Plant Bark and Leaves as Bio-Indicators of Heavy Metals in Environmental Pollution Monitoring

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Environmental pollution from diesel generator emissions contributes to the accumulation of heavy metals in surrounding vegetation, especially in urbanizing areas. This study assessed the bio-indicator potentials of tree bark and leaves from *Terminalia catappa* near diesel generator plants at Mountain Top University. The work focused on toxic metals (As, U, Ag, Pb, Cd, Se), heavy metals (Ba, Ti, V, Cu, Sn), and essential metals (Fe, K, Mg, Zn, Ca, Na, Mn). Atomic Absorption Spectroscopy (AAS) revealed elevated levels of toxic metals such as Pb, Cd, and As, particularly in bark tissues. Notably, Pb reached 6.03 mg/kg in TL1 (tree leaves at location one) and over 6 mg/kg in TB1 (tree bark from location one), Cd ranged between 1.5 and 2.2 mg/kg, Ba (75.01 mg/kg in TB1) and (68.0 mg/kg in TB2), while Ti showed (90.1 mg/kg in TL3), (82.0 mg/kg in TL1) exceeding common phytotoxic thresholds. Barium recorded the highest heavy metal concentration in TB1, followed by Ti in TL3. SEM images confirmed the presence of particulate deposition more embedded in bark than on leaves—corroborating their role in pollution capture. The data highlight bark as a robust long-term indicator of environmental contamination, while leaves serve as responsive short-term sensors.

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INTRODUCTION

Environmental degradation caused by pollution is increasingly becoming a global challenge, with densely populated and industrialized regions such as Nigeria facing heightened concerns (Nwadiogbu *et al*. 2024; Ngueagni *et al*. 2025). Among these pollutants, heavy metals (HMs) are of particular concern because of their persistence, toxicity, and bioaccumulative nature (Priyanka *et al*. 2024). These metals are introduced into the environment *via* anthropogenic activities including industrial emissions, vehicular exhausts, diesel generator discharges, and domestic fuel combustion (Ede *et al*.

2023; Kolawole and Olatunji 2023; Obayagbona *et al*. 2024; El-Rayyes *et al*. 2025). For example, industrial processes release Cd, Pb, Ni, and Cr during manufacturing, smelting, and waste disposal (Kolawole and Olatunji 2023; Nwadiogbu *et al*. 2024), while vehicular emissions contribute Pb, Cu and Zn because of fuel combustion and component wear (Obayagbona *et al*. 2024). In regions such as Nigeria, where unstable electricity supply drives widespread reliance on diesel generators, combustion emissions represent an important source of local air, soil, and water contamination (Maciejczyk *et al*. 2021; Tong *et al*. 2023; Yunusa *et al*. 2024).

Once released, heavy metals are non-biodegrade; instead, they accumulate in soils, water bodies, vegetation, and woody tissues, causing long-term risks to ecosystems and human health (Angon *et al*. 2024; Afzal and Mahreen 2024). They alter the chemistry of the soil and microbial diversity, contaminate surface and groundwater, impair agricultural productivity, and degrade air quality *via* toxic particulate emissions (Das *et al*. 2023; Saidon *et al*. 2024). Over time, bioaccumulation and biomagnification transport metals *via* the food chain, destabilizing ecosystems (Zhang *et al*. 2023). Health impacts are equally severe: Hg and Pb exposure in children leads to neurodevelopmental deficits (Abd Elnabi *et al*. 2023; Ngueagni *et al*. 2025). Cd, hexavalent Cr, and As are classified carcinogens, and inhalation of particulates from these metals contributes to cardiovascular and respiratory diseases (Ede *et al*. 2022; El-Rayyes *et al*. 2025). Chronic exposure further causes liver and kidney dysfunction, reproductive abnormalities, and endocrine disruption (Angon *et al.* 2024; Afzal *et al*. 2024).

From a monitoring perspective, conventional techniques such as Atomic Absorption Spectroscopy (AAS), Gas Chromatography (GC), UV-Vis Vis spectrophotometry , and High-Performance Liquid Chromatography (HPLC) are highly sensitive but constrained by labor intensiveness, cost, lack of real-time capacity, and sample preparation (Shi *et al*. 2022; Ogunseye and Olowokere 2023; Binda 2024; Bujar *et al.* 2025). In response, plants have gained attention as sustainable bioindicators because of their affordability, natural interactions with the environment, and ability to integrate pollutant exposure over time (Olowoyo *et al*. 2021; Akinola *et al*. 2023; Olowokere *et al.* 2023; Ogunrotimi and Adeyemi 2023). Various studies have demonstrated that plant stems, leaves, roots, and bark can accumulate metals depending on organ morphology, species type, and proximity to sources of contamination (Ogunseye *et al*. 2023; Yunusa *et al*. 2024). For instance, *Mangifera indica* and *Terminalia catappa* have been shown to accumulate significant levels of contaminants, making them suitable for biomonitoring (Eze *et al*. 2020; Ajibade *et al*. 2022).

Recent studies reinforce this approach. For instance, Erdem (2023a) documented long-term changes in strontium levels in tree bark and wood, while Koç *et al*. (2024) reported Ba and Ni accumulation in plant tissues. Metals such as Cd, Pb, As, Cr, and Ni remain global priority pollutants due to their environmental persistence and health effects (EPA, ATSDR). For example, Yaşar *et al*. (2025) noted arsenic accumulation in landscape plants, Ozturk *et al*. (2024) highlighted compass orientation and tree species as key factors in Cr uptake, and Erdem (2023b) showed variation in Co, Cr, and V accumulation across tree organs and soil depths. Further, Canturk *et al.* (2024) identified appropriate species for Sb monitoring, Şevik *et al*. (2024) showed long-term uptake of Se, Ag, Ti and Sb by *Pinus nigra*, and Isinkaralar *et al*. (2025) confirmed the value of tree rings for reconstructing atmospheric deposition histories. Kulac *et al*. (2025) evaluated various plant species for Sr monitoring in urban environments.

