio-oil was only 275 kJ.

At 600°C, 700°C, and 800°C, the total output energy for non-catalytic pyrolysis was lower than the input energy (biosolids input energy was 15,800 kJ), indicating these processes were slightly exothermic. However, for autocatalytic pyrolysis, at 700°C and 800°C with a catalyst to feedstock mass ratio of 1, the processes were endothermic because the total output energy was greater than the input energy.

Because autocatalytic pyrolysis is exothermic at 600°C, the energy in the py-gas can be totally used for biosolids drying. At 600°C with the highest catalyst loading, the reduction percentage of energy for biosolids drying was 40%. At 700°C and 800°C, even though a fraction of the py-gas was used to supply the heat for the endothermic autocatalytic pyrolysis, the remaining py-gas could reduce the energy for biosolids drying by approximately 70%.

Conclusions

Autocatalytic pyrolysis of wastewater biosolids can generate, biochar, a value-added product, as well as high-yield py-gas. Py-gas is a renewable clean energy source which can complement the energy requirement at WRRFs. Common micropollutants can be removed from biochar during pyrolysis. Biosolids derived biochar proved to be a cost-effective catalyst during autocatalytic pyrolysis to improve on-site energy recovery. An energy analysis was conducted with the assumption of 10% heat loss and at the highest catalyst loading. The results showed that the autocatalytic pyrolysis at 600°C was slightly exothermic but was endothermic at 700°C and 800°C. Therefore, py-gas was partially used to supply the heat for 700°C and 800°C operation. However, the remaining py-gas still reduced the energy for biosolids drying by approximately 70%. At 600°C, the remaining py-gas could cover 40% of the energy for biosolids drying. In summation, the autocatalytic pyrolysis of wastewater biosolids can be an energy neutral process that produces clean biochar.

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Figure 1. Autocatalytic pyrolysis process and its value-added products

Figure 2. Relevant heat flows during autocatalytic pyrolysis of biosolids. Red arrow indicates uncertain heat required for pyrolysis and blue arrows indicate heat released from products (modified based on McNamara et al., 2016)