

The Potential of Swiftlets (*Aerodramus fuciphagus*) as Bioindicators of Air Pollution Through Heavy Metal (Pb) Analysis

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ABSTRAK

Penelitian ini bertujuan untuk mengevaluasi potensi burung walet (*Aerodramus fuciphagus*) sebagai bioindikator pencemaran udara melalui analisis kualitas udara dan akumulasi timbal (Pb). Penelitian ini dilakukan di dua lingkungan yang kontras: kawasan industri di Gresik, Indonesia dan kawasan non – industri di Lawas, Sarawak, Malaysia. Parameter kualitas udara termasuk PM 2,5, PM 10, dan CO diukur, sedangkan konsentrasi Pb dalam bulu dan sarang dianalisis menggunakan Spektrofotometri Serapan Atom (AAS). Data di analisis menggunakan statistik deskriptif dan ANOVA Dua Arah. Hasil menunjukkan bahwa konsentrasi PM 2,5 di Gresik ($31 \mu\text{g}/\text{m}^3$) melebihi standar baku mutu WHO, sedangkan Lawas ($13 \mu\text{g}/\text{m}^3$) tetap di bawah ambang batas. Konsentrasi Pb pada bulu walet di Gresik berkisar antara 0,328 – 0,341 ppm dan di Lawas antara 0,319 – 0,329 ppm, sedangkan pada sarang walet masing – masing berkisar antara 0,059 – 0,061 ppm dan 0,051 – 0,062 ppm. Hasil Two – Way ANOVA menunjukkan bahwa lokasi penelitian ($p = 0,024$) dan jenis sampel ($p < 0,001$) berpengaruh signifikan terhadap konsentrasi Pb, sedangkan interaksi kedua faktor tidak signifikan ($p = 0,187$). Konsentrasi Pb yang lebih tinggi pada bulu dibandingkan sarang menunjukkan bahwa bulu memiliki kemampuan akumulasi yang lebih tinggi terhadap logam berat. Temuan ini menunjukkan bahwa burung walet, khususnya bulu, berpotensi digunakan sebagai bioindikator pencemaran logam berat di lingkungan dengan tingkat aktivitas antropogenik yang berbeda.

Kata kunci: bioindikator, burung walet, polusi udara, Pb, PM 2.5.

ABSTRACT

This study aimed to evaluate the potential of swiftlets (*Aerodramus fuciphagus*) as bioindicators of air pollution by analyzing air quality and lead (Pb) accumulation. The research was conducted in two contrasting environments: an industrial area in Gresik, Indonesia, and a non-industrial area in Lawas, Sarawak, Malaysia. Air quality parameters—specifically PM_{2.5}, PM₁₀, and CO—were measured, while Pb concentrations in feathers and nests were analyzed using Atomic Absorption Spectrophotometry (AAS). Data were analyzed using descriptive statistics and Two-Way ANOVA. The results showed that the PM_{2.5} concentration in Gresik ($31 \mu\text{g}/\text{m}^3$) exceeded WHO standards, whereas in Lawas ($13 \mu\text{g}/\text{m}^3$), it remained below the threshold. Pb concentrations in swiftlet feathers ranged from 0.328–0.341 ppm in Gresik and 0.319–0.329 ppm in Lawas, while concentrations in nests ranged from 0.059–0.061 ppm and 0.051–0.062 ppm, respectively. Two-Way ANOVA results indicated that the study location ($p = 0.024$) and sample type ($p < 0.001$) significantly influenced Pb concentrations, whereas the interaction between the two factors was not significant ($p = 0.187$). Higher Pb concentrations in feathers compared to nests suggest that feathers possess a greater capacity for heavy metal accumulation. These findings indicate that swiftlets—specifically their feathers—have the potential to serve as bioindicators of heavy metal pollution across environments with varying levels of anthropogenic activity.

Keywords: bioindicators, swiftlets, air pollution, Pb, PM 2.5.

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1. INTRODUCTION

Air is a vital component for the survival of living things. However, its quality continues to decline due to increased anthropogenic activities such as industry, transportation, and residential areas, which have led to a significant increase in the concentration of air pollutants, including heavy metals like lead (Pb),

which are toxic and persistent (Syakbanah, 2018). Air pollution is now recognized as one of the greatest environmental threats to human health globally. Long-term exposure to Pb can damage the nervous system and kidneys, reduce children's intelligence, and even cause death annually (WHO, 2021).

