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Bioaccumulation of Nutrients and Heavy Metals in Plants at a Coal Mine

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ABSTRACT

This study assessed the bioaccumulation of nutrients (N, P, and Ca) and heavy metals (Ni, Pb and Cd) in plants in Onyeama coal mine, Nigeria. The highest concentrations of Ni (9.30 mg/kg) and Pb (7.90 mg/kg) in soil were observed 1 m from the coal mine site while Cd (0.08 mg/kg) was highest 100 m from the site. Ni in soil ranged from 2.16 to 9.30 mg/kg, Pb from 4.01 to 7.90 mg/kg, and Cd from 0.01 to 0.08 mg/kg. The highest concentrations of Ni (0.001-2.01 mg/kg) and Cd (0.001-2.41 mg/kg) were detected in *Landolphia owariensis* and *Canarium schweinfurthii*, respectively. Similarly, the highest concentrations of N (0.14-1.38 cmol/kg) and P (0.11-0.40 cmol/kg) were detected in *L. owariensis*. The level of Cd in soil reflected significant pollution compared to average global concentrations in soils.

Keywords: mining, macronutrient, soil, vegetation

INTRODUCTION

Coal mining is the process of extracting coal minerals from underground. In this process, the overlying soil layer with existing vegetation are removed and deposited in another fresh area, thus, the deposition of million tons of overburdens in the forms of rocks, shale, coarse tailing results in barren, biologically inert overburden dumps called mine spoils (Hazarika *et al.* 2006). Coal, the world's most abundant, most accessible and most versatile source of fossil energy was brought to the fore-front of the global energy scene by the industrial revolution of the 10th century (Akinbami *et al.* 2001). Ranking second to oil amongst the world's different energy resources, coal remains a major source of energy in Nigeria (Ogugbuaja *et al.* 2000), accounts for 75% (up to 49.8 billion tons) of the national energy consumption in China (Yang 2006; Xiao *et al.* 2011), and elsewhere providing an alternative to fuel wood (UNESCO 1983; Campbell 1986; Mishra 2004).

Coal mining as a land-use practice brings wealth and employment opportunity in an area, but simultaneously leads to extensive environmental degradation. Heavy metals from mining wastes, which accumulate in water, soil or plants through leaching or absorption, may be toxic to man, livestock or other animals who depend on the water, plants or soil for food, drinking or shelter (Kakulu 2001). Heavy metal pollution is a world-wide phenomenon that poses serious health hazards to aquatic and terrestrial ecosystems. Metals such as zinc (Zn), boron (Bo), manganese (Mn) and copper (Cu) are essential for plant growth and development at trace quantities but metals like cadmium (Cd), lead (Pb) and mercury (Hg) play no positive role in plant or animal biochemistry and physiology (Fosmire 1990). Heavy metals in soils are released from human activities such as waste disposal (Ogbonna and Okeke 2011), vehicular emission (Turer and Maynard 2003; Suzuki *et al.* 2008; Ogbonna and Okezie 2011), or industrial and energy production (Chon *et al.* 1995; Wong and Mark 1997; Li *et al.* 2001) that releases metal-containing dust and smoke into the atmosphere and subsequently deposited in soil.

The soil constitutes an essential environmental, ecological and agricultural resource that needs to be protected from further degradation for healthy food supply to the world's teeming population (Rashad and Shalaby 2007). The distribution of heavy metals between soil and plants is a key issue in assessing the impact of anthropogenic activities, such as coal mining, on the ecosystem. Studies on soil and vegetation of metal-contaminated sites and their peripheries are essential for an accurate assessment of metal toxicity of soils and aerial plant parts in relation to the possible toxic impacts on herbivorous consumers and human health. Such studies are also necessary to provide valuable information for reclamation of metalliferous sites. Indeed, several studies have been carried out in coal mines, including removal of trace elements from acid mine drainage (Singh and Rawat 1985), low input approach to vegetation establishment on mine and coal ash wastes in Zimbabwe (Piha *et al.* 1995), integrated ecological study on revegetation of coal mine spoil (Singh *et al.* 1995), structure, functioning and impact of young plantations of four native woody species on coal mine spoil (Singh 1999a), restoration of opencast coal mine spoil by planting exotic tree species in Northern Coal Ltd. in the Singrauli coal fields (Dutta and Agrawal 2003) in India, health effects of indoor fluoride pollution from coal burning in China (Ando *et al.* 1998), health impacts of coal (Finkelman 2007), socio-economic profile and quality of life index of sample households of mining areas in coal mines in Orissa (Mishra *et al.* 2008), modeling of coal bed methane production and CO_2 sequestration in coal seams (Ozdemir 2009). Others include the health benefits of mechanization (Asogwa 1988), natural radioactivity associated with bituminous coal mining (Balogun *et al.* 2003), data evaluation of trace elements in coal (Ewa 2004), heavy metal concentrations in coal and sediments from River Ekulu (Adaikpoh *et al.* 2005), preliminary investigation on acid generating potential of coals (Ehinola and Adene 2008), influence of mine drainage on water quality along River Nyaba (Nganje *et al.* 2009) in Nigeria. Despite fairly extensive work, a literature search showed that no work has been carried out on the bioaccumulation of nutrients and heavy metals in plants growing on or near a coal mine. This study, therefore, aimed to

