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Ketapang Leaves (*Terminalia catappa* L.) as Lead (Pb) Bioaccumulators

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Abstract

Study This study aims to determine the ability of the leaf plant Ketapang shade tree (*Terminalia catappa* L.) to accumulate lead (Pb) in Manado City. Purposive sampling is being conducted at three locations. Pb levels in leaves are determined using the Spectrophotometry Atomic Absorption Spectroscopy (AAS) technique. According to research findings, the leaves of *Terminalia catappa* L. can be considered a bioaccumulator in Manado City. Because of their propensity to absorb metal lead (Pb), the concentrations of Pb on Jalan Piere Tendean, Malalayang Beach Walk, and District Wori range from 0.22-0.44 mg/kg. The highest Pb content was found on Jalan Piere Tendean, which has a level density and is rated as high. Recommended To do advanced research on Pb content in plants, another potential shade as a bioaccumulator or hyperaccumulator in Manado City.

Keywords: *Terminalia catappa* L.; Lead (Pb); Bioaccumulator

INTRODUCTION

The *Terminalia catappa L.* tree, commonly planted for its aesthetic appeal and ability to provide shade, contributes significantly to the generation of organic biomass, much of which is often discarded as waste and deposited in landfills. This accumulation leads to the formation of municipal solid wood waste, a byproduct that poses serious environmental concerns, particularly due to the microbial decomposition of organic matter that releases methane a potent greenhouse gas with a high global warming potential (Vinturelle *et al.* 2024). As the production and disposal of wood-based waste continue to rise, there is a pressing need to explore sustainable alternatives that not only minimize ecological harm but also enhance resource recovery and environmental resilience.

This challenge is compounded by broader anthropogenic pressures, as human activities associated with urbanization, industrialization, and recreational practices are increasingly recognized as key drivers of environmental pollution. Among various forms of degradation, air pollution remains one of the most urgent and complex environmental issues, with adverse consequences for biodiversity, ecosystem functioning, and human health. Despite ongoing efforts to monitor and regulate air quality, public awareness of pollution linked to everyday behavior remains limited, hindering collective action and policy effectiveness (Świsłowski *et al.* 2022). Addressing such multifaceted environmental issues requires integrating ecological restoration with community-based awareness, using green infrastructure as a strategic entry point.

In this context, *T. catappa* L. emerges not only as a contributor to biomass waste but also as a versatile and valuable species with the potential to mitigate environmental stress when managed sustainably. Widely known as the tropical almond, this tree is distributed across tropical and subtropical regions and has been extensively utilized for avenue planting and urban greening, owing to its robust canopy and visual appeal. Building on this foundation, the present review synthesizes current scientific literature to highlight the ecological, economic, and functional importance of *T. catappa* L. across global landscapes. Numerous studies have validated its use in traditional medicine, small-scale timber production, environmental remediation through biosorption, and as a component in agroforestry systems, especially due to its salinity tolerance and efficient crown architecture. By connecting these ecological functions with sustainable land-use strategies, *T. catappa* L. holds significant promise for rehabilitating degraded ecosystems and enhancing biodiversity outside traditional forest zones. The evidence presented in this review points toward a broader application of this species in contemporary landscape planning, particularly within the scope of climate-adaptive urban forestry and integrated agroforestry systems. Such multifunctional uses reaffirm the relevance of this tree in future-oriented environmental management, bridging ecological value with practical, scalable solutions (Ramanan *et al*. 2025).

Assessing the global contribution of metals from natural processes presents a considerably greater challenge compared to quantifying those from anthropogenic air pollution sources. This difficulty arises due to the inherently low flux and highly diffuse distribution of metal emissions from natural activities, which makes accurate estimation complex and often uncertain. Despite these methodological constraints, existing evidence suggests that the overall contribution of naturally sourced metals to the atmospheric inventory may, under certain scenarios, be comparable in magnitude to that of human-induced emissions. This equivalence becomes particularly apparent when evaluating major atmospheric metals, where comparative analyses highlight both the relative input levels and the dominant source pathways for each individual element (Sigel *et al*. 2005). Such comparative studies provide valuable context for understanding the full scope of environmental metal pollution and underscore the need to assess natural and anthropogenic sources concurrently when developing regulatory or mitigation strategies.

