National Assessment on Acid Deposition in Malaysia

1. Basic Information on National Monitoring Activities

1.1 Outline of Acid Deposition Activities and National Monitoring Plan

Malaysia has regularly participated in the Acid Deposition Monitoring Network in East Asia (EANET) since its preparatory phase in 1998–2000, jointly implementing monitoring activities since 2001. The Ministry of Natural Resources and Environmental Sustainability serves as the National Focal Point, while the Malaysian Meteorological Department (MET Malaysia) operates as the EANET National Center.

Acid deposition monitoring in Malaysia encompasses five different environmental media, wet and dry deposition, soil and vegetation; and inland aquatic environments. The measured parameters and monitoring intervals for these environmental media are given in **Table 1**.

Table 1 Acid Deposition Monitoring Measurement Parameters and Monitoring Intervals

Items	Measurement Parameters	Monitoring Interval
Wet Deposition	pH, EC, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-, Cl^-, CH_3COO^-, $HCOO^-$, $C_2O_4^{2-}$	2 - Weekly
Dry Deposition	**Gas**: SO_2, HNO_3, NH_3, HCl, **PM Components**: $NH4^+$, Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-, Cl^-	Weekly / Biweekly
Soil	pH (H_2O), pH (KCl) exchangeable (Na^+, K^+, Ca^{2+}, Mg^{2+}, Al^{3+}, H^+) exchangeable acidity	3 – 5 years
Inland Aquatic	Water Temperature, pH, Electrical Conductivity, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-, Cl^-, PO_4^{3-}	6 times a year

1.2 Monitoring Program 2020 - 2024

1.2.1 Wet and Dry Deposition Monitoring

Monitoring Network Configuration

The national monitoring network comprises four strategically classified stations that capture the diversity of Malaysia's atmospheric environments:

Station	Classification	Rationale
Petaling Jaya (Selangor)	Urban	Assessment of acid deposition impacts in urban-industrial areas

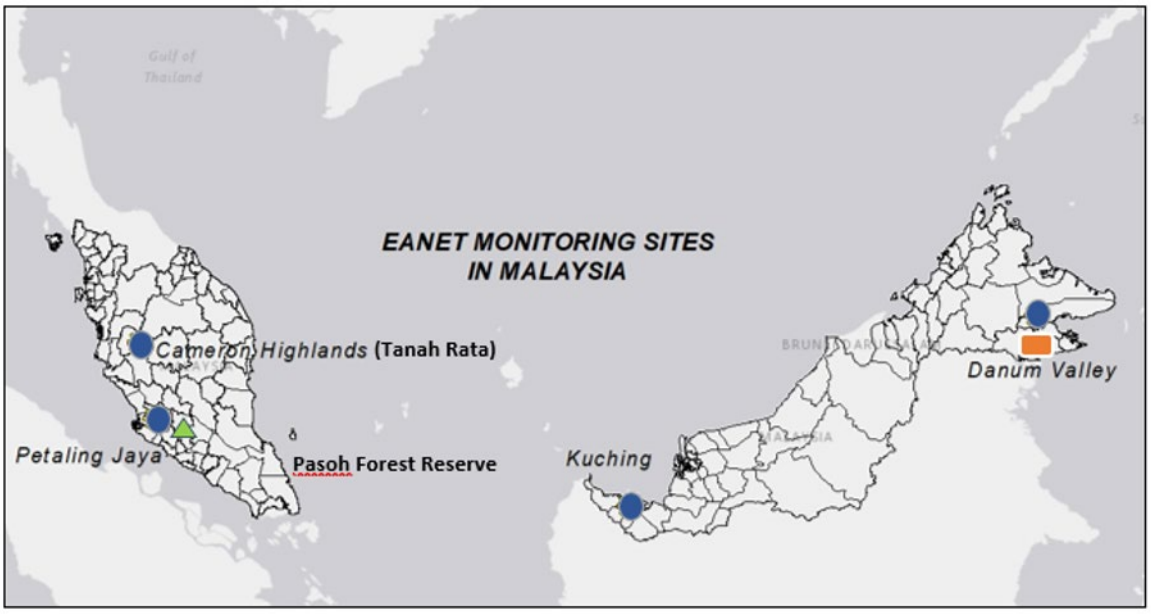
Station	Classification	Rationale
Tanah Rata (Cameron Highlands)	Rural	Evaluation of acid deposition on high-altitude agricultural and forest ecosystems
Kuching (Sarawak)	Urban	Wet deposition monitoring in an urban setting
Danum Valley (Sabah)	Remote	Background monitoring for long-range transport assessment

All precipitation sample analyses are conducted by the Department of Chemistry Malaysia (DOCM) in strict compliance with EANET technical protocols and QA/QC standards. This report extends previous national assessments by integrating updated annual trends through 2024 with detailed monthly seasonal profiles for the 2020–2024 period.

1.2.2 Inland Aquatic Monitoring

One designated EANET monitoring site is presently operated in Malaysia and it is located at the Sungai Baru site, Danum Valley, Sabah, East Malaysia. Sample collection at this site is conducted by the Malaysian Meteorological Department staff. Samples collected are sent to Petaling Jaya, Peninsular Malaysia for chemical analysis. Chemical analysis, as with the wet and dry deposition is duly conducted at DOCM.

