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High plant availability of phosphorus and low availability of cadmium in four biomass combustion ashes

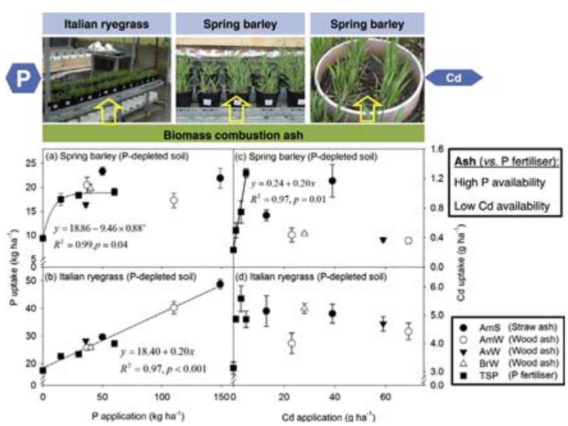
Xiaoxi Li *, Gitte H. Rubæk, Peter Sørensen

Department of Agroecology, Aarhus University, Blichers Allé 20, Post Box 50, 8830 Tjele, Denmark

HIGHLIGHTS

- Effects of four biomass ashes *vs.* a P fertiliser (TSP) on two crops were studied.
- Ashes increased crop yields with P availability similar to TSP on P-depleted soil.
- Barley biomass and Cd uptake did not respond to high ash rates on a normal P soil.
- Cd concentration of crops on ash-amended soil was in the range of TSP treatments.
- High levels of soil available P remained after harvest at high ash applications.

GRAPHICAL ABSTRACT



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ABSTRACT

For biomass combustion to become a sustainable energy production system, it is crucial to minimise landfill of biomass ashes, to recycle the nutrients and to minimise the undesirable impact of hazardous substances in the ash. In order to test the plant availability of phosphorus (P) and cadmium (Cd) in four biomass ashes, we conducted two pot experiments on a P-depleted soil and one mini-plot field experiment on a soil with adequate P status. Test plants were spring barley and Italian ryegrass. Ash applications were compared to triple superphosphate (TSP) and a control without P application. Both TSP and ash significantly increased crop yields and P uptake on the P-depleted soil. In contrast, on the adequate-P soil, the barley yield showed little response to soil amendment, even at 300–500 kg P ha^{-1} application, although the barley took up more P at higher applications. The apparent P use efficiency of the additive was 20% in ryegrass - much higher than that of barley for which P use efficiencies varied on the two soils. Generally, crop Cd concentrations were little affected by the increasing and high applications of ash, except for relatively high Cd concentrations in barley after applying 25 Mg ha^{-1} straw ash. Contrarily, even modest increases in the TSP application markedly increased Cd uptake in plants. This might be explained by the low Cd solubility in the ash or by the reduced Cd availability due to the liming effect of ash. High concentrations of resin-extractable P (available P) in the ash-amended soil after harvest indicate that the ash may also contribute to P availability for the following crops. In conclusion, the biomass ashes in this study had P availability similar to the TSP fertiliser and did not contaminate the crop with Cd during the first year.

* Corresponding author.
E-mail addresses: Xiaoxi.Li@agro.au.dk, lixiaoxi86@gmail.com (X. Li).

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1. Introduction

Biomass combustion is of increasing interest for heat and power generation. Biomass combustion can be considered clean and sustainable only when the production and handling of the biomass feedstock is sustainable, the combustion is environmentally friendly and the scarce elements in the residual products are recovered and recycled appropriately. The development of biomass combustion is mainly driven by a political ambition to decrease greenhouse gas emissions and tackle climate change, e.g., the "2030 climate and energy policy framework" (European Commission, 2014). In order to achieve a fossil-free energy system by 2050 in Denmark, large-scale combined heat and power plants (CHP) are therefore in a process of converting from firing with coal to biomass (Gregg et al., 2014; DONG Energy, 2015).

Combustion of biomass produces a solid by-product - ash - which often is disposed of in landfills as a waste. With a more prevalent use of biomass, the need for disposal of ash will increase, and because of tightening regulations it could be more difficult and costly to find landfill sites for such disposal in many countries (Demeyer et al., 2001; Ochecova et al., 2014). Furthermore, landfill of ash and the essential and scarce elements embedded in the ash is highly unsustainable, such as phosphorus (P), which is a key macronutrient that sustains crop yields. The phosphorus applied to crops is primarily derived from rock phosphate, which is a non-renewable resource, and a global scarcity of rock phosphate is likely to be one of the greatest challenges linked to food security in the future (Cordell et al., 2011). Therefore, to make biomass combustion truly sustainable, it is necessary to recycle P in the ash, for example to agricultural soils.

Soil application of biomass ashes offers huge potentials as a strategy for simple and low-cost waste disposal and nutrient recycling (Patterson et al., 2004). The use of ash as a soil amendment from the firing of biomass has a long history (Vance, 1996; Schiemenz and Eichler-Loebermann, 2010). Due to alkalinity and the element contained in most biomass ashes, many studies have reported increases in soil pH, nutrient content and microbial activity from ash applications (Erich, 1991; Demeyer et al., 2001; Park et al., 2012), and thus also increasing yields, particularly on acid soil (Vance, 1996; Nkana et al., 1998; Patterson et al., 2004; Arshad et al., 2012). However, relevant basic knowledge on the use of ash as a soil amender is still insufficient (Vassilev et al., 2013). For instance, there are fundamental unanswered questions regarding the bioavailability of beneficial (such as P) and hazardous (such as cadmium (Cd)) elements in biomass ashes.

