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Phytoremediation of Lead (Pb) Particulate as a Nature-Based Solution For a Healthier Environment

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ABSTRACT

Lead (Pb) particulates are a serious environmental issue due to their impact on health and ecosystems. These pollutants stem from emissions of vehicles, industries, and mining. This study aims to explore the potential of plants as phytoremediators of Pb using a literature review with data triangulation from scientific journals and institutional reports. Content analysis, tabulation, and exploratory descriptive analysis were conducted. Lead, with an atomic number of 82 and an atomic weight of 207.20, is a hazardous metal that can cause kidney damage, hypertension, anemia, nerve damage, reduced fertility, miscarriages, and lower intellectual quotient. Pb particulates can adhere or fall on leaf surfaces and are absorbed through stomata. This process occurs because the size of Pb particulates (0.2-4 µm) allows them to be absorbed through stomatal area 110.18-643.23 μm^2 when they open to take in CO_2, thus allowing Pb to enter and accumulate in plant tissues. Through this physiological mechanism, plants can be used as effective solutions for absorbing Pb. Some plants with high effectiveness include *Polyaltia longifolia*, *Swietenia macrophylla*, and *Bougainvillea spectabilis*. Planting these species in industrial zones and roads can improve air quality and provide ecosystem benefits, such as clean air, habitat space, thermal comfort, and aesthetic value.

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INTRODUCTION

Air pollution has become one of the most urgent environmental issues to address, as it can affect human health, ecosystems, and overall quality of life (Raj & Das, 2023). One of the harmful pollutants in the air is lead (Pb) particulates (Alqattan et al., 2025). Lead particulates are heavy metals that can be inhaled and accumulate in the human body, causing damage to the nervous system, kidneys, and other vital organs (Rahat et al., 2025). Lead in particulate form is typically carried by the air and can be found in areas with high industrial activity, roadways, or near fossil fuel combustion sites, especially those based on petroleum (Su & Diao, 2025; Q. Wu et al., 2025).

The primary sources of lead in the air include emissions from motor vehicles using leaded fuel (Marinello et al., 2023), fossil fuel combustion in industries (Poudel et al., 2024), and mining and metal processing activities (Alqattan et al., 2025; Hardiyanti et al., 2020). Although the use of leaded fuel has been heavily restricted, lead remains present in the environment due to its long-term accumulation and spread (Bazzano et al., 2016; Pambudi & Panjaitan, 2023). Besides in the air, lead exposure in soil and water can cause persistent pollution, requiring special efforts to reduce its concentration (Briseño-Bugarín et al., 2024; Fawkes & Sansom, 2021).

The potential for lead pollution and its harmful environmental impact must be a concern for all stakeholders (Briseño-Bugarín et al., 2024). Reducing lead concentrations is crucial due to the complex health and environmental risks it poses (Raj & Das, 2023). Continuous exposure to lead can cause severe health issues, such as nervous system damage, kidney failure, prenatal death, and developmental disorders in children (Li et al., 2025; Raj & Das, 2023; Q. Wu et al., 2025). Therefore, efforts to reduce lead concentrations, particularly in the air, are essential to protect public health and environmental sustainability (Thao et al., 2023).

There are several approaches to reduce lead concentrations in air, soil, and water (Hao et al., 2000). This study focuses on exploring plant-based approaches to reduce lead concentrations in the air. Plants have significant potential to reduce pollutants in the air, including heavy metals such as lead (Ravindra & Mor, 2022). Several plant species have proven capabilities to absorb, retain, or deposit heavy metal pollutants through various mechanisms, such as accumulation in leaves, stems, and roots (S. Collin et al., 2022; Lestari & Rosyidah, 2022). Therefore, research on plant species with high efficiency in absorbing lead is essential, especially in industrial zones or along busy traffic routes, as both are often major sources of air pollution. By selecting the right plants, effective pollutant absorption zones can be established in these areas.