Expanding this perspective beyond metals, it is also important to consider other environmentally persistent pollutants that arise from both natural and anthropogenic origins. Polycyclic aromatic hydrocarbons (PAHs) represent a critical class of such compounds, characterized by their molecular structure comprising two or more fused aromatic rings. PAHs are released into the environment through natural events such as wildfires and volcanic eruptions, as well as through a range of anthropogenic activities including the combustion of fossil fuels, wood burning, and vehicular emissions. Due to their chemical stability and resistance to degradation, PAHs persist in various environmental matrices and pose substantial risks to public health. Their hazardous nature stems from their well-documented genotoxic, mutagenic, and carcinogenic properties, which make them priority pollutants in global environmental health research (Mukhopadhyay *et al*. 2022). Understanding the dual origin and toxicological impacts of PAHs further emphasizes the complexity of atmospheric pollution and reinforces the necessity of integrating natural contributions into overall environmental risk assessments.

Considering the growing concern over pollution and sustainability, it becomes increasingly vital to identify and promote natural resources that contribute positively to ecological and human health. Within this context, *T. catappa* L. has garnered attention not only for its environmental adaptability but also for its potential applications in food processing and sustainable product development. Recent investigations have demonstrated that the flour derived from *T. catappa* L. retains essential macronutrients, beneficial minerals, and a rich profile of phenolic compounds even after undergoing drying processes. This nutritional stability highlights the species' value as a matrix for flour elaboration and supports the broader utilization of its underused fruits. As such, the incorporation of *T. catappa* L. into food systems offers promising avenues for enhancing food security, reducing agricultural waste, and promoting circular economy principles within agro-industrial practices (Oliveira *et al.* 2024). By connecting ecological health, pollution mitigation, and sustainable development, this multipurpose species represents a compelling case for interdisciplinary strategies aimed at achieving environmental resilience.

Biogenic emissions, originating from natural biological processes, represent a significant portion of trace element release into the atmosphere and are considered ecologically integral across both terrestrial and marine ecosystems. These emissions involve the volatilization of elements as part of biologically mediated processes that contribute to atmospheric inputs in a manner that sustains ecosystem functioning. Elements such as mercury (Hg), arsenic (As), and selenium (Se) are predominantly released into the atmosphere through these biogenic pathways, accounting for most of their natural atmospheric presence. In addition to these gaseous emissions, various particulate biological materials also contribute to atmospheric composition, including pollen grains, fungal spores, waxes, algae, and marine-originated microorganisms. Particularly, marine aerosols play a minor yet noteworthy role; they are produced when bubbles formed on the ocean surface burst due to wind driven turbulence. These aerosols not only carry dissolved marine salts but may also encapsulate organic and microbial residues from the sea surface microlayer, occasionally containing trace quantities of metallic elements. However, despite the global scale of this process, the concentration of metals in seawater remains low, making marine aerosols a relatively minor contributor to the overall metal budget in the atmosphere.

Continuing from oceanic and biological sources, the Earth's surface also contributes significantly to atmospheric trace metals through the mobilization of mineral dust particles, primarily via wind erosion in arid and semi-arid landscapes. Such dust is a major atmospheric input source for crust-derived elements, especially in regions characterized by low vegetation cover such as deserts. The elemental composition of windblown dust often overlaps with that of soil influenced by anthropogenic activities such as agriculture, making it challenging to distinguish between natural and human-altered contributions. Another important natural source of atmospheric metal input is wildfire activity, which occurs globally in forested regions and mobilizes elements stored in plant biomass, including zinc (Zn) and molybdenum (Mo). Volcanic activity represents a further significant natural pathway, where eruptions emit large quantities of both particulate and gaseous materials, including trace metals. However, due to the episodic and unpredictable nature of volcanic emissions, the quantification of their contribution remains less certain than other sources. This variability poses challenges for comprehensive global inventories of metal fluxes from natural origins.

When comparing global average emissions of trace elements from both natural and anthropogenic sources, a marked imbalance becomes evident. According to findings by Sigel *et al.* (2005), emissions of cadmium (Cd), nickel (Ni), lead (Pb), and vanadium (V) from human activities exceed natural background levels by a substantial margin. Other elements such as arsenic (As), chromium (Cr), copper (Cu), mercury (Hg), molybdenum (Mo), antimony (Sb), selenium (Se), and zinc (Zn) display approximately equal contributions from natural and anthropogenic sources. Manganese (Mn), on the other hand, is more prominently associated with anthropogenic emissions, primarily due to limited natural sources and the relatively small influence of volcanic activity. Moreover, metals released from industrial processes, especially those occurring at high combustion temperatures, are more likely to be present in atmospheric layers as medium-sized (1–5 µm) or fine particles (0.3–0.8 µm). In contrast, metals derived from natural sources such as dust storms, mineral weathering, or wildfire ash tend to be associated with coarser particle sizes and thus exhibit different atmospheric behavior and deposition characteristics.

