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Suitability of marginal biomass-derived biochars for soil amendment

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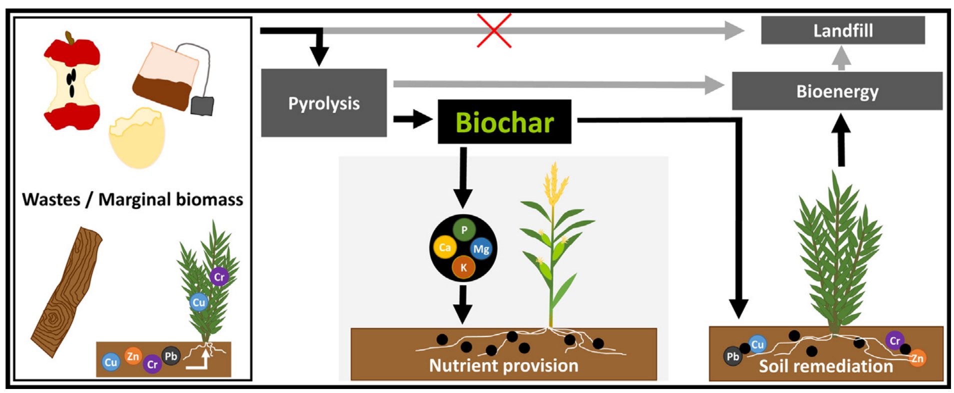
HIGHLIGHTS

- Marginal biomass feedstocks are materials of little economic value.
- Biochar from biomass grown on PTE-rich soils tends to exceed guideline values.
- Biochar from biomass with high mineral content can be a beneficial nutrient source.
- Cr and Ni from the steel reactors can contaminate biochar to a significant extent.

GRAPHICAL ABSTRACT



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ABSTRACT

The term "marginal biomass" is used here to describe materials of little or no economic value, e.g. plants grown on contaminated land, food waste or demolition wood. In this study 10 marginal biomass-derived feedstocks were converted into 19 biochars at different highest treatment temperatures (HTT) using a continuous screw-pyrolysis unit. The aim was to investigate suitability of the resulting biochars for land application, judged on the basis of potentially toxic element (PTE) concentration, nutrient content and basic biochar properties (pH, EC, ash, fixed carbon). It was shown that under typical biochar production conditions the percentage content of several PTEs (As, Al, Zn) and nutrients (Ca, Mg) were reduced to some extent, but also that biochar can be contaminated by Cr and Ni during the pyrolysis process due to erosion of stainless steel reactor parts (average + 82.8% Cr, + 226.0% Ni). This can occur to such an extent that the resulting biochar is rendered unsuitable for soil application (maximum addition + 22.5 mg Cr kg^{-1} biochar and + 44.4 mg Ni kg^{-1} biochar). Biomass grown on land heavily contaminated with PTEs yielded biochars with PTE concentrations above recommended threshold values for soil amendments. Cd and Zn were of particular concern, exceeding the lowest threshold values by 31-fold and 7-fold respectively, despite some losses into the gas phase. However, thermal conversion of plants from less severely contaminated soils, demolition wood and food waste anaerobic digestate (AD) into biochar proved to be promising for land application. In particular, food waste AD biochar contained very high nutrient concentrations, making it interesting for use as fertiliser.

Abbreviations: PTE, potentially toxic element; VOC, volatile organic compound; TGA, thermogravimetric analysis; PAH, polycyclic aromatic hydrocarbon; EC, electric conductivity; AD, anaerobic digestate; IBI, International Biochar Initiative; EBC, European Biochar Certificate.

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1. Introduction

Produced from biomass in a high-temperature, low-oxygen treatment process, biochar is used in soil for its positive properties for increasing fertility and soil remediation (Lehmann and Joseph, 2009; Sohi et al., 2010). To achieve economically viable biochar production in a sustainable context, the use of waste feedstocks is essential. While crop residues fit into this category, they are not considered to be an ideal feedstock (Shackley et al., 2011). On the other hand, plant material from contaminated sites/phytoremediation as well as non-virgin feedstocks (chemically/biologically transformed, amended or treated material (Shackley et al., 2011)) are resources that need additional treatment before re-use, and so these may be more suited to biochar production.

Large areas of land world-wide have been contaminated by inorganic contaminants, whilst the actual size of the area depends on definition. The scale of the problem is still increasing, so the use of plants from this under-utilised land for conversion into biochar could be a valuable treatment option (Evangelou et al., 2012). Non-virgin feedstocks, such as food waste /-anaerobic digestate (AD), sewage sludge /-AD or demolition wood are also readily-available materials; in the UK alone, around 200 million tonnes of anthropogenic waste is produced annually (DEFRA, 2015). If such wastes could be converted into a valuable resource through pyrolysis, a wide variety of feedstocks would be accessible in large quantities for biochar production. To describe biomass of little economic value the term “marginal biomass” is introduced in this study, taken from the established term “marginal land” for land which, for various reasons, has little agricultural importance (e.g. poor soil quality, pollution) (Peterson and Galbraith, 1932). These marginal biomass-derived feedstocks can be untreated virgin materials such as contaminated plant biomass, or non-virgin feedstocks from chemically/biologically transformed materials.

