Environmental aspects of wood residue combustion in forest products industry boilers

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ABSTRACT: We conducted a comprehensive review of air emissions resulting from burning wood residues in industrial boilers and potential methods to control these emissions. This report compares average emissions with similar data published by the U.S. Environmental Protection Agency for the burning of fossil fuels coal, oil, and natural gas in industrial boilers. As compared with coal or oil combustion, wood combustion in boilers generally leads to lower emissions of trace metals, hydrochloric acid, sulfur dioxide (SO_2), and nitrogen oxides (NO_x); higher emissions of carbon monoxide, polyaromatic hydrocarbons, and total volatile organic compounds; and comparable emissions of particulate matter and polychlorinated dibenzo-dioxins and -furans (PCDDs/Fs) (both of which are highly dependent on the efficiency of the ultimate particulate matter control device). Most importantly, wood combustion is carbon dioxide-neutral, a distinct advantage over fossil fuel combustion. Firing wood in stoker units with sulfur-containing fuels, such as coal and oil, leads to a reduction in expected SO_2 emissions because of the high carbon and alkali content of most wood ash, and cofiring wood with coal also has some benefits for NO_x reduction. This report also discusses the generation and types of combustion ashes resulting from wood burning in mostly combination boilers in the United States and Canada, and provides an overview of ash management practices and the salient characteristics of such ashes relative to their trace metal, organic, and PCDD/F contents.

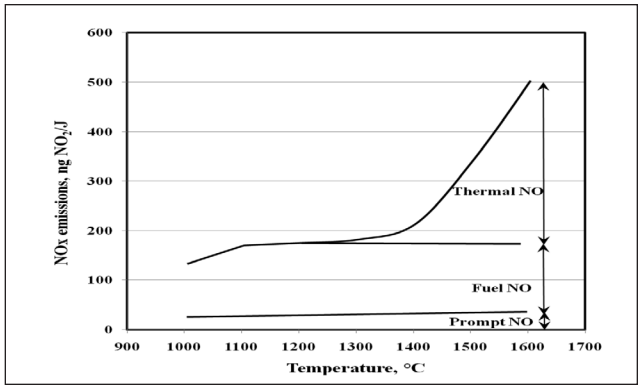
Application: This report will help mills understand the factors affecting air emissions that result from burning wood residues in industrial boilers, compared with burning other common fuels, such as coal, oil, or gas.

In the forest products industry (FPI), energy derived from biomass burned in boilers, recovery furnaces, and other combustion devices is an important component of the total energy needed to produce various products. Biomass combustion in boilers typically involves the burning of wood residues and residuals from manufacturing operations that include bark, wood chips, sawdust, sander dust, shavings, and hog fuel, a mixture of bark and wood, often with some sawdust, wood shavings or wastewater treatment plant (WWTP) residuals (mill sludge) mixed together. Most pulp and paper mills that debark logs on-site burn the bark and other wood residues in on-site power boilers to cogenerate steam and electrical power. Although smaller boiler types, such as the Dutch oven and fuel cell oven, are sometimes used, the majority of boilers with steam generation rates exceeding 50,000 kg/h are of the spreader stoker type. Many of these units routinely fire some fossil fuels (coal, oil, or natural gas in the United States and oil and gas in Canada) along with the wood residues. Most recently built wood products facilities, especially panelboard mills, burn the bark and other wood residues in relatively large, on-site central energy systems that are capable of generating the full thermal energy needs of the facility, typically without the use of supplemental fossil fuels. More recently, fluidized bed combustors (straight, bubbling, or circulating) have been built at pulp and paper and wood products facilities. This paper addresses some of the environmental aspects of burning clean wood residues in FPI boilers.

CHARACTERIZATION OF WOOD COMBUSTION AND EMISSIONS

When wood is burned alone, the principal emissions of concern include particulate matter (PM), carbon monoxide (CO), and nitrogen oxides (NO_x). Uncontrolled PM emissions from wood combustion are a function of the inorganic content of the wood fuel (ash and imbedded dirt or sand) and the unburned carbon in the fly ash. The extent to which unburned or partly combusted wood materials leave a combustion chamber depends on the efficiency of mixing and uniformity of temperature within the chamber. Smaller particles of wood fuel (such as sawdust) dry out quickly and can be carried out of the combustion zone before they have had a chance to burn completely. Consequently, fly ashes resulting from wood combustion can have high levels of unburned carbon, ranging from 7% to 49%, often resulting in high levels of uncontrolled PM emissions [1].

