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CONCENTRATIONS OF HEAVY METALS IN *Eucalyptus* AND *Pinus* WOOD SAWDUST AND SMOKE, COPPERBELT PROVINCE, ZAMBIA

Elisha Ncube ^{1,▲}, Benjamin Phiri ¹

ABSTRACT

The bulk of exotic forest plantations and sawmills in Zambia are within the reach of air pollutants from mines on the Copperbelt province. Up to 60% of every cubic meter of the timber processed is waste, of which 0,12 m³ is sawdust. Sawdust is largely used for various surface amendments and as a source of energy, but the dangers it poses to users are not known. Heavy metals assimilated by trees or adsorbed by sawdust from the environment may be a health hazard at certain levels. The amount of heavy metals in *Eucalyptus* and *Pinus* sawdust was evaluated on samples from Kitwe and Ndola to establish if the use of sawdust for energy and surface amendments was safe. Composite samples for each wood type were collected from each site and digested. The ensuing solution was filtered and analyzed by flame emission Atomic Absorption Spectroscopy for heavy metals. Smoke from a burning test was trapped on Whateman 41 filter paper and the particulate matter that was trapped was extracted. The extract mixture was centrifuged to obtain a clear solution which was then analyzed for heavy metals by AAS. The heavy metal concentrations in *Eucalyptus* sawdust were 11,5-61,1 mg Pb/kg; 3,3-7,9 mg Cd/kg; 4,9-56,9 mg Cr/kg and 20,2-43,4 mg Ni/kg while that in *Pinus* sawdust were 17,1-32,8 mg Pb/kg; 5,1-8,6 mg Cd/kg; 9,9-28,2 mg Cr/kg and 18,7-67,4 mg Ni/kg. The concentrations of chromium and cadmium in both wood types from Kitwe exceeded the limit, and so the sawdust was deemed unsuitable for surface applications. This was the same for nickel in *Pinus* sawdust. The study showed that sawdust from both wood types was not safe for mulching, composting and animal bedding. The annual exposure limits of 0,2 µg Cr/m³, 180 µg Ni/m³ and 0,2 µg Cd/m³ set by the World Health Organization were not exceeded by the smoke from both wood types. This suggested that heavy metals embedded on particulate matter from *Eucalyptus* and *Pinus* sawdust which has been in storage for about two years in conditions found in Kitwe is unlikely to have adverse short-term health effects associated with heavy metals.

Keywords: *Eucalyptus cloesiana*, *Eucalyptus grandis*, heavy metals, *Pinus kesiya*, *Pinus oocarpa*, wood sawdust stove, wood sawdust smoke.

INTRODUCTION

The Zambia Forestry and Forest Industries Corporation (ZAFFICO) supplies timber to about 274 small-to-medium size timber processing enterprises, in Kitwe and Kalulushi districts (ZNAS 2014), from its 48,499 ha plantation establishment of *Eucalyptus* and *Pinus* (ZAFFICO 2008). Estimates indicate that about 60%, i.e. 258000 m³, of the 430000 m³ allowable annual cut is converted to waste during harvesting and timber processing (Per. com.; LUMAZ 2013). As a result, the Copperbelt province's landscape is characterized by large piles of sawdust, slabs, offcuts and bark. This indicates that the current wood waste utilization strategies have a limited impact.

Industrialization coupled with population migration into mining centers has increased energy demand to levels that outstrip installed capacity. The Government of the Republic of Zambia (GRZ) and other players are considering alternative energy sources (Energy Regulation Board 2012) such as solar, mini/micro-hydro, biomass, geothermal and wind (Energy Regulation Board 2008). Efficient woodfuel cook stoves programs supported by GRZ, non-government organizations and the private sector encourage sustainable use of fire wood in rural areas and charcoal in urban settlements (Simfukwe 2010).