1.3 Monitoring Stations



1.3 Monitoring Stations

Legend		No. of stations
●	**Current wet/dry deposition sites** [Cameron Highlands, Petaling Jaya, Danum Valley & Kuching]	**Wet (4) / Dry (3)**
▬	**Current inland aquatic environment sites** [Baru River]	**1**
▲	**Current soil and vegetation sites** [Pasoh Forest Reserve]	**1**

Figure 1. Locations of Acid Deposition Monitoring Sites in Malaysia.

Locations of the four wet and dry deposition monitoring sites, one inland monitoring site, and one soil and vegetation monitoring sites are shown in **Figure 1** above. The Danum Valley GAW Station, Tanah Rata GAW Station and Petaling Jaya GAW Station are designated as remote, rural and urban wet and dry deposition sites respectively, while Kuching is an urban site dedicated to wet deposition measurements only. In addition, geographical locations of the Pasoh Forest reserves and the Baru River Inland Aquatic site are given in **Figure 1** for greater clarity.

1.4 Sampling and Measurements

1.4.1 Wet Deposition Sampling and Analytical Methodologies

Wet deposition samples at all sites were collected using the wet-only sampler and acid precipitation sampler. The rainwater samples are collected on a weekly basis and stored in polyethylene bottles. Biocide (Thymol) is used to retard the degradation of organic compounds as well as ammonium and nitrate ions. The samples are then sent to DOCM for chemical analysis of the principal anions and cations. Analytical methods employed are in accordance with requirements of the technical manual and is given in **Table 1.2**.

Table 1.2 Characteristics of Wet Deposition Chemical Analytical Techniques Employed

Parameter	**rement/analytical methods**	**ıufacturer/Type of equipment**	**Detection limit**
pH	Glass Electrode	Mettler Toledo Education Line EL20	
Electrical Conductivity	Conductivity Cell	Mettler Toledo SevenEasy	0.06 µS/cm
SO_4^{2-}	Ion Chromatography	DIONEX USA / DX600 and ICS-2000 Anion System	0.04 µmol/L
NO_3^-			0.03 µmol/L
Cl^-			0.20 µmol/L
CH_3COO^-			0.05 µmol/L
$HCOO^-$			0.10 µmol/L

$C_2O_4^-$			0.07 µmol/L
NH_4^+	Ion Chromatography	DIONEX USA / DX600 and ICS-2000 Cation System	0.20 µmol/L
Na^+			0.40 µmol/L
K^+			0.08 µmol/L
Ca^{2+}			0.50 µmol/L
Mg^{2+}			0.40 µmol/L

1.4.2 Dry Deposition Sampling and Analytical Methodologies

Dry deposition samples were collected at Tanah Rata, Petaling Jaya and Danum Valley from 2020 to 2024. Three dry deposition approaches, Acid Precipitation Sampler based Dry Bucket, filter pack and passive sample are employed at each of these sites. Dry Bucket sampling at all these sites is carried out once a month. Filter pack and passive sampler sampling at Tanah Rata and Petaling Jaya were done weekly, whereas in Danum Valley it was done biweekly due to the remote locality of the station as well as low concentration of acid deposition at the surrounding area. The Dry Bucket, filter pack and passive sampler samplings were sent to the DOCM for analysis. The measurements and analytical methods are tabulated in **Table 1.3**.

Table 1.3 Characteristics of Dry Deposition Chemical Analytical Techniques Employed

Parameter	rement/analytical methods	ufacturer/Type of equipment	Detection limit
SO_4^{2-}	Ion Chromatography	DIONEX USA / DX600 and ICS-2000 Anion System	0.010 mg/L
NO_3^-			0.006 mg/L
Cl^-			0.009 mg/L
NH_4^+	Ion Chromatography	DIONEX USA / DX600 and ICS-2000 Cation System	0.003 mg/L
Na^+			0.010 mg/L
K^+			0.003 mg/L
Ca^{2+}			0.020 mg/L
Mg^{2+}			0.010 mg/L

1.4.3 Inland Aquatic Sampling and Analytical Methodologies

Surface water samples were collected at 30 cm depth using a grab sampler 6 times a year at the estuary of Sungai Baru site, in Danum Valley. The pH, electric conductivity and temperature measurements were carried out in situ. Water samples to determine Cation and Anion concentrations were collected in polyethylene bottles and sent to the DOCM for analysis. Parameters to be measured for inland samples are listed in **Table 1.4**.

Table 1.4 Characteristics of Inland Aquatic Chemical Analytical Techniques Employed

Parameter	rement/analytical methods	ufacturer/Type of equipment	Detection limit
pH	Glass Electrode	Mettler Toledo Education Line EL20	

Electrical Conductivity	Conductivity Cell	Mettler Toledo SevenEasy	0.06 µS/cm
Alkalinity	Titration by burette with pH meter	Eutech Instrument pH1500 CyberScan	0.01 meq/L
SO_4^{2-}	Ion Chromatography	DIONEX USA /ICS - 1000 Anion System	0.03 mg/L
NO_3^-			0.02 mg/L
Cl^-			0.004 mg/L
PO_4^{3-}			0.02 mg/L
NH_4^+	Ion Chromatography	DIONEX USA / DX - 600 and ICS -2000 Cation System	0.003 mg/L
Na^+			0.01 mg/L
K^+			0.003 mg/L
Ca^{2+}			0.020 mg/L
Mg^{2+}			0.01 mg/L

1.4.4 Submission of data to the Network Center

The monitoring data from the respective agencies were submitted to Met Malaysia. Met Malaysia compiled, validated and submitted the data to National Focal Point for approval before submission to the Network Center. Malaysia also participated in the Inter-laboratory comparison (ILC) project on wet deposition, dry deposition, and inland aquatic environment. The ILC project is a round-robin test which involves 4 analytical laboratories as **Table 1.5** below.