The two main pathways for NO_x formation in industrial boilers are fuel NO_x, where the oxides of nitrogen are formed by oxidation of the fuel-bound nitrogen, and thermal NO_x, where fixation of atmospheric nitrogen occurs at extremely



1. Estimated contributions of the three nitric oxide mechanisms to total nitrogen oxide (NO_x) formation in coal combustion.

high temperatures. (A third NO_x formation mechanism, prompt NO_x, is not generally relevant for industrial boilers.) **Figure 1** provides a generic profile of NO_x versus temperature for coal combustion. The thermal NO_x pathway is relatively ineffective below about 2600°F (or 1427°C). At combustion temperatures above that, however, thermal NO_x emissions increase exponentially with temperature, and NO_x formation becomes increasingly dominated by thermal NO_x mechanisms. Below 2600°F, fuel NO_x is the dominant formation pathway, so fuel-bound nitrogen content and the availability of oxygen in the combustion zone become critical for NO_x formation.

Because of lower heat value and higher moisture content compared with fossil fuels such as oil, gas, and coal, maximum temperatures resulting from combustion of wood residues in boilers rarely exceed 2600°F (or 1427°C), typically ranging between 2000°F and 2500°F. Thus, NO_x formation during biomass combustion occurs predominantly via the fuel NO_x pathway. Wood and bark nitrogen contents typically are quite low (in the range of 0.2% to 0.5%, dry basis); therefore, NO_x emissions from wood combustion in typical FPI boilers are lower than those from residual oil or coal combustion, but somewhat higher than those from natural gas combustion. However, if any of the wood fuels contain nitrogen from extraneous sources (e.g., sander dust from panelmaking that uses urea formaldehyde resin), higher NO_x emissions can be expected.

Volatile organic compound (VOC) and carbon monoxide (CO) emissions from wood residue combustion typically are related to the extent of incomplete combustion. The main VOCs include benzene, formaldehyde, and polyaromatic hydrocarbons (PAHs). VOC and CO emission rates are highly variable and are believed to be a function of boiler design, operating conditions, combustion efficiency, and fuel quality, and largely independent of the type of wood fuel. In general, more robust combustion environments (well mixed with uniformly high temperatures) lead to lower emission rates of VOCs, CO, and other products of incomplete combustion (PICs). Because most fossil fuels burn more completely than

Compound	Mechanical Collector	Wet Scrubber	ESP	EGF/Fabric Filter	
PM	0.095 - 0.23	0.028	0.023	0.043	
PM10	0.086 - 0.21	0.027	0.017	0.032	
PM2.5	0.051 - 0.124[1]	0.027	0.015	0.028	
CPM6	0.0073	0.0073	0.0073	0.0073	
	All Boiler Types				
	"Wet" Wood	**"Dry" Wood**			
NO_x	0.095	0.211			
CO	0.258[2]	0.258[2]	0.073		
Compound	**All Boiler and Control Types**	**Compound**	**All Boiler and Control Types**	**Compound**	**All Boiler and Control Types**
SO_2	0.011	Acetaldehyde	1.17E-04	CO_2	0.0[3]
HCl	6.92E-04	Benzene	4.73E-04	Methane	0.00904[4]
TOC	0.0168[4]	Formaldehyde	1.74E-03	N_2O	0.0056[4]
VOC	0.0073[4]	Phenol	4.07E-05	PAHs	1.1E-05
Acrolein	6.49E-05	Toluene	1.04E-05	PCDD/Fs[5]	1.36E-12

TOC – total organic compounds - includes non-VOCs such as methane; EGF – electrified gravel bed filter; [1]mechanical collector $PM_{2.5}$ and PM_{10} data are for boilers with fly ash reinjection; [2]CO factor for fluidized bed combustors is 0.073 kg/GJ; [3]biomass is considered to be CO_2-neutral; [4]from Table 1.6-3 of EPA's AP-42 document [7] – VOC expressed as sum of all individual reportable VOCs; [5]median value in I-TEQ units; CPM – condensable PM; ESP/FF – electrostatic precipitator/fabric filter.