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Wood smoke is an aerosol, of hazardous gases, wood tars, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons, heavy metals and soot, which is made visible by the presence of particulate matter (PM) (Chaiyo *et al.* 2011, Ravindra *et al.* 2001). The cumulative distribution of PM is 91,8% (< 1 µm); 93,1% (< 2,5 µm) and 95,8% (< 10 µm) (EPA 1984). The hazardous substances embedded on PM especially PM_{2,5} are carried deeper into alveoli where they cause harm and interfere with gaseous exchange (EPA 1984). The toxicity of smoke from wood heating devices, which can be twice as much that from oil and gas heating units, offsets the obvious attractiveness of wood as a renewable material (Larson and Koenig 1993). However, the composition and toxicants concentrations in wood smoke can be controlled by burning of wood with moisture content below 20% with adequate ventilation to realize complete combustion and most usable energy as well as smaller concentrations of harmful substances (Minnesota Pollution Control Agency n.d.). Unfortunately, most of the domestic biomass combustion technologies being used in Zambia discharge unknown mixes and quantities of air pollutants and so expose humans and the environment to hazardous materials.

In Zambia, large exotic forest plantations are located in the Copperbelt province where most anthropogenic heavy metals from mining activities and traffic exhaust gases (UNEP/GPA 2004; Ward *et al.* 1974) are discharged into the environment. The dispersal of heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) in soil from a mine source, especially by rain can extend to over a 20 km radius within which pollution levels can be much higher than is recommended by the World Health Organization (Liteinturier *et al.* 2001). Most sawmills generating sawdust in Kitwe lay within the reach of air laden with heavy metals. Wood exposed to heavy metals during growth or in storage is most likely to be contaminated, but there is no mechanism for protecting sawdust users in Copperbelt province. In the USA, certain local authorities have placed a ban on wood stoves and open burning and the Environment Protection Agency has specified emission standards for wood stoves and encourages consumers to switch to cleaner wood burning appliances (Minnesota Pollution Control Agency n.d.).

Heavy metals are natural components of the environment, but there is a concern on their accumulation in soil, water and air at alarming rates and levels. This is attributed to the rapid population growth, increased urbanization and expansion of industrial activities (Aksoy *et al.* 2000). A heavy metal is defined as any metallic substance with atomic weights between 63,5 and 200,6; and a specific gravity 5 times greater than that of pure water (Duruibe *et al.* 2007, Dimple 2014). There are 53 heavy metals found in nature (Ambulkar *et al.* 1994) as constituents of earth's crust in the form of sulphides and oxides (Duruibe 2007). For example, the sulphides of lead and cadmium are naturally found occurring in trace amounts together with sulphides of iron (pyrite, FeS₂) and copper (chalcopyrite, CuFeS₂) (Duruibe 2007). These trace heavy metals are released as part of exhaust fumes in pyrometallurgical processes.

Heavy metals are persistent environmental contaminants responsible for several human illnesses (Luckey *et al.* 1975). Small amounts of heavy metals can enter the body system through food, air, and water and bio-accumulate over a period of time (UNEP/GPA 2004). Heavy metal contamination is an important environmental issue since they are non-biodegradable (Wu and Zhang 2010). Hence they are not readily detoxified and removed by metabolic activities once they are available in the environment. This may subsequently lead to their build up to toxic levels, through bio-accumulation in ecosystems or human tissues. Bio-accumulation of heavy metals in man, animals and plants result in metal poisoning (Audu and Lawal 2005). The heavy metals documented to commonly cause problems in humans include lead, mercury, cadmium, arsenic, nickel and aluminium as they tend to accumulate and disrupt normal function in the brain, kidneys and immune system (Passwater and Cranton 1993).

The sawdust stove technology on the Zambian market has the potential for use in tobacco curing, domestic heating and cooking, and in organic manure production. However, there is a concern that the proximity of forest plantations and sawmills to flue gas emissions from mining activities contaminate wood with unacceptable levels of heavy metals. Consequently, the suitability of sawdust from the Copperbelt province for surface applications and as a source of energy must be evaluated. Information on the type and amount of heavy metals present on wood sawdust is required to safe guard the health of current and prospective consumers.