Gresik Regency, as one of the largest industrial areas in East Java, faces serious challenges related to air quality due to high emissions from factories, vehicles, and the combustion of fossil fuels (Mahardianti *et al.*, 2024). Gresik is one of Indonesia's main industrial areas with high levels of industrial activity, transportation, and the combustion of fossil fuels. These activities have the potential to increase the concentration of airborne particulates and heavy metals in the atmosphere. In contrast, Kota Lawas, in Sarawak, Malaysia, has a relatively low level of industrialization and is dominated by natural vegetation, potentially offering better air quality. These differences in environmental characteristics make the two areas relevant for comparison in air pollution studies.

Atmospheric lead (Pb) is commonly associated with airborne particulate matter, particularly PM_{2.5}, PM₁₀. Lead emitted from industrial activities, fossil fuel combustion, and transportation sources is often transported in particle bound form, allowing it to remain suspended in the atmosphere and disperse over considerable distances previous studies have demonstrated that Pb is frequently detected as a component of atmospheric PM_{2.5} and PM₁₀, especially in urban and industrial areas. Therefore, particulate matter not only reflects air quality conditions but way also serve as an important pathway for Pb exposure and accumulation in living organisms.

Conventional air quality monitoring is often expensive and limited. Therefore, more efficient and comprehensive alternative methods are needed. One development approach is the use of bioindicators, organisms capable of reflecting environmental conditions through their biological responses. Swiftlets (*Aerodramus fuciphagus*) are attractive candidates because they live in industrial and urban areas, feed on insects that potentially contain lead, and have nests and feathers that can store pollutants. This alternative approach using bioindicators is important for providing a biological and integrative picture of environmental quality (Afani *et al.*, 2021; Widiyani *et al.*, 2023; Sudarwanto *et al.*, 2022).

Swiftlets have been widely used as bioindicators due to their sensitivity to environmental changes and their ability to accumulate pollutants through the food chain. One species with potential use is the swiftlet (*Aerodramus fuciphagus*), which is characterized as an aerial insectivore with high levels of exposure to ambient air. Furthermore, swiftlets produce nests from sticky and porous saliva, which is able to bind airborne particles and pollutants, including heavy metals. Swiftlet feathers are also known to accumulate heavy metals during their growth process, thus reflecting environmental conditions at a given time.

Previous research has shown that swiftlet nests and feathers can contain heavy metals such as Pb, Cd, and Hg, which are related to the level of environmental pollution in their habitat. However, studies integrating air quality analysis (PM_{2.5}, PM₁₀,

and CO) with metal bioaccumulation in swiftlets, particularly through a comparative approach across regions with different industrial characteristics, are still limited.

Various studies have reported the accumulation of heavy metals in bird tissues and nests as an indicator of environmental pollution. However, research integrating air quality parameters (such as PM_{2.5}, PM₁₀, and CO) with lead (Pb) accumulation in the feathers and nests of swiftlets (*Aerodramus fuciphagus*) remains very limited, particularly in Southeast Asia. Furthermore, comparative studies across industrial regions utilizing swiftlets as bioindicators of air pollution are scarce. Therefore, this study aims to compare Pb accumulation in swiftlet feathers and nests from Gresik, Indonesia, and Lawas, Sarawak, Malaysia, and to correlate these findings with air quality parameters measured at each location. The novelty of this research lies in its integrative approach—combining air quality data with Pb accumulation in swiftlets from two distinct environmental settings—thereby providing additional insight into the potential of swiftlets to serve as bioindicators of environmental air pollution.

Recent studies have also emphasized the relevance of birds as bioindicators. Research in Brazil has shown that birds can be used to assess the genotoxic impacts of agricultural activities (Souto *et al.*, 2025). Studies on bird diversity in ecotourism areas have also confirmed that bird communities can be indicators of ecosystem quality and support sustainable ecotourism development (Nurmawan *et al.*, 2019). Research in Kalimantan also adds that swiftlet productivity is strongly influenced by environmental conditions and insect availability, so habitat degradation directly impacts swiftlet populations (Aziz *et al.*, 2021). Furthermore, recent studies have emphasized the importance of understanding swiftlet food sources in tropical ecosystems due to their link to the production of high-value swiftlet nests (Abdullah *et al.*, 2025).