Table 1.5 Inter-Laboratory Comparison (ILC) Project For Malaysia

DEPARTMENT	**CODE**	**Type of ILC Project**			
		Wet	**Dry**	**IA**	**Soil**
Division of Environmental Health, Department of Chemistry MALAYSIA (DOCM)	**MY01**	■	■	■	
Soil Laboratory, Forest Research Institute Malaysia (FRIM)	**MY05**				■

2. State of Acid Deposition in Malaysia Wet Deposition

The acid deposition assessment of Malaysia for this PRSAE report will focus on analysis of wet deposition measurements. Wet deposition sampling undertaken at all the four EANET stations, Petaling Jaya, Tanah Rata, Kuching and Danum Valley is used to assess the situation with Malaysia. The assessment will involve pH values, cations sodium, potassium, magnesium, calcium and ammonium; and anions nitrate, sulphate and chloride.

Data trend analysis will involve both long-term and relatively shorter-term trends. Long-term trends will involve data analysis of data available since implementation of the sampling at the respective stations. Shorter trend analysis will involve data obtained during the last five years at the respective sites. Long-term trends were obtained using the annual means while the short term trend via employing monthly distribution of the data. The period for which data is available with regard to long-term trends differs a bit between the stations. Long-term data is available from the year 2000 onwards for Cameron Highlands and Petaling Jaya, while it

is available from 2005 and 2008 for Danum Valley and Kuching respectively. Present status of acid deposition is assessed using five-year period data from 2020 to 2024.

2.1 Annual Trends of Wet Deposition

Annual trends for selected anions and cations are displayed in various figures from **Figure 2.1** to **Figure 2.9**. Interpretation of **Figure 2.1** will require **Figure 2.7** and **Figure 2.8** representing annual trends of both nitrate and sulphate respectively to be analyzed together. This is due to solubility of both nitrate and sulphate forming nitric and sulphuric acids respectively increasing the acidity of rain water.

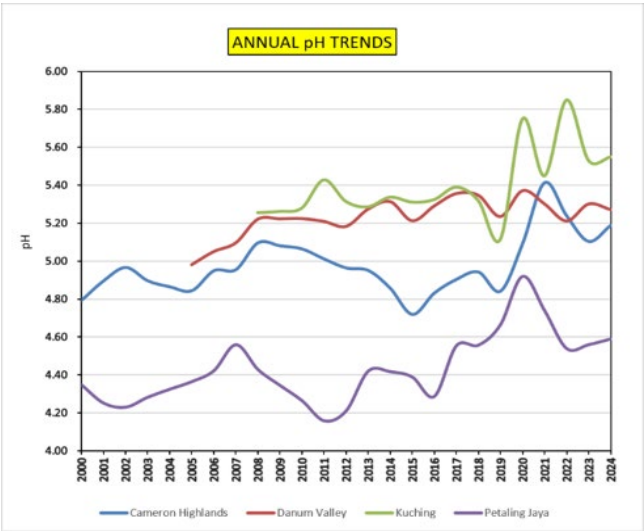


Figure 2.1. Annual pH Values.

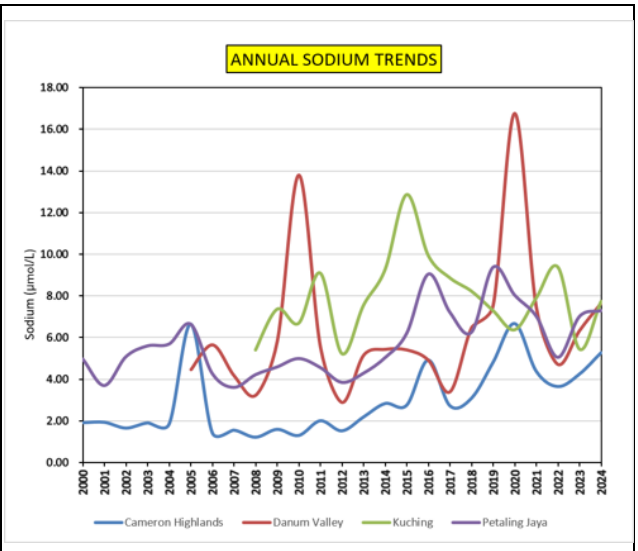


Figure 2.2. Annual Sodium Concentrations (µmol/L).