This was a preliminary study to establish whether heavy metals contamination levels in wood waste and wood smoke comply with national and international air pollution thresholds. This will generate data for assessing the suitability of wood sawdust for energy and surface applications. The authors are not aware of similar studies on heavy metals contamination of wood material from the Copperbelt and their concentration in wood smoke.

MATERIALS AND METHODS

Materials Collection And Preparation

The major *Pinus* species in ZAFFICO plantations are *Pinus kesiya* Royle ex Gordon and *P. oocarpa* Schiede ex Schlechtendal, while *Eucalyptus grandis* Hill ex Maid. and *E. cloesiana* Muell. are the major *Eucalyptus* (ZFFICO 2008).

Freshly cut sawdust originating from the Ndola plantation block was collected from Rainlands Timber Ltd in Kakolo which is 15 km outside Kitwe. The fresh sawdust provided a reference for the quantification of heavy metals assimilated and accumulated by wood during the growth of a tree. Wood sawdust which was produced about two years ago was collected from Kitwe Wood and Logs Ltd in a relatively polluted Kitwe urban area on the Copperbelt province. This sawdust helped determine the effect of airborne pollutants' adsorption by sawdust in storage.

Pinus and *Eucalyptus* sawdust was collected separately at each site. At each point on a site, a 2 kg subsample was collected up to 10 cm below the surface on five points randomly distributed over a sawdust pile and the sawdust kept in airtight polythene bags (ASTM E 872-82 2006) until further testing. A composite sample for each site was made by mixing the subsamples. Sawdust sieve analysis gave a mean particle size of 1,4 mm and 1,1 mm for *Pinus* and *Eucalyptus*, respectively.

The moisture content of each composite sample was determined by oven drying (ASTM D 4442-92 2003).

Analysis of heavy metals in wood sawdust

One gram of *Pinus* and *Eucalyptus* wood sawdust was separately placed in 250 mL beaker and acid digested with 10 mL of concentrated nitric acid (HNO_3). Four replicates were used for each composite sample. The mixtures were boiled for 25-35 minutes to oxidize all the easily oxidizable organic matters. When all the organic matters were acid digested, 4 mL of 70% perchloric acid (HClO_4) was then added following cooling. Heating was repeated until red nitrogen dioxide (NO_2) fume production ended indicating completion of wood sawdust digestion. After cooling, the solutions were transferred in 50 mL volumetric flasks and filled with distilled water. The solution was then filtered using a 45 μm filter paper.

The concentration for heavy metals; lead, chromium, cadmium and nickel, in the solution were determined by flame emission Atomic Absorption Spectroscopy (AAS). This was calibrated using the analytical (working) curve technique and the standard solutions.

Analysis for heavy metals in wood sawdust smoke

A wooden stick of 45,75 mm diameter by 296 mm long was placed at the center of 187 mm diameter by 305 mm long by 1 mm thick mildsteel sheet sawdust stove to link with an air inlet pipe of 71 mm long in order to produce a natural air draft from the base to the top of the stove. Air dry sawdust specimen ($0,006 \text{ m}^3$) with a characteristic density value of 290 kg/m^3 at 13-19% moisture content was burnt until the fire temperature reduced to 20°C after about 2,5 h. The fire was ignited by a 4,4 g pine resin wood stick. Three burning tests were done for each wood type from each of the three sampling sites. Temperature was measured at an interval of 3 minutes by a thermocouple placed between the laboratory jar and stove.