Received: 1 January, 2012. Accepted: 22 March, 2012.

Original Research Paper

assess the accumulation of nutrients and heavy metals in plants on a coal mine.

MATERIALS AND METHODS

Study area

The study on bioaccumulation of nutrients and heavy metals in plants was carried out in Onyeama coal mine, Enugu State, Nigeria. Enugu State is located on the lowland rainforest zone of Nigeria (Keay 1959) but has gradually transformed to derived savanna due to human activities like agriculture, logging, and nomadic activities of cattle rearers from northern Nigeria. It lies within latitude 6° 26' N and longitude 7° 27' E with an altitude of 259 m. The area experiences two seasons (wet and dry) with a mean annual rainfall of about 1600 mm (Ofomata 1965). The rainy season generally lasts from April to October while the dry season lasts from November to March.

Collection and digestion of soil samples

Three replicate soil samples (10 g) each were randomly collected from 1, 50 and 100 m sampling positions in the vicinity of the Onyeama coal mine. The control sample was collected 1 km from the coal mine site. Each replicate sample was homogenized and air-dried in circulating air in an oven at 30°C to a constant weight and passed through a 2-mm sieve. To 5 g of each soil sample 3 ml of 30% hydrogen peroxide was added and left for 60 min until the vigorous reaction ceased. Then 75 ml of a 0.5 M solution of HCl was added and the content was heated gently at 50°C on a hot plate for 2 h (Sharidah 1999). The digest was filtered into a 50-ml standard flask. The concentrations of Ni, Pb and Cd in the digested samples were determined using an atomic absorption spectrophotometer (AAS), model UNICAM 919. Triplicate digestion of each sample together with a blank was also carried out.

Collection and digestion of plant samples

Old leaves were sampled from different branches of plant species 2-6 years of age. The leaves of *Monodora myristica* (African nutmeg, Annonaceae), *Zingiber officinale* (ginger, Zingiberaceae), *Parkia clappertoniana* (Clapperton's parkia, Fabiaceae), *Anacardium occidentale* (cashewnut, Anacardiaceae), *Canarium schweinfurchi* (Schweinfurth's olive), *Ageratum conyzoides* (billygoat weed, Asteraceae), *Vernonia amygdalina* (bitter leaf, Compositae), *Landolphia owariensis* (P. Beauv) (white rubber vine, Apocynaceae) and *Manihot esculenta* (cassava, Euphorbiaceae) were randomly collected in November 2010 (dry season) with a stainless secateur, placed in envelopes, labeled and taken to the lab at ambient temperature. The plant samples were rinsed with deionized water to remove any attached dust and pollen particles, placed in crucibles and oven dried at 80°C for 72 h. The dried samples were milled with a Thomas Wiley milling machine (Model ED-5). Plant samples were digested according to the method of Awofolu (2005). Sieved leaf samples (0.5 g) were weighed and added to a mixture of 5 ml concentrated trioxonitrate (V) acid and 2 ml perchloric acid and digested at 80°C using a hot plate until the content was about 2 ml. The digest was allowed to cool, filtered into a 50-ml standard flask using a 0.45 μm Millipore filter kit. The concentrations of nickel (Ni), lead (Pb) and cadmium (Cd) in the digested samples were determined using a UNICAM 919 AAS. Triplicate digestion of each sample was carried out together with blank digest without a plant sample.