This research is crucial as it aligns with efforts toward more sustainable environmental management. Using plants as a natural solution to reduce air pollution is not only environmentally friendly but also offers additional benefits, such as creating refreshing green spaces in urban and industrial areas (Gupta et al., 2024). Trees that effectively absorb lead can also help improve air quality, provide habitat space for wildlife, and offer comfort to communities (Leo et al., 2024; Qin et al., 2023). Therefore, this study is expected to provide recommendations for plant species that can be widely implemented to reduce lead concentrations in the air, contributing to a healthier environment.

MATERIALS AND METHOD

This study was conducted used a literature review with data source triangulation to obtain credible and valid results. The data source triangulation was carried out by collecting references from scientific articles published in national and international reputable journals, as well as research reports published by relevant ministries or institutions. This approach ensures that the information used in the research comes from reliable sources with high scientific quality. Additionally, using a variety of sources allows the researchers to reduce bias and gain a more comprehensive understanding of the topic being studied.

Data analysis, content analysis was employed to evaluate and interpret the information contained in the references. Tabulation analysis was also conducted to organize the data systematically, allowing comparisons between different findings. Furthermore, desk study methods were used to gather additional information from available documents without the need for field data collection. After the data analysis phase, exploratory descriptive analysis was performed to explain various findings from the analysed data. This approach aims to provide an in-depth explanation of the research results and to conclude findings that can objectively address the research problem based on the existing evidence. Visual representation of the research flow is shown in **Figure 1.**

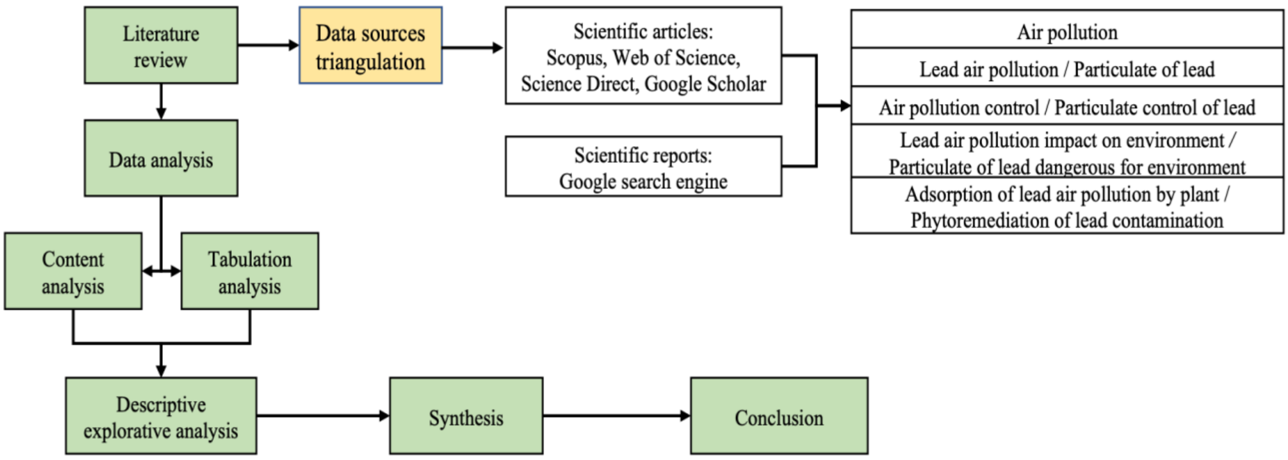

Figure 1. Research process stages data sources triangulation, analysis, synthesis, and conclusion

RESULTS AND DISCUSSION

Definition of Lead (Pb) and Its Impact on Life

Lead, known by its Latin name *Plumbum*, has the chemical symbol Pb and is a soft metal. This compound is one of the heavy metals, often referred to as "black lead." Lead compounds are commonly found in the primary mineral sources of crocite, anglesite, and galena (Steinnes, 2013). Lead has a low melting point, is easily shaped, and exhibits active chemical properties, which is why it is commonly used to coat metals to prevent rusting (Wang et al., 2019). Lead is a soft, bluish-grey metallic element (see Figure 2) with an oxidation number of +2.

