

Characterization of Inorganic Elements in Woody Biomass Bottom Ash from a Fixed-bed Combustion System, a Downdraft Gasifier and a Wood Pellet Burner by Fractionation

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Abstract

The direct combustion of biomass residues produces large quantities of bottom ash. Environmental sustainable management requires that ash recycling should be carried out whenever possible. Suitable applications of bottom ash are based predominantly on its chemical properties. The presence of major ash forming and trace elements along with other intrinsic properties unique to bottom ash, suggest its potential as a soil additive. But, ash quality must be of a high standard to prevent environmental pollution. This comparative study characterizes bottom ash obtained from three types of bioenergy systems - a fixed-bed boiler, a downdraft gasifier and a wood pellet burner. The chemical properties were analyzed and discussed for each bottom ash, together with their respective particle fractions that were obtained by sieving. The pH of the starting ash samples for the gasifier, boiler and pellet burner were 10.36, 12.49 and 13.46, respectively. Ni with a concentration of 229 mg/kg in the pellet burner ash, exceeded the maximum limit for soil amendments (in British Columbia, Canada) within the particle size fraction $\geq 850 \mu\text{m}$ but < 2000 . All samples were significantly enriched in both Ca (50-61%) and K (10-26%). The elements Mg, Al, Mn, Fe, P and Na each contributed 10% or less to the inorganic portion of the ash. Concentrations of inorganic contents varied with particle size. Water soluble phosphates were very low in the samples. The results suggest that size fraction separation can be a useful method to isolate fractions containing higher (or lower) amounts of some metals. This method may be a useful technique for managing ash that contains elements exceeding environmental limits.

Keywords: bottom ash, soil amendment, major elements, trace elements, particle size fraction, ash utilization

1. Introduction

The employment of wood combustion technologies have resulted in a rapid increase in the use of woody-biomass residues for energy production. Boilers, gasifiers and pellet burners are but some of the systems available for wood energy production. A disadvantage of using biomass for energy production is that large amounts of residual ash are generated (Dahl, Nurmesniemi, Poykio, & Watkins, 2010). Ash from these combustion processes vary in quality depending on the fuel type, operating conditions of the system and the type of combustion system (Oberberger, Biedermann, Widmann, & Riedl, 1997). Ideally, biomass ash should be recycled whenever possible, but large amounts of wood ash are typically landfilled (Picco, February 2010). Countries such as Sweden and the United States of America (USA) use landfills to dispose majority of their ash (Clarholm, 1994; Vance, 1996; Demeyer, Voundi-Nkana, & Velow, 2001). The quality of the ash in part determines recycling options; some options such as land spreading require low trace element concentrations to prevent environmental pollution (Pels, de Nie, & Kiel, 2005). The application of wood ash to soils may counteract soil acidification and correct for nutrient deficiencies; this is widely used in regions that carry out extensive forest harvesting, such as Northern Europe and parts of North America (Demeyer et al., 2001; Stupak, Asikainen, Roser, & Pasanen, 2008; Aronsson & Ekelund, 2004). In Canada, biomass ash is mainly landfilled but land applications are more common in some provinces than others. In British Columbia the use of ash as for soil applications is relatively limited due to current provincial regulations. Until adequate research is carried out the majority of ash generated in B.C. may be limited to landfilling or other uses outside of soil applications.

Limiting factors for the use of wood ash in soils include trace element concentrations and potential organic pollutants (Sarenbo, 2009; Knapp & Insam, 2011). Elevated concentrations of trace elements in ashes may limit utilization of ash in soils and therefore also the recycling of nutrient elements (e.g. Ca, Mg, K, P), too. The handling and application of ash is improved by hardening or aggregation; but, ash with a high organic C content does not harden properly (Narodoslawsky & Obernberger, 1996).

The physical and chemical characteristics of wood ash may vary with particle size fraction (Dahl et al., 2010; Liao, Wu, & Yan, 2007; James, Thring, Helle, & Rutherford, 2013). Particle size fractions high in undesirable trace element concentrations could be separated from some ashes, thereby improving the overall quality of the residual ash material (and therefore improving recycling options). Previous research shows that arsenic concentrations in fly ash exceeded the Finnish environmental limits for the particle size fraction less than 0.125 mm (Dahl et al., 2010). Particle separation may be carried out by sieve fractionation and may influence variables such as trace element concentrations, pH, organic carbon concentration, bulk density and other chemical-physical properties.