The macronutrient content in the sieved leaf samples was determined according to the wet digestion method of Novozamsky *et al.* (1983) for multi-element plant analysis. Calcium (Ca) in the digest was determined by EDTA titration; potassium (K) and magnesium (Mg) were determined by the flame photometry while phosphorus (P) was determined by the vanodo-molybdate spectrophotometric method. Nitrogen (N) in the digest was determined by the micro-Kjeldahl distillation method (Bremner and Mulvancy 1982).

Experimental design and data analysis

A factorial experiment was conducted as a randomized complete block design (RCBD) with three replications. Data were subjected to one-way analysis of variance (ANOVA) and Pearson's correlation analysis using Statistical Package for Social Sciences (SPSS) v. 15 and mean separation according to Steel and Torrie (1980) at $P < 0.05$.

RESULTS AND DISCUSSION

Heavy metal concentration in soils

The concentration of heavy metals in soils sampled from Onyeama mine is summarized in **Table 1**. The highest and the lowest metal concentrations were observed at the coal mine site and the control site, respectively. The concentration of Ni in soil ranged from 2.16 to 9.30 mg/kg, which is significantly lower than 27.2-52.9 mg/kg in São Domingos mine, SE Portugal (Freitas *et al.* 2004) but well above 0.27-0.52 mg/kg in soil at Aznalcóllar mine, SW Spain (Madejón *et al.* 2002) probably due to soil chemical composition of the mined area. Nickel is an environmental pollutant observed in areas with high anthropogenic pressure (USEPA 1997) such as mining. Since there were no other sources of contamination in the area, the source of Ni in soil may be attributed to tailings generated during the mining process (Ogbonna *et al.* 2011). Mining activities generate a large amount of waste rocks and tailings which are deposited at the surface (Freitas *et al.* 2004) and can be toxic to plants. The concentration of Pb in soil ranged from 4.01 to 7.90 mg/kg, which is significantly lower than 149,740.3-250,311.3 mg/kg in Sungai Lembing tin mine, Malaysia (Alshaebi and Wan Yaacob 2009), 234.2-12217.5 mg/kg in São Domingos mine, SE Portugal (Freitas *et al.* 2004) and 3.20-66.9 mg/kg Pb in soil at Aznalcóllar mine, SW Spain (Madejón *et al.* 2002), due to differences in geographical location and soil parent material (Ogbonna *et al.* 2011). The source of Pb in soil is presumably from the mine. Pb soil pollution is readily affected by anthropogenic factors (Martin 2001; Gray *et al.* 2003) such as mining, industrial activities, and vehicular emissions. Pb and Cd are known as potential carcinogens and are associated with blood, nervous system and bone diseases (Jarup 2003). The concentration of Cd in soil ranged from 0.01 to 0.08 mg/kg, which is lower than 0.01-4.73 mg/kg Cd in soil (Madejón *et al.* 2002), 1,382 mg/kg in a sample from the Les Avinières tailing ponds in France (Escarré *et al.* 2010), and 267 mg/kg in soil at Trelogan mine, UK (Bradshaw and Chadwick 1980) but higher than background levels of 0.15 ± 0.11 mg/kg in Beijing (Zhang *et al.* 2008) and 0.62 mg/kg in Hong Kong (Wei and Yang 2010) as well as the average concentration (0.06 mg/kg) in world-wide soils (He *et al.* 2005). Soils at a distance of 0.1 km from the Onyeama mine sites were still contaminated, but the concentration decreased exponentially with the distance. In Les Maline mine sites in southern France, such non-linear decreasing metal concentrations in topsoils with increasing distance to the emission source have been shown (Escarré *et al.* 2010). Fortunately, the areas of metal contaminated soils in the Onyeama mine site are limited to only a few hundreds of meters. This is in contrast to other mining sites, for instance in the Sierra of Cartagena, where soil contamination resulting from mining activities covers an area of approximately 1,000 km^2 (Robles-Arenas *et al.* 2006) and in the Les Malines region, where soil contamination from mining activities covers a few hectares of land (Escarré *et al.* 2010). Heavy metal pollution around mine sites can cause health problems; for instance, two children living in the area surrounding the mine at Les Avinières had a Pb blood concentration higher than 100 μg L^{-1}: a critical level for children (Cicchelero 2006). Spills of mining wastes are a relatively frequent source of metals (Madejón *et al.* 2002), thus, soil pollution with toxic metals and metalloids represents one of the most prominent environmental hazards from

Table 1 Heavy metal concentration (mg/kg) in soil (n = 3).