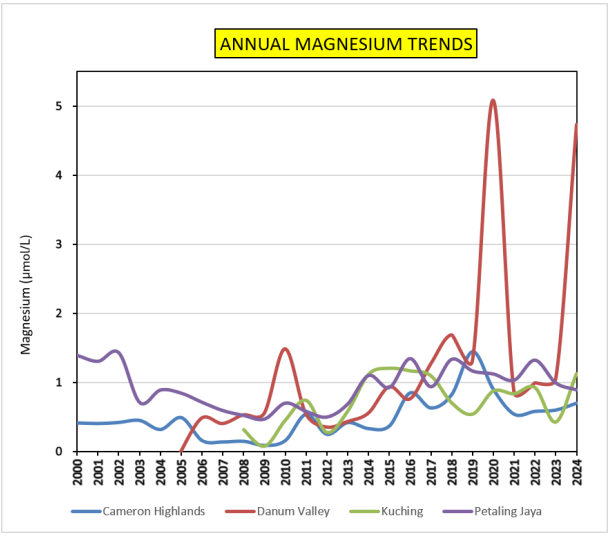


Figure 2.3. Annual Magnesium Concentrations (µmol/L).

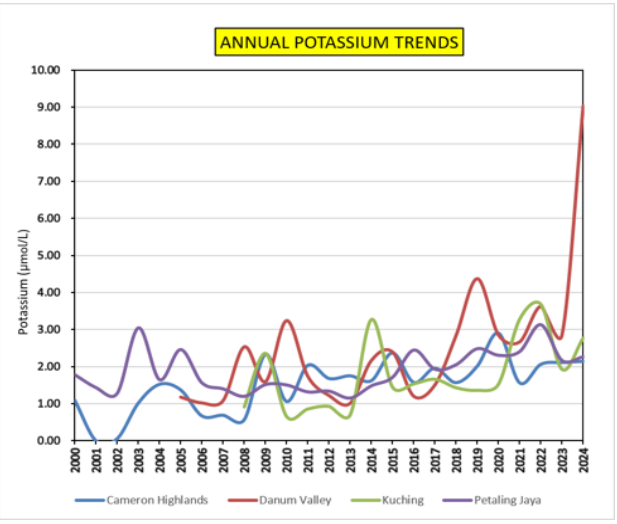


Figure 2.4. Annual Potassium Concentrations (µmol/L).

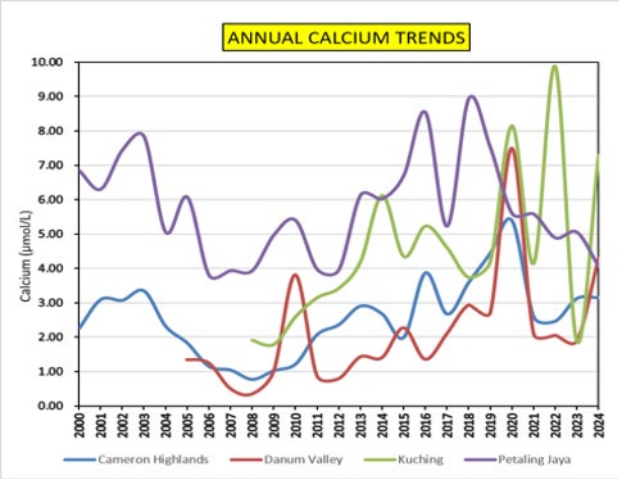


Figure 2.5. Annual Calcium Concentrations (µmol/L).

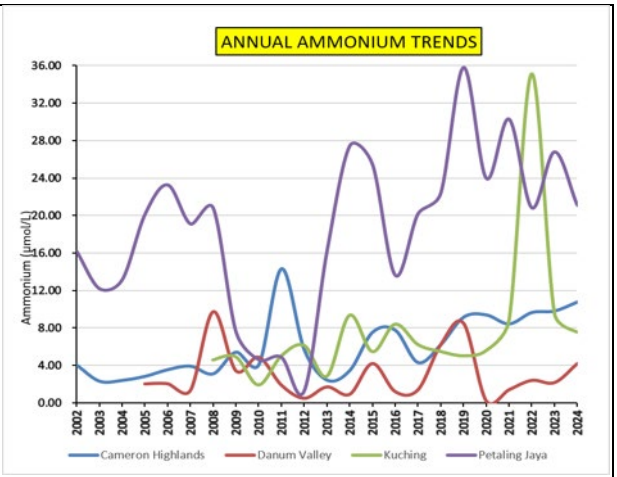


Figure 2.6. Annual Ammonium Concentrations (µmol/L).

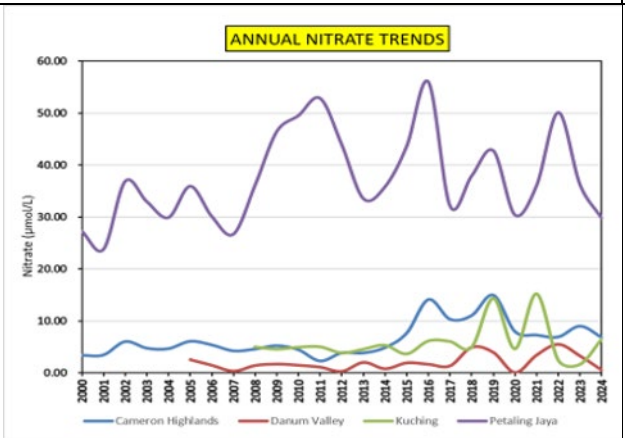


Figure 2.7. Annual Nitrate Concentrations (µmol/L).