Figure 2. The Characteristic of Lead (Pb)
Source: (Kumar, 2020)

Figure 2, as explained by Kumar (2020), indicates that the most important lead ore is galena, or lead sulphide (PbS), which is widely distributed worldwide. Other minerals containing lead include: (1) Anglesite ($PbSO_4$); (2) Cerussite ($PbCO_3$); (3) Pyromorphite ($PbCl2.3Pb_3(PO4)_2$), and Mimetite ($PbCl_2.3Pb3(AsO_4)_2$). Other lesser-known lead-containing minerals are Crocoite or Cholochrome, or red lead ore (PbCrO4), Wulfenite (also known as molybdenum lead spar, or yellow lead ore) (PbMoO4), and Stolzite ($PbWO_4$). The main sources of lead ore being mined today are found in the USA, Australia, Mexico, Canada, Russia, Peru, Morocco, Bosnia, Germany, Spain, South Africa, Italy, and Bolivia.

Based on its position in the periodic table of elements, lead has an atomic number of 82 and an atomic weight of 207.20. Lead's melting point is 1,740°C, and it has a density of 11.34 g/cm3 (Steinnes, 2013). According to Wang et al. (2019), lead metal can vaporize at temperatures between 500-600°C and form lead oxide (PbO) in the air. This vaporization process can lead to emissions, and when the levels exceed the threshold, lead can become a pollutant, posing a significant threat to life. One activity that emits lead into the air is the use of motor vehicle engines.

Due to the nature of pollutants produced by motor vehicles, lead is considered more hazardous than other substances because it accumulates in human body tissues, leading to serious health issues (Lestari & Rosyidah, 2022; Wati et al., 2015). According to Raj & Das (2023), lead levels in the air exceeding quality standards can worsen air quality and pose serious risks to people engaged in activities near areas exposed to lead. Based on *Peraturan Pemerintah Republik Indonesia No 41 Tahun 1999 Tentang Pengendalian Pencemaran Udara*, the national ambient air quality standard for lead (Pb) is 2 $\mu g/Nm^3$ for a 24-hour measurement and 1 $\mu g/Nm^3$ for an annual measurement. According to the World Health Organization (2021) standards, the lead concentration in the air should be 0.5 $\mu g/m^3$. Referring to these standards, lead emissions must be closely monitored and controlled to remain within safe limits, as lead can accumulate in living organisms, including animals, plants, and humans.

One exposure route of lead to humans is through the respiratory system. Research by Huang et al. (2024), found that approximately 25-50% of inhaled lead is absorbed by the lungs due to its small size (<0.5 µm), making it more easily absorbed by the alveoli, with the remainder being trapped by nasal hairs. This finding is supported by Xing et al. (2016) research's, which shows that inhaled lead is absorbed by the lungs at a rate of 10-30%, with 5-10% also absorbed through the digestive system. According to Flora et al. (2012), lead absorbed through the digestive tract is distributed to other tissues via the bloodstream. Health effects from lead exposure include kidney damage, hypertension, anemia, central nervous system damage, behavioural changes, reduced fertility, miscarriages, and lowered Intelligence Quotient (IQ) in children, with effects lasting 10-20 years (Clay et al., 2023; Fine et al., 2011; Gunawan & Masloman, 2014; Raj & Das, 2023; Wu et al., 2018). Based on various previous studies, it is evident that the effects of lead exposure on humans are complex and dangerous. Therefore, it is essential to reduce the potential for lead emissions to ensure the sustainability of life and a healthier ecosystem.

The Main Sources of Particulate Lead (Pb)

Historically, lead was commonly used as an additive in paints, hair dyes, and insecticides, and was also widely used in the production of equipment and/or canned packaging (Gupta et al., 2024; Kumar, 2020). As a result, lead exposure can occur through air, water, soil, and food (such as vegetables, fruits, fish, shellfish, and canned processed foods). Overall, Figure 3 illustrates the sources of lead pollution in the environment.