Sampling distance (m)	Ni	Pb	Cd
1	9.30 a	7.90 a	0.01 c
50	3.08 b	4.01 b	0.03 b
100	2.16 c	4.30 b	0.08 a
Control (1 km)	0.01 d	0.06 c	0.002 d

Means with different superscript are significantly different at $P < 0.05$ according to Duncan's New Multiple Range Test.

Table 2 Heavy metal concentration (mg/kg) in plants at coal site (n = 3).

Plant species	Ni	Pb	Cd
Monodora myristica	1.11 c	0.69 b	1.81 b
Zingiber officinale	0.05 f	0.07 d	0.03 f
Parkia clappertoniana	1.64 b	0.95 a	1.68 c
Ageratum conyzoides	0.54 d	0.09 d	0.18 e
Landolphia owariensis	2.01 a	0.92 a	0.07 f
Anacardium occidentale	0.29 e	0.45 c	1.34 d
Canarium schweinfurthii	1.16 c	1.01 a	2.41 a
Vernonia amygdalina	0.08 f	0.73 b	0.05 f
Manihot esculenta	0.001 g	0.004 e	0.001 g

Means with different superscript are significantly different at $P < 0.05$ according to Duncan's New Multiple Range Test.

abandoned mine sites (Thornton 1996). The source of Cd is presumably from the mine since there were no other sources of pollution in the area. Heavy metals such as Cd, Cr, Pb, Zn and Ni are environmental pollutants observed in areas with high anthropogenic pressure (USEPA 1997) such as coal mining. The accumulation of heavy metals in soils is a serious environmental problem because of its long-term implications for biological, chemical and physical properties of agricultural and forest soil. Soil is an important sink of heavy metals that can be inhaled, ingested, or absorbed, thereby entering the biosphere (Larocque and Rasmussen 1998).

Concentration of heavy metals in plants

The concentration of heavy metals in plants sampled from Onyeama mine is summarized in **Table 2**. The result indicates that the highest and the lowest metal concentrations were observed at the coal mine site and the control site, respectively. The concentration of Ni in plants ranged from 0.05 to 2.01 mg/kg, which is lower than 1.25-7.42 mg/kg observed in *Cynodon dactylon* (syn. *Cynodon incompletes*) and *Sorghum bicolor* (syn. *Syricum grānum*) plants in Aznalcóllar mine, SW Spain (Madejón *et al.* 2002). According to Manta *et al.* (2002) and Boularbah *et al.* (2006), heavy metals may be transported through soils to reach groundwater and cause groundwater contamination or may be taken up by plants. Classic symptoms of Ni toxicity include interveinal chlorosis and development of perpendicular white strips on the above-ground biomass (Hunter and Vergnano 1952; Singh *et al.* 2010). Wang (1993) reported that when the Ni level in plant tissues exceeds 50 mg/kg, it (Ni) inhibits the transfer of iron to the above-ground biomass, thus, resulting in acute iron deficiency and chlorosis. In this study, Ni concentration is well below 50 mg/kg, thus, it (Ni) may not impede the transfer of Fe to the above-ground biomass *vis-à-vis* causing chlorosis. The concentration of Pb in plants ranged from 0.07 to 1.01 mg/kg, which is significantly lower than 2.9-89 mg/kg observed in *Pergularia tomentosa*, *Calotropis procera*, *Acacia tortilis*, *Salsola* sp., *Rhiza strica* and *Convolvulus* sp. in Mahad AD' Dahab mine, Saudi Arabia (Al-Farraj and Al-Wabel 2007) and 0.62-148.0 mg/kg observed in cynodon and sorghum plants in Aznalcóllar mine, SW Spain (Madejón *et al.* 2002). Pb concentrations were not significantly high due to the relatively low soil Pb content and low availability of Pb to plants (Jung and Thornton 1996). The ecotoxicity and mobility of metals in soils depend, among other intrinsic and external soil factors, mainly on their chemical speciation. The spatial distribution and degree of contamination is mainly governed by the ways of dissemination of metal pollutants from the source into the environment such as groundwater contamination by vertical drainage (Dère *et al.* 2006), wind erosion (Fernandez *et al.* 2007), or by the breaking of a mine tailing dike, as that which occurred in Aznalcóllar, Spain (Grimalt *et al.* 1999). Pb is one of the best known toxic heavy metals (Prathumratana *et al.* 2008), a non-essential element in metabolic processes that can become toxic to living organisms in trace quantities (Fulekar and Jadia 2009). Most heavy metals (such as Pb) produce toxicity both in elemental and soluble salt forms and their presence in soil might distort important chemical processes in the ecosystem (Ogbonna *et al.* 2011). The concentration of Cd in plants ranged from 0.03 to 2.41 mg/kg, which is lower than 2,200 mg/kg in plants sampled in the tailing pond within Les Avinières soil (Escarré *et al.* 2010), 14,000 (Lombi *et al.* 2001) and 6,000 mg/kg (Liu *et al.* 2008) obtained in hydroponics but higher than 0.02-0.76 mg/kg observed in cynodon and sorghum plants in Aznalcóllar mine, SW Spain (Madejón *et al.* 2002). Indeed, the value of Cd in leaves of plants (0.03-2.41 mg/kg) were significantly ($P < 0.05$) higher than the level recorded for soil (0.01-0.08 mg/kg). This suggests that Cd concentration in plants was as a result of aerial deposition of metal containing dust on leaves rather than uptake from soil via the roots. Such Cd concentration in plant aerial parts might be detrimental for the local herbivorous fauna, which could be unable to detect the presence of toxic metals in plant tissues as shown for snails (Noret *et al.* 2007). Nevertheless, in several other studies animal could discriminate between toxic metals (Vesk and Reichman 2009). Cadmium accumulates in plants (Navab *et al.* 2006) and by increasing the Cd level in soil, its concentration in plants rises significantly (Gardiner *et al.* 1995). Cadmium is a non-essential element for plant metabolism and disturbs symbiosis between microbes and plants, and predisposes plants to fungal invasion (Kabata-Pendias and Pendias 2001). Generally, the concentrations of heavy metals in plants followed a decreasing order: Cd > Ni > Pb.