Should the properties vary significantly in particle size fractions, greater applications of ash as a soil amendment or as a raw material for products requiring specific properties could be employed. Ash-producing industries may find this particularly useful when considering disposal or utilization methods for ash.

The objective of this research was to characterize ash from the three systems. A comparative study of the chemical properties of each bottom ash, as well as their respective fractions, obtained by sieving, was carried out. This paper will identify the inorganic elemental distribution of specific particle size fractions, pH and anion distribution of boiler, gasifier and wood pellet burner bottom ash. It is hoped that these results will assist in finding specific applications for bottom ash.

2. Experimental

Wood ash from from three types of combustion systems, a fixed-bed boiler (Canfor Pulp Mill), a downdraft gasifier (University of Northern British Columbia - UNBC) and a wood pellet burner (UNBC) were used in the study. The downdraft fixed bed gasifier is capable of producing power of 5 MW, the wood pellet burner 0.4 MW and an industrial scale fixed bed boiler, 27 MW. The fuel for the gasifier and boiler is hog fuel comprised predominantly of softwood sawmill waste and is primarily derived from pine wood. The pellet burner utilizes wood pellets made locally from soft-wood saw dust. Two ash samples were collected from each system. The boiler ash sample was collected on April 27, 2012 – BA. The gasifier ash sample was collected July 18, 2012 – GA. Pellet burner samples was collected March 5, 2010 – PA. Henceforth, the boiler sample is denoted as BA, gasifier sample GA and pellet burner sample, PA. The ash samples were separated into different particle fractions as follows.

2.1 Particle Size Distribution

Approximately 100 g of air-dried starting ash original sample obtained from boiler, gasifier, or pellet burner was separated into different size fractions using a stack of 5 sieves (2000 μm , 850 μm , 425 μm , 250 μm , 150 μm), arranged in decreasing diameter openings (Hermann & Baker, 2002). Ash was poured on the top sieve (largest opening), which was then covered; the sieve stack was then placed on an automatic shaker for 15 minutes after which the stack was removed. Each sieve with the retained material was gently tapped on the sides before being removed from the stack and weighed. Retained ash was removed and stored, while the sieve trays were thoroughly cleaned and reweighed to obtain the mass of ash retained on tray. The analyses were repeated twice and an average of the results taken. The following retained fractions were used for subsequent analyses: starting wood-ash, $\geq 2000 \mu\text{m}$, $\geq 850 \mu\text{m}$ but $< 2000 \mu\text{m}$, $\geq 425 \mu\text{m}$ but $< 850 \mu\text{m}$, $\geq 250 \mu\text{m}$ but $< 425 \mu\text{m}$, $\geq 150 \mu\text{m}$ but less than 250 μm and $< 150 \mu\text{m}$.

For reporting data purposes, the fractions will be denoted as 2000 μm , 850 μm , 425 μm , 250 μm , 150 μm and $< 150 \mu\text{m}$. Each of the retained fractions were weighed and then stored for further analysis.

2.2 pH Analysis

The pH of ash fractions were determined following methods described in (Kalra & Maynard, 1991). The pH was measured potentiometrically using the pH of saturated paste method. A 400 ml beaker was half-filled with ash, then sufficient deionized water was added to saturate sample. The sample was mixed and subsequently left to sit for 1 hour after which pH readings were taken. Analysis of all fractions were repeated twice and an average of the results taken.

2.3 Concentration and Distribution of Trace Elements and Major Ash-Forming Elements

Selected elements within each fraction were determined by ICP-MS at UNBC. 300 mg of sample was mixed

with 10 mL conc. HNO_3 and then diluted to 50 mL with deionized water. This sample mixture was then subjected to microwave digestion, using a Milestone MLS 1200 Mega digestion system. Metal characterization was done by an inductively coupled plasma (ICP-MS) on an Agilent 7500 ICPMS machine. This was used to determine the alkali, alkali earth and trace elements.

2.4 Anion Analysis

Anion concentrations were determined using the Dionnex IC-5000 system. Ten (10) mL of deionized water was added to ~ 400 mg of samples and shaken for 12 hrs. The samples were then removed from shaker and centrifuged for 15 min, after which ~ 2 mL of sample was obtained for analysis using Ion chromatography. All results shown are considered to be only water soluble amounts. Duplicate analyses were conducted and an average concentration reported.

