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Application of self-sustaining smouldering combustion for the destruction of wastewater biosolids

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ABSTRACT

Managing biosolids, the major by-product from wastewater treatment plants (WWTPs), persists as a widespread challenge that often constitutes the majority of WWTP operating costs. Self-sustained smouldering combustion is a new approach for organic waste treatment, in which the waste – the combustion fuel – is destroyed in an energy efficient manner after mixing it with sand. Smouldering has never been applied to biosolids. Column experiments, using biosolids obtained from a WWTP, were employed to identify if, and under what conditions, smouldering could be used for treating biosolids. The parameter space in which smouldering was self-sustaining was mapped as a function of key system metrics: (1) sand/biosolids mass fraction, (2) biosolids moisture content, and (3) forced air flux. It was found that a self-sustaining reaction is achievable using biosolids with water content as high as 80% (with a biosolids lower heating value greater than 1.6 kJ/g). Moreover, results suggest that operator-controlled air flux can assist in keeping the reaction self-sustaining in response to fluctuations in biosolids properties. This proof-of-concept demonstrates the potential for smouldering as a new energy efficient biosolids disposal method for very wet (i.e., minimally processed) biosolids that may offer WWTPs significant operating cost savings. This study emphasizes smouldering's usefulness as a novel waste management technique.

1. Introduction

Wastewater treatment plants (WWTPs) treat sewage via various chemical, physical, and biological processes to remove harmful constituents and mitigate risk to the community and surrounding environment (Metcalf and Eddy, 2003). Municipal WWTPs are energy intensive operations which, combined with drinking water services, account for 3–4% of all energy consumption in the United States and 30–40% of total energy consumed by municipalities, costing \$4 billion/year (U.S. EPA, 2014). Furthermore, as much of North America's WWTP infrastructure approaches the end of its design life, an estimated \$298 billion is required in the United States (and \$39 billion in Canada) to expand and upgrade WWTP infrastructure (ASCE, 2013; Félio et al., 2012). The major by-product from WWTPs is biosolids and approximately 50% of WWTPs capital and operating costs are dedicated to processing biosolids, making it the most expensive component of the WWTP process (Khiari et al., 2004).

Biosolids are defined as the separated solids from WWTPs that undergo additional treatment for beneficial end use (U.S. EPA, 1994). These separated solids, largely organic, are first settled out from the liquid stream either before treatment (primary sludge) or after biological processing (waste activated sludge). The resulting sludge contains 88.00–99.75% moisture content (wet mass basis) (Droste, 1997; Metcalf and Eddy, 2003). This sludge undergoes various processing steps (e.g., dewatering, thickening, conditioning) to reduce its volume and improve aesthetic qualities for easier management, or undergoes stabilization to permit safe land application (Droste, 1997). The major disposal (or end use) methods for biosolids in Canada include incineration, land application for agricultural purposes, and landfilling (Apedaile, 2001). All of these methods are expensive in that they require high energy input, many person-hours, and/or large transportation distances (Bellur et al., 2009; Wang et al., 2008; Werther and Ogada,

Abbreviations: BSS, borderline self-sustaining; CI, confidence interval (%); MC, moisture content (%); *HHV*, higher heating value (kJ/g); HHV_d^b, dry biosolids higher heating value (kJ/g); LHV^b, biosolids lower heating value (kJ/g); LHV_e^s, effective system lower heating value (kJ/g); L_v, heat of vaporization of water (kJ/g); NSS, non-self-sustaining; S/B, sand/biosolids mass ratio (g/g); S/F, sand/faeces mass ratio (g/g); SS, self-sustaining; STAR, Self-sustaining Treatment for Active Remediation; STARx, Self-sustaining Treatment for Active Remediation applied ex-situ; TC, thermocouple; WWTP, wastewater treatment plant.

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1999). In addition, land application is controversial and subject to restrictions and uncertain risks stemming from contaminants of emerging concern (Bolong et al., 2009; Giger et al., 2003; Hale et al., 2001; Ternes et al., 2004; U.S. EPA, 1995; Venkatesan and Halden, 2014). In general, managing biosolids is a major challenge for WWTPs and there is a strong need to provide novel alternatives (Tyagi and Lo, 2013).

This work explores, for the first time, the possibility of using smouldering combustion as a new method for biosolids management. STARx (Self-sustaining Treatment for Active Remediation applied ex-situ) refers to the commercial technology that uses smouldering combustion to destroy organic wastes; to date it has been shown to be promising for a variety of organic industrial liquid wastes including coal tar, crude oil, and mixed hydrocarbons (Pironi et al., 2011; Switzer et al., 2009, 2014). STAR applied in-situ has completed numerous pilot tests in North America and Europe (Scholes et al., 2015) and is now being applied to a coal tar contaminated site in the United States in its first full scale application. STARx has undergone numerous pilot tests for treating mixed oil waste (Switzer et al., 2014) and crude oil sludge but has yet to be applied at the full scale. As explained below, smouldering has the potential to treat organic wastes in an energy efficient and cost-effective manner.