Despite these advances, gaps remain in sub-Saharan Africa, including Nigeria, particularly regarding the role of diesel generator emissions in shaping local metal contamination. This is critical in Nigeria, where widespread generator use contributes significantly to urban air pollution. Due to limited infrastructure for continuous monitoring, the application of plant-based biomonitoring is particularly valuable. Therefore, this study adopted an environmental biomonitoring approach to evaluate toxic, heavy, and essential metals in the bark and leaves of *Terminalia catappa* around diesel generator plants in Ogun State, Nigeria. The objectives are to (1) quantify metal accumulation across organs, (2) examine spatial deposition relative to generator proximity, and (3) evaluate the potential of *T. catappa* as a reliable bioindicator for long-term monitoring of urban air pollution.

MATERIALS AND METHODS

Study Area

The study was conducted at the college of Basic and Applied Sciences (CBAS), Mountain Top University, located in Mowe, Ibafo, within the Obafemi Owode local government area of Ogun State, Nigeria. The study site, CBAS, is located at $3^0$24’41.26” E and $6^0$43’50.15” N (Fig. 1). The chosen locations were selected to reflect gradients of potential exposure: (i) sites directly adjacent to the generator (high exposure), (ii) intermediate zones (moderate exposure), and (iii) control sites located farther away with minimal expected influence. These differences make it possible to assess spatial deposition patterns and evaluate the role of proximity to generator emissions. The sampling points include TL1 and TB1 (leaves and bark from L1), TL2 and TB2 (from L2), and TL3 and TB3 (from L3). Location L3 is noted as farthest from the source of pollution which was approximately 20 m away from the pollutant source. At L1 (closest to the diesel generator (about 5 m away from the pollutant source). The test locations were situated at distances of 5 m, 20 m, 40 m, and 55 m from the generator plant in the [north, south, east, west] directions.

This region is distinguished by a blend of residential, educational, commercial, and religious activities, which collectively contribute to varying levels of environmental pollution, most especially from generator plants. Mowe and Ibafo, situated along the bustling Lagos-Ibadan expressway, are areas experiencing rapid urbanization and industrial growth. Several small-to-medium-scale manufacturing and construction companies has increased industrial emissions in the area. The activities of these industries, along with high vehicular traffic and extensive use of power generators due to inconsistent electricity supply, raise pollution levels in this area. These industrial and infrastructural developments make Mowe and Ibafo an ideal setting for studying the diverse sources and challenges of environmental pollution in a typical Nigerian urbanizing landscape. Figure 1 illustrates the leaves and barks of the plant used in this study.

The selected species is *Terminalia catappa* L. (commonly known as tropical almond), a large, evergreen to semi-deciduous tree widely distributed across tropical and subtropical regions, including Nigeria. The bark is grey to dark brown, which is relatively thick, that enables the adsorption and retention of atmospheric particulates and deposited metals over time. The leaves are large, leathery, simple, and arranged spirally; and their broad lamina and waxy cuticle enhance interception of airborne particulates and gaseous pollutants. Physiologically, *T. catappa* is tolerant of urban stress, and it can adapt well to polluted environments and poor soil, which makes it suitable for biomonitoring. The species was selected in this study for the following reasons: (i) it is abundant and easily accessible in urban and peri-urban landscapes of Nigeria; (ii) its large leaves and fissured bark which enhances ample surface area for pollutant deposition and accumulation, (iii) it is long-lived, allowing for long-term integration of pollution signals, and (iv) its non-invasive sampling (bark and leaf collection) makes it a practical bioindicator species for environmental monitoring.

