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Research article

Biochar produced from biosolids using a single-mode microwave: Characterisation and its potential for phosphorus removal

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ABSTRACT

The amount of biosolids increases every year, and social and environmental concerns are also rising due to heavy metals and pathogen contamination. Even though biosolids are considered as a waste material, they could be used as a precursor in several applications, especially in agriculture due to the presence of essential nutrients. Microwave assisted pyrolysis (MWAP) is a promising technology to safely manage biosolids, while producing value-added products, such as biochar, that can be used to improve soil fertility. This study examined the impact of pyrolysis temperature between 300 °C and 800 °C on the chemical and physical properties of biochar obtained from biosolids via MWAP. Preliminary phosphorus adsorption tests were carried out with the biochar produced from biosolids. This research demonstrated that pyrolysis temperature affects biochar specific surface area, ash and volatiles content, but does not impact heavily on the pH, chemical composition and crystalline phases of the resultant biochar. Biochar yield decreases as the pyrolysis temperature increases. Phosphorus adsorption capacity of biochar was approximately around 15 mg/g of biochar. Biochar resulting from MWAP is a potential candidate for land application with an important role in water and nutrient retention, due to the high surface area.

1. Introduction

Biosolids are the partially or totally stabilised solids from the municipal wastewater treatment process (L. K. Wang et al, 2008). Global population and the proportion of the population that have access to sewage treatment have both been increasing, implying that the production rates of biosolids will continuously increase (LeBlanc et al., 2009). For example, in China the amount of biosolids is increasing 6.25% per annum, and it is estimated to reach 1 billion tons by 2030 (Okumura et al., 2014). As the amount of biosolids grows, so too does the pressure to safely and efficiently dispose of these materials. Current methods for biosolids disposal are land application, incineration and landfill (Agrafioti et al., 2013). Land application is applying the biosolids to land to utilise its nutrient content as a fertiliser substitute (McLaughlin et al., 2008), which is a commonly used method, particularly in less developed countries where human waste has historically been applied to crops (LeBlanc et al., 2009). Application of these wastes to land potentially exposes the community to pathogens and other contaminants, and biosolids are also a potential source of greenhouse gas emissions (Majumder et al., 2014). Incineration is commonly used in countries with a shortage of land and is effective at sterilising and reducing the volume and mass of waste (Saqib and Bäckström, 2015). However, this volume reduction concentrates heavy metal contaminants into the leftover ash, and the energy efficiency of this method is heavily dependent upon moisture content (Lin and Ma, 2012). Landfill involves simply storing the waste at a particular location and is simple and easy to implement. This method is not efficient, though, as it does not utilise either the energy or nutrient content of the waste, and with increasing amounts of sludge being produced, the cost to landfill will only increases.

In Australia, as an example, there is no ubiquitous solution to biosolids management, partly due to the differing regulations that govern biosolids disposal in each state. There has, however, been a general trend to more beneficial use of biosolids, rather than disposal. Beneficial use includes disposal methods, such as land

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application as a fertiliser, forestry, composting, and land rehabilitation, while non-beneficial use includes landfilling, stockpiling and ocean discharge. In the five year period 2008–2013, Australian biosolids production increased from approximately 300,000 dry tonnes to 330,000 dry tonnes (Fact Sheet - Biosolids Profile, 2013), and during this time, the proportion of biosolids disposed with beneficial use increased from 59% to 69%. The majority of this increase was due to the diversion of biosolids from landfill to land application, particularly in the states of Queensland and New South Wales (Fact Sheet - Biosolids Profile, 2013). Of the 102,000 tonnes of dry biosolids that were not beneficially used in 2013, 62% was produced by the state of Victoria, with the majority being placed into stockpiles (LeBlanc et al., 2009). The current size of the Victorian stockpiles, which have been in use for more than two decades, is estimated at 3.2 million dry tonnes. Environmental regulations and local logistical challenges in developing alternative disposal methods contributed to the need to store the majority of Victorian biosolids, and these same factors inhibit the transition to beneficial biosolids use. For this reason it is necessary to explore alternative management approaches of biosolids, such as microwave assisted pyrolysis (MWAP), so that biosolids can be utilised as a resource in places like Victoria where traditional beneficial use methods, such as land application, are not feasible due to heavy metals and pathogen contaminants.