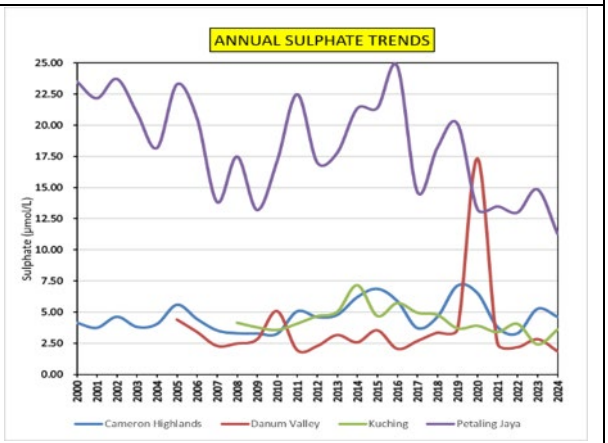


Figure 2.8. Annual Sulphate Concentrations (µmol/L).

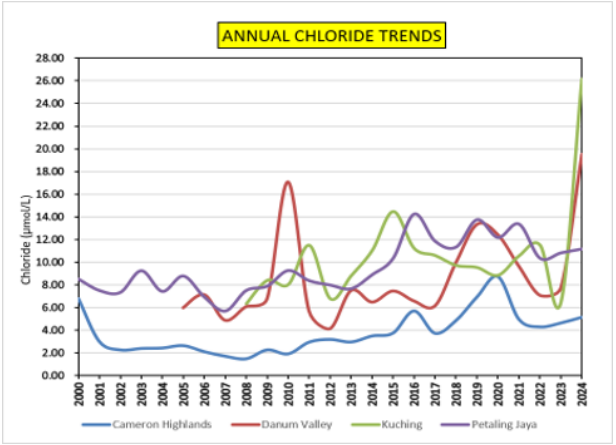


Figure 2.9. Annual Chloride Concentrations.

This report evaluates the long-term trends in rainwater chemistry across four distinct stations in Malaysia: **Petaling Jaya** (urban/industrial), **Cameron Highlands** (high-altitude/agricultural), **Kuching** (regional city),

and **Danum Valley** (pristine forest reserve). By cross-analyzing annual pH levels (**Figure 2.1**) with concentrations of acidifying ions—namely Nitrate (NO_3^-) (**Figure 2.7)** and Sulphate (SO_4^{2-}) (**Figure 2.8)**. Petaling Jaya continues to exhibit the lowest pH values (highest acidity) among all stations, characteristic of its urban-industrial setting. The historical average pH has remained consistently between 4.2 and 4.6 over the 2000–2024 period. Recent trends show relative stabilization at approximately 4.6–4.7 from 2019–2021, with a transient drop to pH 4.5 in 2022 before recovery to 4.6 by 2024.

Danum Valley maintains consistently healthy pH levels between 5.2 and 5.4 throughout 2020–2024, reflecting its remote, pristine forest environment. Meanwhile Cameron Highlands recorded a pH peak of approximately 5.4 in 2021 before experiencing a gradual decline to settle around 5.2 by 2024, indicating slightly increasing acidity at this rural high-altitude site. Kuching exhibited the least acidic profile among urban stations, with pH climbing to 5.7 in 2020 and 5.8 in 2022 before stabilizing around 5.5 in 2024.

Implications for Public Health and Environment:

- pH values below 5.0 are considered acidic enough to potentially harm sensitive ecosystems, aquatic life, and vegetation
- Petaling Jaya's pH levels consistently below 4.6 may contribute to accelerated corrosion of buildings and infrastructure
- Urban populations, particularly children and the elderly, may experience indirect health effects from acid rain precursors (SO_2 and NO_x)

As for the ion concentrations, Nitrate (NO_3^-)Trends (**Figure 2.7**)**,** Petaling Jaya remains Malaysia's dominant nitrate source, primarily from transportation emissions and industrial activities. Following a pandemic-related decline to approximately 31 µmol/L in 2020, concentrations surged past 50 µmol/L in 2022 as economic and transport sectors fully reopened. By 2024, levels normalized to approximately 33 µmol/L, representing a 34% reduction from the 2022 peak. Kuching, Cameron Highlands, and Danum Valley consistently maintained low nitrate concentrations below 15 µmol/L throughout 2020–2024.

For Sulphate (SO_4^{2-}) Trends (**Figure 2.8),** Petaling Jaya displayed a notable peak in 2023 at approximately 15 µmol/L, decreasing to 12.5 µmol/L by 2024. Danum Valley exhibited a remarkable sulphate anomaly in 2020, reaching approximately 17.5 µmol/L—an exceptionally high value for a remote site. This anomaly fully resolved by 2021, with levels remaining well below 2.5 µmol/L through 2024. This pattern strongly indicates episodic transboundary pollutant transport driven by regional monsoonal wind systems.

The 2020 Danum Valley anomaly highlights the ongoing challenges of regional biomass burning and transboundary haze from Indonesia, which significantly impact air quality. This environmental issue is further compounded by the presence of sulphate and nitrate, the primary drivers of acid deposition, which pose serious long-term threats to both forest ecosystem health and the acidification of freshwater resources.