Against this backdrop, anthropogenic activities emerge as the dominant contributors to global atmospheric metal pollution, driven largely by industrial combustion and the processing of non-ferrous metals. Fossil fuel combustion remains the most significant source, followed by emissions from vehicular traffic, iron and steel manufacturing, cement production, and the incineration of municipal and industrial waste. These activities release a broad spectrum of metal elements into the atmosphere, contributing not only to air quality degradation but also to potential human health impacts and ecosystem disruption. The identification and regulation of these emission pathways are therefore essential for mitigating the accumulation of hazardous metals in the atmospheric environment and for developing science based policy responses aimed at environmental protection and public health.

Among the various anthropogenic sources, coal and petroleum-derived fuels stand out as particularly significant contributors due to their widespread use in electricity and heat generation through combustion in thermal power plants. The burning of coal is especially problematic, as it releases a broad array of trace metals into the atmosphere, including chromium (Cr), mercury (Hg), manganese (Mn), molybdenum (Mo), antimony (Sb), selenium (Se), tin (Sn), and thallium (Tl), alongside other highly toxic elements such as arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn). In comparison, the combustion of oil-based fuels is the primary driver of global nickel (Ni) emissions, accounting for nearly all the anthropogenic Ni released into the atmosphere. Additionally, the nonferrous metal manufacturing industry significantly contributes to the emission of several heavy metals, particularly arsenic, cadmium, copper, indium (In), and tin, as well as mercury, nickel, lead, antimony, and selenium. These emissions are often linked to copper production, though notable exceptions include lead and zinc emissions, which are more strongly associated with their respective smelting processes. Zinc manufacturing alone is also a major source of cadmium, mercury, and lead emissions, reinforcing the metallurgical sector's role in shaping the atmospheric metal burden.

These industrial and energy-related emissions have been compounded by historical trends in the transportation sector. Over the past five decades, road traffic has made substantial contributions to environmental lead contamination, primarily due to the widespread use of leaded gasoline, which was a dominant fuel additive until policy changes were implemented in the late 20th century. Although the use of leaded fuel has declined in many countries since the 1990s, vehicle-related emissions remain an ongoing concern. In particular, automobiles equipped with catalytic converters release trace amounts of precious metals from the platinum group, including rhodium (Rh), palladium (Pd), and platinum (Pt), into the atmosphere. Despite their relatively low concentration, these metals enter the environment via exhaust emissions, and yet, comprehensive global inventories documenting these metal emissions are still lacking. The cumulative impact of these various anthropogenic sources has significantly altered the composition of airborne particulates, thereby intensifying the scale of atmospheric pollution in urban and industrial regions.

Given the complex and persistent nature of heavy metal pollution in urban environments, it is important to evaluate localized deposition patterns and potential bioaccumulation pathways. From a geochemical perspective, many heavy metals are not prone to long range atmospheric transport due to their natural tendency to settle near the source of emission, particularly along heavily trafficked roads and industrial corridors. In this context, plants especially urban trees can function as effective bioindicators of metal deposition. Therefore, the present study aims to assess the potential of the Ketapang shade tree (*T. catappa* L.) as a biological collector of atmospheric lead (Pb) in Manado City, Indonesia. Through the examination of leaf tissue composition, this research seeks to understand the extent of Pb accumulation and explore the broader applicability of *T. catappa* as a passive tool for environmental monitoring in tropical urban ecosystems.

RESEARCH METHODOLOGY

Place and Time of Research

Field observations and sample collection were conducted at three distinct locations in Manado, namely Jalan Piere Tendean, Malalayang Beach Walk, and the Wori area. Based on laboratory verification, four samples were initially collected; however, one sample from the Unsrat Campus location was excluded from further analysis due to the absence of *T. catappa* (Ketapang) trees at that site. The remaining samples were subsequently analyzed at the Manado Industrial Research and Standardization Center Laboratory to determine the levels of lead (Pb) accumulation. The research activities, encompassing both fieldwork and laboratory testing, were carried out over a period of less than two months, specifically from June to July 2023.

Figure 1. Map of Research Location I (*Source: Google Earth*)

Table 1. Points Sample Location Coordinates

Location	Point Coordinate	
	Latitude	Longitude
Piere Tendean Street	1°28'10.85"N	124°49'52.54"E
Malalayang *Beach Walk*	1°27'39.73"N	124°47'3.07"E
Wori District	1°35'59.11"N	124°52'0.75"E

Figure 2. Map of Research Location II (*Source: Google Earth*)

MATERIALS AND METHODS

The materials utilized in this study included the leaves of the Ketapang plant (*T. catappa L.*), concentrated nitric acid (HNO_3), distilled water, aluminum foil, and a 1000 ppm stock solution of lead nitrate [$Pb(NO_3)_2$]. The equipment employed comprised plant scissors, an analytical balance, reaction tubes, volumetric flasks, micropipettes, standard filter paper, a scalpel, amber reagent bottles, porcelain crucibles, a furnace, tongs, a hot plate, an oven, a grinding tool, a stopwatch, transparent plastic clips, and appropriate labeling and writing tools. The lead content in the Ketapang leaves served as the primary research variable. Analytical measurements were performed using an Atomic Absorption Spectrophotometer (AAS) to determine the concentration of lead (Pb). The study employed a purposive sampling method and was conducted using a descriptive research design aimed at evaluating the Pb accumulation potential of T. catappa in selected urban locations.