Macronutrient content in plants at Onyeama mine

The macronutrient content of plants sampled from Onyeama mine is presented in **Table 3**. Soil pollution by heavy metals in soils seems to negatively affect the uptake of macronutrients (N, P, and Ca) in *Ageratum conyzoides*, *Venonia amygdalina*, *Zingiber officinale* and *Manihot esculenta*, and to a lesser extent in *Parkia clappertoniana*, *Anacardium occidentale and Monodora myristica*. Soils contaminated by mining activities generate spoils, effluents and dust with large concentrations of metals (Zn, Pb, Cd) or metalloids (As) which have adverse effects on biological receptors and ecosystems (Wiegleb and Felinks 2001). The ecotoxicity and mobility of these elements in soils depend, among other intrinsic and external soil factors, mainly on their chemical speciation (Escarrĕ *et al.* 2010). However, *Landolphia owariensis* and *Canarium schweinfurthii* were less affected by the soil pollution in terms of concentration of N, P, and Ca. These two plants probably have some mechanisms to regulate the internal concentration of mineral nutrients in their tissues in spite of the concentration of heavy metals in the soil solution (Madejón *et al.* 2002). The highest content of Ca was obtained in *Parkia clappertoniana* (8.42 cmol/kg) and *C. schweinfurthi* (8.01 cmol/kg). The value of Ca ranged from 0.86 to 8.42 cmol/kg, and this is higher than 0.203-1.820 cmol/kg obtained from *Gmelina* vegetation in a municipal solid waste dump in Umuahia, Nigeria (Ogbonna and Okeke 2011). The highest content of N was obtained in leaves of *L. owariensis* (1.38 cmol/kg). The value of N in plants ranged from 0.14 to 1.38 cmol/kg, which is higher than 0.13-0.70 cmol/kg obtained from *Pinus caribeae*, *Gmelina arborea*, *Psidium guajava*, *Icacina trichantha*, *Glyricidia sepium*, *Harungana* sp., *Venonia amygdalina*, *Alchornea cordifolia*, and *Lovoa* sp. in roadside vegetation along the Umuahia-Ikot-Ekpene highway,

Table 3 Macronutrient content (cmol/kg) in plants at coal site (n = 3).