The smoke particulates from burning 1,74 kg of wood sawdust was trapped on Whatman 41 filter paper (pore size $\leq 4 \mu\text{m}$) in an assembly of laboratory jar, flat bottom flask and Vacubrand™ 80 bars vacuum pump with a 1,9-2,2 m^3/h air displacement capacity (Figure 1). Each filter paper was clamped at the top of the laboratory jar connected to a vacuum pump to collect particulate matter (PM) as wood sawdust was burnt. PM was retained by a combined mechanism involving electrostatic attraction, Van der Waals forces, inertia and diffusion at a collection efficiency of 63% (PM $0,32 \mu\text{m}$) for a single trial (EPA 1984). At the cessation of smoking, 89 and 83 minutes for *Pinus* and *Eucalyptus* sawdust, the filter paper was removed and then weighed.

Each of the nine blank and PM loaded filter papers was oven dried for 15 minutes at 105°C and weighed on an analytical balance with a sensitivity of $\pm 0,0001 \text{ g}$.

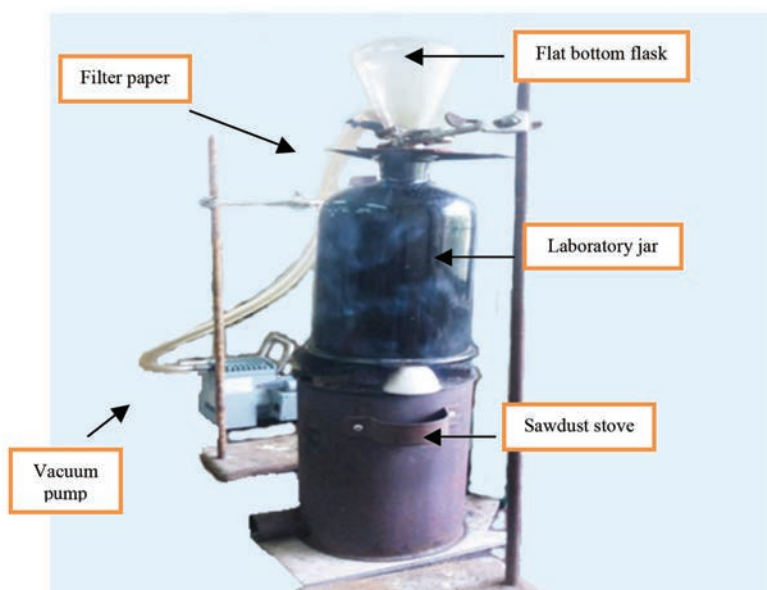


Figure 1. Apparatus for the collection of smoke particulate matters from burning *Pinus* and *Eucalyptus* wood sawdust.

PM trapped on filter paper was extracted in a mixture of 10 mL 3% HNO₃ and 8% HCl in a glass tube for 2 hours at 130°C (Nwajei and Iwegbue 2007). The mixture was centrifuged for 30 minutes at 1500 RPM to obtain a clear solution upon settlement of impurities at the base. The solution was transferred into glass vessels and diluted to 20 mL mark with distilled water and analyzed for heavy metals by AAS. Heavy metal concentration was calculated by equation 1 (Chaiyo *et al.* 2011)

$$C = \frac{\text{Metal} \times \text{Extraction solvent}}{W_{PM}} \quad (1)$$

where *C* equals Concentration of metal in mg/mg of particulate mater (PM) (mg/mg PM), Metal equals Heavy metal concentration in the analyzed solvent (mg/L), Extraction solvent equals Volume of solvent used for extraction of heavy metal (L), and WPM equals Weight of PM collected on a filter paper (mg). The concentrations of heavy metals found in equation 1 were converted to µg M/m³ based on the amount of PM retained on a filter after drawing 2,84 m³ and 3,04 m³ of air in each test run for *Eucalyptus* and *Pinus* sawdust, respectively.

Data analysis

The concentrations of Pb, Cd, Cr and Ni in wood sawdust and in the particulates retained on paper filter from the ensuing smoke were analyzed using one-way analysis of variance (ANOVA) at 5% level of significance. Fisher's least significant difference method was employed to identify significant differences (one-way ANOVA $F_{\text{calc.}} > F_{\text{tab.}}$, $P < 0,05$) by multiple pair comparison technique using Minitab ver. 16.