MWAP is a potential technology for biosolids management. Compared with conventional heating, MWAP uses a microwave field to provide energy for the pyrolysis process. The use of microwave heating has several advantages over conventional heating. In particular, microwave heating is selective, since the microwave field only heats materials that have sufficiently high loss tangent ($\tan \delta > 0.2$), high capacity to absorb microwave energy and transform into heat, and does not heat the pyrolysis atmosphere. At sufficiently small scale, the entire biomass volume is also exposed to the microwave field at once, producing uniform heating throughout the mass for a biomass of homogenous composition. These microwave heating properties are collectively termed ‘volumetric heating’. Due to these properties of microwave heating, MWAP provides faster heating, better overall efficiency, and a faster and more controllable process compared to conventional pyrolysis (Fernández et al., 2011; Tyagi and Lo, 2013; Yin, 2012). However, biosolids are essentially transparent to microwave irradiation (Brodie et al., 2014); therefore the addition of a microwave absorber (also known as a susceptor) plays an important role in achieving the temperatures required for pyrolysis (Omar et al., 2011). These microwave absorbers work as “hot spots”, absorbing microwave energy and transferring it as heat to the cooler surrounding material by thermal conduction. Carbon-based materials, including biochar, are often selected as microwave absorbers because of the high value of their loss tangent, and their relatively low cost (Menéndez et al., 2010).

Pyrolysis of biosolids offers many advantages, such as: significant reduction in biosolids volume, destruction of pathogens, decreased availability of organic pollutants and heavy metals, and increased carbon stability of biochar (T. Wang et al., 2012). Biochar is an important fraction of the biosolids pyrolysis by-products, which are biochar, biogas and bio-oil. Biochar produced from biosolids can be used as fertiliser; it contains important nutrients for plant growth, such as phosphorus, nitrogen, potassium and trace amounts of micronutrients. The properties of biochar depend on feedstock characteristics and pyrolysis conditions (Hossain et al., 2011; T. Wang et al., 2012). Pyrolysis temperature is a key variable with a great impact on biochar properties; for example, specific surface area increases with temperature while lower temperatures can produce hydrophobic biochar (Sohi et al., 2010). Depending upon its physical and chemical properties, biochar can be applied as a soil ameliorant, improving water retention capacity, pH and carbon sequestration (Ahmad et al., 2014). For example, biochar with macropores of around one micron possess a good water retention capacity; however, micropores do not play a relevant role in the soil or plant growth (Sohi et al., 2010). More research is needed to completely understand the chemical and physical mechanisms of biochar to take advantage of it in the future (Crombie and Mašek, 2015).

Biosolids management is an environmental problem due to the amount of biosolids produced and the costs associated with its disposal. Recently, research has been developed to use alum sludge as an inexpensive phosphorus adsorbent in wastewater treatment plants (Babatunde and Zhao, 2010; Yang et al., 2008). Some researchers claimed that alum biosolids applications can prevent phosphorus run-off from soil; however, heavy metals in the biosolids can leach trough the soil and groundwater, which is another environmental problem. Finding a solution with the advantages of phosphorus removal capacity and without heavy metal leaching is ideal. Using biochar for contaminant removal has been studied, particular metals removal from aqueous solutions (Ahmad et al., 2014; Mohan et al., 2014; Rajapaksha et al., 2016). To this point biochar from biosolids for phosphorus removal has not been studied. This study aims to use the biochar produced via MWAP biosolids for phosphorus removal, which is a new approach to beneficial reuse biosolids.

Therefore this study has three main objectives: explore the impact of pyrolysis temperature on biochar properties, examine the MWAP process with focus on the challenges and peculiarities of single-mode microwave fields, and perform tests on phosphorus adsorption with biochar produced at different temperatures, compared against untreated biosolids phosphorus removal capacity.

2. Materials and methods

2.1. Materials

Biosolids were extracted from clay settling ponds at a sewage treatment facility (Euroa Wastewater Treatment facility in Victoria, Australia), stored for one month and used in the laboratory experiments. To minimise inconsistencies, a 10 kg lot of biosolids was blended to obtain a homogenous sample. The homogeneous lot was stored in a sealed container in a refrigerator at 4 °C to minimise bacterial activity. Using the cone and quarter method, three random samples were taken for characterisation. The main properties of the biosolids are presented in Tables 1 and 2. Activated carbon, obtained from Sigma Aldrich (Ref.242276), was used as a microwave susceptor in all experiments.

Table 1
Chemical composition of biosolids determined by ICP.

Classification	Nutrients					Heavy metals				
Element	Ca	Fe	Mg	P	K	Cr	Cu	Ni	Pb	Zn
(mg/kg)[a]	6142	18,995	1895	13,300	1910	52.9	236	24.7	24.3	548

[a] Values on dry weight basis.