I. Emission averages in kilograms/gigajoule (GJ) heat input for wood combustion boilers.

wood residue fuels (i.e., less unburned carbon in ashes), fossil fuel combustion generally results in lower VOC and CO emissions than wood residue combustion.

Trace levels of polychlorinated dibenzo-dioxins and -furans (PCDD/Fs) are emitted from combustion of almost all fuels, including biomass. Available data suggest that on a heat input basis (nanograms toxic equivalent [TEQ] per gigajoule [GJ] heat input), average PCDD/F emissions from clean, inland wood combustion [2] are comparable to those from black liquor [2], coal, and oil combustion [3]. Current understanding points to formation of PCCD/Fs in fuel combustion as being driven mostly by post-combustion phenomena, with the level of PICs present in post-combustion flue gases playing an important role. Also, the sulfur (S)-to-chlorine (Cl) ratio in the combined fuel is increasingly viewed as a critical parameter that influences PCDD/F formation in a boiler; the higher this ratio, the lower the potential for PCDD/F formation [4].

Hydrochloric acid (HCl) emissions from wood combustion are negligible (<0.001 kg/GJ heat input), unless bark from logs stored in salt water or wood material containing resins with sodium chloride is burned. Because wood and other biomass fuels have negligible sulfur content, sulfur dioxide (SO_2) emissions resulting from biomass combustion also are negligible [5]. Emissions of trace and heavy metals from biomass combustion are also low, principally because the metals content in biomass is much less than in coal, oil, or other solid/liquid fossil fuels (except possibly for manganese).

Three greenhouse gases – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – are released when wood is burned; however, the CO_2 released has been considered "neutral" and included in the accounting of carbon in forests [6]. This is because the carbon in trees started as CO_2 in the atmosphere, and the trees removed this CO_2 from the atmosphere in the relatively recent past. When this carbon returns to the atmosphere as CO_2, as a result of decay or combustion, this merely completes a cycle. As long as this cycle is in balance, it neither adds carbon to, nor removes carbon from, the atmosphere.

CHARACTERIZATION OF AIR EMISSIONS FROM WOOD COMBUSTION

Chapter 1.6 on woodwaste combustion in EPA's AP-42 emission factor document [7] and various National Council for Air and Stream Improvement (NCASI) reports are the main sources for the bulk of the data on air emissions from wood residue combustion in FPI boilers. **Table I** provides estimates of emissions for several criteria air pollutants (CAPs), selected VOCs, PCDD/Fs, PAHs, and greenhouse gases (CO_2, CH_4, N_2O) resulting from wood residue combustion in boilers [8]. **Table II** lists emissions of trace metals from wood residue combustion in FPI boilers [8].

Table III compares emissions from wood combustion shown in Tables I and II with those provided in EPA's AP-42 emission factor document for No. 6 fuel oil, natural gas, and coal [7]. The type of fuel used and the pollution control device also are specified, and emissions of CAPs, select VOCs, greenhouse gases, and trace metals are compared.

Although some pulp mill boilers use wood as the sole fuel, most boilers burn wood in combination with one or more fossil fuels. Studies by NCASI have shown that as a result of in-furnace SO_2 capture by carbonaceous and alkaline wood ash [9], burning wood in combination with oil or coal results in lower than expected SO_2 emissions. The degree of reduction is a function of the ratio of wood to sulfur content in the combined fuel. Cofiring of biomass in coal utility boilers also has been shown to lead to a reduction in NO_x emissions [10]. A 1% NO_x reduction is expected from baseline levels for every 1% cofiring percentage of biomass (heat input basis). This reduction is brought about by several factors, including reduced total fuel nitrogen, lower firing temperatures because of increased fuel moisture, and increased staging of the combustion process because of early volatiles burnout in the biomass fraction.