Procedure Study

Leaf samples of *T. catappa* (Ketapang) were collected from each study location, with approximately 200 grams of leaves taken per site using a digital analytical balance. The leaves were placed into transparent plastic clip bags and labeled according to their respective sampling locations. Sampling was conducted by selecting mature green leaves (neither too young nor too old) from branches facing the roadside, targeting the lower, middle, and upper canopy positions to ensure representative sampling. Once transported to the laboratory, the leaf samples were chopped into smaller pieces, and a portion weighing between 5 to 10 grams was placed into a porcelain crucible. The samples were initially heated over a Bunsen burner until smoking ceased and then subjected to ashing in a muffle furnace at 550 °C until a consistent white ash was produced.

Following ashing, 0.5 mL of concentrated nitric acid (HNO_3) was added dropwise, followed by the addition of distilled water. The mixture was stirred and filtered using Whatman No. 42 filter paper into a 50 mL volumetric flask, then diluted to the calibration mark with distilled water. The resulting solution was analyzed using an Atomic Absorption Spectrophotometer (AAS AA700) set at a wavelength of 283.3 nm, employing the flame atomization method. A standard calibration curve was prepared from a series of lead (Pb) solutions to correlate absorbance with metal concentration, and the Pb content in each sample was determined accordingly.

Data Analysis

AAS (Atomic Absorption Spectrophotometer) was used to analyze the concentration of lead (Pb), a heavy metal, in the leaves (*T.catappa* L.). .

Figure 3. (A) Weighing of *Terminalia catappa L*. samples. (B) Chopped leaf samples. (C) Dead Aphis gossypii specimens from Kasemen Subdistrict.

Figure 4. Combustion using a Bunsen burner (D), ashing in a furnace (E), filtration using Whatman No. 42 filter paper (F), filtration using Whatman No. 42 filter paper

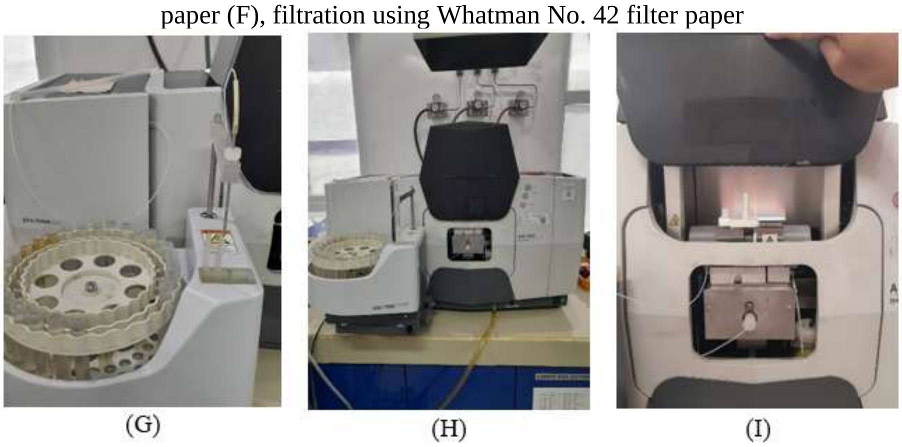

Figure 5. Solution in the Atomic Absorption Spectrophotometer (G), Atomic Absorption Spectrophotometer (H), Flame Method (I), Experimental Design and Analysis Results of Pb Content in *Terminalia catappa L*. Leaves at the Laboratory of the Research and Standardization Center, Ministry of Industry.

RESULTS AND DISCUSS

E. Lead (Pb) content in Ketapang leaves in Manado City

Lead (Pb) is absorbed by Ketapang leaves which function as tree shade on the road or on the beach around Manado city, each in Malalayang *Beach Walk*, Piere Tendean and Wori Streets different in each location. Analysis results content particle metal Weight of lead (Pb) absorbed by Ketapang leaves at 4 locations the presented in Table 2.

Based on the analysis results in Table 2, the content particle metal weight of lead (Pb) absorbed by leaves ketapang show difference results on each location. The most abundant Ketapang leaves absorb particle metal heavy lead (Pb) is located on Jalan Pierre Tendean, namely of 0.44 mg/kg, followed by Malalayang Beach Walk, namely of 0.41 mg/kg and at the location The least control in Wori that is of 0.22 mg/kg.