1.1. Smouldering combustion

Smouldering combustion is a flameless, heterogeneous (i.e., fuel and oxidant in different phases) oxidation reaction limited by the rate at which oxygen diffuses into the surface of a solid or liquid fuel (Ohlemiller, 1985; Switzer et al., 2009; Rein, 2016). Smouldering is self-sustaining when, after a short and localized energy input for ignition, the reaction propagates using only the heat produced by the fuel's oxidation (Switzer et al., 2009). Self-sustained smouldering requires a porous material, which provides a high surface area for reaction and adequate permeability for air flow (Drysdale, 2011). The majority of smouldering research has been performed in the context of fire prevention, and thus has focused on solid fuels such as polyurethane foam or stored biomass under natural air flow (e.g., He and Behrendt, 2009; Palmer, 1957; Quintiere et al., 1982; Rein et al., 2006). STARx accelerates the reaction by using forced air flow and, taking advantage of the buoyant hot combustion gases, utilizing upwards forward smouldering. In this configuration, the reaction propagation and oxidizer flow are both in the upward direction against gravity (Torero and Fernandez-Pello, 1996).

Upwards forward smouldering promotes efficient heat transfer ahead to unburned fuel, which extends the fuel's limits with respect to quenching (i.e., the suppression of chemical processes driving combustion) relative to those for flaming combustion (Hadden and Rein, 2011; Howell et al., 1996; Ohlemiller, 1985; Yermán et al., 2015). This means that smouldering is much less susceptible to extinction than flaming and can achieve a self-sustaining reaction using fuels with very low effective calorific values and/or significant moisture content (Hadden and Rein, 2011; Yermán et al., 2015).

Several studies have explored the self-sustained smouldering of peat in the context of forest fires, which is relevant in this context because peat, like biosolids, exhibits high moisture and inorganic contents (Rein, 2013). Frandsen (1987) detailed the impact that moisture and inorganic contents had on self-sustaining smouldering of peat moss between 0–1 moisture/organic ratio and 0–5 inorganic/organic ratio. It was found that the moisture/organic ratio limit that permitted self-sustaining smouldering linearly declined with increasing inorganic/organic ratio. Using an ignition protocol roughly equivalent to the heating from a flaming stump, 100 W for 30 min, Rein et al. (2008) found the critical moisture content for smouldering ignition to be 55 ± 2% (wet mass basis). Huang et al. (2015) and Huang and Rein (2015) developed a numerical model to explore the effects that the moisture and inorganic contents have on self-sustaining smouldering within peat. The latter study revealed that in a peat sample with little inorganic content a self-sustaining smoulder is possible with moisture content as high as 72% (wet mass basis) with a critical moisture content for ignition of 54% (wet mass basis). Prat et al. (2014) found a dramatic drop in smouldering propagation velocity above 20% moisture content (wet mass basis).

1.2. Application of smouldering for waste management

Intentional smouldering for mass destruction was first developed for the in-situ remediation of soil contaminated by organic industrial liquid wastes (Pironi et al., 2011, 2009; Salman et al., 2015; Switzer et al., 2009) and is commercially available as the STAR technology (Self-sustaining Treatment for Active Remediation). In this case, the fuel (i.e., contaminant) occupies a fraction of the pore space of an inert porous medium (i.e., soil). STARx extends this concept to intentionally mixing liquid wastes in above ground applications, which may be recently produced by industrial operations or were historically disposed in lagoons, with sand to form a smoulderable mixture. In addition to providing increased surface area for reaction and permeability for air (oxidant) flow, the sand promotes the efficient storage, transfer, and recycling of the released reaction energy (Switzer et al., 2014). Smouldering of organic liquids in sand typically achieves peak temperatures between 500 and 800 °C for many minutes in one location resulting in upwards of 99% consumption of fuel, effectively producing clean, sterile sand that can be reused (Switzer et al., 2009).

In examining the sensitivity of a smouldering reaction, of interest is the effect of a variable on peak temperatures and reaction propagation rates in the self-sustaining regime, and the boundary between self-sustaining and non-self-sustaining reactions. Pironi et al. (2011) studied the influence of the fraction of pore space occupied by water on the smouldering of coal tar in sand at the laboratory scale. Though increasing water content reduced the peak temperature and propagation velocity, a self-sustaining reaction was achieved in all cases from 0% to 75% water-filled porosity and 25% coal tar-filled porosity. This demonstrated the ability of an exothermic smouldering reaction to propagate itself and, with the excess energy generated, to sustain a water boiling/evaporation front ahead of the reaction. The propagation rate of the reaction (and thus the waste destruction rate) was shown to be linearly dependent on air injection rate across the range of air flow rates examined, which is expected for an oxygen-limited reaction (Dosanjh et al., 1987; Pironi et al., 2009; Schult et al., 1996). Smouldering was also shown to be sensitive to sand grain size and initial contaminant concentration; the reaction was non-self-sustaining for sands with average grain sizes greater than 10 mm and initial coal tar concentration lower than 25,000 mg/kg. These specific numbers are expected to be a function of experimental scale, with larger grain sizes and lower initial concentrations likely to be self-sustaining at larger scales (Switzer et al., 2014). This is because self-sustainability depends on a positive energy balance (heat generation minus heat losses) and increased scale means less relative heat loss to the external boundary due to lower surface area/volume ratio (Switzer et al., 2014). At a given scale, a boundary between self-sustaining and non-self-sustaining smouldering behavior depends on complex interactions between variables that affect heat generation (e.g., fuel energy content, oxygen supply), heat retention (e.g., sand and fuel heat capacities) and heat loss (e.g., volatile compounds, moisture content) and thus needs to be determined experimentally (Torero and Fernandez-Pello, 1996).