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Bioindicator-Based Approach to Deposition of Heavy Metals in Roadside Vegetation: A Case Study of Benin-Auchi Road, Edo State, Nigeria.

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Abstract

The study investigates the deposition of atmospheric heavy metals in roadside vegetation using a bioindicator-based approach along the Benin-Auchi Road in Edo State, Nigeria. Two commonly occurring plant species Mangifera indica and Chromolaena odorata were selected as bioindicators due to their widespread presence and morphological suitability for capturing airborne pollutants. Vegetation samples were collected at three distances from the roadside (0–5 m, 5–10 m, and >10 m) in urban, peri-urban, and rural segments of the expressway. The concentrations of lead (Pb), zinc (Zn), copper (Cu), cadmium (Cd), and nickel (Ni) were analyzed using Atomic Absorption Spectrophotometry (AAS) after wet acid digestion. The results revealed significantly higher concentrations of all tested metals in vegetation within 0–5 meters of the road, particularly in urban areas. Pb ranged from 15.2 mg/kg in urban roadside vegetation to 9.3 mg/kg in rural areas; Zn ranged from 22.6 mg/kg to 15.5 mg/kg across the same gradient. Similar declining patterns were observed for Cd (3.6–2.1 mg/kg), Cu (9.4–6.5 mg/kg), and Ni (6.7–3.4 mg/kg). Statistical analysis indicated strong positive correlations between Pb and Zn ($r = 0.89$), and between Cu and Ni ($r = 0.76$), pointing to shared sources, mainly vehicular emissions. No significant differences were found between the two plant species in terms of heavy metal accumulation, confirming their effectiveness as bioindicators. These findings highlight the utility of roadside vegetation in monitoring airborne heavy metal pollution and suggest that proximity to vehicular traffic strongly influences the degree of atmospheric deposition. The bioindicator-based approach proves effective in environmental assessment, offering a cost-efficient and reliable method for air quality surveillance along major transportation corridors like the Benin-Auchi Road.

Keywords: Bioindicator, heavy metals, roadside vegetation, mangifera indica, chromolaena odorata, environmental monitoring atmospheric deposition.

Introduction

Atmospheric pollution has emerged as a critical global environmental issue due to its pervasive and detrimental impacts on ecosystems and public health. Among the various pollutants, heavy metals stand out because of their toxicity, persistence in the environment, bioaccumulation tendencies, and potential to adversely affect biological systems (Alloway, 2013). Heavy metals such as lead (Pb), cadmium (Cd), zinc (Zn), nickel (Ni), copper (Cu), and chromium (Cr) are not biodegradable and may persist in the atmosphere, soil, water, and living organisms for extended periods. Unlike organic pollutants, heavy metals cannot be broken down into harmless byproducts, making them particularly hazardous in urban and industrial environments (Kabata-Pendias *et al*, 2007).

A significant source of heavy metal emissions is vehicular activity. In urban centers where traffic congestion is common, motor vehicles contribute substantially to airborne metal contamination through fuel combustion, brake wear, tire wear, engine oil leakage, and corrosion of metallic components (Charlesworth *et al.*, 2011; Adamiec *et al*., 2016). Roadsides and highways are thus considered hotspots for heavy metal accumulation due to direct atmospheric deposition and surface runoff (Wei *et al*, 2010). With the steady rise in urbanization and the proliferation of motor vehicles, this issue is becoming increasingly relevant, especially in developing countries with limited air quality monitoring systems.

Atmospheric deposition is the process by which airborne pollutants, including heavy metals, settle from the atmosphere onto land or water surfaces. This deposition can occur via two primary mechanisms: dry and wet deposition. Dry deposition involves the direct transfer of particles and gases onto surfaces without precipitation, whereas wet deposition includes the removal of pollutants through rainfall, snow, or fog (Pacyna *et al*, 2001). Both processes play a vital role in determining the spatial distribution of heavy metals in terrestrial ecosystems, especially in areas adjacent to roadways. The rate and intensity of deposition are influenced by several factors, including meteorological conditions, particle size, the physicochemical properties of the pollutants, and the type of receiving surface (Sharma *et al*, 2005). Vegetation plays a critical role in intercepting these pollutants due to its surface roughness and physiological characteristics, making it a natural sink for airborne metals. This ability of plants to accumulate atmospheric pollutants forms the basis for their use as bioindicators of environmental quality.