Table 2. Contents metal lead (Pb) weight in Ketapang leaves (*Terminalia catappa* L.) in Manado City

Parameter	Test Results			Unit	Test Method
	W	MBW	JPT		
Lead	0.22	0.41	0.44	mg/kg	SNI 01-2896-1998

Description: W (Wori), MBW (Malalayang Beach Walk) and JPT (Jalan Piere Tendean).

Figure 6. Lead (Pb) content in Ketapang leaves (*Terminalia catappa* L.*) at 3* research locations

As illustrated in Figure 6, the concentration of lead (Pb) in *Terminalia catappa* L. (Ketapang) leaves varied significantly across the different sampling locations. These differences are likely influenced by multiple factors, including plant age, duration of exposure to Pb pollutants, soil Pb content, proximity to emission sources, the density of surrounding vegetation, and the presence of other plant species in the area. Among the locations studied, Jalan Piere Tendean exhibited the highest Pb content in Ketapang leaves. This result corresponds to the area's dense traffic conditions, which serve as a continuous source of vehicular emissions. Additionally, the trees at this site are spaced farther apart, which reduces canopy overlap and increases direct exposure of individual trees to airborne pollutants. Moreover, the relatively taller stature of Ketapang trees at Jalan Piere Tendean places their leaves in closer proximity to emission sources, potentially enhancing the absorption of lead particulates from the air.

In contrast, Ketapang leaves collected from the Malalayang Beach Walk site showed moderately high Pb levels, but lower than those observed at Jalan Piere Tendean. This discrepancy aligns with the relatively lower traffic density at the Malalayang site. Furthermore, the presence of numerous shading trees in close proximity likely contributes to pollutant dispersion and dilution, thereby limiting Pb deposition on individual Ketapang trees. The shared canopy structure may act as a buffer that distributes airborne pollutants across multiple trees, reducing localized Pb accumulation.

The lowest concentration of Pb was recorded at the Wori site, which served as the control area. The reduced Pb levels can be attributed to minimal vehicular traffic, the site's remote location from the main road, and the spatial positioning of Ketapang trees, which are situated along the beachfront and far from major pollution sources. Although Pb concentrations were low, trace amounts were still detected in the leaves, suggesting that airborne Pb particles may have been transported to the area by wind and deposited on the foliage. Environmental conditions such as wind speed and direction, relative humidity, and atmospheric temperature can influence the transport and deposition of airborne pollutants. Hidayati *et al*. (2020) that certain plant species exhibit varying capacities for contaminant uptake, with differences attributed to both environmental exposure and species specific physiological traits. Plants such as *Eichhornia crassipes*, *Acorus calamus*, and *Hydrocotyle amplexicaulis* have demonstrated rapid growth and strong phytoremediation potential in polluted environments. Notably, *H. amplexicaulis* and *E. crassipes* showed high bioconcentration factors (BCF) in their shoots, while H. amplexicaulis and *A. calamus* exhibited elevated BCFs in their roots. Additionally, *E. crassipes*, *S. spontaneum*, and *H. amplexicaulis* had the highest translocation factors (TF) for Pb accumulation.

These findings underscore the complex interaction between environmental conditions and internal plant characteristics in determining Pb accumulation in foliage. Intrinsic factors such as plant morphology, physiology, leaf structure (compound vs. simple), leaf surface properties, stomatal density and size, canopy architecture, and plant age all influence pollutant uptake. External factors include wind patterns, topography, temperature, humidity, and urban density, along with the intensity and nature of surrounding human activities. Vehicle type and age, fuel composition, and proximity to emission sources further contribute to spatial variability in Pb distribution. Therefore, understanding the interaction of these factors is crucial for selecting effective plant species for urban phytoremediation and environmental monitoring.

In a recent study, Su *et al*. (2022) investigated the dry deposition of particulate matter (PM) and associated heavy metals using camphor trees (*Cinnamomum camphora*) as bioaccumulators in urban green spaces. Their findings revealed that the dry deposition flux of $PM_{2.5}$ on leaves yielded comparable outcomes in the ZHP area and notably higher efficiency in the TBG site. When accounting for mass loss due to solubility during water filtration, the $PM_{2.5}$ deposition values estimated from field data closely matched those projected by the i-Tree Eco model. This alignment suggests that i-Tree Eco could serve as a reliable tool for evaluating $PM_{2.5}$ removal capabilities of urban green infrastructure in Taiwan. In addition to particulate accumulation, the study also analyzed the presence of nine heavy metals within deposited PM. Results showed significantly higher concentrations of these elements outside park boundaries compared to within, indicating that urban parks may reduce not only airborne particulate matter but also the toxicity of associated heavy metal pollutants. The research provides strong empirical evidence for the ecological role of urban green spaces in air purification and environmental biomonitoring.