3. Results

3.1 Particle Size Distribution of Ash

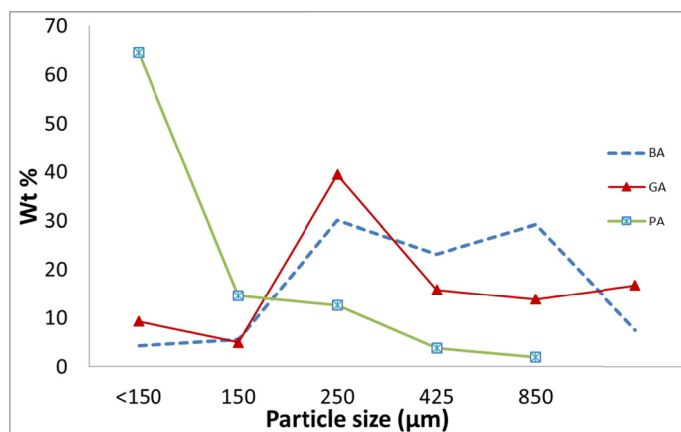


Figure 1. Retained Weight as a function of particle size distribution for boiler ash (BA), gasifier ash (GA) and pellet burner ash (PBA) samples (Data referenced) (James et al., 2013)

Table 1. Total carbon contents and pH of bottom ash samples of boiler, gasifier and pellet burner

Particle size / µm	*Carbon			pH		
	BA wt. %	GA wt. %	PA wt. %	BA	GA	PA
<150	17.17	3.67	5.75	12.22	10.43	13.53
150	13.85	6.11	36.08	12.56	10.41	13.36
250	21.56	3.24	19.16	12.12	10.36	13.20
425	52.76	5.76	6.62	10.74	10.28	12.13
850	66.41	3.71	5.94	10.49	10.05	11.16
2000	70.73	3.07		10.41	9.69	
Starting ash	51.79	5.13	5.64	12.49	10.36	13.46

*Data referenced from (Hermann & Baker, 2002) and on a dry basis.

3.2 pH Analysis

Table 1 shows the distribution of the pH for the PA, GA and BA samples. Ash from all three systems was high in pH but recorded different pH readings. Ash from the gasifier was the least alkali, followed by the boiler then the pellet burner. The starting ash samples for the gasifier, boiler and pellet burner were 10.36, 12.49 and 13.46 respectively. It was observed that the pH increased for all ash samples as the particle size fraction decreased, with the exception of the particle size fractions < 150 µm for the for BA. The increase in pH may have been due to the increase in concentrations of the alkali earth metals (refer to Table 4) as the particle size fractions decreased potentially leading to higher concentrations base-forming metal salts.

Table 2. Concentration and distribution of trace elements for samples of boiler, gasifier and pellet burner bottom ash (dry basis)

Particle Size (μ m)	Cr mg/kg	Cu mg/kg	Ni mg/kg	Pb mg/kg	V mg/kg	Co mg/kg	Mo mg/kg	As mg/kg	Cd mg/kg
PA									
850	49.58	61.23	229.59	7.22	14.70	6.74	3.13	0.49	0.50
425	47.32	108.91	175.40	3.55	15.03	6.90	3.55	0.80	1.91
250	79.91	135.53	109.48	4.17	14.30	7.67	4.01	0.85	3.69
150	52.09	153.60	69.70	2.07	12.85	7.54	4.52	0.84	4.45
<150	52.38	170.72	40.65	2.74	10.18	7.93	5.24	0.98	9.46
Starting ash	54.13	132.47	54.50	0.44	10.55	7.20	4.82	0.92	7.71
Gasifier ash									
2000	23.40	16.66	20.00	0.63	29.37	5.29	0.48	1.39	0.03
850	12.81	37.75	19.09	7.36	21.95	4.17	1.15	1.76	0.04
425	18.54	31.30	27.23	1.72	20.71	4.63	0.74	1.40	0.07
250	35.33	60.97	68.13	5.12	29.65	7.35	4.30	6.31	0.30
150	44.54	66.37	67.74	4.10	28.57	7.04	3.33	4.85	0.31
<150	47.57	207.57	78.81	4.20	33.41	7.86	5.33	7.49	0.44
Starting ash	33.51	43.38	60.74	1.64	28.53	6.78	4.13	5.42	0.27
Boiler ash									
2000	5.84	34.01	6.89	3.34	3.50	1.56	1.51	0.52	2.21
850	4.64	81.52	6.31	9.59	4.14	1.86	1.40	0.69	2.85
425	10.36	50.42	11.06	7.09	12.16	3.23	1.61	1.14	4.11
250	19.87	77.59	19.05	9.99	18.54	5.17	2.29	1.82	6.18
150	30.00	107.49	25.07	9.00	24.49	6.70	2.71	2.07	6.18
<150	28.97	419.58	25.36	13.86	24.66	6.99	2.79	2.37	7.52
Starting ash	11.82	32.85	13.39	4.89	12.44	3.79	1.88	1.45	4.76
*Environmental Limits	1060	2200	180	500		150	20	75	20