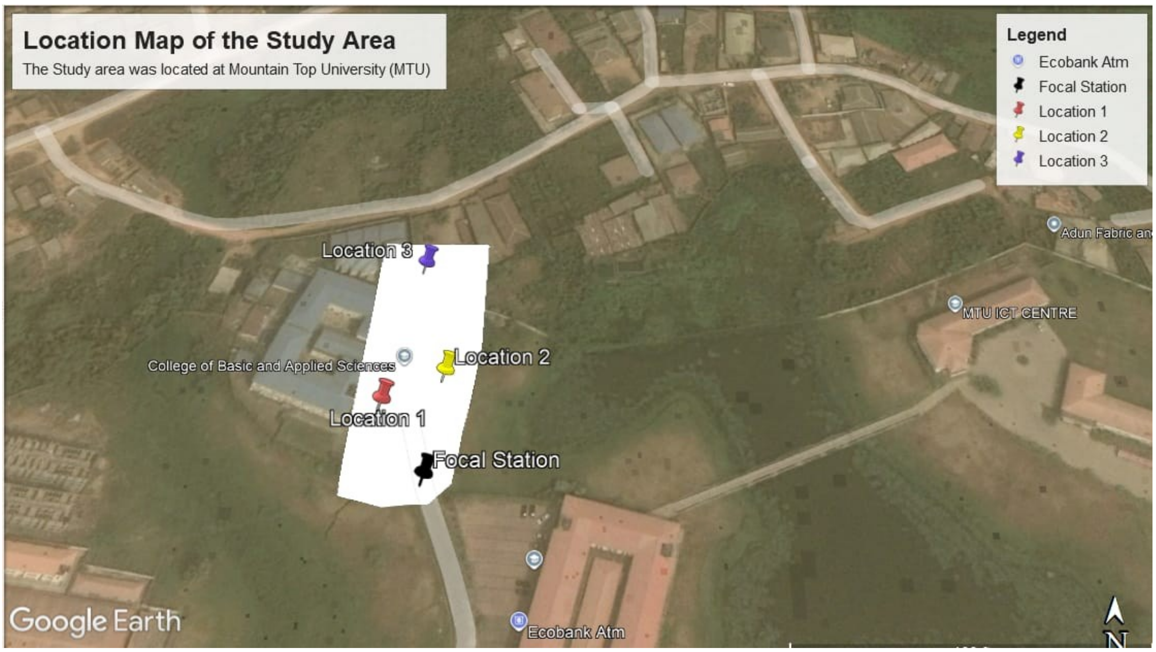

Fig. 1. Study location near generator plant, CBAS, MTU

Characterizations

Fourier Transform Infrared Spectroscopy (FT-IR; CARY630 NBY, Thermo Fisher Scientific, Waltham, MA, USA) was used in identification of the functional groups involved in dye adsorption. Scanning Electron Microscopy (SEM; Phenom ProX, USA) was used in the examination of surface morphology and porosity. Brunauer-Emmett-Teller (BET) Analysis (Quantachrome NOVA 2200C, USA) was utilized for the determinations of pore size distribution and specific surface area. The point of zero charge (pH_{PZC}) was investigated using a Nano ZS analyzer (Malvern, UK) to assess surface charge behavior across pH ranges.

Materials

The chemicals used in this study were carefully selected to simulate environmental pollution and assess the bioaccumulation of pollutants in plant barks and leaves. The following chemicals were utilized: lead nitrate (Sigma-Aldrich, USA, 98%), cadmium chloride (Merck, Germany, 99%), copper sulfate (Fisher Scientific, USA, 99%), zinc sulfate (Alfa Aesar, UK, 99%), nickel sulfate (VWR International, USA, 99.5%), potassium dichromate (Acros Organics, Belgium, 99%), iron(III) chloride (Chem-Supply, Australia, 98%), sodium hydroxide (Brenntag, Germany, 98%), ammonium nitrate (Yara International, Norway, 99%), and manganese(II) sulfate (Sigma-

Aldrich, USA, 98%). Each of these chemicals was used to prepare solutions for evaluating the pollution levels in plant barks and leaves.

Sample Collection and Preparations

Leaf and bark samples of *T. catappa* were collected in July 2024, during the peak of the rainy season in southwestern Nigeria, when the leaves were mature and bark tissues physiologically stable. This period was selected because rainfall and high atmospheric activity enhance the deposition of airborne particulates and metals, allowing representative biomonitoring results. Sample collection was carried out systematically to ensure that plant barks and leaves from different exposure levels were adequately analyzed. Two primary sampling positions were considered: one directly facing the pollution source (*e.g.*, generator plant), and another positioned at the back of the tree, which was not in direct exposure to the pollution source. This selection ensured the assessment of pollution effects from varying exposure levels. In this study, a total of 3 trees were sampled across different locations from the pollution source and from each tree, two sets of samples were collected including the bark and leaves. Each sample was carefully placed in a separate, labeled container to avoid cross-contamination. The samples were transported to the laboratory for further processing. Upon arrival, they were thoroughly washed with distilled water to remove surface dust, soot, and other potential contaminants. The washed samples were then air-dried at room temperature under shade in a clean, dust-free laboratory environment, thereby allowing for improved accuracy in analytical procedures. The dried samples were subjected to microwave heating at different temperatures and pressures to remove any remaining moisture. The dried samples were pulverized using a disintegrator at a controlled atmospheric pressure to break down the samples into finer particles. The pulverized samples were further ground into a fine powder using a laboratory-grade grinder to enhance uniformity for chemical analysis. The finely ground samples were stored in separate, airtight containers to prevent contamination before undergoing laboratory analysis. Figure 2 shows samples of leaves (a) and bark (b) of the plant as collected.

Fig. 2. Leaves (a), and bark (b) of *Terminalia catappa* plant

Heavy Metals Contents Analysis

The sample was homogenized, and 0.5 g of each sample was weighed and transferred into beakers containing 20 mL of Aqua Regia. The digestion was carried out on a heating block in a fume hood for about an hour. The beakers were allowed to cool, and 2 mL of hydrogen peroxide was added to each beaker and heated for 10 min. After the digestion was completed, the digestate volume of each sample was measured. The digestate was then filtered and diluted to 50 mL using ultra-pure deionized water for Atomic Absorption Spectroscopy (AAS) analysis *via* ICP-OES method.

Data Validation

To verify the consistency and reliability of the collected data, triplicate samples from each treatment group were prepared and analyzed. The results from these triplicate analyses and average value were recorded.

RESULTS AND DISCUSSION

Toxic Metals Analysis

Figure 3 illustrates the concentrations of six toxic heavy metals As, U, Ag, Pb, Se, and Cd in tree leaves and barks collected from three different locations (*i.e.,* locations 1, 2, and 3, respectively) around diesel generator plants at CBAS, Mountain Top University. As shown in Fig. 3, high concentrations of heavy metals were observed.