Referring to Figure 3, it can be seen that lead is one of the air pollutants that originates from motor vehicle exhaust. Lead is a by-product of combustion that occurs between fuel and the vehicle's engine (Marinello et al., 2023). Through vehicle exhaust, lead is released into the air, and some of it forms particles in the atmosphere combined with other elements. Approximately 85% of the lead in the air is in the form of particulate matter (total suspended particulate matter) with a diameter of less than 4 µm, and about 80% of these particles have a diameter of less than 2 µm (Khan & Bederka, 1974). According to Surani (2002), 10% of lead emissions from motor vehicles will contaminate areas within a 100-meter radius, 5% will affect locations within a 20-kilometer radius, and the remaining 35% will be carried by the atmosphere over long distances. This issue needs to be addressed seriously, as the number of motor vehicles in Indonesia continues to rise, and the use of environmentally friendly alternative fuels, which can reduce lead pollution in the air, is still not optimal.

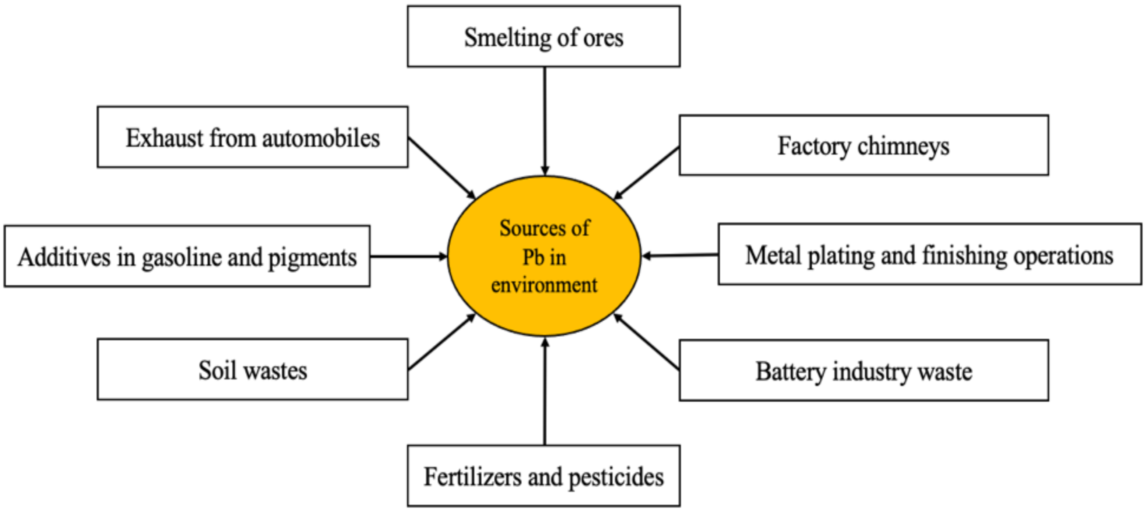

Figure 3. Various sources of Pb in the environment from human activities
Source: (Ur Rahman et al., 2024)

The Role of Lead Adsorption by Plants

According to a Utami (2021) study's, the Pb concentration in Pertalite at gas stations in Makassar ranges from 0.13291 to 0.2594 mg/L, while the Pb concentration in Pertamax at gas stations in Makassar ranges from 0.0063 to 0.5126 mg/L. The Pb levels found in the study are in accordance with the maximum allowable limits for Pb content as a byproduct in the processing of crude oil into Premium and Pertamax fuel, as set by the Ministry of Energy and Mineral Resources (ESDM), which is 0.013 g/L (Direktorat Jenderal Minyak dan Gas, 2020). According to Pauwelussen (2015), about 25% of Pb remains in the engine, and the remaining 75% is released into the air as exhaust smoke. Based on Sassykova et al. (2019) study's, it was found that passenger transportation generates varying emissions of particulate matter pollutants, including 0.09 g/person/km from trains, 0.05 g/person/km from high-speed trains, 0.07 g/person/km from motorcycles, and 0.03 g/person/km from airplanes. As for freight transportation, emissions are 0.08 g/ton/km from cargo trains, 0.04 g/ton/km from trucks, and 0.04 g/ton/km from cargo ships.