RESULTS AND DISCUSSIONS

Time-temperature curves

The moisture content of *Eucalyptus* and *Pinus* sawdust from Kitwe was 11,8% and 18,5%; which was much similar to material from Ndola, i.e. 13,4 % and 19,0%. *Pinus* sawdust fire reached a lower maximum temperature (567°C) than for *Eucalyptus* sawdust (710°C) (Figure 2) due to heat loss associated with energy expended on drying the additional 6% moisture.

Figure 2 shows time-temperature curves for *Eucalyptus* and *Pinus* sawdust. The combustion of sawdust was characterized by simultaneous drying over 6 minutes, which was followed by degassing (arrows in Figure 2) and carbonization in the last phase. The longer degassing periods for both *Eucalyptus* (66 minutes) and *Pinus* (75 minutes) sawdust from Kitwe indicated that exposed sawdust released potentially toxic gases over a longer period compared to fresh sawdust from Ndola. As the fire spread during degassing, wet sawdust was encountered and the effect caused slight temperature depression in wetter sawdust from Ndola. As degassing progressed, wood sawdust degraded into charcoal layers during carbonization and burnt at decreasing rate to 73°C over about 2 hours. These conditions are appropriate for cooking an ordinary family meal using the sawdust stove.

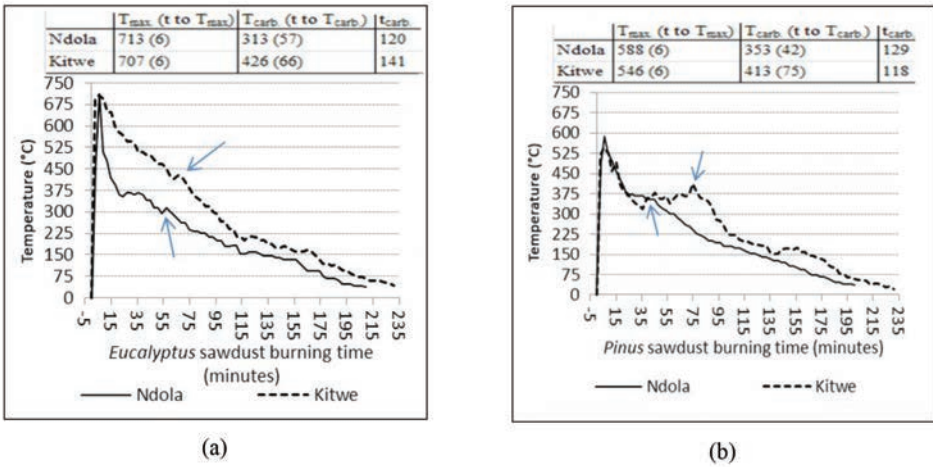


Figure 2. Time-temperature curves for (a) *Eucalyptus* and (b) *Pinus* sawdust.

The arrows show degassing termination point. T_{max} stands for maximum temperature (°C), t to T_{max} stands for time (minutes) taken to reach the maximum temperature, T_{carb} stands for temperature at the beginning of carbonization, t to T_{carb} stands for time it takes to reach carbonization and T_{carb} stands for the duration of carbonization up to 73°C.

Heavy metals concentrations wood sawdust

A one-way ANOVA ($F_{calc.} 37,9 > F_{critic.} 2,1$; $P < 1,8 \times 10^{-16}$) at a 5% level of significance in conjunction with Fisher's least significance different analysis showed that *Eucalyptus* sawdust from Kitwe had higher concentrations of Pb^a and $Cr^{a,b}$ than sawdust from Ndola (Figure 3a). This was not the case with *Pinus* sawdust where Ni^a is the only one which showed significantly different concentrations (Figure 3b). The fresh sawdust from Ndola only shows the amount of heavy metals which trees assimilated together with essential trace metals from the soil. It is possible that sawdust which had been in storage for over two years adsorbed additional heavy metals from the polluted air in Kitwe urban. Airborne particulates accumulate on the wood surface, forming a mono- or multi-layer film (Dimple 2014).

