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APPLICATIONS OF WOOD ASH BY MATCHING ITS CHARACTERISTICS WITH END-USER QUALITY REQUIREMENTS: A CASE STUDY

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ABSTRACT

Despite being a bio-based material, wood ash generated by pulp and paper mills is mainly landfilled in Canada. This is because it is perceived as waste material and the certification requirements and regulations controlling its use are complex. To promote wood ash utilization, ash samples from mills in British Columbia (BC), Canada were characterized, and the properties were compared to quality specifications for potential applications. Three types of ash samples were collected: bottom ash, multi-clone (MC) ash, and electrostatic precipitator (ESP) ash. Each type of ash was characterized, and their suitability for various applications was determined. The study found that ESP ash had a higher calcium carbonate equivalent (CCE) value than MC ash, making it more useful as a liming material in agricultural land. The study identified quality criteria for industries where wood ash can be used, such as construction, agriculture, composting, stabilization/solidification, liming, mining, and fire-retardant. Each type of ash was evaluated for its use in these industries, and the environmental regulations for each application were considered. It was observed that the quality criteria for one application could differ dramatically from those for another. Intuitively, an ash producer would cross-check the characteristics of their ash types against the quality requirements for potential uses near the ash source because different applications have different quality requirements. This article is believed to help identify promising applications of ash thereby removing ash from landfilling and promoting the circular economy.

1. INTRODUCTION

Canadian pulp and paper mills mainly use woody residues, also known as hog fuel, to generate green energy by biomass boilers. Although most of the fuel turns into water and carbon dioxide after combustion, a portion remains and is called power boiler ash. This ash derived from wood is generally believed to contain fewer metals than coal ash. However, if the wood is chemically treated, the presence of toxic metals in the ash cannot be ignored (NWR, 2020). Despite its relatively cleaner nature, most of the produced wood ash in Canada ends up in landfills (Elliott and Mahmood, 2015; Gravesande, 2018; Stantec, 2011). According to the IEAB (2020) report, Canada produces more than 1,000 kilotons of wood ash, with over 60% of it being sent to landfills. This makes Canada the second-largest contributor to wood ash landfills, after Germany, among the selected European Union (EU) countries (Figure 1).

Landfilling wood ash conflicts with the concept of circular economy. As well, landfilling of ash consumes precious landfill space, and the deposited ash becomes an environmental concern for years to come. Since the ash is treated as waste when landfilled, no economic value is created from this bio-based material resulting in poor economics. As such, there is a strong need to promote beneficial uses of ash rather than landfilling it for sustainable ash management with favourable economics.

To achieve this goal, four factors must be considered simultaneously: properties of the ash to be utilized, requirements of a specific ash end-use, regulatory environment, and process economics. Although there is limited information regarding ash end-use requirements and regulations controlling ash use in Canada, there are promising large-scale applications in the construction industry, agricultural sector, and forest/rural road construction, among others (Brand et al., 2021; Naylor and Schmidt, 1986; Vilane et al., 2021). Additional end uses of ash residues have been identified, albeit at relatively smaller scales. Included among these applications are ash use for mine tailings and mine-affected waters remediation, acidic waste neutralization, waste stabilization and solidification, adsorption, compost production, and structural fill to name a few

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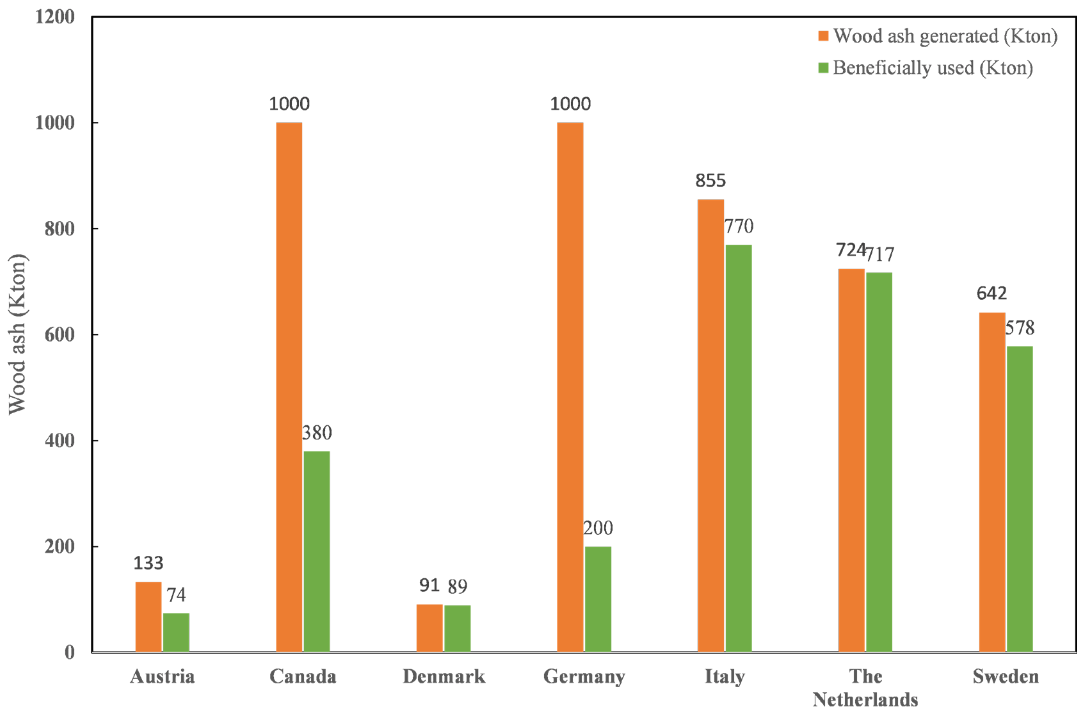

FIGURE 1: A comparison of wood ash generation and beneficial use for Canada and selected EU countries (Adapted from Bioreg, 2020; IEAB, 2018; Lazick et al., 2020).