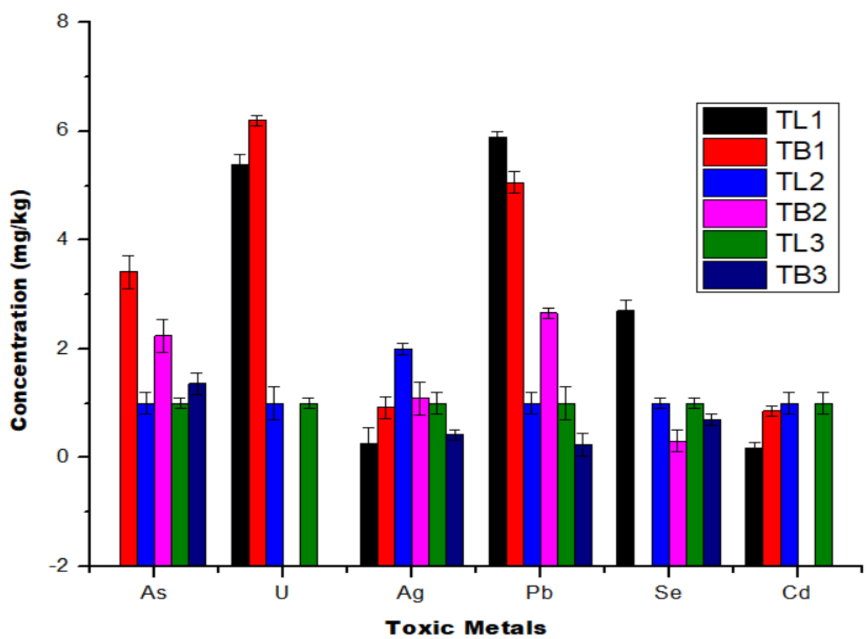

Fig. 3. Level of toxic metal concentrations in leaves and bark of trees located at diesel generator plant (TL1 and TB1 are samples of leaves and bark, respectively, from location 1, TL2 and TB2 are from location 2, and TL3 and TB3 are from location 3)

Arsenic levels in TB1 reached about 3.5 mg/kg, while TL1 did not recorded any values. Uranium also peaked in this location, with TB1 showing concentrations of 6.3 mg/kg. Lead presents one of the most pronounced spikes, especially in TL1, with values approaching 6.03 mg/kg. Selenium and cadmium were also elevated here, with TL1 showing Se at nearly 3.01 mg/kg and Cd across all samples ranging from 1.5 to 2.2 mg/kg. Overall, tree bark at location 1 accumulated more heavy metals than leaves, indicating its effectiveness in capturing long-term airborne pollutants.

At location 2 (approximately 10 m away from the pollutant source), metal concentrations showed a moderate decline. For example, uranium levels dropped to around 1.5 mg/kg in TL2, while arsenic in TB2 was 2.5 mg/kg. Interestingly, silver was relatively higher in TL2 (around 2.03 mg/kg) compared to other locations. Lead and selenium were also slightly lower compared to location L1, indicating a reduction in pollution load with distance. Location L3, being the farthest from the generator, recorded the lowest metal concentrations across most categories. The elements As, U, and Pb levels were considerably reduced in both leaves and bark, falling well below 2 mg/kg in most cases. This supports the assumption that the impact of diesel generator emissions diminishes with distance. However, Cd levels remained relatively consistent across all locations, suggesting that Cd may have other contributing sources or persistent environmental presence. When compared with typical plant tolerance or safety limits for these metals, several exceedances are evident. For instance, As (tolerance ~1 mg/kg) exceeded safe levels in all bark and leaf samples. Uranium levels in location 1 surpassed the approximate 2 mg/kg threshold and Pb with a tolerance range of 2 to 3 mg/kg, exceeded safe limits especially in TL1 and TB1. Cadmium also consistently exceeded its plant tolerance limit of about 0.5 to 1 mg/kg in all samples. The data revealed that both leaf and bark samples across all three locations recorded elevated levels of toxic metals, with bark samples generally showing higher concentrations compared to leaves. This could be attributed to the bark's ability to adsorb airborne pollutants over time, acting as a long-term reservoir for environmental contaminants. Among the toxic metals, Pb exhibited the highest concentration, particularly in TB1, indicating greater deposition at location L1, possibly due to proximity to the generator exhaust. This pattern suggests that tree barks, more than leaves, are reliable bio-indicators for long-term exposure to toxic pollutants emitted from diesel generators.

A study by Mulenga *et al*. (2023) investigated tree bark and leaf concentrations of Cu, Cd, Zn, Ni, and Mn near a copper-leaching plant, and it was found that Cd concentrations were higher in bark than in leaves across multiple species of the plant, confirming that tree bark is often a more effective long term bioindicator of heavy metal deposition. A study on the level of leaves and bark by Odunlami *et al*. (2024) around mechanical workshops reported that Pb and Zn were highest, with upper bark showing the greatest heavy metal accumulation when compared with other parts of the plant. Another study by Adereti *et al*. (2017) observed that Pb concentrations in tree leaf was as high as ~ 90 mg/kg, which far exceeded what was reported in this present study.

Although the sampling site was not located near any mining activity, the elevated levels of Cd, Cr, Pb, Zn Ni, and other metals are consistent with emissions from generator operation and diesel combustion. Studies such as Onwukwe *et al*. (2021) noted substantial Fe, Pb, and Al in soot from power plants and small generators in Lafia, Nigeria, while Okorie *et al*. (2009) observed elevated Cr, Pb, Cu, and Mn from generator exhausts in Kogi State, Nigeria. Further, ambient air studies by Ayua *et al*. 2020 show similar profiles of heavy metals including Cd, Pb, Zn, Cr, *etc.* near industrial/combustion sources. These findings corroborate the hypothesis that generator emissions are a plausible source of the metals measured in the leaves and bark.