The Waste and Regeneration Action Program and the British Standard Institution stipulate contaminant upper limits in waste wood (British Standard Institution 2012) as 90 mg Pb/kg, 25 mg Cr/kg; 1,5 mg Cd/kg and 50 mg Ni/kg. The sawdust from both sites and species is not safe for particleboard manufacture as it had Cr concentrations which exceeded the upper limit. Similarly, the *Eucalyptus* and *Pinus* sawdust from both sites is not safe for surface applications such as, mulching, composting and animal bedding, as the concentrations of Cd exceeded the maximum value of 1,5 mg/kg. Nwajei and Iwegbue 2007, detected 40-250 Pb mg/kg; 0,05 Cd mg/kg and 1,46-160,50 Cr mg/kg in sawdust at Sepele sawmill in Nigeria. Unlike in this study, the concentration of Cd in sawdust from Sepele was the only one safe. The Ni concentration of 67,4 mg/kg in *Pinus* sawdust from Kitwe also indicated that the material is also not suitable for surface applications as it was above the 50 mg/kg limit.

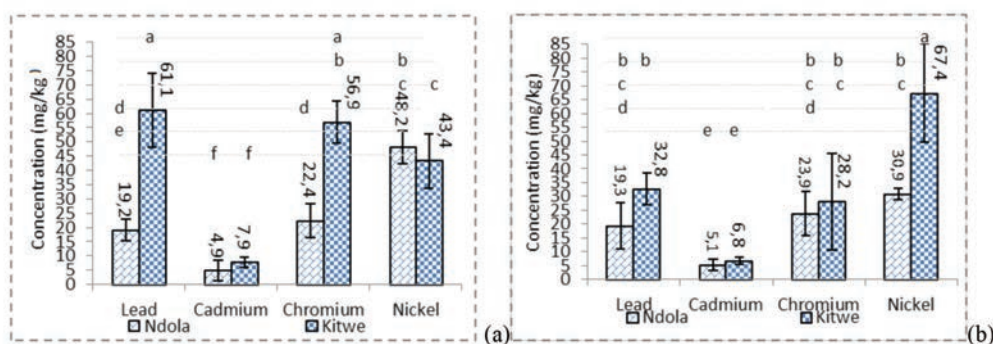


Figure 3. Heavy metal concentrations in *Eucalyptus* (a) and *Pinus* (b) wood sawdust from Ndola and Kitwe in Copperbelt province. Values represent means for four replicates per site. Values followed by the same letter(s) are not significantly different from one another. $\alpha = 0,05$.

Eucalyptus and *Pinus* sawdust from Kitwe had been exposed for over two years to air pollutants at a sampling site within a 5 km radius of the business district and copper mines. The principal anthropogenic sources of trace metals in the atmosphere are smelting of metallic ores, industrial fabrication and commercial applications of metals, as well as burning of fossil fuels. This was different for fresh sawdust from Ndola where the major source of heavy metals was the natural environment. Trace heavy metals have been detected in tree leaves, roots and anatomical features of the stem (Mala *et al.* 2007, Lawal *et al.* 2011).

It has been reported that climate variables, atmospheric depositions, the concentrations of heavy metals in soil, the nature of soil on which the trees are grown and the degree of maturity of the plants at time of harvest have a bearing on uptake and bioaccumulation of heavy metals in trees (Lake *et al.* 1984, Voutsas *et al.* 1996). The uptake of heavy metals by *Pinus sylvestris* is a complex process whose efficiency depends on the soil pH, redox potential, soil texture, soil organic matter content, soil metal content and metal availability (Seregin and Ivanov 2001).