Plant availability of P and other elements in ash may vary greatly and depend on many factors, such as the types of feedstock, combustion methods, soil types and plant species (Kuligowski et al., 2010; Schiemenz and Eichler-Loebermann, 2010). The total P concentrations were reported to vary between 0.04 and 2.6% in the ashes from a range of agricultural crops and wood, depending also on combustion temperatures (Schiemenz and Eichler-Loebermann, 2010 and references therein). Bottom ash from combustion of biomass with high growth rates (e.g., agricultural crops) is often rich in P. It has been suggested that P availability decreases with increasing combustion temperature. However, at high temperatures P compounds may vaporise in a simple form, e.g., as KPO_3 (Wu et al., 2011), and precipitate again when the gas temperature decreases. The final composition is nevertheless dependent on the concentrations of ash-forming elements and can be difficult to predict (Boström et al., 2012). During powder combustion of pulverised biomass in big power plants, temperatures can reach 1200–1500 °C and most of the ash generated is fly ash. The conventional grate-fired boilers normally operate at a lower temperature and produce both fly and bottom ash. It is uncertain how this difference influences the P availability in the ash. The plant availability of P in P-containing additives may also change across soils with different P status. Soil P status on arable land is normally maintained by fertilisation, and crop growth does not usually rely on in-season P fertilisation (Delin, 2015). Therefore, on soils with adequate P status, crop P uptake may not correctly reflect the amount of plant-available P from P-containing additives such as ash, which thus makes plant experiments on P-depleted soils valuable.

Undesirable elements such as Cd typically accompany the desirable nutrients in the ash. It is therefore equally important to ensure that application of ash does not result in higher heavy metal concentrations in the harvested crops (Knapp and Insam, 2011). A number of countries have established stringent regulations on land application of ash (Narodoslawsky and Obernberger, 1996; Hansen et al., 2001). Such regulations normally prohibit the application to agricultural or forested land of ashes with heavy metal concentrations above a certain threshold and impose limits on the total amount of heavy metals that can be applied. This, however, also limits the amount of nutrients in the ashes that can be recycled. There is a need to simultaneously evaluate both the P (nutrient) and Cd (heavy metal) availability in biomass ashes to crops, which very few studies have done (e.g., a Canadian study by Park et al. (2012) on ryegrass and oats; a Czech study by Ochecova et al. (2014) on spring wheat; and a Swedish study by Lindvall et al. (2015) on reed canary grass), and no such studies have been conducted using Danish soils and growing conditions and comparing soils with low and adequate soil P status.

The objective of the present study was to evaluate the first-year plant availability of P and Cd in three ashes from combustion of wood and straw pellets and one ash from traditional grate combustion of wood chips. The availability of P and Cd in the ashes was compared to triple superphosphate (TSP) in two pot experiments on a low-P-status soil with Italian ryegrass and spring barley as the test crop, and one field experiment on an adequate-P-status soil with spring barley as the test crop. We hypothesised that: (1) availability of ash P (evaluated as plant P uptake) applied shortly before the growing season would be lower than for P in TSP; (2) availability would vary with the type of ash, soil and crop; (3) plant uptake of Cd would depend on the dose given and on the type of fertiliser/ash; (4) increases in soil pH due to ash application would be able to reduce Cd availability.

2. Materials and methods

2.1. Soil

In order to evaluate the plant availability of P and Cd in biomass ashes, two pot experiments on a P-depleted coarse sand soil and one field mini-plot experiment on a loamy sand soil were carried out in 2013. The soil for the pot experiment was from a treatment in a long-term field experiment on liming and P fertilisation with continuous spring barley situated in southern Denmark (St. Jyndevad). The soil was from the treatment which had not received P fertiliser since 1942 but had been limed regularly (once per 6–9 years) in order to maintain a soil pH of approximately 6.2 (Rubæk, 2008). The soil contained 4.2% clay and the soil P status measured as bicarbonate-extractable P (Olsen et al., 1954) was 11 mg P kg^{-1}. The soil was sampled shortly after a lime application.

The field experiment was located at Research Centre Foulum, Aarhus University, Denmark (56°29′ N, 9°34′ E). The soil was a loamy sand soil with 8.0% clay, 12.5% silt, 76.0% sand, 3.5% organic matter, 21 g total C kg^{-1}, 2.1 g total N kg^{-1}, and pH 6.2 (H_2O). The concentration of soil bicarbonate-extractable P was 48.5 mg P kg^{-1}, which is an adequate to high P content in agricultural soil according to Danish recommendations (Jordan-Meille et al., 2012). Climate data was obtained from a climate station near the experimental site (Fig. 1).

2.2. Ash

Four types of biomass ash (Table 1) from Danish power/heating plants were used: (1) pulverised straw pellets (AmS) and (2) wood pellets (AmW) fired at 1200–1500 °C in a power plant at Amagerværket,