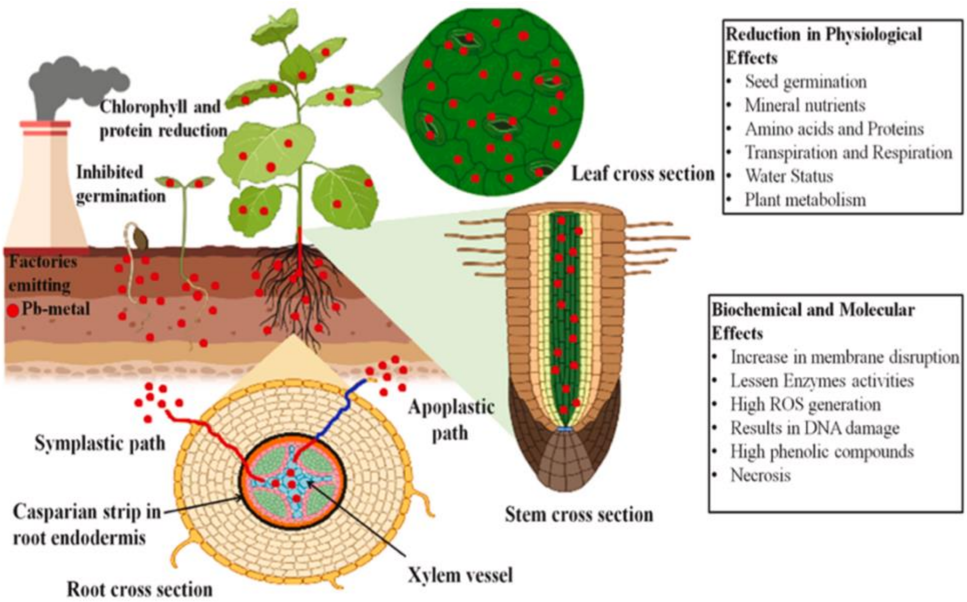

Figure 4. Lead (Pb) particulate adsorption, accumulation, and translocation
Modified from Gupta et al. (2024)

Based on **Figure 4**, it can be observed that plants have the ability to adsorb Pb through physiological mechanisms. Lead enters the plant through passive absorption, where lead particles dispersed in the air are adsorbed onto the surface of the leaves. According to Zhao et al. (2011), morphologically, wide and hairy leaf blades can adsorb larger lead particles compared to narrow and smooth leaf surfaces. Referring to Figure 4, lead particles enter the leaf tissue through passive absorption via stomatal gaps and then accumulate. Prolonged exposure can lead to increased Pb accumulation in the plant's organs and tissues (Figure 5). This passive absorption process can be seen positively, as it helps reduce the concentration of lead particles in the air and the environment. However, it can also be seen negatively, as it can affect seed quality, reduce nutrients and minerals, lower amino acids and protein content, reduce transpiration and respiration abilities, decrease leaf water content, and impair metabolic functions. Therefore, if lead particles are absorbed by plants whose leaves are consumed, such as vegetables, it can be highly detrimental, as it may enter the human body and accumulate, leading to various adverse health effects. However, if absorption occurs in non-consumable plants, this can be an important effort to reduce lead particle concentrations in the air while also improving environmental quality.

