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Valorizing municipal solid waste: Waste to energy and activated carbons for water treatment via pyrolysis

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ABSTRACT

Globally, as societies urbanize and demand for energy increases, the need to manage mounting quantities of municipal solid waste (MSW), produce renewable energy, and insure clean water supplies becomes more pressing each year. These issues could be addressed by integrating pyrolysis of MSW to recover liquid and gaseous biofuels and a solid biochar, with CO_2 activation of the latter to produce activated biochars for water treatment. This potential conversion pathway is experimentally demonstrated by pyrolyzing a model MSW stream at 408 °C, the peak mass loss rate pyrolysis temperature and compared to pyrolysis at 900 °C. As pyrolysis temperature increases, we see conversion of plastic intermediaries into paraffins and polycyclic aromatic compounds, though the desirable gas components (methane, hydrogen, carbon monoxide) of the pyrolysis gas increase substantially. The CO_2 activated biochars (activated at 600 °C and 900 °C) show surface areas over 300 m^2/g, with the lower pyrolysis temperature and higher activation temperature yielding the highest areas. Adsorption experiments were performed with methylene blue to determine the ability of the activated MSW-biochar to remove organic pollutants from water. Adsorption is well described by the Langmuir isotherm, with equilibrium adsorption capacities upwards of 250 mg_{dye}/g for all activated biochars.

1. Introduction

Fifty years ago, the primary concern of most municipal waste management policy makers was the carting and disposal of solid waste. This began to change with the "Reduce, Reuse, Recycle" campaigns of the 1970–1990s, which dramatically altered the composition of municipal solid waste (MSW). While curbside recycling and other policy initiatives reduced the amount of metal, glass, and paper sent to landfills, one of the most pressing challenges confronting contemporary policy makers is the abundance of landfilled organic waste. In 2013, 254 million tons of trash were generated in the United States. Of this, only about one third is recycled and composted, and only one quarter of the remaining organic waste present in post-recycled MSW is utilized [1]. This squanders a rich carbon source and produces greenhouse gases during decomposition of the organic waste. States across the U.S., including MA [2], CT [3], and VT [4], have enacted regulations to eliminate the landfilling of organic waste, both from commercial and, increasingly, residential producers. A primary challenge with the generation of such massive quantities of MSW is to develop a method to manage and convert the carbonaceous fraction to useable energy and/or byproducts. The present work investigates converting carbonaceous MSW to renewable energy and activated carbons, which could be integrated into a larger system to treat landfill leachate, another issue plaguing MSW management. Across the literature, new integrated approaches to waste management are emerging to mitigate environmental issues in an economic manner. These include linking pyrolysis and anaerobic digestion for conversion of biomass to biomethane and biochar [5], pyrolysis of comingled wastes [6] and upgrading of resulting chars to sorbents and activated carbon [7,8], use of thermal solar energy for pyrolysis [9], and the integration of gasification and pyrolysis systems [10].

There are several technologies for MSW to energy conversions: incineration, gasification, pyrolysis (all thermal treatments) and biological treatments such as generation of biogas for combined heat and

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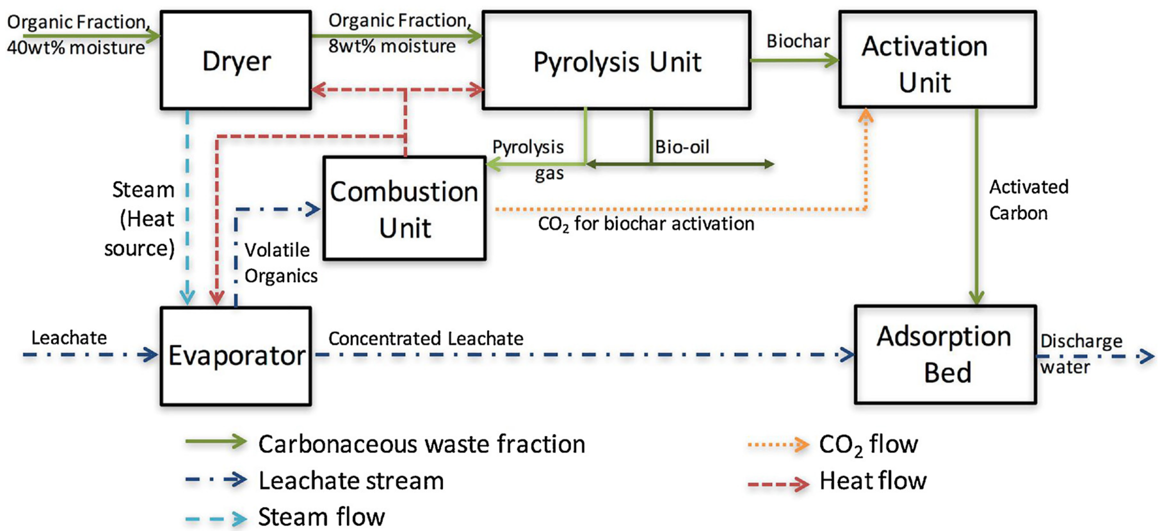