Complementing these findings, Santos *et al.* employed *Nerium oleander* L. as a biomonitor to assess atmospheric contamination in a sub-region of the Metropolitan Area. Leaves were collected from both urban and remote control sites to compare elemental deposition patterns. Concentrations of thirteen elements including sulfur (S), chlorine (Cl), potassium (K), calcium (Ca), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), bromine (Br), rubidium (Rb), strontium (Sr), barium (Ba), and lead (Pb) were quantified across all seasons. In most cases, urban sampling locations exhibited higher median concentrations than control areas, indicating increased pollutant exposure in populated zones. A principal component analysis (PCA) grouped the elements into two major components: the first associated with soil-derived elements such as Cl, K, Ca, Cu, Rb, and Sr, and the second linked to anthropogenic sources, including Fe, Cu, Zn, and Pb commonly attributed to vehicular and industrial emissions. The study validated the use of X-ray fluorescence (XRF) analysis on Nerium oleander leaves as an effective, rapid, and cost-efficient method for monitoring urban pollution. Its suitability for long-term observation underscores its potential as a practical tool in environmental surveillance programs in metropolitan regions.

The principal component analysis (PCA) splits the elements into two primary variables that can be associated with their emission sources. The elements Cl, K, Ca, Cu, Rb, and Sr may be affected by soil. On the other hand, Fe, Cu, Zn, and Pb have been related to automobile and industrial pollutants. The study discovered that the XRF method employed on *N. oleander* L. leaves is beneficial for environmental pollution analysis in Metropolitan Regions because it is precise, quick, and economical, and it allows for long-term monitoring of pollution levels.

Hegazy *et al*. (2017) investigated the phytoremediation potential of duckweed in removing lead (Pb) from contaminated water and observed that Pb removal efficiency was approximately 50% after 12 days at the lowest treatment concentration of 10 mg/L. However, the removal efficiency declined significantly with increasing Pb concentrations, particularly at 100 mg/L. The study further noted that the highest bioconcentration factor (BCF) was achieved under the lowest Pb exposure, increasing from roughly 200 mg/L on day two to 943 mg/L by day twelve, suggesting that uptake was driven by active mechanisms rather than passive diffusion. Additionally, bleaching recovery for photosynthetic pigments was consistent at approximately 50% for plants exposed to Pb concentrations between 10 and 40 mg/L, reflecting moderate stress resilience. These results underline duckweed's sensitivity to Pb contamination and its potential utility as a biosensor or biomonitor for heavy metal pollution due to its responsive absorption dynamics and recovery behavior.

In a complementary study on epiphytic species. Gonzales *et al*. (2025), compared the metal accumulation capabilities of *T. bergeri* and *T. aeranthos*, revealing interspecific differences in elemental uptake. *T. bergeri* exhibited a superior capacity to accumulate trace elements, particularly Fe, Zn, and Co, which contributed significantly to overall metal retention in both species. The accumulation profiles for five elements As, Cr, Ni, Pb, and Zn were benchmarked against data from nearby air quality monitoring stations, confirming the validity of both species as reliable biomonitors. Notably, both *T. bergeri* and *T. aeranthos* demonstrated unusually high uptake rates of cobalt (Co), despite the absence of Co data from local monitoring stations, suggesting their strong physiological affinity for this metal. These findings reinforce the suitability of these Tillandsia species as passive biomonitors for atmospheric deposition of key pollutants, particularly in regions where conventional monitoring infrastructure may be limited or incomplete.

Solgi *et al*. recent findings indicate that tree bark tends to accumulate higher concentrations of lead (Pb) compared to leaves, whereas leaves show greater retention of copper (Cu) and zinc (Zn). In both *Fraxinus excelsior* (Ash) and *Pinus eldarica* (Pine), the bioconcentration factor (BCF) for Pb was consistently higher in bark than in leaves. Conversely, the BCF values for Cu and Zn were notably greater in leaves than in bark, suggesting differing uptake and deposition mechanisms depending on the metal and tissue type. The average BCF for Pb and Cu in Ash leaves exceeded that of Pine, while Pine exhibited higher Zn accumulation, highlighting species-specific variations in metal uptake efficiency. Additionally, the study demonstrated that rinsing leaf surfaces reduced metal concentrations by approximately 20% to 46%, indicating that a substantial portion of the detected heavy metals existed as dry atmospheric deposition on the leaf surface rather than internalized within the tissues. The comparatively higher BCF values for Pb over Cu and Zn suggest that both species, particularly *F. excelsior*, may serve as effective accumulators of atmospheric Pb. Overall, the findings support the use of both broadleaf and coniferous tree species as reliable biomonitors of urban air pollution. However, F. excelsior appears to be more effective for monitoring Pb contamination in urban settings, while P. eldarica may be better suited for tracking Zn. Moreover, leaves are found to be more effective than bark for biomonitoring applications, due to their greater sensitivity to recent atmospheric deposition.