CONTROL OF AIR EMISSIONS FROM WOOD COMBUSTION

Uncontrolled PM emissions can be relatively high in wood-fired boilers because of high levels of unburned carbon, often making PM the air pollutant of primary concern. The four most commonly used devices to control particulate emissions from wood-fired boilers are mechanical collectors, wet scrubbers, electrostatic precipitators (ESPs), and fabric filters. A few units use an electrified gravel bed filter (EGF). Particulate collection efficiencies for wood-fired boilers range from 65% to 95% for two multiclones in series, to more than 90% for wet scrubbers, 93% to 99.8% for ESPs and fabric filters, and about 95% for EGFs [7].

Wet scrubbers are widely used for PM emission control, operating at gas pressure drops ranging from 3 in. to 25 in. of

	Sb	As	Be	Cd	Cr	Cr^{+6}	Pb	Mn	Hg	Ni	Se
with MC	-	4.48	12	2.58	22.6	3.00	37.5	1338	0.46	26.5	3.29
with WS	0.21	1.23	0.53	1.75	5.21	0.10	20.3	16.2	0.29	5.94	0.60
with ESP/FF	0.18	0.35	1.41	0.72	1.87	0.12	4.26	41.1	0.37	1.14	0.73
MC – multiclone; WS – wet scrubber; ESP/FF – electrostatic precipitator/fabric filter.											

II. Trace metal emissions from wood combustion boilers (mean - kg/10^{15} J).

Compound	Wood[1], kg/10^9 J		No. 6 Oil[2]	Gas[3]	Coal[4]
	with WS	with ESP	kg/10^9 J	kg/10^9 J	kg/10^9 J
PM	0.028	0.023	0.0072	0.0008	0.099
PM_{10}	0.027	0.017	0.0068	0.0008	0.070
$PM_{2.5}$	0.027	0.015	0.0016	0.0008	0.050
Condensible PM	0.007		0.0043	0.0024	0.0086
NO_x	0.095		0.092	0.059	0.248
CO	0.258		0.014	0.035	0.008
SO_2	0.011		0.452	2.5E-04	0.628
VOC	0.0073		0.0008	0.0023	0.0010
CO_2	0.0[5]		70.0	49.7	103.7
Methane	0.00904		0.0029	0.00095	0.0172
N_2O	0.0056		0.0015	0.0009	0.0344
Acrolein	6.49E-05		--	--	5.7E-07
Acetaldehyde	1.17E-04		--	--	1.1E-05
Benzene	4.73E-04		6.4E-07	9.0E-07	2.5E-05
Formaldehyde	1.74E-03		1.9E-07	3.2E-05	4.5E-06
Phenol	4.07E-05		--	--	3.0E-07
Toluene	1.04E-05		1.8E-05	1.4E-06	4.5E-06
PAHs	1.10E-05		1.7E-07	1.9E-08	1.0E-07
PCDD/Fs[6]	1.36E-12[7]		2.04E-12	--	2.68E-12
Trace Metals	**kg/10^{15} J**	**kg/10^{15} J**	**kg/10^{15} J**	**kg/10^{15} J**	**kg/10^{15} J**
Sb	0.21	0.18	15.06	--	0.31
As	1.23	0.35	3.79	0.08	7.06
Be	0.53	1.41	0.08	<0.005	0.36
Cd	1.75	0.72	1.14	0.46	0.88
Cr	5.21	1.87	2.42	0.58	4.48
Cr^{+6}	0.10	0.12	0.71	--	1.36
Pb	20.3	4.26	4.33	--	7.23
Mn	16.2	41.1	8.61	0.16	8.43
Hg	0.29	0.37	0.32	0.11	1.43
Ni	5.94	1.14	242.40	0.87	4.82
Se	0.60	0.73	1.96	<0.010	22.38

[1]wet wood residues burned in a spreader stoker with wet scrubber (WS) or ESP; [2]residual fuel oil (1% S) tangentially fired in a boiler with multiclones; [3]wall-fired with low NO_x burners; [4]bituminous coal (1% S) with 10% ash fired in a dry-bottom, tangentially fired, pulverized coal boiler with wet scrubber; [5]CO_2-neutral biomass; [6]in I-TEQ units; [7]median value.