Based on the identified research gap, this study aims to analyze air quality and Pb concentration in swiftlet feathers and nests collected from Gresik, Indonesia, and Lawas, Sarawak, Malaysia. The study also evaluates the potential of swiftlets as Bioindicators of environmental pollution by comparing Pb accumulation under different environmental conditions.

Several studies have reported that airborne particulate matter (PM_{2.5}, PM₁₀) can act as carriers of heavy metals, including lead (Pb). Fine particles are capable of adsorbing and transporting Pb emitted from industrial activities, fuel combustion, and traffic emissions. Consequently, areas with elevated particulate matter concentrations often exhibit increased levels of atmospheric Pb was not directly measured in the present study, the higher PM_{2.5} concentration observed in Gresik may indicate a greater potential for Pb exposure compared with Lawas.

2. METHODOLOGY

2.1. Study Area

The research will be conducted at swiftlet houses located in Sidayu District, Gresik Regency, East Java (Indonesia), and Lawas Town, Sarawak (Malaysia). These two locations were selected due to their differing environmental characteristics: Gresik is an area with relatively high industrial activity, whereas Lawas has a lower level of industrial activity.

2.2. Sample Collection

The research samples consisted of feathers and nests of the edible-nest swiftlet (*Aerodramus fuciphagus*) collected from swiftlet houses in Gresik, East Java, Indonesia, and Lawas, Sarawak, Malaysia. Fifty feathers and nine nests were collected from each study site. The collected samples were cleaned of surface contaminants and stored in sterile containers prior to laboratory analysis.

For the lead (Pb) content analysis, feather and nest samples from each location were pooled and divided into three analytical replicates, resulting in a total of 12 laboratory replicates for feathers and three for nests per study site.

Sample were collected from active swiftlet houses and selected to represent the environmental conditions of each study area. The collected sample were considered representative because they originated from locations with different environmental characteristics, namely an industrial area (Gresik, Indonesia) and a less industrialized area (Lawas, Malaysia).

2.3. Air Quality Measurement

Air quality measurements were conducted directly at the research sites to assess environmental conditions within each swiftlet house. The parameters monitored included particulate matter (PM_{2.5} and PM₁₀), carbon monoxide (CO), temperature, and humidity. PM_{2.5}, PM₁₀, and CO levels were measured using a portable air quality detector, while temperature and humidity were measured using an HTC-1 thermo-hygrometer. Measurements were taken over a 24-hour period; PM_{2.5} and PM₁₀ values are expressed in $\mu\text{g}/\text{m}^3$, and CO levels in ppm.

2.4. Pb Analysis

Analysis of lead (Pb) content in feather and nest samples was conducted at the Nutrition Laboratory of the Faculty of Public Health, Universitas Airlangga, using the Atomic Absorption Spectrophotometry (AAS) method to determine Pb concentrations. The results were expressed in ppm (mg/kg). The Pb concentrations in the feathers and nests were then compared based on study location and sample type to evaluate the potential of swiftlets as bioindicators of heavy metal pollution.

To ensure data reliability, all laboratory analyses were conducted following standard operating procedures. Measurements were performed in triplicate, and the instrument was checked prior to

analysis to minimize measurement errors. Data were reviewed before statistical analysis to ensure consistency and accuracy.

2.5. Statistical Analysis

Data analysis was performed using statistical software. Normality was assessed using the Shapiro-Wilk test, while the homogeneity of variance was evaluated using Levene's test. The effects of the study location and sample type on Pb concentration were analyzed using Two-Way Analysis of Variance (Two-Way ANOVA) at a 5% significance level ($\alpha = 0.05$). As this study did not directly measure ambient air Pb concentrations, a correlation analysis between atmospheric Pb and Pb levels in swiftlet feathers or nests could not be conducted. Therefore, the relationship between air quality and Pb accumulation is discussed descriptively based on the air quality parameters measured at each study location.