(Elliott et al., 2022; Elliott and Mahmood, 2015; Mandpe et al., 2021; Wilk, 2020).

Characterizing wood ash is the first step toward identifying its best applications. Numerous studies have investigated the potential applications of wood ash, focusing on its physical, chemical, and mineralogical characteristics. Etiegni and Campbell (1992) have shown that wood ash yield decreases by 45% at higher combustion temperatures, with significant reduction in potassium, sodium, zinc, and carbonate content. Moreover, wood ash application has been found to have positive effects on soil properties and plant growth, making it an ecologically sound alternative for managing this industrial by-product (Demeyer et al., 2001).

Studies have also demonstrated that how wood ash varies from different materials and their impacts on the amelioration effects on acidic soils (Shi et al., 2017). Furthermore, wood ash has shown potential as a soil conditioner and an alternative nutrient source for agricultural soils (Baloch et al. 2024). While it has been found to enhance trace elements and alter microbial processes in soil, its overall positive impact on soil and plant growth makes it a promising option for sustainable soil management.

Mahmood and Kamal (2022) characterized wood ash collected from ten pulp paper mills in British Columbia, Canada. They demonstrated how the quality of wood ash varied from mill to mill and within a single mill while also exploring the relationship between different ash parameters. However, the wood ash quality was not used to identify its beneficial applications in that study. The main goals of the study are to thoroughly analyze the wood ash produced by a typical pulp paper (PPM) mill in BC, Canada. This includes examining all three ash streams—bottom ash, multi-clone ash, and ESP ash. The objective is to match the properties of the wood ash with specific application requirements and provide recommendations for its optimal use. This innovative approach, as described in the article, will help ash producers make well-informed decisions about using their wood ash. Failure to utilize wood ash effectively results in disposal in landfills. Implementing this method would enable ash producers to divert wood ash from landfills, thereby extending the service life of landfills and fostering a circular economy. By promoting the beneficial uses of wood ash, there is potential to create economic value from this bio-based material, reduce waste, and minimize the environmental footprint.

2. MATERIALS AND METHODS

2.1 Production of wood ash in pulp paper mills

During the burning of hog fuels in boilers, the flue gases pass through multi-clone (MC) separators and are finally captured using scrubbers, baghouses, or electrostatic precipitators (ESP). Thus, fly ash (MC and ESP ash) is generated. Another type of residue is the relatively dense ash that accumulates at the bottom of the boiler and is called bottom ash or grate ash. Most ash in PPM in BC is managed after the two ash types are combined. In some mills, the fly ash and bottom ash are separated. According to the recent trend of PPM, three types of wood ash are generated: bottom ash, MC ash, and ESP ash. Ashes were named after the location where they were produced in the boiler.

2.2 The case study area

Ten pulp paper mills that were located in both inland and coastal areas of British Columbia, Canada were investigated. Some of these mills produce combined wood ash (Figure 2a), while others produce bottom ash and fly ash (Figure 2b). Most mills generate bottom ash, MC ash, and ESP ash (Figure 2c). The study focused on one of the mills that generate three streams of ash. Since the mill was located inland, the logs used in the mill were not transported by marine water. Ash produced from logs transported by marine water may contain dioxins and furans (GoC, 2024).

2.3 Sampling and analysis

We collected representative samples of bottom ash, MC ash, and ESP ash of the studied mill. Each sample was collected at the sampling point in a 20L full bucket and was not exposed to rain. Each sample was analyzed in triplicate for accuracy (n=3x3). Samples were analyzed for their physical, chemical, and engineering properties. A comprehensive list of parameters, along with the corresponding instruments used for their determination, are presented in Table 1. The details of sample preparation, methods, and tools used to determine each parameter were discussed in the first phase of the study (Mahmood and Kamal, 2022).

3. RESULTS AND DISCUSSION

3.1 Wood ash characteristics

The parameters of wood ash needed for ash applications were determined. The analytical results are listed in Table 2.

3.1.1 pH

pH is a key parameter for wood ash applications, such as soil amendment, waste stabilization, and composting. Generally, wood ash is highly alkaline (pH>10.5). The pH of MC and ESP was highly alkaline (at about 12.5) while bottom ash had a pH of 10.7 (Table 2).

3.1.2 Moisture

It has been observed that the quality of ash deteriorates and the transportation costs increase as the moisture content increases. As expected, no sample of wood ash contained any moisture, meaning all of them had 100% total solids (Table 2). A wood ash application may require adding water to ash to achieve the desired moisture level.