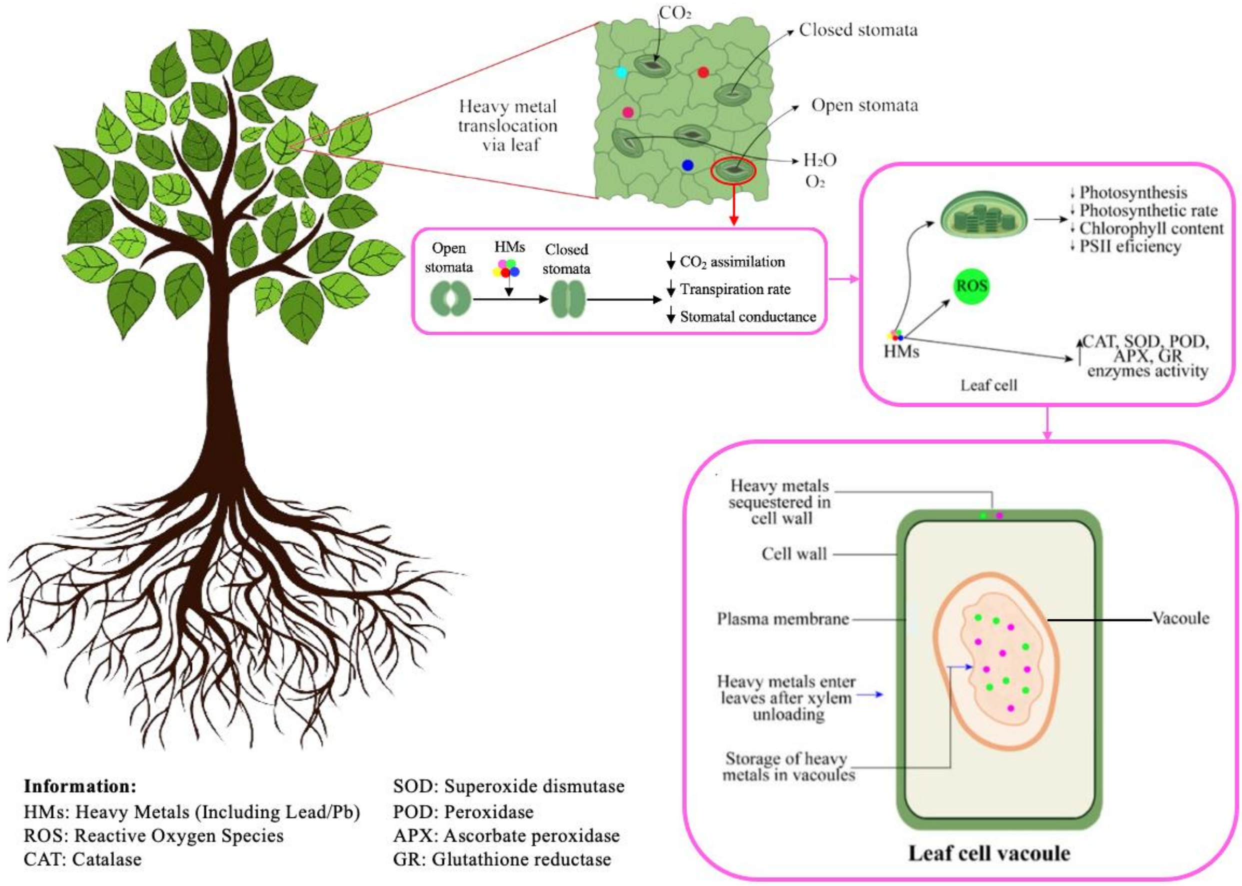

Figure 5. Lead (Pb) accumulation in leaves
Source: Modified from (Zhang et al., 2024)

Figure 5 illustrates that Pb particles in the air can adhere to and/or fall onto the surface of the leaves, then be absorbed through the stomata during the process of photosynthesis. When the stomata open, CO_2 enters the leaf tissue, and Pb is absorbed into the leaf tissue as well. This event leads to a decrease in CO_2 assimilation, a reduction in transpiration rate, and a decline in stomatal conductance (the degree of stomatal opening, CO_2 and O_2 exchange rates, and water exchange rates). The entry of Pb into the leaf tissue causes the O_2 produced to react easily with other molecules, including free radicals, which can lead to cellular and tissue damage. Other consequences include reduced photosynthesis, decreased photosynthetic rate, lower chlorophyll content, and a decline in photosystem efficiency. Additionally, there is an increase in the activity of enzymes such as catalase, superoxide dismutase, peroxidase, ascorbate peroxidase, and glutathione reductase, indicating physiological stress in the plant. Prolonged exposure to Pb over time leads to accumulation in the vacuoles of the leaf cells, where this Pb accumulation can undergo translocation or movement through the phloem tissue to other parts of the plant.