Heavy Metals Analysis

Figure 4 shows the concentrations of five heavy metals – Barium (Ba), Titanium (Ti), Vanadium (V), Chromium (Cr), and Tin (Sn) – in tree leaves and bark samples from three locations (location 1, 2, and 3) near generator diesel plants. As shown in Fig. 4, Ba concentrations varied noticeably among locations and sample types. The highest levels were recorded in TB1 (about 75.01 mg/kg) and TB2 (around 68.0 mg/kg), both being bark samples from the closest and mid-range locations, respectively. TL1 and TL2 show relatively moderate concentrations (50 to 55 mg/kg), while TL3 showed a marked decrease to around 20.1 mg/kg. This suggests a general trend where Ba levels decline with increasing distance from the diesel source, although TB3 retains a moderate concentration (58.01 mg/kg), indicating potential persistence in bark. Titanium (Ti) shows an interesting pattern. TL3 (leaves from the farthest location) recorded the highest concentration of Ti (almost 90.1 mg/kg), surpassing all other locations. TL1 also showed a high value (about 82.0 mg/kg), while TB1 (bark at L1) and TB2 (bark at L2) exhibited much lower concentrations (below 20 mg/kg). This suggests that Ti might accumulate more in leaves than bark, and its presence may not be solely influenced by proximity to diesel generators, possibly reflecting differences in plant uptake or soil content.

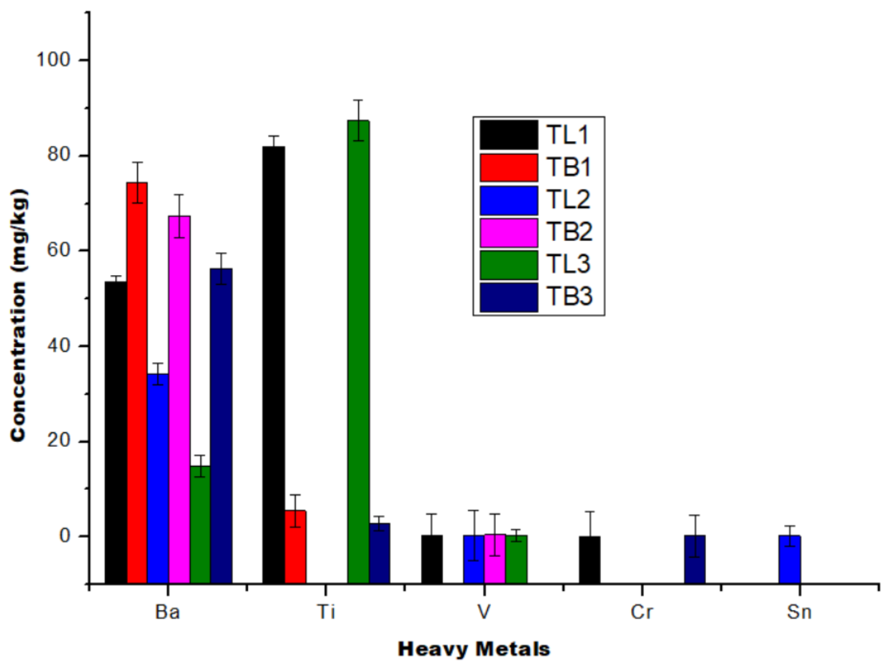

Fig. 4. Level of heavy metal concentrations in leaves and bark of tree located at diesel generator plant.

Vanadium (V) was present in low concentrations across all samples, typically ranging from 10 to 15 mg/kg, with no dramatic variation across the locations or between leaf and bark. This indicated a relatively uniform distribution and potentially lower environmental mobility or uptake by the plants. Chromium (Cr) and Tin (Sn) appeared only in TL1, TB3, and TL2, respectively, with low concentrations (around 5 to 10 mg/kg). The absence of Cr and Sn in many samples may indicate localized contamination or limited uptake. Their low and inconsistent presence across locations suggests they are not dominant pollutants in this area or may be below detection limits in certain samples.

Similar to the toxic metals, the bark samples (TB1–TB3) exhibited consistently higher concentrations of heavy metals compared to the leaves (TL1–TL3). Location L2 (TB2 and TL2) showed moderate levels, while L3 (TB3) showed lower levels, suggesting a gradient of exposure possibly influenced by wind direction or distance from the pollution source. These results confirm that environmental deposition of heavy metals from diesel generator emissions is spatially variable and that barks accumulate more due to their porous and fibrous structure, making them excellent passive samplers for atmospheric heavy metals.