The concept of using plants as bioindicators for environmental monitoring has gained prominence over the past decades. Bioindicators are living organisms that respond to environmental changes in a measurable way, allowing for the indirect assessment of pollutant levels (Markert *et al*., 2003). In the context of atmospheric heavy metals, certain plant species can accumulate these elements through foliar deposition or root uptake, providing valuable information on the spatial and temporal distribution of pollution. Mosses and lichens, in particular, have been widely used as passive biomonitors due to their high surface area, lack of roots, and dependence on atmospheric sources for nutrients (Garty, 2001; Fernández *et al*., 2010). Unlike vascular plants, mosses and lichens absorb water and nutrients over their entire surface, making them highly sensitive to air pollutants. Moreover, their ability to trap particulate matter and retain heavy metals has been demonstrated in numerous studies across urban and industrial environments (Szczepaniak *et al*, 2003; Ares *et al*., 2012).

Tree leaves also serve as useful bioindicators, albeit with lower sensitivity compared to cryptogams. Species such as Platanus acerifolia, Alnus glutinosa, and Tilia cordata have been used in studies to estimate metal loads in urban air (Simon *et al.*, 2011). The advantage of using tree leaves lies in their wide distribution, seasonal availability, and ease of sampling, which makes them suitable for large-scale and long-term monitoring programs. Roadside environments are subject to complex interactions between natural and anthropogenic factors. Vehicular emissions are among the primary anthropogenic sources of heavy metals, especially in urban areas where traffic volume is high. Lead, once a major pollutant due to the use of tetraethyl lead in gasoline, has declined in many countries following the adoption of unleaded fuel. However, residual Pb contamination remains a concern, and other metals such as Zn, Cu, and Cd continue to pose significant risks (Al-Khashman, 2007; Wong *et al*., 2006).

Tires, for instance, contain substantial quantities of ZnO, which is released during wear and contributes to Zn accumulation in roadside soils and vegetation (Thorpe and Harrison, 2008). Brake pads and linings are sources of Cu, Pb, and Sb, while engine oils and lubricants may contain Ni and Cr. These metals, released in fine particulate form, can travel through the atmosphere and deposit onto surrounding surfaces, including vegetation. Natural factors such as wind speed, direction, and rainfall intensity influence the dispersion and deposition patterns of these pollutants. Topography, vegetation type, and roadside architecture also play a role in determining where and how pollutants are deposited. For instance, the presence of vegetation buffers or barriers can reduce the penetration of airborne metals into adjacent ecosystems (Zhou *et al*, 2014).

The accumulation of heavy metals in the environment has far-reaching implications for both human health and ecological integrity. Chronic exposure to metals such as Cd, Pb, and Ni is associated with various health disorders including kidney damage, neurological impairments, cardiovascular diseases, and carcinogenic effects (Jaishankar *et al*., 2014). Children and pregnant women are particularly vulnerable due to their higher absorption rates and sensitivity to toxic substances.

In ecosystems, heavy metal contamination can lead to soil degradation, loss of biodiversity, and disruption of nutrient cycling processes. Plants exposed to elevated metal concentrations may exhibit reduced growth, chlorosis, and impaired photosynthesis (Nagajyoti *et al*., 2010). Furthermore, metals accumulated in plant tissues can enter the food chain, affecting herbivores and higher trophic levels. The role of vegetation in mediating these effects is twofold. While plants serve as reservoirs for atmospheric metals, reducing their dispersion, they may also act as conduits for metal transfer into ecological systems. Thus, understanding the dynamics of metal accumulation in roadside vegetation is essential for assessing environmental risks and formulating mitigation strategies.

Material and Methods

Study Area

This study was conducted along the Benin-Auchi Expressway in Edo State, Nigeria. The expressway spans approximately 130 km and connects urban Benin City with smaller towns such as Ekpoma, Irrua, Uromi, and Auchi. The area experiences heavy vehicular traffic and is characterized by both urban and semi-rural settings, which makes it ideal for assessing spatial variability in atmospheric heavy metal deposition. The region lies within a humid tropical zone with a bimodal rainfall pattern and supports a variety of roadside vegetation suitable for use as bioindicators.

Research Design

The research adopted a stratified random sampling design to select representative sampling sites at intervals along the Benin-Auchi Expressway. Each site was categorized based on land use and traffic density into Urban (e.g., Benin City outskirts), Peri-urban (e.g., Ekpoma, Irrua) and Rural (e.g., Ewu, Uromi). At each site, vegetation samples were collected at three different distances from the road edge; 0–5 meters (high exposure zone), 5-10 meters (moderate exposure zone) and >10 meters (control zone) The selection of plant species was based on the following criteria; Abundance and availability at all sites, Broad leaves for efficient deposition capture and Non-edibility to avoid ethical concerns related to food safety. Two primary species were selected such a s Mangifera indica (Mango tree) and Chromolaena odorata (Siam weed). These species are commonly found along the expressway.

Sample Collection

Leaves were plucked randomly from multiple points on each plant (approximately 1.5–2 m above the ground) using sterilized gloves and scissors. About 150–200 grams of fresh leaf material was collected per species per site. Samples were stored in labeled, airtight polyethylene bags and transported to the laboratory in a cooler box.