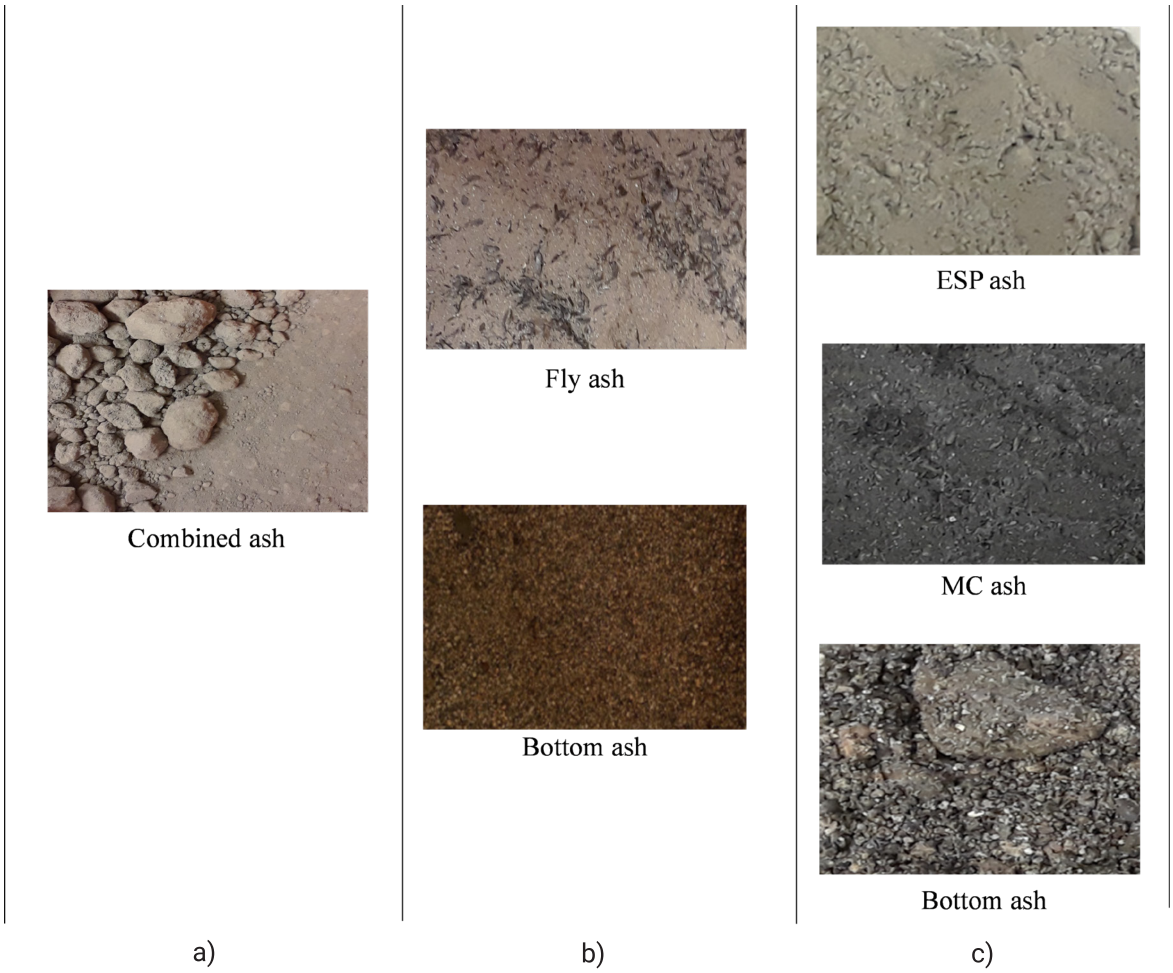

FIGURE 2: Pulp paper mills generally produce one of the three types of ash: (a) combined ash, (b) fly ash and bottom ash, (c) Electrostatic Precipitator (ESP) ash, Multi-clone (MC) ash, and bottom ash.

TABLE 1: Analytical tools/instruments used to determine the parameters of wood ash.

Parameters	Tools/Instruments	Model/Make/Place
pH	pH meter	Accumet 925 pH meter, Thermo Fisher Scientific, Burnaby, BC, Canada
Biochar/carbon	Gas chromatography	7890A, Agilent Technologies, Santa Clara, California, USA
Density	Graduated cylinder	213I11 Karter Scientific 50ml Glass Graduated Cylinder, Karter Scientific, Los Angeles, USA
Heating value	Oxygen combustion vessel	Parr 1108, Parr Instrument Company, Moline, Illinois, USA
Metals/elements	Optical Emission Spectroscopy-Inductively Coupled Plasma, OES-ICP	Thermo Scientific, Santa Clara, California, USA
Metal oxides	X-ray Fluorescence, XRF	A18-05132, Malvarn Panalytical Axios, Malvern, UK
Minerals	X-ray Diffraction, XRD	D8 Discover, Bruker, Billerica, Massachusetts, USA
Chloride, Cl^-	Optical Emission Spectroscopy- Inductively Coupled Plasma, OES-ICP	Thermo Scientific, Santa Clara, California, USA

3.1.3 Biochar

Biochar is a solid carbon-rich material available in wood ash. It is beneficial for soil amendment but not for the concrete. There was a significant amount of biochar (i.e., total carbon) in both types of fly ash, but bottom ash had the least amount (Table 2).

3.1.4 Loss-on-Ignition (LOI)

LOI indicates the amount of organic matter present in ash, with the organic matter being the unburned carbon in ash (unburned coal). Thus, a higher LOI indicates the presence of more biochar. A concrete mix with a higher LOI of wood ash (i.e., a higher amount of biochar) may produce poor-quality concrete by impeding air entrainment, reducing freeze-thaw resistance and increasing permeability. The MC ash contained a higher amount of LOI than ESP ash (Table 2). For concrete, this makes ESP ash a better choice than MC ash.

3.1.5 Density

The higher the density, the lower the volume occupied. As expected, bottom ash had the highest density of 1640 kg m^{-3}, whereas the MC ash had the lowest density of 430 kg m^{-3} (Table 2). As a result, when wood ash is disposed of in landfills without segregation, MC ash occupies the most space.

3.1.6 Heating value

The heating value of wood ash helps decide if any wood ash stream needs to be recycled with fuel feedstocks. The heating value of MC ash (8,200 kj kg^{-1}) was higher than those of the other two ash streams (Table 2). If the heating value of any wood ash stream is comparable to that of wood (19,073 kj kg^{-1}), then the wood ash stream may be recycled.

3.1.7 Size classification (Fineness)

The fineness of ash is the particle size. Compared to the fly ash, the bottom ash was found to be coarse (Table 2). Fly ashes used in concrete must meet the fineness requirements of ASTM C618 or CSA 3000 standards.