Correlation Matrix: pH vs. Acidifying Ions

The inverse relationship between pH and acidifying ions is clearly illustrated by comparing the distinct profiles of the monitoring sites:

Station	Average pH Range	Nitrate (NO_3^-) Profile	Sulphate (SO_4^{2-}) Profile	Acidification Risk
Petaling Jaya	4.20–4.60 (High Acid)	Extreme (23.00–56.00 μmol/L)	Extreme (12.50–25.00 μmol/L)	Critical
Cameron Highlands	4.70–5.20 (Moderate)	Low-Moderate (2.00–15.00 μmol/L)	Low-Moderate (3.00–7.50 μmol/L)	Moderate-High
Kuching	5.10–5.85 (Low Acid)	Low (2.00–15.00 μmol/L)	Low (2.50–7.50 μmol/L)	Low
Danum Valley	5.00–5.40 (Low Acid)	Very Low (0.00–5.00 μmol/L)	Very Low (2.00–5.00 μmol/L)*	Minimal

*Excluding the 2020 anomaly.

Petaling Jaya remains the most acidic site due to dense vehicle traffic and manufacturing, its long-term pH has slowly improved due to two primary factors:

- Fuel Standard Upgrades: The nationwide transition from Research Octane Number (RON) 92 to cleaner RON 95 petrol formulations in 2009—followed by subsequent adoptions of higher Euro standard fuels—significantly suppressed sulphur and nitrogen impurities in vehicle exhaust. This directly capped the atmospheric formation of Nitric and Sulphuric acids.

- Cleaner Industrial Tech: The implementation of stricter industrial air emission regulations over the past decade forced local factories to adopt cleaner burning technologies and better exhaust scrubbers, resulting in the downward macroscopic trend of Sulphate.

Danum Valley shows stable and low rainwater acidity is mainly because of the Reforestation & Buffer Zones. From 2008 onward, significant land-use changes occurred at the periphery of the Danum Valley Forest Reserve, where historical commercial palm oil plantations were phased out in favor of active forest regeneration. The reduction in fertilizer usage (which releases nitrogen compounds) combined with the natural filtration capacity of expanding canopy buffers explains the pristine, low-nitrate chemical composition of the rain.

A striking observation is that **Cameron Highlands exhibits significantly more acidic rain than Kuching**, despite both locations sharing similarly low concentrations of Nitrate and Sulphate. This occurs due to unique physical geography rather than high emission volumes:

- **Thermal Inversion Layers:** Because Cameron Highlands is situated in a high-altitude geographical valley, it experiences lower surface temperatures. This frequently creates a "low-lying inversion layer"—a atmospheric phenomenon where a layer of warm air traps cooler air beneath it like a lid.
- **Pollutant Entrapment:** This inversion layer prevents local emissions (from agricultural machinery, transport, and localized fertilizers) from dispersing upward into the upper atmosphere. The pollutants are trapped close to the ground, concentrating them in the localized cloud and moisture layer, resulting in higher rainfall acidity despite relatively low overall pollutant volumes.

The dramatic, isolated spike in Sulphate at Danum Valley in 2020 which completely decoupled from its historical baseline is highly characteristic of a localized, short-term event. This was likely driven by transient biomass burning (forest fires) upwind or transboundary haze active during that specific dry season, rather than changes in local industrial baseline activity

The temporal and spatial variability of major cationic species (NH_4^+, Ca^{2+}, Na^+, and Mg^{2+}) provides critical insight into the sources and transport of atmospheric neutralizing agents across Malaysia. While some stations exhibit pristine conditions, others demonstrate significant anthropogenic and marine influences.

Ammonium (NH_4^+) (**Figure 2.6**) concentrations displayed pronounced urban-industrial signatures, with a dramatic anomaly recorded in Petaling Jaya. The data reveals an extreme peak of 23.0 µmol/L in 2010, followed by a period of moderate fluctuation. Subsequently, the site experienced a second, more sustained elevation beginning in 2014, culminating in a peak of 16.5 µmol/L. By the end of the observation period in 2024, concentrations stabilized at approximately 1.7 µmol/L.

In contrast, Cameron Highlands exhibited a similarly episodic pattern, with a notable increase starting in 2003 (5.5 µmol/L) and persisting through the late 2000s, before settling at a baseline of approximately 10.5 µmol/L from 2022 onward. Danum Valley and Kuching maintained consistently low concentrations throughout the entire dataset, with levels rarely exceeding 0.2 µmol/L. This stark contrast highlights the minimal impact of agricultural and combustion-related emissions in the remote ecosystems of East Malaysia compared to the heavily industrialized west coast.

As for Calcium (Ca^{2+}) (**Figure 2.5**), the calcium data reveals a distinct urban-rural gradient, with Petaling Jaya exhibiting exceptionally high and variable levels. This urban station recorded a significant peak of 15.0 µmol/L in 2015, followed by a gradual rise to a maximum of 7.0 µmol/L by 2021 before fluctuating near 5.0 µmol/L in the final years. This trend is likely attributable to commercial construction activities, industrial manufacturing, and the resuspension of soil dust—common contributors to particulate matter in dense urban centers.

Kuching displayed an anomalous pattern as well, experiencing a notable surge in calcium beginning in 2007 (10.0 µmol/L) and peaking dramatically at 15.0 µmol/L in 2015 before declining to 7.0 µmol/L in 2024. This suggests a significant local or regional dust source that may be distinct from the industrial emissions affecting Petaling Jaya. Cameron Highlands and Danum Valley maintained baseline concentrations below 4.0 µmol/L and 1.0 µmol/L, respectively, confirming the pristine nature of these environments.