A study conducted by Youssef (2020) examined heavy metal accumulation in leaves of urban trees such as *Quercus robur* and *Ficus nitid*, and it was observed that Ti was level across leaf samples 3.6 mg/kg, and V was also detectable but generally less than 1 mg/kg, which are both far lower than the levels reported in this current study. They also reported that Ti accumulation varied between species, indicating environmental or physiological uptake differences and inconsistent spatial trends, which is similar to what was reported in this study. Also, the very low V concentrations which is uniformly distributed across samples is also a trend which is consistent with the present finding of V in the 10 to 15 mg/kg range with minimal spatial variation. Ejidike and Onianwa (2015) observed that the levels of metal concentration as found in the tree bark (mg/kg) were Pb, 5.99 ± 5.25; Cd, 0.09 ± 0.07; Zn, 27.64 ± 29.66; Cu, 6.90 ± 5.54; Co, 0.87 ± 0.45; and Cr, 2.84 ± 1.58, which varied from 0.75 to 29.74, < 0.01 to 0.26, 3.70 to 166.13, 1.81 to 39.12, 0.23 to 2.35, and < 0.01 to 8.34 mg /kg, respectively. Their findings confirmed the present observation that tree bark served as a strong indicator of atmospheric heavy metal deposition when compared with leaves. A study by Al-Gizzi *et al*. (2020) assessed leaves of *Phoenix dactylifera*, *Ficus carica*, exposed to diesel-generator emissions found Cr to be 7.23 µg/g in leaves, and Cd to 10.6 µg/g which align with the present low but detectable Cr (5 to 10 mg/kg) restricted to only some samples (TL1, TL2), and absence of Cr/Sn in most samples suggesting localized presence or detection limits.

Essential Metals Analysis

Figure 5 displays the concentrations of essential metals such as Potassium (K), Magnesium (Mg), Iron (Fe), Zinc (Zn), Copper (Cu), Sodium (Na), Calcium (Ca), and Manganese (Mn) in tree leaves and bark at three locations (L1 to L3) near generator diesel plants. As mentioned before TL1–TL3 represent tree leaves, and TB1–TB3 represent tree bark, with L3 (TL3 and TB3) being the farthest from the pollution source. From Fig. 6, K shows consistently high concentrations across all samples, ranging from about 135 mg/kg in TL3 to nearly 200 mg/kg in TL1 and TB2. This indicates a high physiological demand for K in plant metabolism and suggests that its uptake remains robust regardless of proximity to pollution sources. Magnesium (Mg) also showed high values, especially in TL1, TL2, and TB2 (around 180 to 200 mg/kg). However, Mg concentrations were significantly lower in TB1 and TB3, suggesting some influence of location or tissue type on its availability or accumulation.

Iron (Fe) showed its highest concentration in TL1 (about 185.21 mg/kg), with levels decreasing gradually in other samples. TL3 showed a notably high Fe level (~110 mg/kg) compared to bark at the same location. This indicates that Fe uptake may be more active in leaves and could be influenced by soil conditions or atmospheric deposition closer to the generator. The metals Zn and Cu appeared in much lower concentrations across all samples. Zn ranged from about 10 to 25 mg/kg, with the highest values in TL1 and TL2. Copper was uniformly low, barely reaching 10.05 mg/kg, which is typical given its micronutrient status. These low values are within normal ranges for plant health and indicate no signs of contamination or deficiency. Sodium (Na) showed interesting variability and TB2 recorded the highest Na concentration (around 145.02 mg/kg), while TL2 and TL3 followed with moderate levels (~100 mg/kg). This could reflect site-specific soil salinity or environmental exposure. Also, Ca varied, with the highest values in TL3 and TB3 (around 90 to 100 mg/kg), indicating good mineral uptake even at the farthest location. Mn was relatively consistent but highest in TL3 (55.0 mg/kg), again reinforcing that location L3 may not be significantly nutrient-deprived despite its distance.

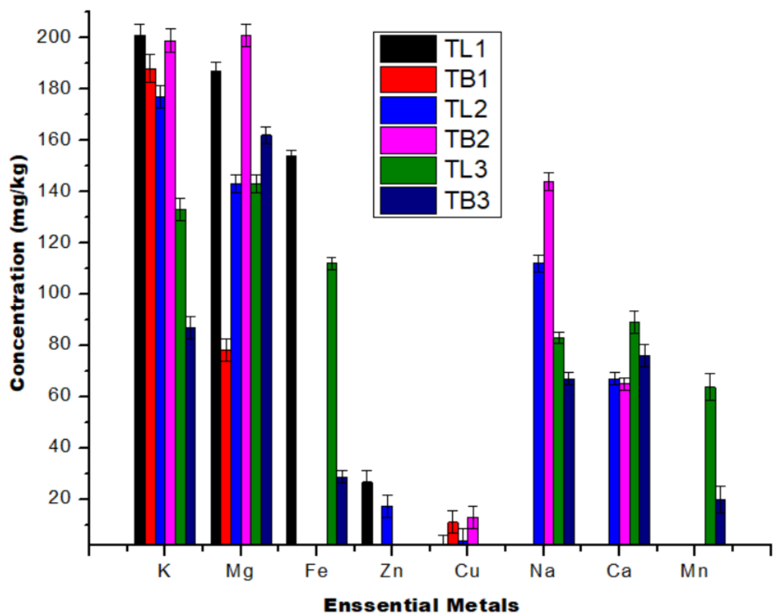

Fig. 5. Level of essential metal concentrations in leaves and bark of tree located at diesel generator plant

While these metals are necessary for plant metabolism, excessive accumulation due to pollution could become phytotoxic. Interestingly, leaves (TL1–TL3) contained relatively higher levels of essential metals than the bark samples. This is likely because essential metals are more actively taken up through root absorption and transported to photosynthetically active parts like leaves. However, elevated levels in leaves located close to the diesel generator plant (TL1 and TL2) may also indicate surface deposition of particulates rich in these elements, possibly altering their physiological functions. These findings suggest that diesel generator emissions not only contribute toxic elements but also affect the natural metal uptake in plants, potentially disrupting metabolic balance. A conducted by Solgi *et al*. (2020) which investigated camphor trees (*Cinnamomum camphora*) in an urban area impacted by coal and traffic emissions found that Zn ranged between 24.2 and 250.8 mg/kg, and Cu ranged from ~3.9 to 26.3 mg/kg, aligning with the observed Zn (10 to 25 mg/kg) and Cu (~10 mg/kg) concentrations.