*Environmental limit's for ash intended for land application in B.C., Canada (BC Ministry of Environment, 2008).

3.3 The Concentration and Distribution of Elements in Ashes and Anion Distribution

3.3.1 Trace Elements

The concentrations of elements for the starting ash and within specific particle size fractions of Cr, Cu, Ni, Pb, V, Co, Mo, As and Cd are shown in Table 3.2. Of the starting ash samples analysed, Cu from the Pellet burner system was highest in trace element concentration; 132 mg/kg for Cu (Table 3.2). Cu was enriched in pellet burner ash by ~ 3 and ~ 4 times that of the gasifier and the boiler samples, respectively. The elements Ni and Cr followed next in concentrations, ranging from 33 - 55 mg/kg for the pellet burner and gasifier starting ash. The boiler samples were ~ 5 times lower than the pellet burner ash in both Ni and Cr contents. In most results, the boiler samples were slightly lower in trace metal concentrations. All elements in the starting ash fractions of the 3 ash samples were well within the British Columbia soil amendment limits (BC Ministry of Environment, 2008).

Table 2 also shows the distribution of trace elements within particle size fractions for the respective ash. For most elements, a slight increase in concentration was observed as the particle size fraction decreased in all ash types. All fractions for each element were within the environmental limits for soil amendments in British Columbia, except the 850 μ m fraction of Ni, obtained from the pellet burner ash; concentration of 229 mg/kg. While not exceeding the limit, the 425 μ m fraction also had a high concentration of 176 mg/kg Ni. It is evident that some elements are more concentrated in specific fractions of ash. The results suggest that fraction separation can be a useful method to isolate fractions containing higher amounts of some metals. This method may be a useful technique for isolating elements exceeding environmental exposure limits and at the same time rendering the residual ash useful.

Table 3. Percent total metal distribution in boiler, gasifier and pellet burner ash

Elements	BA wt.%	GA wt.%	PA wt.%
Ca	60	61	55
K	15	10	21
Mg	6	6	11
Al	4	7	2
Mn	4	3	6
Fe	3	6	1
P	3	3	2
Na	2	2	1
Remaining elements	2	2	1

Table 4. The concentration of major ash forming elements within particle size fractions for boiler, gasifier and pellet burner on a dry basis

Particle Size (μ m)	Ca mg/kg	Al mg/kg	Mg mg/kg	Na mg/kg	K mg/kg	P mg/kg	Mn mg/kg	Fe mg/kg
PA								
850	136392	9266	25062	1607	61751	3880	11185	9973
425	195843	10538	35162	2756	99339	6606	16921	9055
250	239720	9758	46113	3459	112781	8109	22630	8883
150	253148	9193	51437	3414	105948	8264	25198	7993
<150	262728	7555	56533	2854	95660	8551	28115	6168
Starting ash	246186	7689	50910	2851	95232	8075	25845	6659
GA								
2000	20910	11888	4966	4966	5006	932	854	12652
850	19848	9897	4213	4213	9120	1083	1018	10707
425	27422	11904	5363	5363	12933	1382	1509	11911
250	140745	16083	13992	13992	20778	6955	7267	12732
150	112986	16250	12220	12220	20677	5569	6072	12903
<150	167030	15936	15733	15733	18430	8178	8463	12814
Starting ash	124946	14852	12308	12308	20077	6026	6522	12339
BA								
2000	46393	2427	4518	2456	25997	2086	2693	1558
850	51562	2728	4946	2548	25342	2419	2971	1797
425	62728	6208	6450	2466	22548	3057	3615	4732
250	122267	10015	12189	2616	22393	6481	7229	7613
150	153376	12080	14939	2786	20800	8259	9084	10131
<150	166787	12079	16256	2788	21529	9144	10084	9756
Starting ash	92564	6763	8974	2507	23354	4846	5394	5186