III. Comparison of criteria air pollutants, volatile organic compounds (VOCs), greenhouse, and trace metal emissions from wood, oil, gas, and coal combustion in industrial boilers.

water. Liquid-to-gas ratios in the venturi system typically range from 8 gal to 10 gal of water per 1000 acfm (saturated). Solids buildup in the recirculation loop rarely is allowed to exceed 5% by weight.

High carbon ash resulting from wood combustion is more difficult to remove with an ESP because of its high conductivity. Thus, specific collection areas (ratio of ESP plate area to gas flow volume through the ESP) for ESPs on wood-fired boilers are greater than for those on other solid-fuel boilers, ranging from about 300 ft^2 to 500 ft^2 per 1000 acfm. Power requirements range from 150 W to 400 W per acfm [11]. To address fire concerns, ESPs on wood-fired boilers are sometimes operated in wet mode, where the collection plates and internal parts are wetted continuously with water. In such "wet" ESPs, a prequench section is generally used to saturate the gas stream and ensure that condensable pollutants have condensed into particulate forms and can be collected in the unit.

Fabric filters are rarely used on wood-fired boilers because of concerns about bag flammability. Gravel-bed filters use a slowly moving bed of granular rock as the filtration medium

through which the flue gas must travel. These systems are electrostatically augmented (10-20 W/1000 acfm). A high voltage (about 50 kV) is applied to an electrical conductor positioned within the bed, and this creates an electrical field between the conductor and the inlet and outlet louvers.

Fuel NO_x is the dominant NO_x formation mechanism during biomass combustion. However, common combustion modification techniques needed to control fuel NO_x, such as air staging (suppression of combustion air levels below the theoretical amount required for complete combustion followed by addition of air to complete combustion), have not been successfully demonstrated to work for wood-fired boiler NO_x control. Overfire air ports are claimed to lower NO_x emissions from wood-fired stoker and fluidized bed combustion units [7]. However, reports of such installations with credible data showing NO_x reduction are lacking. As for other fuels, such as natural gas and fuel oil, post-combustion controls include the selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR) processes. However, the use of SCR on wood-fired boilers operating in pulp mills or wood products facilities has not been demonstrated. Inadequate flue gas temperatures after the PM control device and high PM levels before such a device are major drawbacks to SCR operation. SNCR for NO_x control has been applied to several base-loaded wood-fired boilers. However, its efficacy (besides when used to remove small amounts of NO_x to meet regulatory limits) on wood-fired boilers with changing or fluctuating loads has not been demonstrated. The use of ammonia injection (SNCR) on at least one pulp mill wood-fired boiler met with significant problems because of inadequate dispersion of the injected ammonia and had to be abandoned [12]. Significant ammonia slip was to blame.

Products of incomplete combustion, such as CO, can be minimized through the use of good combustion practices. However, CO emissions from wood-fired boilers often exhibit large temporal variability resulting from varying fuel quality and boiler load swings [13].

CHARACTERISTICS AND MANAGEMENT OF COMBUSTION ASHES

The forest products industry generates and uses substantial quantities of energy from the burning of wood, bark, and other biomass material generated in the manufacturing process. This energy generation results in production of combustion ashes that requires proper management. The characteristics of these ashes often make them suitable for a variety of beneficial uses.

Ash composition

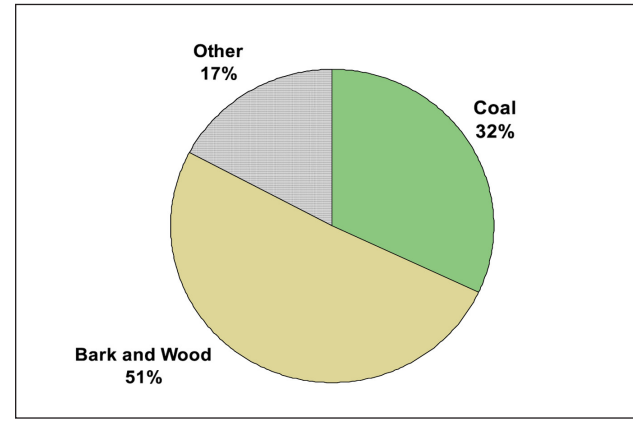
Like all combustion ashes, wood ashes contain metals and trace levels of organic compounds. During the past decade, NCASI has characterized wood ashes in some detail [1,14] and arrived at the following conclusions:

- Trace and heavy metals compositions in wood combustion ashes are comparable to those in other potential soil amendments such as coal ash, mill WWTP residuals, and limestone, but lower than those in municipal wastewater treatment biosolids.
- Available data suggest that cofiring other solid fuels such as coal, WWTP residuals, non-recyclable paper, etc., along with wood residues has little impact on ash metals composition.
- Organics of environmental concern, including PAHs, PCBs, chlorobenzenes, and chlorophenols, were found to be either nondetectable or present only in trace quantities in wood-fired boiler ashes.

Dioxin and furan levels in boiler ashes are very low (typically <150 ppt TEQ), except perhaps in a few instances where the total chlorine level in the combined fuel has been enhanced significantly by the addition of chlorine-containing solid wastes. Available data indicate that for combustion of inland wood residue or wood fuel with low levels of chloride (<0.03%), the dioxin concentrations in the ashes are very low. However, higher levels of chloride in the fuel mix from whatever additional source (salt water, bleached kraft mill WWTP residuals, etc.) have the potential to create higher levels of PCDD/F in ashes. Nevertheless, the correlation between fuel chloride and combustion ash PCDD/F concentration is not yet fully understood. Limited full-scale trials have shown that dioxin formation and ash dioxin concentrations can be suppressed by lowering the chlorine-to-sulfur ratio in salt-laden wood-fired boilers [15].

Distribution of ash by fuel source

Figure 2 presents the estimated ash distribution by fuel source at 239 North American pulp and paper mills (183 U.S. mills in 2008, 56 Canadian mills in 2007), based on the most recent available data to NCASI on fuel sources. The largest fraction of ash is from combustion of bark and wood. Coal ash, the vast majority (99%) of which is from U.S. mills in the sample, is the second largest fraction. The balance of ash is from other fuels, such as tire-derived fuel, wastewater treatment residuals, petroleum coke, and varioous other fuels from bio-



2. Ash type by fuel source at 239 North American pulp and paper mills 2007/2008.

mass and fossil sources. Of the ash produced by the 239 mills, the U.S. mills produced about 91%.

The ash that is ultimately managed at a mill is often a mixture of ashes from different fuels. The mixture depends on what fuels are burned together in each boiler and on how ash from different boilers is combined before final management. NCASI [16] explored this issue at U.S. mills in 1995 and found that mixing of ash types before final disposition was common practice. Of the ash destined for final disposition, only 22% was from wood/bark alone and 15% was from coal alone. The remaining ash being managed was a mixture of wood, coal, and other ash types.

Overview of ash management practices

Ash from wood-fired boilers can be collected in various ways. The most important factor with respect to management of the ash is whether the collected ash is wet (e.g., from a wet scrubber) or dry (e.g., from a baghouse). If the ash is suspended in a water stream, it may be transported to the wastewater treatment system where it is settled out and becomes part of the wastewater treatment residuals. Alternatively, it might be separately dewatered to facilitate further handling. Most ash dewatering is done by gravity in ponds or on drainage pads. Some facilities use mechanical dewatering devices such as filter presses or vacuum filters to dewater ash.

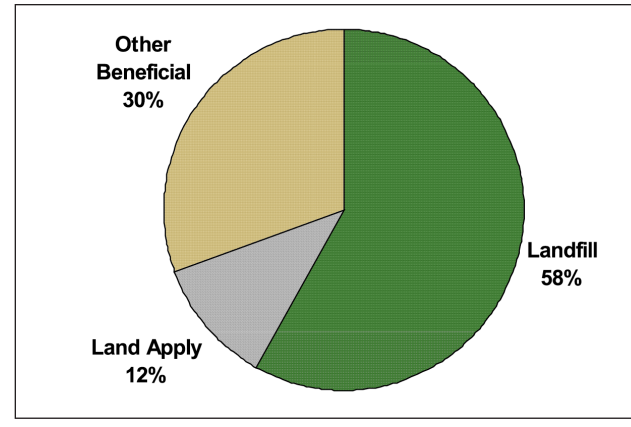
Figure 3 depicts how North American pulp and paper mills managed ash for final disposition based on data reported to NCASI by 175 North American pulp and paper mills that managed ash (125 U.S. mills in 2008, 50 Canadian mills in 2007). Landfilling (landfill/lagoon) was the predominant option used. More than 10% of the ash was beneficially applied to agricultural, silvicultural, or other land, and nearly one third of the ash was used in other beneficial ways.