Sample Preparation

Leaf samples were washed with distilled water to remove loosely adhered particles, followed by deionized water rinse to prevent ionic contamination. They were then oven-dried at 60°C until a constant weight was achieved, ground into fine powder using a ceramic mortar and pestle, and stored in airtight containers prior to digestion. 1g of dried plant powder was digested in a flask by adding 10ml of concentrated nitric acid (HNO_3) and it was allowed to stand for 12hours (cold digestion). The mixture was heated at 95ºC on a hot plate until near dryness, after which 5ml of perchloric acid $HClO_4$ and it was reheated until a clear digest was obtained. It was further cooled and filtered through Whatman No42 filter paper and made up to 50ml with deionized water.

Heavy metals like (Pb, Zn, Cd, Cu, and Ni) were quantified using Atomic Absorption Spectrophotometry (AAS) (Model: PerkinElmer AAnalyst 200). The equipment was calibrated using standard metal solutions of known concentrations.

Results

The concentrations of five heavy metals (Pb, Zn, Cu, Cd, and Ni) in the leaves of the selected bioindicator plants (Mangifera indica and Chromolaena odorata) were analyzed for three distinct zones along the Benin-Auchi Expressway (urban, peri-urban, and rural), at varying distances from the roadside (0–5 meters, 5–10 meters, and >10 meters). The results of the metal concentrations are presented in Table 1.

Heavy Metal	Urban Zone (0–5m)	Peri-Urban Zone (5–10m)	Rural Zone (>10m)
Pb	15.2 ± 2.1	12.5 ± 1.8	9.3 ± 1.4
Zn	22.6 ± 3.4	19.8 ± 2.9	15.5 ± 2.0
Cu	9.4 ± 1.2	8.1 ± 1.1	6.5 ± 0.9
Cd	3.6 ± 0.5	2.8 ± 0.4	2.1 ± 0.3
Ni	6.7 ± 1.0	5.2 ± 0.8	3.4 ± 0.6

Table1: Mean Concentrations (mg/kg) of Heavy Metals in Vegetation Samples

Spatial Variations in Metal Concentrations

The analysis revealed significant variations in the concentrations of all five heavy metals across the three zones. The urban zone (0–5 meters) showed the highest concentrations for all metals, followed by the peri-urban zone (5–10 meters), and the rural zone (>10 meters), which recorded the lowest concentrations.
Lead (Pb) concentrations were highest in the urban zone (15.2 mg/kg) and lowest in the rural zone (9.3 mg/kg), indicating a clear gradient of deposition from the road. Pb is primarily associated with vehicular emissions and industrial activity along the highway.
Zinc (Zn) also followed a similar trend, with the highest concentration in the urban zone (22.6 mg/kg). Zn is commonly associated with automotive wear (e.g., tire wear) and combustion processes.
Copper (Cu) and Nickel (Ni) concentrations were found to be moderately high in the urban zone (9.4 mg/kg and 6.7 mg/kg, respectively), suggesting these metals are primarily emitted by vehicle exhausts, which are more concentrated in urban areas.
Cadmium (Cd), often associated with industrial and vehicular emissions, showed a decreasing concentration from the urban (3.6 mg/kg) to the rural zone (2.1 mg/kg), further supporting the hypothesis of increased metal deposition closer to the highway.

Comparison of Plant Species

When comparing the two plant species (Mangifera indica and Chromolaena odorata), there were no significant differences in the concentrations of metals absorbed by either species ($p > 0.05$). Both species were equally effective in capturing heavy metals, making them reliable bioindicators for roadside pollution studies. The highest concentrations of all metals in both species were observed in the urban zone (0–5 meters). There was a slight variation in the metal concentrations between the species, with Chromolaena odorata generally showing slightly higher uptake of Zn and Cu, whereas Mangifera indica accumulated higher levels of Pb and Cd.s

Statistical Significance

Results of ANOVA indicated that metal concentrations differed significantly ($p < 0.05$) between the three zones (urban, peri-urban, and rural). Post-hoc Tukey's HSD tests further confirmed that metal deposition near the roadside (0–5 meters) was significantly higher than at further distances (5–10 meters and >10 meters), with the rural zone showing the least contamination.

Discussion

The findings from this study suggest that heavy metal deposition along the Benin-Auchi Expressway is closely linked to traffic-related pollution, with the highest concentrations observed near the roadside in urban areas. These results align with similar studies conducted in other urban environments (Baba et al., 2010; Omole et al., 2014), where roadside vegetation was found to accumulate high levels of vehicular pollutants. The spatial gradient of pollution observed highest near the road and gradually decreasing with distance supports the conclusion that atmospheric deposition is a localized phenomenon, with the potential for long-range dispersion in some instances, depending on the specific metal and environmental factors.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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