The heavy metals in the environment are absorbed by plants via the roots from which they are transported to the leaves or absorbed directly into the leaves by air or precipitation (Kord *et al.* 2010) and accumulate in small amounts (Cambra *et al.* 1999). Studies have shown that heavy metal concentrations in wood increment correlate with metal concentrations in the environment and can indicate local environmental contamination (Baltreinaite *et al.* 2010) levels from anthropogenic, biogenic, or geogenic sources (Daly and Zannetti 2007). Various plants, such as spot pine (Yilmaz and Zengan 2003), have been used as bioindicators to assess the impact of pollution source on mine vicinities (Onder and Dursun 2006). So the heavy metals found in fresh sawdust from Ndola were largely assimilated by trees from biogenic and geogenic sources (Daly and Zannetti 2007). As an area becomes more industrialized, the level of environmental pollution escalates. This effect explained the significantly lower concentrations of heavy metals in freshly sawn sawdust from Ndola compared to that from Kitwe.

Heavy metal concentrations wood sawdust smoke

The visible smoke in the air from wood-burning stoves and fireplaces is a complex mixture of gases and a collection of particulate matter (PM), i.e. small collections of materials that had not quite burnt or have burned into ash that is light enough to float up the air. PM tends to be bits of wood fiber, burnt wood tar, and other light deposits, usually inhalable PM₁₀ (coarse particulates less than 10 μm in diameter) as well as respirable PM_{2.5} (fine particulates less than 2,5 μm in diameter) (Gingrich and Macfarlane 2002, WHO 2000, EPA 1984). A kilogram of wood burnt in a new wood stove produces about 21 g of fine particulates (EPA 1984; Larson and Koenig 1993; Abelson 1994). Dry wood sawdust was used because wet sawdust emits more heavy smoke containing a lot more PM (Levine 1990; Butcher and Sorenson 1979). "Dried wood used for fuel typically has a moisture content of 5-20%" (Ragland and Aerts 1991).

Figure 4 shows an array of selected heavy metals concentrations in smoke realized when wood sawdust specimens were burnt in laboratory conditions. The heavy metals concentrations in wood were much lower than what was found in wood sawdust smoke. This indicated that the bulk of the metals were retained in the ash fraction (Lupupa 1997) or where attached to ultrafine PM that was not retained by the filter paper. So, the wood ash contained similar levels of heavy metals and so could restrict the use of ash as a surface amendment.

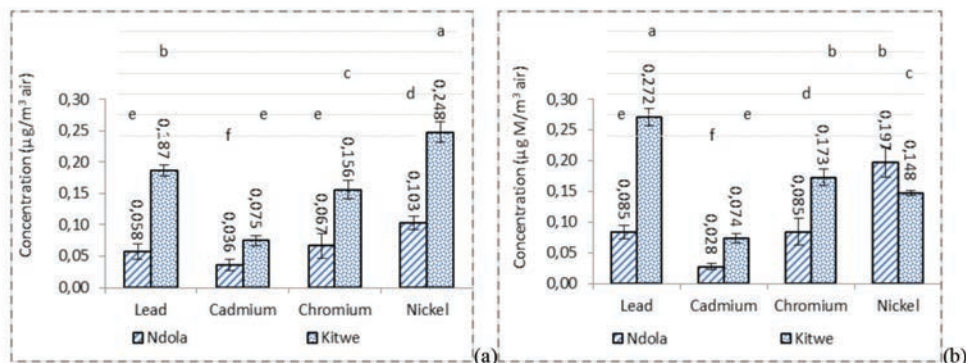


Figure 4. The concentrations of heavy metals in smoke from *Pinus* (a) and *Eucalyptus* (b) wood sawdust obtained in Ndola and Kitwe in Copperbelt provinces. Values represent means for three replicates per site. Values followed by the same letter(s) are not significantly different from one another. $\alpha = 0,05$.