Fig. 1. Proposed integrated pathway for conversion of MSW to energy and activated carbons for water (and leachate) treatment.

power plants. While gasification is perhaps a cleaner technology for electricity generation than incineration, the thermal energy production is markedly lower and capital costs higher [11,12]. The capital costs of biogas plants are lower than thermal cycles and the greenhouse gas capture scenario is appealing. However, the thermal energy recovery and potential profit of biogas technologies are lower than other liquid biofuels. To control emissions from MSW incineration, intensive control of air/fuel mixing and temperature is required [13,14]. One of the largest problems with incineration is the production of 10–30 wt% fly and bottom ashes, which must be treated to remove metals such as lead, chromium and copper, and organics such as dioxins [15,16]. Another potential management option is vitrification (atomizing waste in a plasma arc), however this is cost-prohibitive for most municipalities [17]. Conversely, one of the goals of pyrolysis is to obtain the solid residue, or biochar remaining from pyrolysis, in addition to the capture of syngas and bio-oil. Biochar is a carbonaceous solid matter exhibiting high surface areas that can be converted to an activated carbon. Due to the lower temperatures and absence of oxygen, pyrolysis essentially negates issues associated with dioxin and NO_x formation [18]. The oil, gas and char yields vary between 22 and 49 wt%, 18–30 wt% and 30–50 wt%, respectively, depending on pyrolysis temperature (between 300 and 700 °C) [19]. As such, by using pyrolysis to convert MSW to energy we can design a flexible process to maximize char production when more activated carbon is needed, or maximize bio-oil or syngas when more fuel is desired to capitalize on the energy content, upwards of 15 MJ/kg, of MSW [20].

Rain and water percolating through a landfill produces leachate, an aqueous phase high in organics and inorganics. A plethora of potential treatment strategies exist for leachate management. For example, sequencing batch reactors (SBR) augmented with activated carbons can reduce up to 65% of Chemical Oxygen Demand (COD). However, the efficiency of SBR treatment for landfill leachate is considerably lower than for wastewaters due to the low Biochemical Oxygen Demand (BOD)/COD ratio and high NH_3-N concentrations in leachate [21]. Biotreatment methods are simple and cost-effective ways to reduce BOD, but treating stabilized leachate from mature landfills requires more than biological treatment due to recalcitrant organic carbon [22]. Solid-liquid separations can be effected via micro- and ultrafiltration techniques, but such methods cannot remove dissolved compounds. Application of powdered activated carbon (PAC) may partially overcome these issues, though concentration polarization leading to flux decrease and membrane fouling wreak havoc with PAC addition [23]. PAC adsorption can be used in conjunction with physical separation methods such as coagulation and flocculation, however this requires further separation downstream [24]. Advanced Oxidation Processes (AOP) are touted for their potential to mineralize recalcitrant organic compounds [25,26]. One of the more widely applied is the Fenton reaction, comprising four stages (oxidation, neutralization, coagulation/flocculation and solid-liquid separation). However, because of long settling times and tank volumes for the solid-liquid separation, some groups have proposed the incorporation of membranes into the process [27], though this adds to the relatively high energy requirements of most AOP [28]. Combined evaporation-reverse osmosis (RO) systems have been proposed, whereby a large fraction of volatile organics is first recovered, followed by reverse osmosis of the distillate containing mostly inorganic compounds. These components, and the ammonia present, decrease RO performance, which is energy-intensive [29–32].

A recurring theme in many integrated processes for leachate management is the use of granular activated carbons (GAC) and PAC to remove both organic and inorganic/metallic compounds [33–37]. However, the majority of ACs are "designer" carbons, whereby feedstocks, particle sizes and processing conditions are carefully controlled; some are impregnated with catalytic materials while others have caustic and costly chemical activation techniques, making their application to leachate treatment economically unfeasible. Prior research demonstrates the potential for pyrolysis to convert carbonaceous wastes, including MSW, to activated carbons to treat leachate; [33] some granular activated carbons can achieve 95% removal of various organic and heavy metal adsorbates [38].

Across one literature we find processes for leachate treatment, and another literature that concerns MSW-to-energy conversions. No one has yet to propose an integrated system that combines organic and leachate management, a key to managing MSW efficiently and cost-effectively. The present work addresses municipal solid waste management by using pyrolysis to produce energy and biochar, which is converted to activated carbon used for water treatment; the proposed process is illustrated in Fig. 1. Such an integrated process could improve the economic viability of MSW management while potentially providing an environmentally compliant, cost-effective long-term strategy for solid waste management.

2. Materials and methods

To demonstrate the proposed concept to divert the carbonaceous fraction of MSW from landfills and produce an activated carbon that could be used to remove contaminants from water, a representative MSW sample was created using the "average" composition of the carbonaceous fraction of MSW across the United States (after accounting