3. RESULTS AND DISCUSSION

3.1. Air Quality

The results of air quality measurements show that there are differences between industrial and non-industrial areas. The parameters measured include PM_{2.5} (Particulate Matter 2.5) PM₁₀ (Particulate Matter 10) CO (Carbon Monoxide) air quality research and analysis of Lead (Pb) levels in feathers and nests of swiftlets (*Aerodramus fuciphagus*) conducted in two research locations, namely Gresik, East Java (Indonesia) and Lawas, Sarawak (Malaysia). From the data obtained and analyzed to determine differences in environmental conditions and levels of heavy metal accumulation in each location.

Table 1. Results of Measurements of PM_{2.5}, PM₁₀, and CO Parameters

Parameter	Observation result		Measurement Time	Quality Standards
	Indonesia	Malaysia		
PM _{2.5} , $\mu\text{g}/\text{m}^3$	31	13	24 O'clock	15
PM ₁₀ , $\mu\text{g}/\text{m}^3$	41	20	24 O'clock	45
CO ppm	0	0	24 O'clock	4

Description:

PM_{2.5} (Particulate Matter 2.5)

PM₁₀ (Particulate Matter 10)

CO (Carbon Monoxide)

Based on a 24-hour study of ambient air quality, data on PM_{2.5}, PM₁₀, and CO parameters were obtained at two locations: Lawas, Sarawak (Malaysia) and Gresik, East Java (Indonesia). Significant differences were found in several air pollution parameters. The observed differences were influenced by the surrounding environmental conditions, where Sarawak has more green areas and relatively lower industrial activity compared to Gresik, which is an industrial area with numerous factories. The observation results show that the concentration of PM_{2.5} in Indonesia shows a result of $31 \mu\text{g}/\text{m}^3$ while in Malaysia it is $13 \mu\text{g}/\text{m}^3$. When compared to the 24-hour quality standard of 15

$\mu\text{g}/\text{m}^3$, the concentration of PM 2.5 in Indonesia exceeds the quality standard while Malaysia is still below the quality standard. This indicates that the air quality in the Indonesian region (Gresik) is not good in terms of fine particles PM 2.5. PM 2.5 particles or particulates suspended in the air, have very fine particles, can enter the alveoli of the lungs and even reach the bloodstream, PM 2.5 generally comes from motor vehicle emissions, fossil fuel combustion, industrial activities, and waste incineration processes. PM 2.5 levels in Gresik exceed WHO standards, while those in Lawas, Sarawak remain below these standards. This indicates that air quality in Gresik is considered poor for fine particles. PM 2.5 particles are extremely dangerous due to their extremely small size, allowing them to penetrate the alveoli of the lungs and carry heavy metals such as lead. These particles generally originate from fossil fuel combustion, motor vehicle emissions, industrial activities, and waste incineration (Fu *et al.*, 2021). The high concentration of PM2.5 in the Gresik area is thought to be related to industrial activity and the high density of transportation in the area. Fine particles such as PM2.5 also have the potential to carry various types of heavy metals, including lead (Pb), which can be decomposed in the atmosphere and then deposited in the surrounding environment (Fu *et al.*, 2021). Therefore, increasing PM2.5 concentrations not only impact air quality but also have the potential to increase heavy metal exposure in organisms living in the area.

In the PM 10 parameter, the measurement results in Indonesia were $41 \mu\text{g}/\text{m}^3$ and Malaysia was $20 \mu\text{g}/\text{m}^3$. Both values are still below the PM 10 quality standard of $45 \mu\text{g}/\text{m}^3$, but the PM 10 concentration in Indonesia is higher than in Malaysia. The high PM 10 in Indonesia is thought to originate from industrial activities, motor vehicles, and dust from construction activities. PM 10 particles are coarser, generally retained in the upper channel, PM 10 usually comes from road dust, industrial activities, large-scale industrial processes. In the PM 10 study, the values in both regions were still below the quality standard ($45 \mu\text{g}/\text{m}^3$), but the Gresik area was close to the maximum limit, although it had not yet exceeded the threshold, values close to the standard indicate the potential for long-term uncontrolled risks. PM10 particles have a larger size than PM2.5 so that most of them are retained in the upper respiratory tract. These particles generally originate from road dust, construction activities, industrial processes, and resuspension of soil particles due to vehicle activity (Arya *et al.*, 2025).