3.3.2 Major Elements General Trends (Starting Ash)

Table 3 displays the percent of total ash forming elements in each ash sample. These percentages were obtained by taking the sum of all the total metal content found in 1 kg (d.b) of ash. All samples were significantly enriched in both Ca (50-61 wt.%) and K (10-26 wt.%). The high weight percent metal content found in these ash are expected

for woody biomass ash. The elements Mg, Al, Mn, Fe, P and Na each contributed 10% or less to the total elemental portion of the ash. The other inorganic elements present in ash, though not mentioned in the table cumulatively contributed 2% or less to the total metal content of the ash under study and are not discussed in this paper. All analysis were based on the top eight most concentrated elements Ca, K, Mg, Al, Mn, Fe, P and Na.

The elements Al, P, Mg, Mn, Na, Fe, K, and Ca are shown in Table 4. The table shows that the concentration of P, Mn, Mg, K and Ca were found to be higher in pellet burner ash when compared to the other two ash types. The elements Al, Fe, and Na were present in higher quantities in the gasifier ash when compared to the other two ash types. Additionally, the pellet burner ash contained ~ 4 times higher concentrations of K, Mg and Mn, than the other ash types. However, Ca was only ~2 times higher in pellet ash. Some degree of variation in concentrations is expected due to the likely variation of fuel types, temperatures and other factors. Research has shown that calcium concentrations increase at temperatures below 900 °C which is primarily due to the decomposition of calcium carbonates (Misra, Ragland, & Baker, 1993). Above 900 °C, the Ca concentration also increases due to the dissociation and volatilization of potassium oxide formed after dissociation. The variation in oxide and/or carbonate concentrations bound to the ash will affect the concentration of the elements in samples when concentration is calculated on a weight basis.

3.3.3 Major Elements General Trends (within Fraction)

Within fractions, it was observed that P, Mg, Mn, Na, and Ca either increased with decreasing particle size or remained relatively constant. Ca was highest in concentration within each fraction and for all ash types (Table 4). The highest values reported for Ca were seen in Pellet burner ash, from ~136,000 to ~262,000 mg/kg moving from fractions 850 µm to < 150 µm. Additionally, K was found to be highest in the pellet burner ash, containing concentrations ranging from ~62,000 to ~112000 mg/kg when moving from 850 µm to 250 µm fractions. While most of the elements were present in higher quantities in pellet burner ash as compared to other ash types, Al, Na and Fe were present in higher concentrations in gasifier ash.

The concentration of each element not only varies across different systems but within fractions as well. This variation in concentrations poses a difficulty in the general application of bottom ash to soils due to the lack of standardization in ash quality. According to Obernberger and Supancic (2009), ash recycling to agricultural lands can help reduce the use of artificial fertilizers and close the natural mineral cycle. This is largely due to the presence of N, P and K in biomass ash. However, Pels et al. (2005) suggests that the use of biomass ash as a soil fertilizer is limited due to a number of deficiencies in ash. The author noted that biomass ash can only be a source of K because ash from thermal sources is low in N and the P present has a very low solubility at soil conditions. In previous research on the same ash, the ultimate analysis showed N content all less than 1 wt.% on a dry basis for all ash samples (James et al., 2013). Wood naturally has low N contents. Furthermore, due to the conversion of most of the wood N to NH₃, NO_x and/or N₂ during the combustion of the wood, it is expected that the nitrogen content be low (Misra et al., 1993; Steenari, Karlsson, & Lindqvist, 1999; Knapp & Insam, 2011).