Plant species	Ca	N	P
Monodora myristica	7.60 b	0.28 cd	0.14 def
Zingiber officinale	0.86 f	0.36 c	0.11 f
Parkia clappertoniana	8.42 a	0.34 c	0.21 cde
Ageratum conyzoides	2.81 d	0.21 cd	0.16 def
Landolphia owariensis	4.50 c	1.38 a	0.40 a
Anacardium occidentale	1.28 f	0.14 d	0.12 ef
Canarium schweinfurthii	8.01 ab	1.13 b	0.26 bc
Vernonia amygdalina	2.16 e	1.02 b	0.22 cd
Manihot esculenta	2.42 de	0.20 cd	0.32 b

Means with different superscript are significantly different at $P < 0.05$ according to Duncan's New Multiple Range Test.

Nigeria (Ogbonna and Okezie 2011) but lower than 0.163-1.753 cmol/kg obtained from a *Gmelina* plantation (Ogbonna and Okeke 2011). Similarly, the highest content of P was obtained in *L. owariensis* (0.40 cmol/kg) and the value of P in plants ranged from 0.11 to 0.40 cmol/kg, which is significantly lower than 26.20-42.0 cmol/kg obtained from *Pinus caribeae*, *Gmelina arborea*, *Psidium guajava*, *Icacina trichantha*, *Glyricidia sepium*, *Harungana* sp., *Venonia amygdalina*, *Alchornea cordifolia*, and *Lovoa* sp. in roadside vegetation (Ogbonna and Okezie 2011) and 0.143-1.490 cmol/kg obtained from a *Gmelina* plantation (Ogbonna and Okeke 2011). Generally, the macronutrient content of plants followed an increasing order: P < N < Ca.

CONCLUSION

This study on bioaccumulation of nutrient and heavy metals by plants in an abandoned coal mine indicate that coal mining is one of the anthropogenic sources of metals in the environment. The concentrations of heavy metal in the soils were lower than corresponding levels observed in Aznalcóllar mine, SW Spain (Madejón *et al.* 2002) but higher than the background levels of 0.15 ± 0.11 mg/kg in Beijing (Zhang *et al.* 2008) and 0.62 mg/kg in Hong Kong (Wei and Yang 2010). Similarly, the concentration of Ni, Pb, and Cd in plants was lower than the corresponding values obtained in cynodon and sorghum plants in Aznalcóllar mine, SW Spain (Madejón *et al.* 2002). The value of N and Ca in plants is higher than corresponding levels (0.13-0.70 cmol/kg and 0.203-1.820 cmol/kg) observed in *Pinus caribeae*, *Gmelina arborea*, *Psidium guajava*, *Icacina trichantha*, *Glyricidia sepium*, *Harungana* sp., *Venonia amygdalina*, *Alchornea cordifolia*, *Lovoa* sp. (Ogbonna and Okezie 2011) and *Gmelina* vegetation (Ogbonna and Okeke 2011), respectively in Umuahia, Nigeria. However, the level of P in plants is significantly lower than 26.20-42.0 cmol/kg and 0.143-1.490 cmol/kg observed in *Pinus caribaea*, *Gmelina arborea*, *Psidium guajava*, *Icacina trichantha*, *Glyricidia sepium*, *Harungana* sp., *Venonia amygdalina*, *Alchornea cordifolia*, *Lovoa* sp. (Ogbonna and Okezie 2011) and a *Gmelina* plantation, respectively (Ogbonna and Okeke 2011). Emphatically, the plant species sampled in this study (*M. myristica*, *P. clappertoniana*, *A. occidentale*, *C. schweinfurthii*, *L. owariensis*) are important forest fruit trees consumed by Nigerians due to their high content of vitamins (Lower and Agyente-Badu 2009; Uhegbu *et al.* 2011), minerals (Sivagurunathan 2010; Akinmutimi *et al.* 2011) and essential oil (Agu *et al.* 2008; Ekeanyanwu *et al.* 2010), and medicinal value (Patrick-Iwuanyanwu *et al.* 2010). The accumulation of heavy metals in these forest fruit trees (*M. myristica*, *P. clappertoniana*, *A. occidentale*, *C. schweinfurthii*) can be a route of introduction of metals in the human system, thus, constituting a serious health hazard for herbivorous consumers and human health.

ACKNOWLEDGEMENTS

The authors are grateful to the Management of Michael Okpara University of Agriculture Umudike for the provision of stand-by generators in various Colleges (Faculty), which has made laboratory work to be done with or without supply of electricity by the National Electric Power Authority (NEPA). The findings and conclusions in the report are those of the authors. The authors declare they have no conflicting financial interests.

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