3.1.8 Trace elements

Coal ash contains contaminants, such as Hg, Cd, and As (USEAP, 2024). These elements can affect plant growth and the environment in both positive and negative ways. When used for any agricultural applications, wood ash concentration in wood ash is controlled by the Canadian Food Inspection Agency (CFIA) regulations (CFIA, 1997). Generally, wood fly ash contains fewer toxic metals than coal fly ash for As, Pb, Hg, and Se. All these trace elements were below the detection limit (<0.1 ppm) of wood fly ash (Table 2).

3.1.9 Metal oxides

Wood ash contains several types of metal oxides determined to compare the chemical specifications of wood ash with those is cementitious materials. Among all metal oxides, calcium oxide (CaO) is the main ingredient that contributes to the strength of concrete. However, other oxides such as silicon dioxide (SiO_2), ferric oxide (Fe_2O_3), and alumina (Al_2O_3) also contribute to concrete strength by forming the C-S-H gel. Due to these oxides, wood ash exhibits both pozzolanic and hydraulic properties in concrete. Considering these metal oxides, fly ashes of the representative mill had a high potential to use in concrete than bottom ash (Table 2).

3.1.10 Chloride

Chloride affects the durability of concrete. Chloride may be available with the ingredients of concrete mix or may ingress into the concrete from the environment. In either case, chlorde can attack the reinforcing bars of concrete. None of the ash streams of the representative mill exceeded the ACI (318) standard for chloride (Cl^-<1%) (Table 2).

3.1.11 Sulfur trioxide (SO_3)

SO_3 is responsible for sulphate (SO_4^{-2}) attacks in concrete. Like chloride, sulphate can penetrate concrete structures. Sulfate attack forms Ettringite in concrete that expands, creates cracks and weakens the concrete. The higher the amount of SO_3, the greater the loss of concrete strength. Each stream of wood ash contained less SO_3 than the ASTM C618 standard (5% by weight) (Table 2).

3.1.12 Calcium carbonate equivalent (CCE)

The CCE value of wood ash indicates its ability to neutralize acidity. A higher CCE indicates better ash quality as a liming material/agricultural application. The CCE of ESP ash was higher than MC ash (Table 3).

TABLE 2: Characteristics of wood ash streams (n=3x3) collected at different boiler locations from a representative pulp paper mill in BC. Units are in ppm otherwise mentioned.

Parameters/Elements	Bottom ash	MC ash	ESP ash
pH	11±0.3	13±0.1	12±0.2
TS, %	100±1.5	100±1.2	100±0.5
Total carbon, %	0.7±0.0	20.1±0.3	10±0.0
Ash content, %	100±1.3	75±1.0	87±0.9
LOI, %, 550°C	0.4±0.0	25±1.2	13±0.6
Density, kg/m^3	1600±0.0	400±0.0	800±0.0
Heating value, kj/kg	135±3.0	8200±35	4143±20
Fineness / particle size, %, < 0.04 mm	5.2±0.0	42±1.5	39±1.2
Aluminum, Al	50510±597	33940±302	20690±230
Arsenic, As	<0.1±0.0	<0.1±0.0	<0.1±0.0
Boron, B	<0.1±0.0	<0.1±0.0	285±8.9
Barium, Ba	697±15	1389±25	1971±38
Calcium, Ca	53360±498	103100±842	211300±2012
Cadmium, Cd	BDL	BDL	10±0.2
Cobalt, Co	BDL	BDL	11±1.5
Chromium, Cr	38±0.5	45±0.7	669±1.7
Copper, Cu	38±0.6	42±0.7	139±1.5
Iron, Fe	21370±312	17670±245	17925±265
Potassium, K	18190±297	27610±542	75965±998
Magnesium, Mg	8151±97	11150±160	18645±312
Manganese, Mn	735±22	3893±105	7445±237
Mercury, Hg	BDL	BDL	BDL
Molybdenum, Mo	BDL	BDL	8.8±0.1
Sodium, Na	15610±292	8532±119	5580±91
Nickel, Ni	19±0.2	25±0.3	40±0.5
Phosphorous, P	807±1.1	5049±8.9	9525±22.5
Lead, Pb	<0.1±0.0	<0.1±0.0	<0.1±0.0
Selenium, Se	<0.1±0.0	<0.1±0.0	<0.1±0.0
Sulfur, S	BDL	BDL	13830±149
Silicon, Si	632899±1459	553746±1609	48770±1005
Strontium, Sr	452±5.0	605.9±6.3	934±10.4
Titanium, Ti	2032±29	1643±18	1117±22
Vanadium, V	68±0.9	38±0.5	38±0.6
Zinc, Zn	94±1.5	221±3.6	1679±10.2
Cobalt tertoxide, Co_3O_4	BDL	BDL	BDL
Copper oxide, CuO	BDL	BDL	BDL
Nickel dioxide, NiO_2	BDL	BDL	0.1±0.0
Silicon dioxide, SiO_2	67.5±3.4	36.2±1.5	16±0.9
Aluminium trioxide, Al_2O_3	12±0.2	7±0.1	4.6±0.1
Ferric oxide, Fe_2O_3	4.7±0.0	3.2±0.2	3.0±0.2
Manganese oxide, MnO	BDL	0.6±0.0	1.1±0.1
Magnesium oxide, MgO	2.1±0.0	2.2±0.1	3.4±0.2
Calcium oxide, CaO	5.9±0.1	16±0.2	32±0.8
Sodium oxide, Na_2O	2.6±0.0	1.3±0.0	1.3±0.0
Potassium oxide, K_2O	2.6±0.0	3.1±0.0	5.8±0.0
Titanium oxide, TiO_2	0.5±0.0	0.4±0.0	BDL
Phosphorus pentoxide, P_2O_5	0.3±0.0	1.3±0.0	2.3±0.0
Chromium oxide, Cr_2O_3	BDL	BDL	BDL
Vanadium oxide, V_2O_5	BDL	BDL	BDL
Loss-on-Ignition (LOI), %, 1000°C	2.5±0.0	29±0.0	26±0.0
Chloride, Cl^-	BDL	BDL	BDL
Sulfur trioxide, SO_3	<0.3±0.0	<0.3±0.0	<0.3±0.0

MC: Multi-Clone, ESP: Electrostatic Precipitator, BDL: Below Detection Limit (<0.005)

3.2 Possibility of using wood ash

Wood ash has various uses, such as in the production of concrete, as fertilizer in forests, construction material on roads, embankments and in agriculture. However, these applications are subject to specific standards, regulations, and best practices. In the next sub-sections, we will compare the quality requirements of each application with the wood ash parameters studied.