According to the Collin et al. (2022) study's, Pb particles adhering to the surface of leaves come from three processes: (1) sedimentation due to gravitational force, (2) impact caused by wind turbulence, and (3) deposition related to rainfall. Based on Primawati & Daningsih (2022) research's, the average of dicot plant stomatal area is around 110.18-643.23 μm^2. Due to the small size of Pb particles, which are less than 4 µm with an average size of 0.2 µm, it is easier for these particles to enter the leaves through the stomatal openings. Referring to Amin et al. (2018), this process results in Pb particles settling in the leaf tissue and accumulating between the cells of the epidermal layer or palisade tissue and/or spongy tissue. According to Utomo et al. (2021), plants respond differently to airborne pollutants, whether in gas or particulate form. These differences depend on the plant species, genetic makeup, tree growth rate, proximity to the pollution source, pollutant concentration, and duration of exposure.

The risk of Pb absorption, accumulation, and translocation varies greatly depending on the morphological characteristics of the plant, environmental conditions, and the intensity and frequency of exposure Collin et al. (2022). Some plant species have the ability to reduce the concentration of airborne Pb particles, as plants can enhance air flow turbulence (Ha et al., 2021). According to Qin et al. (2023), the ability of leaves to capture particles is highly influenced by the leaf surface condition, such as wetness, stickiness, and leaf hairs. The higher the concentration of Pb particles in the air, the greater the risk of Pb absorption by the leaves. This occurs because the higher the concentration of Pb particles in the air, the greater the potential for Pb exposure on the leaves and the higher the chance for Pb to enter the stomata and accumulate in the epidermal and mesophyll layers. Essentially, the greater the plant's ability to adsorb Pb particles, the larger the concentration of Pb that can be removed from the air. Pambudi et al. (2025) emphasized through this adsorption mechanism, Pb accumulation in the leaf tissue tends to be higher compared to other parts of the plant.

The List of Lead Absorbing Plant Species

Considering the significant potential for air pollution due to transportation activities and industrialization, which increases the concentration of heavy metal particles, including lead, effective control measures are necessary. One approach to controlling heavy metal particulate pollution in the air is by using plants as pollutant adsorbers. Plants have the ability to adsorb and accumulate lead, which can improve air quality. On the other hand, using plants as lead pollutant adsorbers also provides benefits such as creating microclimate stability, thermal comfort, habitats for epiphytic plants and fauna, reducing wind speed, and enhancing the aesthetic value of a landscape area. Due to the importance of utilizing plants in air pollution control and their various additional benefits, Table 1 presents a list of lead-absorbing plant species that can be used for air pollution control.

Table 1. List of lead (Pb) adsorbing plant species commonly in Indonesia

No	Common Name	Scientific Name	Areas	Pb Content (ppm)	References
1	Amboyna wood	*Pterocarpus indicus* Willd.	Road	0.103	(Arif et al., 2024)
2	Tamarind	*Tamarindus indica* L.	Road	0.34-1.80	Manik et al., 2015)
3	Bougainvillea	*Bougainvillea spectabilis* Wild.	Laboratory Scale	1.22-1.45	(Nurhikmah et al., 2015)
4	Indian Mast Tree	*Polyaltia longifolia* (Sonn.) Thwaites	Industry	1.21-2.42	(Hardiyanti et al., 2020)
5	Wedding Plumeria	*Plumeria pudica* Jacq.	Road	0.49	(Alamsyah & Rachmadiarti, 2021)
6	Mexican Petunia	*Ruellia simplex* C. Wright	Road	0.75	(Alamsyah & Rachmadiarti, 2021)
7	Mahogany	*Swietenia macrophylla* King	Road	1.247	(Erwinda et al., 2022)
8	Crape Jasmine	*Tabernaemontana* sp. var. variegate	Road	0.64	(Alamsyah & Rachmadiarti, 2021)

9	Garden Croton	*Codiaeum variegatum* (L.) Rumph. Ex A.Juss.	Road	0.33	(Rois & Muryani, 2023)
10	Pink Trumpet-Tree	*Tabebuia aurea* (Silva manso) Benth. & Hook.fil. ex S.Moore	Road	0.09-0.187	(Fida et al., 2022)
11	Bullet Wood	*Mimusops elengi* L.	Road	0.07	(Arif et al., 2024)
12	Rain Tree	*Samanea saman* (Jacq.) Merr.	Road	0.27-8,3	(Manik et al., 2015)