Leaf Capacity (*Terminalia catappa* L.) In Absorbing Lead (Pb)

The use of biological organisms as biomonitors represents an efficient, low-cost, and straightforward approach for evaluating environmental pollution levels. In a study conducted by Świsłowski *et al*. (2022), three moss species *Sphagnum fallax*, *Pleurozium schreberi*, and *Dicranum polysetum* were employed to assess urban air quality. The mosses were exposed for a period of 90 days, during which time they were used to evaluate the influence of vehicular traffic and automobile workshop activities on elemental accumulation. Elemental concentrations were quantified using instrumental neutron activation analysis (INAA) and flame atomic absorption spectrometry (F-AAS). In addition to chemical analysis, the study also assessed moss vitality by measuring the effective quantum yield of Photosystem II (PSII), thereby allowing for the evaluation of physiological responses to pollutant exposure.

The results revealed significant variability in elemental concentrations depending on the exposure site, reflecting differences in atmospheric aerosol composition across locations. Notably, moss samples exposed indoors, specifically within automobile workshops, accumulated higher concentrations of elements such as aluminum (Al), chromium (Cr), iron (Fe), and barium (Ba), compared to outdoor samples. These findings suggest that the primary sources of these contaminants were emissions related to automotive maintenance and mechanical activities. Despite prolonged exposure to pollutant laden environments, the mosses remained viable throughout the study period, functioning effectively as natural sorbents. This study underscores the potential of moss species not only as passive biomonitors of air pollution but also as tools for source identification in complex urban microenvironments.

In a recent study by Davis *et al*. (2023), the accumulation and translocation of lead (Pb) and cadmium (Cd) in selected plant species were evaluated using atomic absorption spectrometry (AAS). The study found that Ipomoea fistulosa demonstrated the highest Pb accumulation capacity, with a notable growth rate of 27.07 g/week under a Pb treatment concentration of 300 mg kg^{-1}. This species also exhibited a bioconcentration factor (BCF) of 1.46 and a translocation factor (TF) of 0.87, suggesting efficient Pb uptake and moderate mobility within plant tissues. In contrast, Colocasia esculenta showed a strong affinity for Cd accumulation, achieving a BCF of 0.95 and a TF of 0.65 under 75 mg kg^{-1} Cd exposure. This was accompanied by a significant increase in relative biomass (124.9%) and the highest recorded growth rate among all tested species, at 36.96 g/week. These findings highlight the potential of specific plant species for targeted phytoremediation based on their differential uptake and tolerance to heavy metal contaminants.

Supporting these insights, earlier research by Chehregani *et al*. (2009) examined the heavy metal accumulation capabilities of five dominant plant species *A. retroflexus*, *P. aviculare*, *G. tournefortii*, *N. mucronata*, and *S. orientalis* in polluted environments. Among them, *N. mucronata* was identified as the most effective accumulator of multiple heavy metals, including Pb, Zn, Cu, Cd, and Ni, whereas *A. retroflexus* was found to be the most efficient in accumulating iron (Fe). Further investigations into the phytoremediation potential of N. mucronata under controlled pot experiments confirmed its capacity to tolerate and absorb heavy metals from contaminated soils. Collectively, these studies underscore the importance of species specific evaluations when selecting plants for environmental remediation strategies, particularly in regions affected by Pb and Cd contamination.

The environmental persistence and toxicity of polycyclic aromatic hydrocarbons (PAHs) have raised significant concerns, particularly regarding their accumulation in plant tissues. PAH uptake in plants is facilitated by transpiration and the lipid content of root tissues, which enhance the adsorption of PAHs onto cell walls and promote their translocation from roots to aerial parts such as stems and leaves. Consequently, species with higher lipid concentrations tend to accumulate greater levels of PAHs, making them effective bioaccumulators. These bioaccumulative properties enable certain plants to serve as biomonitors for detecting ambient air pollution, especially in urban and industrial settings. As reviewed by Mukhopadhyay *et al*. (2022), a wide range of organisms including vascular plants, mosses, and lichens have demonstrated potential as biomonitors of airborne PAHs. The review also outlines conventional and modified extraction techniques, alongside advanced analytical approaches, to improve the accuracy of atmospheric PAH assessments, thereby enhancing air quality monitoring through biological indicators.