PM10 values at both locations remained below the environmental quality standard threshold. The relatively higher concentrations in the Gresik area indicate the influence of anthropogenic activities such as industrial activity and infrastructure development. Previous research also shows that areas with higher levels of urbanization and industrial activity tend to have higher concentrations of airborne particulates

than areas with more extensive vegetation cover (Zhou *et al.*, 2025).

Meanwhile, the CO (Carbon Monoxide) parameter showed a value of $0 \text{ mg}/\text{m}^3$ in both Indonesia and Malaysia. Both values are still well below the environmental quality standard of $4 \text{ mg}/\text{m}^3$, thus concluding that CO was not a dominant pollutant at the time of measurement. Carbon monoxide is a colorless, odorless gas produced by the incomplete combustion of carbon-containing fuels such as gasoline, diesel, and other fossil fuels. The main source of CO in the environment generally comes from motor vehicle emissions and industrial combustion processes (WHO, 2021).

In general, air quality in Lawas, Sarawak (Malaysia) shows better results compared to Gresik, East Java, especially in the parameters of PM 2.5 and PM 10. Conditions are influenced by differences in land use, industrial levels, and the presence of vegetation that plays a role in absorbing air pollutants. The results of this study indicate that industrial activity and transportation density significantly influence the increase in particulate concentrations in ambient air and the presence of vegetation in both areas. Vegetation is known to play a role in reducing the concentration of airborne particles through the process of particle deposition on leaf surfaces and absorption of air pollutants (Kumar *et al.*, 2022). According to WHO, the safe limit for lead (Pb) concentration in the air is $0.5 - 0.15 \mu\text{g}/\text{m}^3$ (annual average). If the concentration exceeds this value, it has the potential to cause negative impacts on human health and living organisms. The heavy metal Lead (Pb) in the air is generally bound to particulate particles such as PM 2.5 and PM 10. These particles act as a medium for transporting heavy metals in the atmosphere, so that increasing PM concentrations can increase the potential for Pb exposure in the environment. Pb is not measured directly from PM, but Pb usually sticks to PM particles so that PM becomes a carrier medium for Pb in the air.

Although PM 2.5 concentrations were higher in Gresik than in Lawas, Pb concentrations in swiftlets feathers and nests showed relatively small differences between locations. This finding suggests that Pb accumulation in swiftlets may be influenced by multiple factors, including feeding behavior, pollutant deposition, environmental exposure history, and local ecological conditions. Therefore, the present study provides preliminary evidence regarding the potential of swiftlets as bioindicators however direct measurements of atmospheric Pb are required to confirm this relationship quantitatively verify this relationship.

Table 2. Results of Temperature and Humidity Measurements

Parameters	Indonesia	Malaysia
Temperature	27,0 °C	26,5°C
Humidity	81%	52%

Differences in temperature and humidity can be influenced by several factors, such as the temperature and humidity in Gresik, East Java (Indonesia), which was 27.0°C and 81% humidity. This is influenced by several factors, such as Gresik being an industrial area with numerous factories, high traffic volumes, and the burning of fossil fuels. These activities increase the ambient temperature, and concrete, asphalt, and industrial building surfaces can absorb and reflect more heat than areas with dense vegetation. As a result, the temperature around the swiftlet house increases, impacting the temperature inside the building.

The Gresik region, an industrial area, experiences significant production, transportation, and fossil fuel use. These activities can increase ambient temperatures through heat release from industrial machinery, motor vehicles, and building surfaces such as concrete and asphalt, which absorb and reflect more heat than areas with dense vegetation. This phenomenon of increased temperatures due to human activity is known as an urban heat island, a condition in which urban areas experience higher temperatures than surrounding areas. (Lestari dan Fitri, 2013)

Commercial houses have different designs. If ventilation in Gresik (Indonesia) is inadequate or air circulation is suboptimal, heat will be trapped inside the building, water vapor from bird respiration will accumulate, and humidity will be relatively high. A larger swiftlet population in a building can also increase metabolic heat production, water loss from respiration, and indoor humidity will be higher (Lim & Cranbrook, 2021).