Table 5. The concentration (dry ash basis) of water soluble phosphates relative to particle size distribution for boiler gasifier and pellet burner ash

sieve size/ µm	BA mg/kg	GA mg/kg	PA mg/kg
<150	-	0.23	0.66
150	-	0.1	1.87
250	-	0.22	1.67
425	0.35	0.32	3.64
850	2.57	0.15	0.29
2000	2.29	0.74	
AR	-	0.08	0.83

While the percent mass of phosphorus in the metal contents of the samples ranged from 1-3%, the amount that is available for plant uptake or that is water soluble must be considered, this was measured in the form of phosphates (PO₄³⁻). Phosphorous, may exist in both organic and inorganic forms (BC Ministry of Environment, 2008). The total and plant available phosphorous may vary. Water soluble phosphorus is the amount of phosphorus that is

readily available to plants (Fuhrman, Zhang, Schroder, & Davis, 2005; Nurmesniemi, Manskinen, Poykio, & Dahl, 2012). Research conducted on wood based biomass in an incinerator reported that the water soluble phosphorus content in bottom ash sample is negligible (Nurmesniemi et al., 2012). The research concluded that the poor water solubility of phosphorus was a draw back in the application of wood ash to soils since only a small portion P is extractable and available for plants when used in forest fertilizers. Our research showed some amounts of water soluble phosphorus present in the form of phosphates, though low in concentrations (Table 5). The starting ash for the pellet burner and gasifier were 0.83 mg/kg and 0.08 mg/kg, respectively, while the boiler ash was below the detection limit. Concentrations varied within particle size fractions. The pellet ash ranged from 0.66 – 3.6 mg/kg; lowest observed in particle size fraction < 150 µm and the highest in 425 µm fraction. The gasifier ash ranged from 0.1 – 0.74 mg/kg for the different fractions. The water soluble phosphate were only detected within the three largest particle size fractions for the boiler ash and ranged between 0.35 – 2.57 mg/kg. While the three largest fractions of the boiler samples had higher concentrations of phosphorus, water soluble phosphorus were not detected for these fractions. It does suggest that the phosphorus present in these fractions may be insoluble in water.

The presence of relatively high Ca and Mg, typically in the form of oxides, hydroxides and carbonates, suggests use of these ashes as potential liming agents. This could help in controlling soil pH. As the particle size fraction decreased, the concentrations of Ca and Mg increased and so did the pH. Therefore, specific fractions could be used to achieve appropriate liming requirements.

3.3.4 Inorganic Relationship to Total Carbon Content

The results were also analysed to identify the possibilities of any relationship that may exist between the elemental distribution of major inorganic components and the total carbon content (James et al., 2013). Figures 3a and 3b show a graphical display of the elements Ca, and P versus total carbon. These two elements showed a linear correlation for boiler sample; most of the carbon (over 60%) in this sample was organic carbon. A strong correlation was obtained with R^2 value of 0.9272 and 0.9218 for Ca and P, respectively. The equations are displayed in Equations 1 and 2. As a general trend, as the total carbon content increases the elemental concentrations for Ca and P decrease. These equations may help in determining the approximate amount of certain nutrients that may be present in ash. It would be worth removing as much carbon as possible to increase the concentration of nutrients.

$$y = -1969C + 182159 \quad R^2 = 0.9272 \quad (1)$$

$$y = -113.92C + 9973.5 \quad R^2 = 0.9218 \quad (2)$$

No major trend or correlation was observed when samples from the gasifier and pellet burner were analysed. This may have been due to the very low carbon distribution within the particle size fractions for each sample.