In parallel, the integration of microbial assistance, particularly through phosphate solubilizing bacteria (PSB), has shown promise in enhancing phytoremediation of heavy metals such as lead (Pb). Yuan *et al*. (2022) investigated the synergistic effect of a Pb-tolerant PSB strain, *Leclercia adecarboxylata* L1-5, on the Pb uptake efficiency of *Celosia cristata* L. Under Pb-contaminated conditions (800 mg kg^{-1}), PSB inoculation significantly improved plant biomass by 34.90% in shoots and 55.56% in rootswhile simultaneously increasing Pb accumulation in both plant compartments by 3.06 fold in roots and 0.72 fold in shoots. These enhancements translated into a bioaccumulation factor (BCF) of 0.2 and a translocation factor (TF) of 1.92, with a maximum Pb extraction value of 222.94 µg kg^{-1}. The observed improvements in Pb uptake were attributed to the PSB's ability to solubilize phosphorus, thereby increasing its availability in the rhizosphere and facilitating heavy metal mobility and absorption by the host plant. Together, these studies underscore the expanding toolkit of biological agents from passive biomonitors like mosses to microbial-assisted phytoextractors in the environmental management of toxic pollutants.

Medicinal plants cultivated in geothermal environments are known to synthesize relatively high concentrations of bioactive secondary metabolites, which are believed to support their adaptive responses to thermal stress. However, their therapeutic potential may be compromised by the risk of heavy metal contamination in these naturally mineral rich soils. A recent study by Abubakar *et al.* (2023) reported trace concentrations of arsenic (0.0482 ± 0.004 to 0.0639 ± 0.007 mg/kg) and lead (0.0219 ± 0.004 to 0.0672 ± 0.006 mg/kg) in geothermal *C. odorata* leaf extracts values that remain within Indonesia's permissible safety limits (≤5 mg/kg for As and ≤10 mg/kg for Pb). Mercury was undetectable across all samples. In contrast, cadmium concentrations ranged from 0.0219 ± 0.005 to 1.1472 ± 0.006 mg/kg, with some samples significantly exceeding the maximum safe threshold of 0.3 mg/kg. This elevated cadmium level poses a potential health risk, as long-term exposure is associated with severe organ toxicity. Consequently, while geothermal medicinal plants may offer pharmacological benefits due to their enriched phytochemical profiles, their application should be approached with caution due to possible heavy metal bioaccumulation particularly cadmium.

In parallel with concerns over soil borne contamination, airborne pollutants such as polycyclic aromatic hydrocarbons (PAHs) have also prompted the exploration of plant based biomonitoring systems. Mukhopadhyay *et al*. (2022) highlighted the effectiveness of various plants, lichens, and mosses in accumulating and mineralizing atmospheric PAHs, thereby functioning as passive indicators of environmental pollution. The study also reviewed a range of classical and modified solvent extraction techniques, including the Soxhlet method, for isolating PAHs from biological matrices. Key process parameters such as solvent type, temperature, extraction time, pressure, and matrix composition were found to significantly influence extraction efficiency. Together, these findings support the dual role of vegetation in both phytopharmaceutical development and environmental pollution monitoring, while also underscoring the importance of evaluating potential toxicological risks associated with their growth environments.

CONCLUSIONS

The findings of this study confirm that *Terminalia catappa* L., commonly known as Ketapang, possesses notable potential as a bioaccumulator of lead (Pb) in urban environments. Through atomic absorption spectrophotometry (AAS) analysis of leaf samples collected from three distinct locations in Manado City Jalan Piere Tendean, Malalayang Beach Walk, and Wori it was observed that the concentration of Pb in leaf tissues ranged between 0.22 mg/kg and 0.44 mg/kg. The highest accumulation was recorded at Jalan Piere Tendean, a location characterized by high vehicular density and minimal canopy coverage, which likely facilitates increased direct exposure to atmospheric pollutants. These spatial variations in Pb content strongly suggest that environmental factors such as traffic intensity, proximity to emission sources, vegetation density, and microclimatic conditions significantly influence metal deposition patterns on foliage.

This study reinforces the ecological utility of *Terminalia catappa* L. not only as a shade tree in tropical urban landscapes but also as a passive biomonitor for atmospheric lead pollution. Its widespread distribution, physiological resilience, and capacity for trace metal absorption make it a suitable candidate for environmental surveillance programs. Moreover, the results align with a growing body of literature that highlights the role of urban vegetation in mitigating air pollution and improving environmental health. Therefore, the continued integration of *T. catappa* and similar species into urban green infrastructure planning can support both ecological monitoring and sustainable urban development. Future research should focus on expanding sampling coverage, evaluating seasonal and temporal variations, and exploring additional heavy metal pollutants to further elucidate the phytoremediation potential of this species in diverse urban contexts.

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