Fourier Transform Infrared Spectroscopic Analysis

The FT-IR data provided for tree bark and tree leaves revealed important differences in their chemical composition as shown in Fig. 6. The FT-IR spectra show absorption peaks corresponding to different functional groups. The strong absorptions in both bark (3418.0 and 3317.3 cm^{-1}) and leaves (3298.7 cm^{-1}) correspond to O–H and N–H stretching vibrations, commonly associated with hydroxyl groups found in alcohols and phenols, or amine groups (Md Salim *et al*. 2021). The broader and stronger O–H signals in bark may indicate a higher concentration of phenolic compounds such as tannins or lignin, which contribute to the protective structure of the bark or the O-H stretch of water. In the aliphatic C–H stretching region around 2922 cm^{-1}, both bark and leaves exhibit strong absorption peaks (Md Salim *et al*. 2021). These are attributed to $-CH_2$ and $-CH_3$ stretching vibrations commonly found in cellulose, hemicellulose, and other lipid-containing structures. This similarity suggests that both tissues contain structural polysaccharides, though possibly in different concentrations.

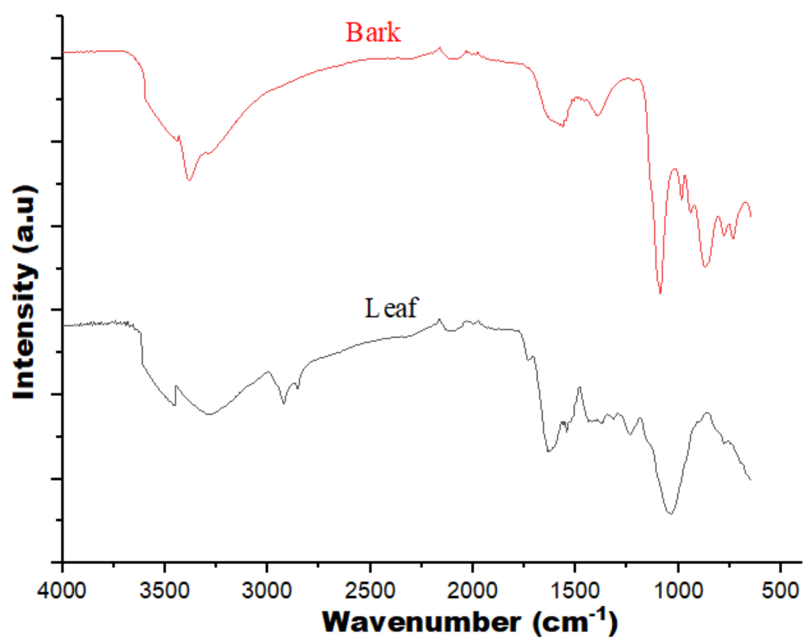

Fig. 6. FT-IR Analysis of bark and leaf of tree located at diesel generator plant.

Notably, the bark sample exhibited a peak at 2087.3 cm^{-1}, and the leaf sample showed similar peaks at 2359.9 and 2117.1 cm^{-1}, which may indicate atmospheric CO_2 interference. The leaves' broader activity in this region might be linked to metabolic compounds or environmental exposure. The leaves show a strong peak at 1722.0 cm^{-1}, associated with C=O stretching vibrations found in esters, aldehydes, and ketones compounds, which are often present in leaf waxes and pigments. This peak was absent in the bark, highlighting a difference in surface chemistry and metabolic activity. Both bark and leaves showed peaks around 1610 to 1615 cm^{-1}, associated with aromatic C=C stretching, indicating the presence of aromatic rings typical of phenolic compounds. These are more abundant in lignin-rich tissues such as bark but are also present in leaves due to their secondary metabolites. In the fingerprint region, bark showed distinct peaks at 1446.2, 1315.8, 1159.2, 1028.7, and 887.1 cm^{-1}, reflecting complex polysaccharide and aromatic structures (Ozgenc *et al*. 2017), including cellulose and lignin were linked to C–O–C and C–O stretching vibrations. The leaf sample showed peaks at 1520.8, 1438.8, 1315.8, 1226.3, 1162.9, and 1028.8 cm^{-1}, with more emphasis on carbonyl-related vibrations, which could be tied to esterified compounds or surface waxes.

An FT-IR analysis of *Leucaena leucocephala* bark by Md Salim *et al*. (2021) revealed a prominent, broad absorption band at 3296 cm^{-1}, indicative of hydroxyl groups originating from both phenolic and aliphatic components, while distinct peaks at 2918 cm^{-1} and 2850 cm^{-1} were attributed to C–H stretching vibrations in aromatic methoxyl and methyl/methylene groups, respectively which are similar to our findings in this current work. A subtle shoulder at 1735 cm^{-1} signaled the presence of carbonyl functionalities; meanwhile, peaks observed at 1612 cm^{-1} and 1442 cm^{-1} corresponded to C=C stretching within aromatic structures (Md Salim *et al*. 2021). The investigations on various tree barks using ATR-FTIR spectroscopy by Ozgenc *et al*. (2017) revealed distinctive polysaccharide-related bands within the 890 to 1400 cm^{-1} region, which can be attributed to C–OH and C–O–C glycosidic bond vibrations, as these results emphasize the prevalence of carbohydrate structures in the composition of bark cell walls.