3.2.1 Ash use in the construction industry

Concrete is a regulated product that must adhere to strict specifications. Standards have been established to govern the use of coal ash in concrete. The Canadian Standard (CSA, A3000) identifies three types of ash for use in concrete production: F, CI, and CH. Similarly, the American Standard (ASTM, C618) classifies ash into three categories: N, F, and C. Each type or class has specific requirements that must be met, as outlined in Table A.1 (in the appendix).

Table A.1 (in the appendix) compares the chemical specifications of cementitious materials required in concrete by ASTM and CSA standards with those of Bottom ash, MC ash, and ESP ash. The results show that Bottom ash is unsuitable for concrete manufacturing due to its low CaO content. However, MC ash has a good amount of metal oxides and CaO, which meet the requirements of ASTM Class C, Class F, and CSA-type CH fly ash. Not only that, but it also has lower amounts of SO_3, moisture, and chloride than the maximum value. ESP ash has the highest amount of CaO among the three ash streams, which satisfies the requirements of each class of ash for both ASTM and CSA standards. It also has a lower LOI than MC ash and SO_3, moisture, and chloride content than the maximum values of both standards, making it an ideal choice. Therefore, if these ashes are allowed in terms of their use in concrete, ESP ash should be followed by MC ash and bottom ash.

Numerous investigations have been conducted to determine the degree of ash substitution for cement, with some recommending much higher ash substitution rates than others (Amran et al., 2021; Tosti et al., 2019, Rajamma et al., 2009). For instance, paper mill fly ash can replace up to 10% of Portland cement, resulting in mortars with positive effects on their mechanical properties (Fava et al., 2011). However, due to fly ash fineness and water absorption properties, it requires a greater amount of water. Other studies suggest much higher ash substitution rates, indicating that ash can be a suitable alternative to cement in concrete manufacturing rates (Barathan and Gobinath, 2013; Hemalatha and Ramaswamy, 2017; Rajamma et al., 2009). Therefore, it is evident that ash can have a strong impact on the mechanical properties of concrete.

3.2.2 Ash use in agriculture (soil amendment)

Canada uses most of its ash for fertilizing agricultural lands, unlike Europe, where it mainly goes to forest fertilizing (Herbert and Breton, 2009; IEAB, 2018). Wood ash contains essential nutrients like calcium, potassium, and magnesium that are crucial for plant growth. However, wood ash samples may also contain harmful heavy metals that can harm soil quality. That's why the Canadian federal and provincial governments have set maximum concentration limits for eleven metals/elements of concern for ash application on land, including cadmium and mercury, which can be particularly concerning (Pöykiö et al., 2004).

To ensure that ash is used as a soil amendment safely, users need to follow guidelines and regulations set by the Canadian Food Inspection Agency (CFIA) and the Canadian Council of the Ministers of the Environment (CCME) at the federal level, as well as by provincial governments. As per CFIA guidelines, the maximum acceptable product metal concentrations are determined based on the maximum acceptable cumulative metal additions to the soil over a 45-year period. Each province may also have their own requirements in addition to the federal ash applications as a soil amendment.

For instance, British Columbia's "Code of Practice for Soil Amendments" includes fly ash from wood combustion (other than wood that has been exposed to marine water) in the definition of a soil amendment. This code sets strict requirements for soil amendments, such as no substances exceeding the values shown in Table A.2 (in the appendix), no sharp foreign matter, such as glass or metal, and no more than 1% (dry weight basis) foreign matter (GoBC, 2017).

Table A.2 (in the appendix) provides a comparison of the limits of toxic elements in standards with those of wood ash for materials used as soil amendments. The bottom ash, primarily composed of rocks, sands, stones, and debris, is unsuitable as a soil amendment. However, MC ash and ESP ash are suitable for use as soil amendments as they contain no foreign materials or sharp objects. Moreover, the elemental/metal concentrations in MC ash and ESP ash were much lower than those established by the BC guideline for soil amendment. Therefore, ESP ash and MC ash of the representative mill were of great interest for use as soil amendments.

The use of fly ash from PPMs as a soil amendment has also been studied by Maheswaran et al. (2019) in Newfoundland, Canada. Common uses of wood ash in Canadian provinces/territories are shown in Hannam et al. (2016). It is essential to follow guidelines and regulations to use ash safely and sustainably and maintain soil quality for future generations.

3.2.3 Ash use as a composting recipe

The use of fly ash from PPMs as a composting recipe has increased over time due to its nutrient content, low costs, and chemical nature. In general, the C/N ratio in the composting recipe mix is 30 (Tchobanoglous et al., 1993). The content of nitrogen in wood ash is minimal as nitrogen is released with flue gases during hog combustion in boilers. Predominant essential elements present in ash are Ca and K. Other desirable elements include P, S, and Mg. They are smaller in concentrations in wood ash but are essential for plant growth.

Maintaining a moisture content of 50-70% in the composting mix is crucial to ensure optimal conditions for microorganisms during composting (CWMI, 1996).). Luckily, both wet and dry ash can be used for composting, depending on the moisture content of other available ingredients.

