



The effect of biochar feedstock, pyrolysis temperature, and application rate on the reduction of ammonia volatilisation from biochar-amended soil



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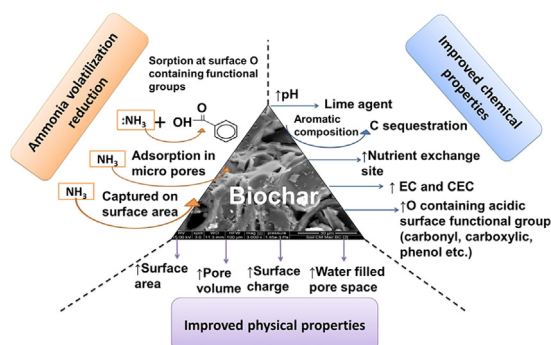
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HIGHLIGHTS

- Biochars prepared at lower temperature (250–350 °C) are effective in reducing NH₃.
- The largest reduction in NH₃ was obtained by adding poultry manure biochar.
- Reduction in NH₃ volatilisation is the result of physical, chemical and microbiological factors.

GRAPHICAL ABSTRACT



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ABSTRACT

Ammonia (NH₃) volatilisation is one of the most important causes of nitrogen (N) loss in soil-plant systems worldwide. Carbon-based amendments such as biochar have been shown to mitigate NH₃ volatilisation in agricultural soils to various degrees. In this study, we investigated the influence of biochar feedstocks (poultry manure, green waste compost, and wheat straw), pyrolysis temperatures (250, 350, 450, 500 and 700 °C) and application rates (1 and 2%), on NH₃ volatilisation from a calcareous soil. The 15 biochars were chemically characterized, and a laboratory incubation study was conducted to assess NH₃ volatilisation from the soil over a period of four weeks. Furthermore, changes to the bacterial and fungal communities were assessed via sequencing of phylogenetic marker genes.

The study showed that biochar feedstock sources, pyrolysis temperature, and application rates all affected NH₃ volatilisation. Overall, low pyrolysis temperature biochars and higher biochar application rates achieved greater reductions in NH₃ volatilisation. A feedstock related effect was also observed, with poultry manure biochar reducing NH₃ volatilisation by an average of 53% in comparison to 38% and 35% reductions for biochar from green waste compost and wheat straw respectively. Results indicate that the biogeochemistry underlying biochar-mediated reduction in NH₃ volatilisation is complex and caused by changes in soil pH, NH₃ sorption and microbial community composition (especially ammonia oxidising guilds).

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1. Introduction

Nitrogen (N) is one of the six major elements essential to life and a key nutrient for plant growth and development (Clough et al., 2013). When N fertilisers or organic amendments are added to soils, N can be lost from the soil (prior to plant uptake) in three major ways, 1) via ammonia (NH₃) volatilisation, 2) through leaching (e.g. as nitrate), and 3) through denitrification (e.g. as nitrous oxide or gaseous nitrogen under oxygen limiting conditions). Among these, NH₃ volatilisation is a serious concern in alkaline soils, which represent approximately 60% of agricultural soils worldwide (FAO, 2001). In fact, when urea-N fertilisers are added to soil, ammonia and an unstable intermediary compound (carbamate) is produced. In alkaline soils carbamate can release NH₃ gas, whereas in acidic soils ammonium ions (NH₄⁺) are formed and can be sorbed by soil components (Singh et al., 2013). It is estimated that an average 32 Tg (3.2×10^{10} kg) NH₃-N year⁻¹ is emitted from agricultural soils. This is clearly a significant environmental issue (Taghizadeh-Toosi et al., 2012a, 2012b) and a substantial economic cost (Beusen et al., 2008).

The use of carbon-based materials has been advocated as a means of reducing pollutant bioavailability and increasing the nutrient retention capacity of soil (Lal, 2016). Biochar is produced during pyrolysis, in a limited oxygen environment, of various organic biomasses at low temperature (<800 °C) in order to obtain bio-oils (Lehmann and Joseph, 2009). Biochars have higher surface areas, pore volumes, and oxygen-containing surface functional groups in comparison to their original feedstocks and these properties can be deliberately altered by varying the pyrolysis conditions (Clough et al., 2013; Singh et al., 2010; Taghizadeh-Toosi et al., 2011). For example, Cantrell et al. (2012) reported that biochar produced at high temperatures (700 °C) has a much larger surface area (186 m² g⁻¹), and pH (9.9) compared with biochar produced at low temperatures (350 °C; surface area: 1.6 m² g⁻¹; pH: 9.2).

