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Review

Opportunities and challenges in the use of coal fly ash for soil improvements – A review

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ABSTRACT

Coal fly ash (CFA), a by-product of coal combustion has been regarded as a problematic solid waste, mainly due to its potentially toxic trace elements, PTEs (e.g. Cd, Cr, Ni, Pb) and organic compounds (e.g. PCBs, PAHs) content. However, CFA is a useful source of essential plant nutrients (e.g. Ca, Mg, K, P, S, B, Fe, Cu and Zn). Uncontrolled land disposal of CFA is likely to cause undesirable changes in soil conditions, including contamination with PTEs, PAHs and PCBs. Prudent CFA land application offers considerable opportunities, particularly for nutrient supplementation, pH correction and ameliorating soil physical conditions (soil compaction, water retention and drainage). Since CFA contains little or no N and organic carbon, and CFA-borne P is not readily plant available, a mixture of CFA and manure or sewage sludge (SS) is better suited than CFA alone. Additionally, land application of such a mixture can mitigate the mobility of SS-borne PTEs, which is known to increase following cessation of SS application. Research analysis further shows that application of alkaline CFA with or without other amendments can help remediate at least marginally metal contaminated soils by immobilisation of mobile metal forms.

CFA land application with SS or other source of organic carbon, N and P can help effectively reclaim/restore mining-affected lands. Given the variability in the nature and composition of CFA (pH, macro- and micro-nutrients) and that of soil (pH, texture and fertility), the choice of CFA (acidic or alkaline and its application rate) needs to consider the properties and problems of the soil. CFA can also be used as a low cost sorbent for the removal of organic and inorganic contaminants from wastewater streams; the disposal of spent CFA however can pose further challenges.

Problems in CFA use as a soil amendment occur when it results in undesirable change in soil pH, imbalance in nutrient supply, boron toxicity in plants, excess supply of sulphate and PTEs. These problems, however, are usually associated with excess or inappropriate CFA applications. The levels of PAHs and PCBs in CFA are generally low; their effects on soil biota, uptake by plants and soil persistence, however, need to be assessed. In spite of this, co-application of CFA with manure or SS to land enhances its effectiveness in soil improvements.

1. Introduction

Coal has been and continues to be one of the largest sources of energy production in the world, showing a dramatic rise in its use, despite direct impacts of coal combustion on climate change and human health. In 2006, coal accounted for 25% of the world's primary energy supply, with its worldwide consumption totaling a record 3090 million tons of oil equivalent. China is the biggest consumer of coal, accounting for about 39% of the total world coal consumption in 2006, followed by the United States (18%), the European Union (10%) and India (8%) (Vom Berg, 1998; Feuerborn, 2011).

Globally, coal fly ash (CFA) generated in huge quantities from coal fired power plants, is a problematic solid waste (Skousen et al., 2013; Ram and Masto, 2014). Most estimates in the current literature put annual global CFA production somewhere in the region of 500 million tons (Ahmaruzzaman, 2010). These estimates, however, are based on at least 10 years old data. Over the intervening period coal consumption has already increased by 50%, largely due to the economic growth in China (International Energy Statistics, 2011). Taking this into account, a more up to date estimate would mean

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that globally about 750 million tons of CFA is generated annually. Coal fly ash production and utilization data for 2005 (Pandey and Singh, 2010) show that India generates the greatest amount of CFA (118 million tons/year), followed by China (100 million tons/year), the USA (75 million tons/year), Germany (40 million tons/year), the UK (15 million tons/year), while Denmark, Italy and the Netherlands generate smaller CFA amounts (2 million tons/year). However, India utilizes a relatively smaller percentage (38%) of the CFA produced compared to other countries e.g., China (45%), the USA (65%), Germany (85%), the UK (50%) while Denmark, Italy and the Netherlands utilize 100% of their CFA production (Pandey and Singh, 2010). The relatively lower amount of CFA utilization in India (mainly in construction industry) is due to unavailability of appropriate cost-effective technologies (Bhattacharjee and Kandpal, 2002; Dhadse et al., 2008).

Clearly a significant proportion of the annual production of CFA must be disposed of especially in the highest production countries such as India, China, and the USA. Traditionally this has been achieved by diverting the ash to landfills which incurs a landfill tax or by storing it in ash lagoons. These large lagoons have been known to breach, causing environmental problems (Dewan, 2008). Environmental concerns and increasingly stringent regulations are gradually increasing the cost of CFA disposal by landfilling (Haynes, 2009). The problem of CFA disposal is expected to get worse as the demand for energy grows.