Both *Eucalyptus* and *Pinus* sawdust smoke from the control and treatment site contained significantly different Pb, Cd, Cr and Ni concentrations (ANOVA at 5% level: $F_{\text{calc.}} 126,5 > F_{\text{critic.}} 2,2$; $P < 1,8 \times 10^{-18}$; $F_{\text{calc.}} 127,8 > F_{\text{critic.}} 2,2$; $P < 2 \times 10^{-18}$) (Figure 4 a, b).

The concentrations of heavy metals were below the World Health Organization guidelines' annual exposure limits of $0,2 \mu\text{g Cr/m}^3$, $180 \mu\text{g Ni/m}^3$ and $0,2 \mu\text{g Cd/m}^3$, respectively as well as $2 \mu\text{g Pb/m}^3$ (WHO_Exoert_Task_Force 2000). These concentrations $0,0004 \text{ mg Cr/kg}$; $0,0034 \text{ mg Ni/kg}$ and $0,00074 \text{ mg Pb/kg}$ for both wood types, were much lower than what has been observed in wood smoke from Oregon in the United States of America; $0,02\text{-}4 \text{ mg Cr/kg}$; $0,001\text{-}1 \text{ mg Ni/kg}$ and $0,1\text{-}3 \text{ mg Pb/kg}$ of cordwood (Koenig 1993).

The significantly high concentrations of Pb in smoke from *Eucalyptus* ($0,27 \mu\text{g/m}^3$) and *Pinus* ($0,19 \mu\text{g/m}^3$) wood sawdust originating from Kitwe reflects the impact of industrialization and urbanization (Figure 4 a, b). These Pb concentrations in wood sawdust smoke that had been in storage for over two years in Kitwe compared very well with what had been observed for traffic related pollution in cities of developing countries; $0,3\text{-}1 \mu\text{g/m}^3$ with extreme annual mean values of $1,5\text{-}2 \mu\text{g/m}^3$ (WHO Expert Task Force 2000, Simukunga 1999). Ambient air levels of over $10 \mu\text{g Pb/m}^3$ have been reported in urban areas near smelters, whereas Pb level below $0,1 \mu\text{g/m}^3$ have been found in cities where leaded petrol is no longer used (WHO Exoert Task Force 2000). These results indicated that *Eucalyptus* and *Pinus* sawdust smoke is unlikely to pose a danger to users of small-scale heating and domestic energy appliances.

The cooking stoves being used in most developing countries are mostly inefficient (10 to 15%) which leads to production of considerable amounts of smoke particles (DeKoning *et al.* 1985). Efficiency of sawdust stoves and other stoves being promoted in the Zambia is commonly assessed in terms of usable thermal output and the associated biomass savings. Studies on heavy metal air pollution potential of these stoves are sparse. This study showed accepted short-term heavy metal concentrations in wood smoke, the long-term concentrations of at least 24 h is yet to be established. This is important because most women, infants and children who spend long hours in the proximity of cooking areas in poorly ventilated houses are more likely to be exposed to high dosages of heavy metal pollutants. The consideration of both stove efficiency and smoke quality (Staton and Harding nd), is a necessity to the wellbeing of biomass users in woodfuel dependent households. The reduction in risks of respiratory symptoms by women in rural Mexico who switched to using Patsari improved stove demonstrates the potential to reduce the health burden related to smoke from incomplete biomass combustion process (Zuk *et al.* 2006).

CONCLUSIONS

The study indicated that the sawdust stored for a long duration of about two years at air pollution levels similar to Kitwe urban was not suitable for mulching, composting and animal bedding as chromium; cadmium and nickel concentrations will most likely exceed the acceptable thresholds of 25; 1,5 and 50 mg/kg respectively.

It was also found that wood smoke generated under experimental conditions in this study was unlikely to endanger users of small-scale heating and domestic energy systems as the level of toxic substances investigated complied with the World Health Organization guidelines on annual exposure limits of 0,2 $\mu\text{g Cr/m}^3$; 180 $\mu\text{g Ni/m}^3$ and 0,2 $\mu\text{g Cd/m}^3$.

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