Fly ash's high pH level is perfect for increasing soil pH and neutralizing acidic soils. However, it is important to maintain an optimal pH level of 5.5-8.5 during the composting process. To ensure the best results, it is recommended to use up to 16% of wood ash at the beginning of the composting process (Kuba et al., 2008). Additionally, the final application of wood ash should be regulated based on the selection of a high amount of biochar, and toxic elements that are lower than the standard set by the CCME composting guidelines and OMRR for BC (OMRR, 2002). While the nutrient content and CCE of ESP ash are higher than MC ash, wood ash as a composting recipe needs to be regulated by the selection of plant types, application rate, and potentially toxic elements standards.

The MC and ESP ash from PPMs have high pH levels, high nutrient content, and greater CCE values compared to literature values of wood ash and limestones. Table A3 (in the appendix) shows that the nutrient content of Ca, Mg, S, K, and P, as well as the CCE of ESP ash were higher compared to MC ash. However, MC ash had a greater amount of biochar than ESP ash. When it comes to composting, MC ash is more desirable due to its dark colour, which gives the resulting compost a darker hue.

In a survey regarding the management of solid residues from the pulp and paper industry, it was found that 14% of the total ash residues generated by 67 responding mills were blended with wastewater treatment (WWT) sludges before the mixture was composted for land application (Elliott and Mahmood, 2015). The MC ash of a PPM has been used in biosolids composting in a municipality of BC for its high nutrient values and low toxic elements.

In summary, using fly ash from PPMs as a composting recipe is an excellent choice for those looking for a cost-effective and nutrient-rich option. With its high pH level, low toxicity, and high nutrient content, this ash is an excellent choice for creating optimal composting conditions.

3.2.4 Ash as a liming material

In general, the quality factors that are used to consider wood ash as a liming material are moisture, purity as determined by CCE, particle size, and plant species selection (Lickacz, 2002). Wood ash could be an excellent liming material for your soil. Wood ash is rich in essential nutrients such as P, S, and K, making it a great option for improving soil fertility. However, not all wood ash is created equal. The quality factors that determine wood ash as a liming material are moisture, purity, particle size, and plant species selection (Lundström et al., 2003; Manan and Abdullah, 2020). For best results, the wood ash should have less than 2% moisture content and a CCE value ranging between 25-60% (Risse, 2013).

Table A3 (in the appendix) compares the characteristics of mill ash, literature ash, and limestone. While bottom ash is not suitable for liming, MC and ESP ash are. Among the two, ESP ash is preferred due to its higher CCE value. CCE values for the MC ash and ESP ash were 32% and 53%, respectively.

In BC, the Code of Practice for Soil Amendments (CoPSA) governs the use of wood ash as a soil amendment/liming material. The CoPSA allows the use of 5 m^3 wood ash (equivalent to 2,150 kg of wood ash with a specific gravity of 430 kg m^{-3}) without going through the approval process, but larger-scale applications must go through a stringent approval process (GoBC, 2016). It is essential to maintain the levels of toxic metals in ash to ensure that the soil is safe for plant growth.

Approximately 6.3 million acres of land in western Canada have a pH of 6.0 or less (Lickacz, 2002). Maheswaran et al. (2019) showed that the agricultural land in Western Newfoundland was acidic and can be neutralized using fly ash generated from Corner Brook Pulp and Paper Ltd. As there is a high demand for liming materials in Canadian agricultural land, the ESP ash of the representative mill is a good candidate for this purpose. With high demand for liming materials in Canadian agricultural land, using wood ash can be an affordable and sustainable solution for soil improvement.

3.2.5 Ash use as an adsorbent

Sorption has been identified as the potential end use of biomass fly ash (Anderson et al., 2012; Gomez et al., 2020; Karim et al., 2013). The unburned carbon (biochar) contained in ash is the primary sorbent. Other factors to be considered are specific surface area and toxic metals.

Interestingly, MC ash had a higher LOI than ESP ash, which falls within the range of the FPInnovations database (3-59%), as shown in Figure 3. Mills that have a high LOI (unburned carbon) can opt to separate this biochar fraction through dry or wet classification processes (Mahmood and Elliott, 2017) and sell this fraction (biochar) as low-grade activated carbon. MC ash, with its fineness and higher char content, is a better option than ESP ash as an adsorbing material, as indicated in Table A3 (in the appendix).

Furthermore, recent research has shown that fly ash can effectively remove contaminants from in-mill streams in pulp and paper facilities (Gao and Fatehi, 2018; Yonghui et al., 2018). The study targeted the removal of COD and lignocellulosic compounds, along with their associated colour, and found that unburned carbon adsorbs these compounds. Additionally, the inorganic fraction of ash plays a significant role in the removal efficiency, as the aluminum and calcium compounds cause coagulation, leading to the removal of contaminants (Yonghui et al., 2018).

It is an excellent way to maximize the benefits of biomass fly ash by using sorption. The biochar fraction can be used for various purposes, and the inorganic fraction of ash can significantly contribute to removing contaminants from in-mill streams, making it an effective and persuasive solution.