For biochar application to soil to be acceptable, adverse ecosystem effects need to be avoided and contaminant levels kept to a minimum. The contaminants of concern in biochar are organic compounds that are formed during production and can attach loosely or tightly to the biochar framework (PAHs, VOCs, dioxins) (Buss and Mašek, 2014; Buss et al., 2015; Hale et al., 2012) as well as potentially toxic elements (PTEs) originating from the feedstock (Evangelou et al., 2014; Méndez et al., 2012; Van Wesenbeeck et al., 2014). Total PTE concentrations have been analysed in biochars from virgin biomass sources (materials which have not been chemically/biologically transformed, amended or treated) and the results have not indicated any reasons for concern for soils and plants so far (Freddo et al., 2012; Lucchini et al., 2014a). However, the use of the term “marginal biomass” here describes materials that have a high probability of being somewhat contaminated and predominantly contain elevated levels of PTEs. Thus, the resulting biochars could exceed legislation values applied to soil amendments. This makes it essential to investigate separately the levels of PTEs in each biochar produced from a new, marginal biomass for compliance with existing regulations. According to the International Biochar Initiative (IBI) (International Biochar Initiative, 2013), arsenic, cadmium, chromium, cobalt, copper, lead, mercury, molybdenum, nickel and zinc are the PTEs of concern in biochar which, with the exception of cobalt and molybdenum, are also part of the priority pollutant list of the US EPA (Environmental Protection Agency, 1982).

Sewage sludge is a marginal feedstock that could be used for biochar production but often contains elevated levels of PTEs. It is available in large quantities and will be so into the future. For example, in 2008 1.6 million t of sewage sludge was produced in the UK (DEFRA, 2011), which could make commercial biochar production viable. Sewage sludge biochar has already been investigated intensively regarding risks and benefits with variable results, mostly related to its heterogeneity and varying composition (Liu et al., 2014; Luo et al., 2014; Méndez et al., 2012; Van Wesenbeeck et al., 2014; Zielińska and Oleszczuk, 2015). In several recent studies single feedstocks from contaminated biomass were investigated regarding their usefulness for conversion into biochar (Evangelou et al., 2014; Jones and Quilliam, 2014; Lucchini et al., 2014b). However, to our best knowledge, no studies to date have carried out systematic and extensive assessment of PTE in biochars from a range of marginal biomass under different pyrolysis conditions.

Besides PTEs, elements with positive effects on plant growth are present in the ash of feedstocks. The PTEs Cu, Zn, Ni and Mo are phytotoxic in elevated concentrations in soil, in contrast however, low concentrations are needed by plants as micronutrients (Broadley et al., 2011). N, P and K are the major elements in fertilisers and are macronutrients by definition, which means they are the elements needed by plants in high quantities (Hawkesford et al., 2011). All of these nutrients can be found in biochar (Enders and Lehmann, 2012; Mukome et al., 2013). Thus, use of nutrient-rich marginal feedstocks for biochar production could be an alternative way of supplying nutrients to plants through application of the resulting biochar to soil.

During pyrolysis P and K mostly remain in the solid fraction and are therefore applied with the biochar to soil. However, N in the feedstock is mostly evaporated, together with the majority of the organic material, and this results in a N-poor material (Antal and Grønli, 2003; Liu et al., 2014). During the high temperature treatment of biomass, part of the mineral matrix evaporates as well (Kistler et al., 1987). The “loss” of elements from the solid char material can be beneficial when PTEs are concerned, but are a drawback when nutrients are vaporised (Kistler et al., 1987; Nzihou and Stanmore, 2013). Investigation of volatilisation of elements from pyrolysis solids is essential to select the best suitable production conditions of biochar from mineral-rich feedstocks.

The aim of this research was to investigate whether feedstocks contaminated with PTEs through various routes: (i) plant uptake through soil; (ii) plant uptake through water, and (iii) direct anthropogenic contamination, are suitable for biochar use in soil in relation to their PTEs compositions. Furthermore, the main objective was to identify the best marginal biomass feedstock for conversion into biochar and the most suitable highest treatment temperature (HTT) judged on the basis of PTE concentrations, nutrient concentrations and basic biochar characteristics (pH, EC, ash, fixed carbon). For this purpose 19 biochars were produced from 10 different materials: feedstocks included various plant species that were grown in PTE contaminated soils, a plant grown in contaminated water and two non-virgin feedstocks.

2. Materials and methods

2.1. Feedstocks

Ten marginal biomass-derived feedstocks were sourced from five different countries to provide a variety of materials and plant species for biochar production. The feedstocks used were as follows:

Seven biomass samples grown on contaminated land: 1) Wheat straw (*Triticum aestivum*), “WSI” from the village Madlauda (Panipat, Haryana, India) in the vicinity of Panipat thermal power station (coal fired plant; village Assan, Jind road, Panipat, India) and 2) sugarcane bagasse (*Saccharum* spp., species unknown), “SBI” from the vicinity of the river Yamuna close to the village Sarurpur (Uttar Pradesh, India) were sourced from India. Both locations have problems with PTE (and organic) pollution: Panipat thermal power station (Hajarnavis, 2000) and river Yamuna (Mehra et al., 2000). 3) Winter rye straw (*Secale cereal*) (WRB) and 4) willow logs with bark (*salix* spp., species unknown), “WLB” originated from the Campine region in Belgium from heavy metal (Cd, Zn, Pb) contaminated soil (Van Slycken et al., 2013). 5) Whole plant without roots of *Salix purpurea* “SLP”, 6) *Paulonia tomentosa*, “PAT” and 7) *Arundo donax*, “ADX” were sourced from Italian industrial waste sites. Salix and Paulonia were grown on a site of an old Zn smelter that covers approximately 50 ha near the city of Crotone, Italy (Marchiol et al., 2013). *A. donax* was harvested from an industrial area located in Torviscosa from soil contaminated by various metals (Fellet et al., 2007). PTE levels of the various contaminated sites the