In contrast to Lawas, Sarawak (Malaysia) which has a temperature and humidity below the temperature and humidity of Indonesia, Lawas, Sarawak (Malaysia) is 26.5°C for indoor, 25.0°C outdoor and 52% humidity, this is because Lawas, Sarawak (Malaysia) still has a lot of green areas compared to Gresik, with the presence of green plants can reduce the temperature through evapotranspiration, absorb solar radiation, and maintain the microclimate. Lawas, Sarawak has a relatively natural environmental condition with vegetation that is still quite extensive. Vegetation has an important role in maintaining microclimate balance through the process of evapotranspiration, namely the process of releasing water vapor from the soil that can help reduce environmental temperatures (Zhong et al., 2021).

In addition, it can also be seen that Lawas, Sarawak (Malaysia) has a lower industry because fewer industrial and vehicle activities cause lower heat emissions, the design of the swallow house is also an influence, some swallow houses in Lawas, Sarawak (Malaysia) use a very large PVC pipe ventilation system so that hot air can easily escape and humidity does not accumulate too much. Thus, the difference in temperature and humidity between the two research locations is not only influenced by regional climate

factors, but also by human activities, environmental conditions, and the design of the swallow house building which affects the microclimate conditions inside the building.

Table 3. Results of Lead Pb Sample Tests

Location	Repetition	Pb Concentration in the Sample (ppm)	
		Feathers	Nest
Indonesia	1	0,328	0,06
Indonesia	2	0,336	0,061
Indonesia	3	0,341	0,059
Malaysia	1	0,319	0,055
Malaysia	2	0,329	0,051
Malaysia	3	0,319	0,062

3.2. Results and Discussion

This discussion is conducted to interpret the results of research on the levels of heavy metal lead (Pb) in feathers and nests of the species (*Aerodramus fuciphagus*) obtained from two different locations, namely Gresik (Indonesia) and Lawas, Sarawak (Malaysia). The analysis not only focuses on statistical differences in concentration values, but also on biological, physiological and environmental factors that have the potential to influence the process of heavy metal accumulation. The research results obtained showed significant differences based on sample type and location, which were analyzed to understand the bioaccumulation mechanism and the potential of swiftlets as bioindicators of air pollution.

3.2.1. Pb Content as a Bioindicator

Based on the results of the analysis of Lead (Pb) levels using the Atomic Absorption Spectrophotometry (AAS) method, the concentration of Lead (Pb) in feathers and nests of swiftlets (*Aerodramus fuciphagus*) from two research locations, namely Gresik Regency (Indonesia) and Lawas, Sarawak (Malaysia). The results of Indonesia Gresik from feathers (Wings): 0.328 - 0.341 ppm in nests: 0.059 - 0.061 ppm. While in Malaysia Lawas feathers (Wings): 0.319 - 0.329 ppm and in nests 0.051 - 0.062 ppm. It can be seen that the Pb levels in feathers are higher than in swiftlet nests and the Pb levels in Gresik are slightly higher than in Lawas, Sarawak. The Pb levels in swiftlet feathers are higher than in bird nests in both locations, both in Gresik and in Lawas, Sarawak. These differences in concentrations demonstrate that the sample type significantly influences the level of heavy metal accumulation in the swiftlet's body. Physiologically, bird feathers are tissues formed through the growth of epidermal cells supplied by the bloodstream. Heavy metals, such as lead (Pb), that enter the body through polluted air or the consumption of contaminated insects, circulate in the circulatory system and are deposited during feather formation. Once the feathers undergo keratinization, the heavy metals are permanently trapped within the keratin structure. Bird feathers are capable of accumulating heavy metals at higher concentrations than other tissues,

reflecting systemic exposure during the growth phase (Swistowski 2025).

Pb concentrations in bird feathers can increase in areas with high anthropogenic exposure, making feathers a potential bioindicator of environmental pollution (Bjedov et al., 2024). Bird feathers are a type of tissue formed by the keratinization of epidermal cells, which receive nutrients through the bloodstream. Heavy metals enter the bird's body through inhalation of polluted air or through the circulatory system and are then deposited in growing tissues, including feathers. After the feathers undergo keratinization, heavy metals are trapped in the keratin structure, thus reflecting heavy metal exposure during the feather growth period (Bjedov et al., 2024).