Based on **Table 1**, it is evident that there are 12 plant species commonly planted in Indonesia as shade trees along roads and as boundary or shade trees in industrial areas. Among these twelve plant species, *Polyaltia longifolia* has the highest Pb absorption capacity, with Pb content in the leaves ranging from 1.21 to 2.42 ppm, followed by *Swietenia macrophylla* at 1.247 ppm, and *Bougainvillea spectabilis* at 1.22 to 1.45 ppm. The plant with the lowest Pb absorption capacity is *Mimusops elengi*. Based on these results, when selecting trees for road shading and ecological buffer zones in industrial areas, plant species with high Pb absorption capabilities can be utilized to improve the air quality of the surrounding environment. In addition to this, the following factors should also be considered: strong root system; vegetation profile that does not damage building structures; resilient trees that are not prone to falling or breaking branches; lants that are non-toxic, free from harmful compounds, or have dangerous morphological characteristics for humans and other living organisms; architectural profile that supports optimal emission absorption and oxygen production; architectural profile that helps reduce wind speed; morphological structure that provides thermal comfort; and esthetic value, especially from the morphological structure (trunk, branches, twigs, leaves, and flowers).

The fundamental factors influencing Pb absorption ability, as explained earlier, are the concentration of Pb particles in the air, which is affected by the distance from the pollution source, pollution intensity, and frequency of pollution. Besides Pb particle concentration, the physical and chemical properties of plants also play an essential role in their ability to absorb pollutants. Some plants have leaf morphology and structures that are more efficient at absorbing heavy metals, such as lead, from the air. For example, plants with wide and rough-textured leaves tend to be more effective at capturing airborne pollutants. Additionally, environmental conditions such as humidity, temperature, and soil quality can also affect how optimally plants absorb lead.

Currently, most parks along roadsides, green open spaces in industrial zones, and open spaces in government buildings prioritize aesthetic appeal over ecological function. Many of the plants in these areas are selected for their visual beauty, rather than for their vital role in environmental health. However, the ecological function of plants, particularly their ability to absorb hazardous pollutants like lead (Pb), should take precedence. Plants with the ability to absorb and accumulate pollutants can significantly improve air quality, reduce harmful health impacts, and create a healthier environment. Therefore, it is essential to choose plants that not only provide aesthetic value but also serve ecological functions, especially in areas prone to air pollution, such as roads, industrial zones, and public spaces around government buildings.

This study limitation is a literature review, where data were gathered from various sources, and as such, the environmental conditions, exposure intensity, and lead concentrations could not be standardized. The studies referenced have different growing conditions and varying levels of pollution, which makes it difficult to control for external factors. Consequently, the findings may not fully reflect the actual lead absorption capacity of the plants under controlled conditions. The variability in the methods and settings of the original studies introduces potential discrepancies. Further research is needed to understand these mechanisms and identify the most effective plants as biofilters for air pollution. To accurately determine the Pb absorption capacity of each plant, it is necessary to control the concentration of Pb particles, such as by conducting laboratory experiments or planting all the plant species in the same location.

CONCLUSION

Lead (Pb) is a toxic heavy metal that originates from galena and is harmful to human health and the environment. It can be absorbed by the lungs, particularly from emissions by vehicles and industries. Lead exposure damages organs, lowers IQ in children, and disrupts metabolic functions. Plants can effectively absorb lead, both through their roots and leaves. Species such as *Polyaltia longifolia*, *Swietenia macrophylla*, and *Bougainvillea spectabilis* are efficient in absorbing lead. Planting these species along roadsides and industrial zones can improve air quality and offer ecosystem benefits. Further research is needed to identify the most effective plants for lead absorption in controlled conditions.

AUTHORS CONTRIBUTION

P.A.P. research designed, data analyzed, data interpretation, and manuscript finalization. R.S.H. references searching, data visualization, and manuscript preparation.

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