Current forecasts predict that the next two decades will see the installation of the same amount of power generation capacity as that installed over the whole of the 20th century. Part of this increase in demand is likely to be met by renewable energy sources; however, due to its abundance in energy intensive countries such as China and India, coal is likely to become an increasingly dominant fuel for power generation (Lior, 2010). Clearly the huge quantity of CFA produced annually not only poses serious environmental concerns but also requires large areas of land for its storage and disposal. Thus, appropriate measures for its safe disposal and means of utilization are necessary for sustainable management of this waste (Singh et al., 2010). So far, two distinct alternatives CFA disposal options have been used i.e. its utilization in construction materials and land application as a soil amendment. In the first case, CFA is either used as raw material in the production of cement clinker or is blended with cement. Coal fly ash is used as the main component in blended cements, as a sand substitute in manufacturing of low strength materials, for foundation support and backfilling excavations, and for filling abandoned tunnels, as well as numerous others construction works (Siddique, 2010; Skousen et al., 2013). The other important alternative use of CFA is its land application, utilizing its properties as a soil amendment and possibly as a source of nutrient supplementation. Coal fly ash, however, can contain significant amounts of potentially toxic trace elements (PTEs) and other chemicals, presenting challenges to its land application for soil improvement.

Utilization of CFA as an ameliorant for improving soil quality has received a great deal of attention over the past four decades. Several extensive reviews on recycling of CFA have been conducted in recent years (e. g., Jala and Goyal, 2006; Basu et al., 2009; Malik and Thapliyal, 2009; Blissett and Rowson, 2012; Yunusa et al., 2012; Skousen et al., 2013; Ram and Masto, 2014). However, they have focused on the multi-component utilization of CFA with a limited coverage of the environmental challenges. A review by Malik and Thapliyal (2009) analyzed the general uses of CFA in various industries with only a brief coverage of its use in the agricultural sector. Blissett and Rowson (2012) focused on the multi-component utilization of CFA (agriculture, glass and ceramics manufacturing, zeolites and mesoporous materials productions, geopolymers synthesis, and use as catalysts and catalyst supports). Yunusa et al. (2012) considered how CFA can be strategically used to ameliorate specific soil constraints to crop production but focussing only on soil salinity, alkalinity and mainly from economic and regulatory considerations. However, none of these previous reviews critically analyzed all of the major relevant environmental issues, which include practices and problems considerations in devising sustainable use of CFA as a soil amendment. This article reviews the current status of the CFA disposal practices and problems, particularly focussing on its use as a soil amendment and the challenges it presents.

2. Physical and chemical properties of CFA

The mineralogical, physical and chemical properties of CFA depend on the nature and properties of the parent coal and conditions under which they were produced, and they have been extensively reviewed (e.g., Adriano et al., 1980; Elseewi et al., 1980a). The composition and properties of CFA can also vary considerably, depending on the boiler type and the gas emission control system (Skousen et al., 2013). It is these properties which together determine the usefulness of CFA in soil improvement.

2.1. Physical properties

Coal fly ash is comprised of very fine particles, with an average diameter <10 μm, aggregated into spherical particles of 0.01–100 μm sizes which are hollow spheres (cenospheres) filled with smaller amorphous particles or crystals (pelospheres) (Jala and Goyal, 2006). These cenospheres make CFA particles easily airborne (El-Mogazi et al., 1988). Coal fly ash generally has a silt loam texture, with 65–90% of the particles having diameters of less than 0.010 mm (Chang et al., 1977; Pandey and Singh, 2010; Nyambura et al., 2011). Ash from bituminous coal is usually finer than that produced from lignite combustion (Tolle and Arthrur, 1983; Dudas and Warren, 1987).

Due to the small size of CFA particles (cenospheres) and the pelospheres, CFA has a large specific surface area ranging from 2500 to 4000 $cm^2\ g^{-1}$, as measured by the Blaime method (Alonso and Wesche, 1991); consequently CFA has a high sorption capacity. Because of this, CFA is used as a sorbent for flue gas cleaning from sulphur components, NOx, gaseous organics such as toluene vapours and is also used for removal from wastewater of several toxic metal ions, such as Cu, Pb, Cd, Ni, Zn, Cr, Hg, As and Cs and inorganic anions such as, fluoride and boron. In addition CFA sorbs considerable amounts of dyes and pigments and has thus been used for their removal from aqueous waste streams (El-Mogazi et al., 1988; Alonso and Wesche, 1991). The specific gravity of CFA varies from 2.1 to 2.6 $g\ cm^{-3}$ and it has a low to medium bulk density, ranging from 1 to 1.8 $g\ cm^{-3}$. Its moisture retention capacity ranges from 6.1% at 15 bars to 13.4% at 1/3 bar (El-Mogazi et al., 1988). The colour of CFA ranges from water-white to yellow-orange to deep red or brown to opaque, depending mainly on the Fe_2O_3 and carbon contents. The un-burnt coal content, corresponding to loss on ignition, ranging from 0.5 to 12% is responsible for the black or grey appearance of CFA. The presence of high amounts of Fe_2O_3 gives CFA dark colour (Alonso and Wesche, 1991).

2.2. Chemical properties

The chemical characteristics of CFA depend largely on geological factors related to the coal deposits and on different operating conditions/practices employed at the power plants. Thus, CFA from every coal-fired plant has its own chemical characteristics. The main constituents of CFA are silica, alumina and iron oxides, with varying amounts of carbon, calcium, magnesium, and sulphur.