This study indicate that swiftlet feathers accumulated higher Pb concentrations than net sat both study locations. This finding suggests that feathers may be more sensitive than nests in reflecting environmental exposure to heavy metals. Feather tissues are formed through biological processes involving blood circulation, allowing heavy metals to be incorporated during growth and retained within the keratin structure. In contrast, swiftlet nest are formed from hardened salivary secretions and mainly accumulate contaminants through external deposition from the surrounding environmental monitoring because atmospheric Pb concentrations were not measured directly in this study, the quantitative relationship between environmental Pb exposure and Pb accumulation in swiftlets could not be established. Consequently, the findings should be considered as preliminary evidence supporting the potential use of swiftlets as bioindicators rather than definitive proof of their effectiveness.

3.2.2. Comparison of Pb Levels Based on Location

The research location of Gresik (Indonesia) Pb levels in samples from Gresik tended to be higher than Lawas, Sarawak, (Malaysia), especially in feather samples. This difference indicates the influence of environmental factors on the level of heavy metal accumulation in swiftlets. Gresik Regency has many industrial activities such as the cement industry, petrochemicals, manufacturing, and transportation are quite high. These activities can show a large potential to produce heavy metal emissions, including lead (Pb), which can pollute the air and the surrounding environment. These particles can be dispersed in the atmosphere and then deposited in the surrounding environment (Li et al., 2021). Continuous exposure results in air particles containing lead (Pb), allowing food transfer into the birds' bodies. Birds living in highly industrialized areas have significantly higher concentrations of heavy metals in their feathers compared to non-industrial areas (Leal-Aguayong et al., 2026). These results can support the interpretation that the difference in Pb levels between Gresik and Lawas, Sarawak can be influenced by the level of anthropogenic activity.

The study results indicate that Pb concentrations in swiftlet feathers and nests remain within the ranges reported by various studies on heavy metal accumulation in birds across Southeast Asia. The higher Pb concentrations in the Gresik area compared to Lawas are suspected to be linked to industrial activities and anthropogenic emission sources.

However, this study did not identify a specific source confirming direct contamination, as measurements of ambient air Pb were not conducted. Further research combining air quality measurements with atmospheric Pb content analysis is essential to obtain more comprehensive insights into the mechanisms of Pb accumulation in swiftlets.

the Lawas region of Sarawak has a relatively lower level of industrial activity and extensive vegetation cover. Vegetation is known to play a significant role in reducing air pollutant concentrations through particle deposition and pollutant absorption by leaf surfaces (Kumar et al., 2022). Therefore, the difference in Pb levels between Gresik and Lawas, Sarawak, is likely influenced by differences in anthropogenic activity levels, transportation density, and vegetation conditions in the two regions.

3.2.3. Intersample Variation

Differences in location values for each sample indicate natural variations in Pb accumulation. This variation can be influenced by several biological and technical factors, such as differences in bird age, duration of exposure to polluted environments, differences in bird diet and roaming area, differences in sample weight and condition during preparation, and technical variations in the laboratory analysis process can affect the level of heavy metal accumulation in the organism's body. Individuals with longer exposure times tend to show higher heavy metal concentrations in their body tissues (Wang et al., 2022). Variation in heavy metal concentrations between individual birds is a common phenomenon influenced by physiological and microenvironmental factors (Swislowski, 2025). Differences in diet and environmental stress levels can affect the distribution of heavy metals in bird tissues (Nzabanita et al., 2025). Swiftlets' diet and roaming area can also influence their levels of heavy metal exposure. Swiftlets are insectivorous birds that catch insects in the open air. If insects consumed are contaminated with heavy metals from the environment, these metals can accumulate in the birds' bodies through biomagnification (Rahman et al., 2021). Small variations between samples can also be influenced by technical factors such as sample preparation, sample homogenization, and minor variations in the laboratory analysis process. However, the relatively small variations in this study indicate that the analytical method used has a fairly good level of precision.

3.2.4. Implications of Swiftlets as Bioindicators

The results of this study indicate that swiftlet feathers and nests are capable of accumulating Pb from the surrounding environment. The significantly higher Pb concentrations observed in feathers compared with nests suggest that feathers may serve as a more sensitive biological matrix for environmental monitoring. However, because atmospheric Pb concentrations were not measured directly, the present study cannot quantitatively confirm the relationship between environmental Pb exposure, the findings should be considered as preliminary evidence supporting the potential use of swiftlets.