Environmental Significance:
The high calcium concentrations observed in Petaling Jaya and Kuching serve as a neutralizing buffer, capable of offsetting acidification effects from acidic precursors (e.g., SO_2 and NO_x). However, elevated cation levels are often indicative of increased particulate matter ($PM_{2.5}$) loading, which poses significant health risks. This is particularly relevant given the public health implications highlighted by the *Lancet Countdown 2025* report, which attributed over 22,500 deaths in Malaysia in 2022 to anthropogenic $PM_{2.5}$ pollution, with fossil fuel combustion accounting for a substantial proportion (61%) of these fatalities.

Analyzing both sodium (**Figure 2.2**) and magnesium (**Figure 2.3**) exhibited distinct temporal patterns

indicative of marine aerosol influence and long-range transport. For Sodium, the most severe anomaly occurred in 2016, with Danum Valley recording a peak of 17.0 μmol/L, significantly higher than other stations. This was followed by a sharp decline to baseline levels (<5.0 μmol/L) by 2020. The data for 2000-2011 is incomplete for Sodium, but the available data suggests that by 2024, all stations converged to a common low concentration of approximately 5.0 μmol/L.

For Magnesium, concentrations were consistently near-zero across all stations for the first decade of the record. However, a slight upward trend emerged around 2005, with Cameron Highlands showing a persistent albeit low signal (~0.8-0.9 μmol/L) while other stations remained near the detection limit. The 2016 Danum Valley spike was also reflected in Magnesium, though at much lower levels (~0.8 μmol/L). This is consistent with the strong correlation between marine-derived ions in bulk precipitation.

Atmospheric Interpretation:
The 2016 Danum Valley peak is a notable feature for both elements and strongly suggests an episodic atmospheric transport event. The elevated sodium, combined with a corresponding but smaller magnesium increase, points to a marine aerosol influence. The fact that this anomaly was most pronounced at Danum Valley, a remote site exposed to prevailing winds from the South China Sea, supports the hypothesis of a sea-salt intrusion event, possibly exacerbated by specific meteorological conditions such as monsoonal surges or cyclonic activity. The convergence of all stations to low, uniform levels by the end of the observation period indicates a return to baseline background conditions.

2.2 Present Status of Wet Deposition

Wet deposition monitoring is a core component of the Acid Deposition Monitoring Network in East Asia (EANET), which systematically measures major acidifying species and related chemical substances in precipitation, including sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), and hydrogen ions (H^+) as indicated by pH. The five-year period from 2020 to 2024 represents a critical window for assessing the present status of wet deposition across Malaysia's four EANET monitoring stations: Petaling Jaya (urban-industrial), Cameron Highlands (high-altitude rural), Kuching (urban), and Danum Valley (remote forest reserve). This analysis examines the monthly box-plot distributions of pH measurements, as well as nitrate, sulphate, and ammonium concentrations (**Figures 2.10–2.13**), utilizing the methodological framework established in the PRSAE Malaysia report. By incorporating contemporary developments in air quality management and transboundary pollution, the study leverages this spatial diversity to allow for a comprehensive assessment of wet deposition patterns across various Malaysian land-use types and emission source influences.

The pH of rainwater (**Figure 2.10**) serves as a fundamental indicator of atmospheric acidity, with values below 5.6 indicating acidification due to anthropogenic emissions of sulphur dioxide (SO_2) and nitrogen oxides (NO_x). The Malaysian Meteorological Department classifies rainfall pH into five categories: >5.6 (Very Good), 5.2–5.6 (Very Low Acidity), 4.8–5.2 (Moderately Acidic), 4.4–4.8 (Acidic), and <4.4 (Highly Acidic).

Petaling Jaya consistently exhibits the **most acidic rainwater** among all four stations, with median pH values ranging between approximately 4.4 and 4.8, placing it within the "Acidic" to "Highly Acidic" classification.

Monthly Distribution:

- **Maximum acidity** is observed in **February**, with the lowest median pH values recorded during this month.
- **Minimum acidity** (highest pH) occurs in **December**, representing the annual peak in rainwater pH.
- A **notable pH increase is observed in June**, corresponding to a significant reduction in atmospheric pollutants during this period.
- The station exhibits a shorter interspersed acidity cycle of approximately three months between June and August, nested within two longer annual cycles

The sustained acidity at Petaling Jaya is characteristic of its urban-industrial setting, where dense vehicle traffic and manufacturing activities generate substantial emissions of acidifying precursors. The February maximum acidity coincides with the Northeast Monsoon period, when regional air masses transport pollutants from continental sources. Conversely, December marks the period of lowest acidity, likely attributable to increased rainfall frequency during the inter-monsoon season facilitating more efficient atmospheric scavenging of acidic compounds. Studies have confirmed that rainfall at Petaling Jaya is more acidic due to higher concentrations of Cl^-, SO_4^{2-}, and NO_3^-.

Cameron Highlands presents a **more complex acidity profile**, with median pH values generally ranging between 4.8 and 5.2, categorised as "Moderately Acidic".

Monthly Distribution:

- **Two distinct acidity minima** (maximum acidity) are observed in **March** and **July**, representing a pronounced double-cyclic variation throughout the year.
- **Maximum pH** (least acidic conditions) is recorded in **January**.
- The March minimum represents a notable departure from the otherwise moderate pH regime.