3.2.6 Ash use in forest/rural roads

Wood ash is a valuable resource that can be utilized for rural or forest road construction, but there aren't any specific standards for its use. However, standards for coal ash use as a cementitious material can be applied to wood ash, specifically for ESP fly ash, as indicated in Table A.1 (in the appendix). The use of ash in this area has been document-

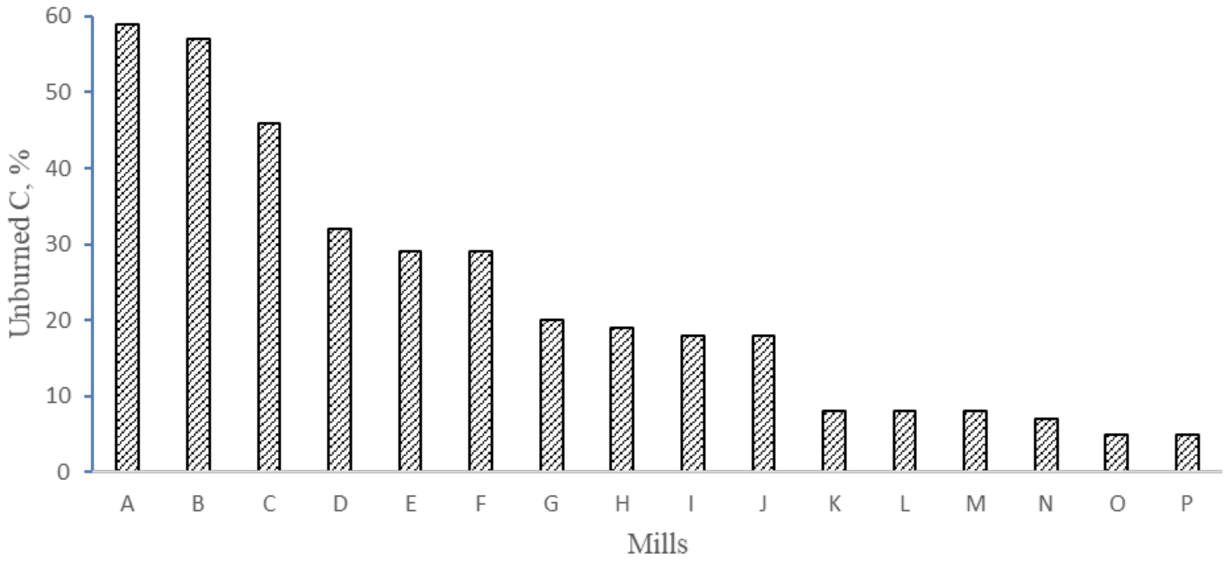

FIGURE 3: Unburned carbon content of fly ashes from 18 pulp and paper mills (FPInnovations database).

ed in various literature sources, making it a viable option (Minergy, 2021; Dalton, 2018; Fava et al., 2011).

One of the major parameters to be considered for wood ash for road construction is the leaching test of toxic elements. Cherian and Siddiqua (2021) conducted a leaching test of pulp paper mill fly (PFA) ash from the studied mill. Their study on leachate studies of PFA and PFA-stabilized soils confirmed that the cementation process reduced the bio-availability of toxic metals in the treated soil by encapsulating them in newly formed water-stable compounds. This suggests that PFA can be a safe raw material for environmentally friendly applications.

Particle size is a critical parameter when using ash for road stabilization, as it significantly affects the free lime content. The analysis required to determine its suitability as a road stabilization material includes free CaO content, total solids and LOI, inorganic elemental composition, carbon species, acid neutralization capacity, and leaching properties determined through field evaluations on test sites.

Although the representative mill did not have all the necessary parameters to consider wood ash for rural or forest roads, based on the two main criteria of CaO and LOI, it was observed that ESP ash was the most suitable, followed by MC ash, and finally bottom ash (Table A.1 in the appendix).

Geotechnical studies (Hottenroth et al., 2003) have shown that ash from the combustion of lignocellulosic materials and pulp mill residues improves soil-bearing capacity when the free CaO content of the ash is higher. The higher CaO content also reduces soil moisture and gravel requirements (Supanci and Obernberger, 2011). The CaO/SiO_2 ratio, which is the basicity of ash, is another essential parameter to predict ash performance as a soil or road stabilizer.

In conclusion, using wood ash for rural or forest road construction is a cost-effective and sustainable solution. With the right analysis and selection, wood ash can be used as a reliable and effective road stabilization material.

3.2.7 Ash use in waste stabilization/solidification

When it comes to stabilizing and solidifying waste, it's crucial to use the right binding agent. The process involves two steps: stabilization to reduce toxicity, and solidification to immobilize toxic elements. Cement, fly ash, or kiln dust can all work as binding agents, but when using fly ash, it must meet ASTM (C 618) standards for either Class C or Class F (Table A.1 in the appendix).

Choosing wood ash for waste stabilization/solidification (S/S) requires careful consideration of several factors, such as waste characterization, compatibility between cementing and waste materials, durability of treated waste or soil, and cost-effectiveness (Shi and Spence 2004, Trussell and Spence 1994). BC Hazardous Waste Guide recognizes S/S as an approved method for treating hazardous wastes containing asbestos, chromium, cyanides, fluorides, and heavy metals (GoBC, 2016).

Table A.1 (in the appendix) indicates that using bottom ash is not recommended for this purpose. Instead, ESP ash is the preferred option, but if the waste odour is an issue, MC ash is the better choice.

Waste solidification/stabilization has been used successfully for years to clean up contaminated sludge and soil in Arkansas. Limestone, fly ash, and Portland cement were used to treat 40,000 cubic yards of sludge and soil in the pit (USEPA, 2012).

In 2013, the Kruger mill in Brompton Ville, Quebec, Canada became the first pulp and paper mill in Canada to have its fly ash certified as a cement substitute, with substitutions as high as 20% (Minergy, 2021). This end-use application is the principal one currently being practiced by the mill to manage its fly ash by solidifying hazardous waste.

Therefore, to ensure the safe and effective stabilization/solidification of waste, binding agents need to be carefully chosen, considering all the factors mentioned above. The use of fly ash and cement has already been proven to work to keep the environment safe.