In another study, Kloss et al. (2012) observed that biochars from three different sources (spruce, straw, and poplar) had higher pH, surface area, and C and N contents when produced at a higher temperature (i.e. 525 °C vs 400 °C). In our previous work (Mandal et al., 2016) we reported that biochar produced from poultry litter could reduce NH₃ volatilisation by up to 70% when applied to a calcareous soil at a rate of 5% (w/w). A study by Taghizadeh-Toosi et al. (2012a) showed that after the application of washed biochar to soil (15–30 t ha⁻¹ soil), NH₃ volatilisation from ruminant urine-patches was reduced by up to 45%. C.R. Chen et al. (2013) also found that the application of green waste biochar can reduce NH₃ volatilisation, by increasing the adsorption capacity of soils. In that study, the authors investigated the effects of different application rates of biochar on enhancing NH₄⁺-N adsorption and lowering NH₃ volatilisation. On the other hand, Schomberg et al. (2012) reported increased losses of NH₃ as a consequence of increased soil pH upon addition of high ash content, alkaline biochar.

The mechanism responsible for ammonia retention in biochar-amended soils is often attributed to the formation of ammonium salts or amide and amines following reaction with surface carboxylic groups present on biochars (Jansen and Van Bekkum, 1994). Spokas et al. (2012) suggested that differences in the surface group chemistry of biochars may be the main reason for inconsistent results in the literature on biochar's effects on the soil nitrogen cycle and indicated that further studies are needed in this area. However, biochar addition can also modify a number of soil parameters including pH, microsite humidity, and nutrient contents and these factors play important roles in shaping soil microbial communities and regulating the N cycle (Carson et al., 2010; Kuramae et al., 2010; Kuramae et al., 2014). In fact, Lehmann et al. (2011) demonstrated that biochar addition could alter both the abiotic and biotic properties of soil. Similarly, a study by Chen et al. (2015) found that biochar application increased the microbial biomass as well as the bacterial diversity (including bacteria driving N cycling).

Most studies to date have focused on the effect of biochar addition on nutrient transformation, greenhouse gas mitigation, and crop productivity. However, the influence of feedstock and pyrolysis temperature on the biochar properties associated with the NH₃ volatilisation phenomenon remains unclear. The objective of this study was to test the hypothesis that both the raw materials and the pyrolysis temperatures play a role in reducing the rate of NH₃ volatilisation from calcareous soils and that the difference between raw materials is reduced at high pyrolysis temperature (as the resulting biochars become more similar). Furthermore, we tested the hypothesis that the reduction in ammonia volatilisation is not simply due to a pH effect but also to sorption mechanisms and changes in soil microbial communities.

2. Materials and methods

2.1. Soil

A surface soil (0–10 cm depth) classified as a Calcarosol (Northcote et al., 1975) was collected from the Eyre Peninsula in South Australia. The soil sample was air dried and ground to pass through a 2 mm stainless steel sieve prior to further use. The properties of the soil were determined as described below (Section 2.3).

2.2. Biochar

Three different feedstocks and five pyrolysis temperatures (250, 350, 450, 550 and 700 °C) were used to prepare 15 biochars. The raw materials used were poultry manure (PM), green waste compost (GW), and wheat straw (WS). These feedstocks were combusted for 2 h under N₂ in a pyrolysis unit (OTF-1200X). The temperature was raised at a rate of 10 °C min⁻¹ to reach the desired temperature. After the pyrolysis process, the material was allowed to cool inside the pyrolyzer unit; then the biochar powder was collected and passed through a 150 μm sieve and stored in plastic containers until required. The 15 biochar samples were labelled as described in the following example: PM-BC 250 indicates a poultry manure biochar obtained through pyrolysis at 250 °C.

2.3. Analysis of soil and biochar

The pH of the soil and biochar samples was measured using a pH meter with a solid solution ratio of 1:10 (soil mass: water volume). Electrical conductivity (EC) was measured using an EX electrode (smartCHEM-LAB Laboratory Analyser). Total C and N content of the soil and biochar samples were analysed using a Leco TruMac CNS Analyser (LECO Corporation, USA). The cation exchange capacity (CEC) of the 15 biochars was determined using the method of Zelazny et al. (1996).

Biochar specific surface areas and pore volumes were determined from the N₂ adsorption isotherms obtained at -196 °C using a Gemini 2380 Surface Area Analyser. Surface functional groups were investigated using Fourier Transform Infrared (FTIR) spectroscopy on an Agilent Cary 660 FTIR Analyser. Samples for FTIR were mixed homogeneously with dry potassium bromide (KBr) (0.01% w/w) in an agate mortar and a hydraulic press was used to produce composite pellets for analysis. FTIR spectra were collected in the 400 to 4000 cm⁻¹ range (Griffiths and De Haseth, 2007). X-ray photoelectron (XPS) spectra of selected samples (PM-BC 250 and 700) were collected using a Kratos Axis-Ultra spectrometer, using a monochromatic Al K-α source (1487 eV) operating at 15 kV and 14 mA, 10⁻⁸ Pa vacuum in the analyser chamber and an analysis spot size of 300 × 700 μm. A spectrophotometer pass energy of 20 eV was used for all elemental spectral regions. The spectrophotometers binding energy scale was calibrated using the metallic Cu 2p_{3/2} and Cu 3p_{3/2} lines and Au Fermi-Edge of the respective reference metals. All measurements were performed at a take-off angle of 90°, and the sample stage temperature was reduced

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