3.2.5. Study Limitations

The study utilized analytical replicates derived from pooled feather and nests sample. Therefore, the replicates do not represent independent biological samples, which may limit the generalization of the findings. Future studies should include a larger number of independent biological replicates from multiple swiftlet houses and sampling periods.

3.3. Statistical Analysis Results

Table 4. Normality Test

	Kolmogorov-smirnov			Shapiro-wilk		
	Statistic	df	sig	Statistic	df	sig
Standardized residual for Pb_ppm	.162	12	.200	.935	12	.435

The Shapiro-Wilk test produced a significance value of 0.435 ($p > 0.05$), indicating that the residual data were normally distributed. Therefore, the assumption of normality required for parametric statistical analysis was fulfilled. The normal distribution of residuals suggests that the observed variation in Pb concentrations among samples did not deviate substantially from the expected distribution pattern. Consequently, the dataset was considered appropriate for further analysis using Two Way ANOVA.

Table 5. Homogeneity Test

F	df1	df2	sig
1.969	3	8	.197

Levene's test produced a significance value of 0.197 ($p > 0.05$), indicating that the variances among groups were homogeneous. The assumption of homogeneity of variance was fulfilled, and the data were considered suitable for analysis using Two Way ANOVA.

The Two-Way ANOVA results indicate that the location factor has a influence on Pb concentration ($p = 0.024$), revealing a difference in Pb accumulation levels between the study sites in Gresik and Lawas. Sample type also exerts a influence on Pb levels, with accumulation in feathers differing from that in nests. The interaction between location and sample type did not show a significant effect ($p = 0.187$); this is

because the patterns of Pb accumulation in feathers and nests were relatively consistent across both study sites, allowing the effects of location and sample type on Pb accumulation to be interpreted independently.

Table 6. Two Way ANOVA Test

Source	Type III Sum of Squares	df	Means Square	F	sig
Corrected Model	220.046.000	3	73.348.667	2.708.258	.000
Intercept	448.533.333	1	448.533.333	16.561.231	.000
Location	208.333	1	208.333	7.692	.024
Sample	219.781.333	1	219.781.333	8.115.003	.000
Location x Sample	56.333	1	56.333	2.080	.187
Error	216.667	8	27.083		
Total	668.796.000	12			
Corrected Total	220.262.667	11			

The results show very significant because they have different environmental characteristics such as traffic density, industrial activity, fossil fuel combustion, construction or development activities. Lead Pb is a heavy metal that comes from vehicle emissions and industrial activities. The higher the activity, the higher the potential for Pb accumulation in the surrounding environment.

The interaction between location and sample type was not significant ($p = 0.187$; $F = 2.080$), indicating that the pattern of Pb accumulation in feathers and nests was consistent across both study locations that nests, suggesting that the influence of sample type on Pb accumulation remained similar regardless of location. Therefore, the effects of location and sample type can be interpreted independently.

The results indicate a significant difference in Pb concentrations between feathers and nests. This shows that the sample type has a significant effect on the results of Pb levels. So there are differences in Pb levels between the types of samples studied. Significant Pb results indicate that the biological or physical ability to accumulate heavy metals, wing feathers can absorb heavy metals through direct air deposition and the surface of the wing feathers has a large surface area so it is easy to capture Pb particles from the air. While in the nest accumulates metals through the composition of the material and environmental exposure. From the results of sig 0.000 and the F value of 8115.003 shows that the differences obtained are very strong between feathers and nests, it is caused by the biological mechanism of feathers formed through the blood supply, the Pb formed is deposited during growth, the surface of the feathers is wide so that it captures more air particles, while the nest is made of saliva which only captures environmental particles not through the body's metabolic system, but captures from the results of swiftlet food.

4. CONCLUSION

Swiftlets (*Aerodramus fuciphagus*), particularly their feathers, demonstrated potential as bioindicators of environmental pollution. Higher Pb

concentrations were consistently observed in feathers that in nests at both study locations. Although location and sample type significantly influenced Pb accumulation, direct measurements of atmospheric Pb were not conducted. Therefore, further studies incorporating atmospheric Pb monitoring are necessary to validate the effectiveness of swiftlets as bioindicators of air pollution.

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