Figure 4 demonstrates that the trend in ash management by North American mills in the past eight years has been away from landfilling and toward more beneficial uses. The move away from landfilling is a continuation of the trend in the previous decade. In 1988, the fraction of ash landfilled by U.S. pulp and paper mills was more than 80%, declining to 72% in 1995 [16]. Although Canadian data for those years are unavailable, more recent data indicate that ash landfilling rates in Canada are consistently higher than in the United States, so the North American ash landfilling rate likely was 75% or higher in the mid-1990s.

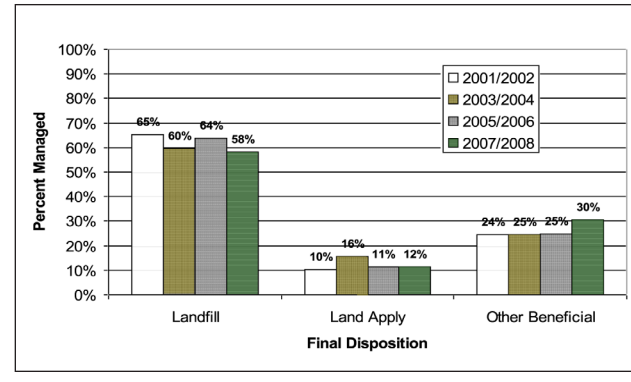
Beneficial use of wood ash

Wood ashes have a variety of potential uses [17,18]. The utility of a particular ash depends on its chemical and physical characteristics, which are affected by factors such as the fuels used, combustion conditions, and post-combustion handling or processing.

Land application is an important beneficial use for combustion ash. This is particularly true for wood ash. Wood ash is useful because of its liming ability, although benefits may be obtained from the presence of phosphorus, potassium, and



3. Management of ash at 175 North American pulp and paper mills in 2007/2008.



4. Trends in ash management at North American pulp and paper mills.

other nutrients. The allowable application rate might be limited by the ash's lime equivalency or by an ash contaminant, such as a heavy metal [18,19].

The application of wood ash to soil may be further advantageous if the ash can be considered a biochar, a form of stabilized carbon produced by the pyrolysis of biomass that is intended to be incorporated into soil for the long-term sequestration of carbon and to enhance soil properties [20]. Biochar is an area of intense research worldwide, including investigations with high-carbon wood ash [21].

As a compost feedstock, wood ash can contribute nutrients, reduce moisture, and darken the final product. It is increasingly recognized for the ability to reduce odors during composting, because the unburned carbon in the ash acts as an adsorbent. Wood ash can be pozzolanic or cementitious, and it is used to some degree in geotechnical applications such as soil stabilization and the construction of road bases and embankments. Wood ash can be desirable as a raw material for cement manufacture, particularly for its significant calcium content. Ash can improve the strength and durability of concrete, but this use normally is limited to coal fly ash because ASTM standards specify this material and high levels of unburned carbon in wood ash can be detrimental. Wood ash as a concrete additive is the subject of research [22,23]. **TJ**

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This study is a continuation of our investigation of combustion, especially biomass-related combustion. A comprehensive data summary on biomass combustion has never before been presented, mainly because NCASI is the prime "keeper" of such forest products-related data.

From this review, we discovered that biomass combustion has many advantages compared with fossil combustion, but also has some disadvantages. Mills might benefit from this information by having a better idea about environmental aspects of biomass combustion, especially as juxtaposed with other types of combustion.

The next step is to make the public aware of the full ramifications of going "green" with biomass combustion.

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