3.2.8 Ash use for mine remediation

Mining industries are in dire need of an effective solution to neutralize mine tailings, control acid mine drainage (AMD), and remediate abandoned mining sites. Fortunately, recent research has shown that ash may hold the key to solving these problems (Somerset, 2005; Wang, 2009). Ash contains alkaline minerals such as CaO, MgO, K_2O, $CaCO_3$, and $Ca(OH)_2$, which can be an effective substitute for purchased alkalinity (Somerset 2005). This means that fly ash generated from the coal industry and woody residues in pulp and paper power boilers can significantly reduce the acidity of waste sites (Hu et al., 2021; Yehevis et. al., 2009). By using ash for mine remediation, we can avoid the use of calcium oxide or limestone, which are commonly used but come at a high cost. Additionally, wood ash contains cementitious and pozzolanic materials that make it an ideal candidate for the mine remediation.

However, it is important to note that not all ash is generated equal. To ensure that ash is effective for mine remediation, it must be characterized by its alkaline content. By prioritizing ESP ash first, followed by MC ash and bottom ash.

3.2.9 Other end uses for ash residues

Ash has several potential applications based on its crystalline content. It can be used as a fire retardant for low-density polyethylene materials, making it an ideal material for construction and manufacturing (Dong et al., 2015; Porabka et al., 2015). Additionally, it can be used for vitrification in applications requiring glass aggregates, such as roofing shingles and ceramic processing (Minergy, 2021; Cheeseman, 2003). The key minerals - SiO_2, Al_2O_3, and CaO - present in ash are critical for these end uses. The inert fraction of ash is low-volume, making it cost-effective and efficient. Fly ash could also be considered for these applications if the LOI is low. However, wood ash has a higher LOI than the common natural fire retardants, such as concrete and brick making it unsuitable for use as a fire retardant. Upon analyzing the results provided in Table A.1 of the appendix, it is evident that the bottom ash from the representative mill, with the lowest LOI among the three ash streams studied and falling below both the ASTM C618 and CSA 4000 standards, stands out as the optimal option for use as a fire retardant. By utilizing ash effectively, we can reduce waste and create sustainable solutions for a better future.

3.3 Prioritizing the wood ash applications for the representative mill

The quality of wood ash determines its potential applications. To produce high-quality ash, segregation of wood ash is necessary. The representative mill produces three types of wood ash, each with unique characteristics and qualities. As illustrated in Table 2, the bottom ash has distinct applications compared to the other types, and it's preferred for use as a gravel substitute in concrete structures and as a fire retardant. MC ash has a high char content, and therefore, it can be used for adsorbing materials, stabilizing waste, and composting. On the other hand, ESP ash has better pozzolanic and cementitious properties, making it the best choice for concrete-related applications. It's also an excellent mining material. When it comes to agricultural liming, ESP ash is a better choice than MC ash because of its higher CCE values. Choosing the right type of wood ash can make a significant difference in the outcome of any project.

3.4 Why inland mills are preferred to coastal mills

The pulp paper mills in British Columbia can be found either in the coastal areas or inland. The coastal mills rely on logs that are transported and stored in marine water, which increases the risk of saltwater contamination. This contamination can lead to the production of toxic chlorinated organics, such as dioxins and furans, which are hazardous to the environment. Therefore, it is essential to implement strict environmental regulations, especially for coastal mills. On the other hand, inland mills are unaffected by this type of contamination.

In both inland and coastal mills, the wood ash use must comply with BC regulations. Fortunately, the wood ash generated from inland mills can be used as a soil amendment if it complies with the Fertilizer Act (1997) of the Canadian Food Inspection Agency (CFIA). Wood ash has a pH of 10-12.5, making it a non-hazardous material suitable for use as a soil amendment. However, wood ash from coastal mills must comply with regulations that prohibit agricultural use, as stated in the code of practice for soil amendment in BC (GoBC, 2016). Nonetheless, such ashes can be used in the concrete industry or waste solidification.

Table 3 highlights the potential use of biomass ash generated in inland mills as a cementitious material, agricultural-related applications, and others. Meanwhile, Table A.4 (in the appendix) outlines the regulations concerning the land application of ash. It is crucial to adhere to these regulations to protect both the environment and public health.

TABLE 3: Potential applications of wood ash: bottom ash, multiclone (MC) ash, and ESP ash of the studied mill.

Ash uses	Bottom ash	MC ash	ESP ash
Cementitious related applications			
concrete material	●	●●	●●●
road/forest [1]	●	●●	●●●
waste stabilization	●	●●●	●●●
Agriculture related applications			
oil amendment	●	●●	●●
composting recipe	●	●●●	●●
liming materials	●	●●	●●●
Other applications			
adsorbent	●	●●●	●●
mining	●	●●	●●●
fire retardant (other use)	●●●	●	●●

●: minimal use, ●●: moderate use, and ●●●: best potential use of an ash stream of the studied mill.
[1] In road construction, bottom ash is a better substitute for gravel than MC and ESP ashes.

4. CONCLUSIONS

The effective and optimal use of ash is crucial, and it depends on careful consideration of specific factors such as end-user ash quality requirements and environmental regulations. An in-depth exploration of these factors in a representative pulp and paper mill in BC, Canada has uncovered valuable insights that can revolutionize ash application methods in other mills. This analysis has revealed that each wood ash stream, encompassing bottom ash, MC ash, and ESP ash, possesses unique characteristics that render them ideal for specific applications. It is imperative to consider that environmental regulations and standards also wield significant influence over ash utilization, with different regulations governing various ash applications. The initial evaluation of wood ash application, based on the wood ash characterization of the studied pulp paper mill, indicated that the ESP ash is the most suitable for cementitious-related applications and as a liming agent for agricultural land application, while the MC ash is best suited for waste stabilization, composting recipes, and adsorbents. On the other hand, the bottom ash demonstrates optimal efficacy as a fire retardant. These findings emphasize the critical importance of aligning end-user ash requirements with the ash quality of a mill to pinpoint promising applications for comprehensive follow-up. By taking all these factors into account, ash utilization can be optimized, leading to the implementation of sustainable and environmentally friendly practices.

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