Scanning Electron Microscopy

The SEM image of the tree leaf (Fig. 7) reveals a relatively smooth surface with visible stomata and trichomes. The distribution of particles suggests that the leaf surface actively traps airborne pollutants, especially in areas with higher exposure. This microstructural evidence validates the FT-IR results by showing physical accumulation of pollutants, supporting the use of leaves as bio-indicators of ambient air pollution.

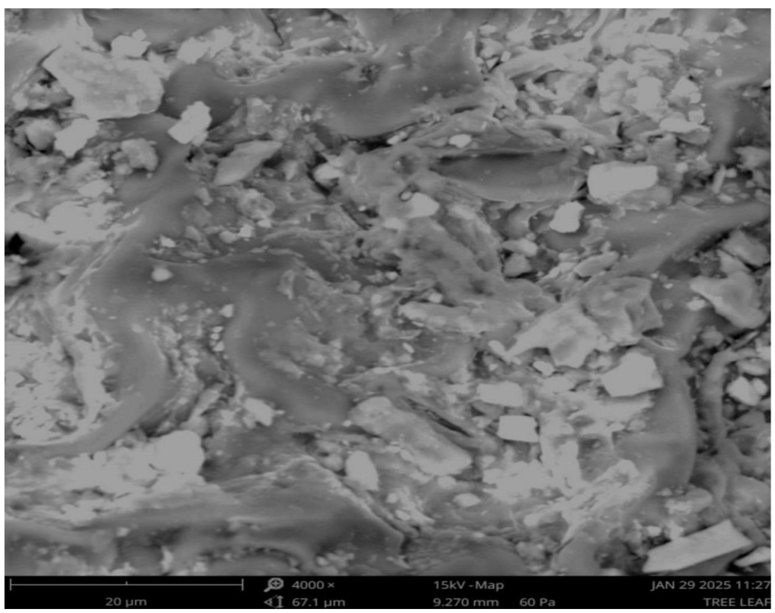

Fig. 7. SEM image of tree leaf

The SEM image of the bark (Fig. 8) reveals a rugged, fibrous surface with deep grooves and rough textures, providing a larger surface area for pollutant adherence. Numerous micro-particulates are embedded within the bark layers, indicating long-term accumulation. Unlike the smoother leaf surface, the bark's morphology allows it to trap and retain more particulate matter, aligning with the chemical data that showed higher concentrations of heavy metals and broader functional group representation. This microstructural observation supports the conclusion that bark is more suited for assessing cumulative and historical pollution exposure, while leaves are more reactive to recent or short-term atmospheric changes.

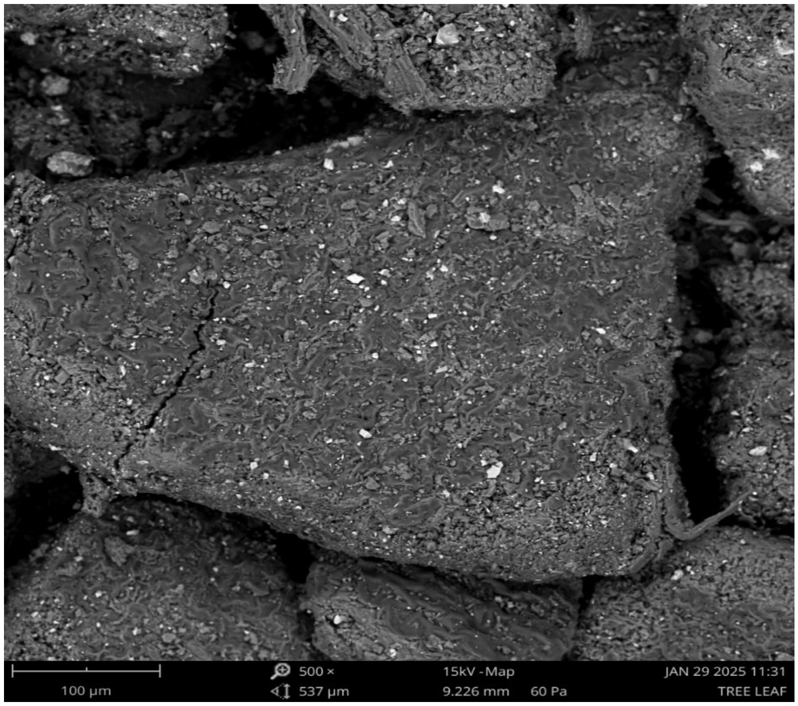

Fig. 8. SEM image of tree bark

CONCLUSIONS

1. Tree bark and leaves from three locations near diesel generator plants were analyzed, revealing elevated metal concentrations, especially in bark closer to the pollution source.
2. Barium concentrations decreased with distance from the generators, while Ti levels spiked in leaves at the farthest location, indicating differing sources or transport behaviors.
3. Metals Va, Cr, and Sn appeared in lower amounts and showed minimal variation across locations or plant tissues.
4. Essential nutrients such as K and Mg remained consistently high, while Fe, Na, and Ca varied by location and tissue, with leaves generally showing higher concentrations.
5. Tree bark proved to be a reliable bioindicator of heavy metal pollution due to its strong accumulation pattern near emission sources.
6. Analyses by FT-IR and SEM showed that bark is rich in structural compounds for long-term adsorption, while leaves offer fine pores suitable for rapid surface-level metal uptake.

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