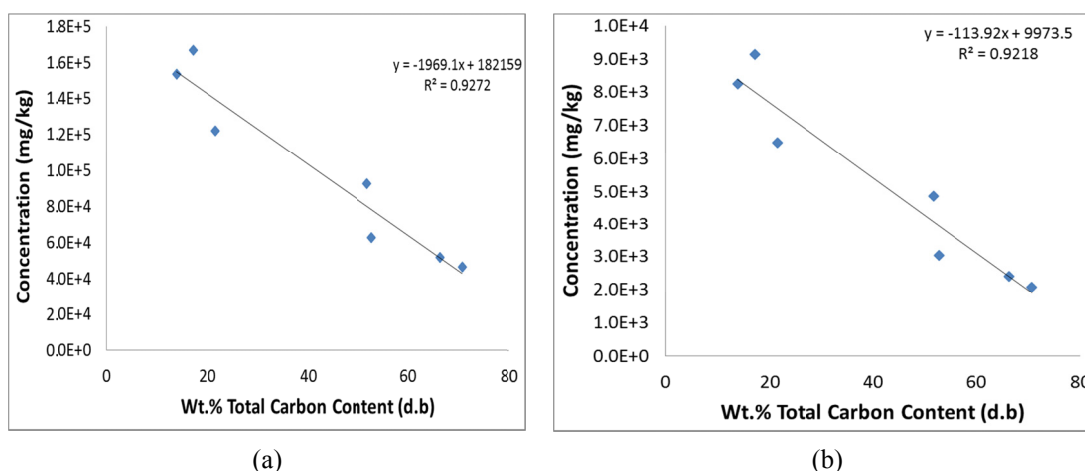


Figure 3. The correlation of calcium (Ca) and phosphorus (P) concentrations, respectively shown by (a) and (b), as a function of total carbon found in boiler ash

The presence of organic carbon in ash, if recycled to forest soils presents a challenge. Unburned carbon creates a dilution effect which reduces the concentration of inorganic nutrients available in the ash (Sarenbo, 2009). This is

evident from the two correlations above where the metal content increases with the decreasing carbon contents. If a high concentration of carbon is present in ash, greater amounts of ash will be required to fulfill the nutrients demand by the soil. It should be noted that high carbon ash has also been associated with elevated concentrations of environmentally harmful products of incomplete combustion, such polycyclic aromatic compounds (PAH) (Sarenbo, 2009; Bundt, Krauss, Blaser, & Wilcke, 2001); other work with these ashes has shown very low concentrations of PAHs, dioxins and furans (data not shown). The presence of carbon also reduces the ability of the ash to harden, which is integral to improving the handling of ashes and reducing its solubility (Sarenbo, 2009). This property limits its application to soil. Perhaps, if suitable methods for recirculating and reburning high carbon ash are determined, higher nutrient concentrations could be obtained while at the same time tackling some of existing ash related issues.

On the other hand, should high carbon ash possess similar properties as biochar then it could be used to obtain positive results in soil applications. Research has shown that biochar addition to soil may enhance properties, increasing plant growth nutrient availability, cation exchange capacity, water retention and with a reduction in the release of some greenhouse gases (Robertson, Rutherford, Lopez-Gutierrez, & Massicotte, 2012; Laird, 2007; Lehmann, 2007). Further studies are needed to determine if high carbon ash could also have these positive effects.

4. Conclusion

The inorganic element contents, pH and phosphate distribution of wood ash samples obtained from a fixed-bed boiler, fixed-bed gasifier and pellet burner were characterised. The samples showed variations in pH values both within particle size fractions and across the three systems. The starting ash samples for the gasifier, boiler and pellet burner ash had a pH of 10.36, 12.49 and 13.46, respectively. The pH increased with decreasing particle size fractions. This increase in pH may have been due to the increase in concentrations of the alkali earth metals as the particle size fractions decrease, forming higher concentrations of base-forming metal salts.

The trace element contents for the starting ash samples of the three ash types were all within the environmental limits for soil amendments in British Columbia, Canada. However, when analyzed within particle fractions, Ni with a concentration of 229 mg/kg from the pellet burner ash, exceeded the limit within the particle size fraction $\geq 850 \mu\text{m}$ but < 2000 . The starting ash samples were significantly enriched in both Ca (50-61 wt.%) and K (10-26 wt.%) on a total metal composition. The highest values reported for Ca were seen in Pellet burner ash, from $\sim 136,000$ to $\sim 262,000$ mg/kg. Very low concentrations of water soluble phosphates were obtained for all ash types in some case below the detection limit. A strong correlation was developed between the total carbon present and the metal contents for Ca and P.

These results suggest that fraction separation can be a useful method to isolate fractions containing higher amounts of some metals. This method may be a useful technique for elements exceeding environmental exposure limits.

However, the variation in concentrations poses a difficulty in the general application of bottom ash to soils due to the lack of standardization in ash quality. As shown from the research, the inorganic content of the ash samples varied across systems and within fractions. In addition to known factors such as fuel type and temperature, the research showed that other factors such the carbon content and particle size could play a role in determining the concentrations of the available inorganics. It is therefore difficult to determine standard compositions of ash.

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