The double-cyclic acidity pattern at Cameron Highlands is attributable to its unique geographical setting. Situated in a high-altitude valley at 1,545 metres above sea level, the area frequently experiences **thermal inversion layers** that trap pollutants near the surface, preventing their dispersion into the upper atmosphere. This topographical constraint explains why Cameron Highlands exhibits significantly higher acidity than Kuching despite both locations sharing similarly low concentrations of nitrate and sulphate. The March and July acidity peaks correspond to periods of enhanced agricultural activity (fertiliser application) and tourism-related emissions, combined with meteorological conditions that favour pollutant entrapment. A 2023 study confirmed that pH in Cameron Highlands shows a strong positive correlation with Na^+, K^+, and Ca^{2+}, attributed to atmospheric neutralisation reactions between acids (HNO_3 and H_2SO_4) and alkaline compounds present in suspended fine particles.

Kuching demonstrates the **least acidic profile** among all stations, with median pH values typically exceeding 5.2 and frequently reaching 5.6–5.7, placing it in the "Very Low Acidity" to "Very Good" categories.

Monthly Distribution:

- **Maximum acidity** is observed in **February**, though this remains relatively mild compared to other stations.
- **Minimum acidity** (least acidic) occurs in **July**.

- A clear seasonal trend is evident, with atmospheric acidity progressing from minimum levels during the **Boreal summer** (July) to maximum levels during the **Boreal winter** (February).

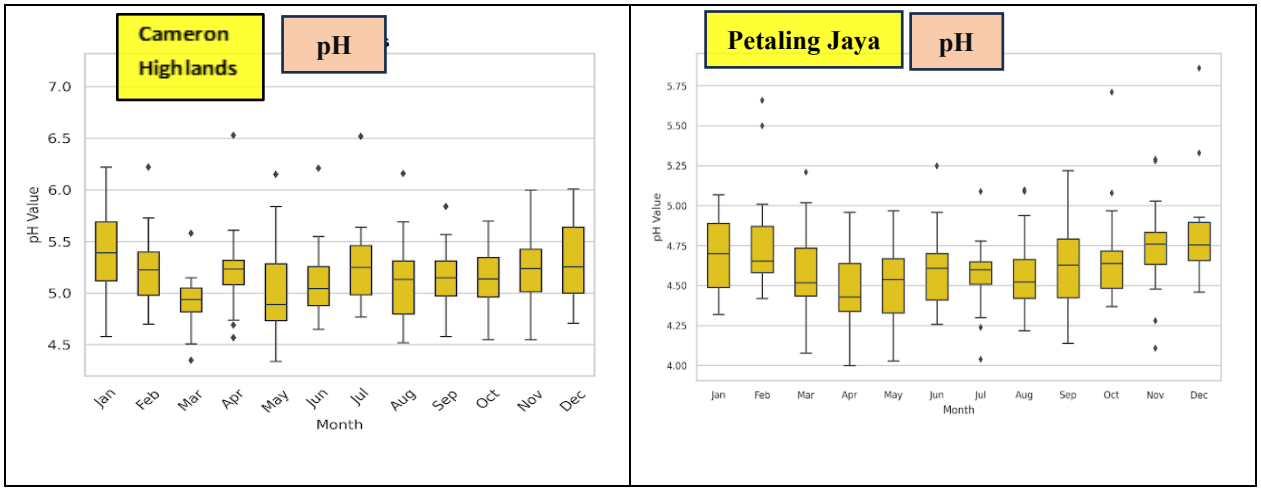
The relatively clean profile of Kuching reflects both its coastal location, which benefits from marine air masses, and the effectiveness of pollutant dispersion in the absence of topographical confinement. The seasonal variation aligns with regional wind patterns that govern pollutant transport across the South China Sea. The February acidity peak, while present, is notably less severe than at Petaling Jaya, indicating lower local anthropogenic emissions. The July minimum coincides with the Southwest Monsoon, bringing cleaner marine air from the South China Sea.

Danum Valley, representing Malaysia's **remote background monitoring site**, maintains the healthiest pH profile with median values consistently between 5.2 and 5.4, categorised as "Very Low Acidity".

Monthly Distribution:

- **Maximum acidity** is observed in **February**, coinciding with elevated pollutant transport during the Northeast Monsoon.
- **Minimum acidity** (least acidic) occurs in **March**, following the decline of monsoon-driven pollutant transport.
- Monthly pH fluctuations from February to April represent the most significant observations, with generally stable conditions throughout the remainder of the year.

The pristine nature of Danum Valley's rainwater chemistry underscores the effectiveness of the surrounding forest reserve in maintaining atmospheric quality. Located at 427 metres above sea level within the Danum Valley Forest Conservation area, the station is surrounded by tropical rainforest with no significant local pollution sources. The February acidity peak reflects the influence of long-range pollutant transport during the Northeast Monsoon, while the March recovery indicates the cessation of this transport pathway. The station's pH values have remained remarkably stable, with recorded values of 5.2–5.6 throughout the 2020–2023 period. However, the 2020 sulphate anomaly—reaching approximately 17.5 µmol/L—serves as a stark reminder of the vulnerability of even remote ecosystems to episodic transboundary pollution events, particularly biomass burning and haze from Kalimantan.



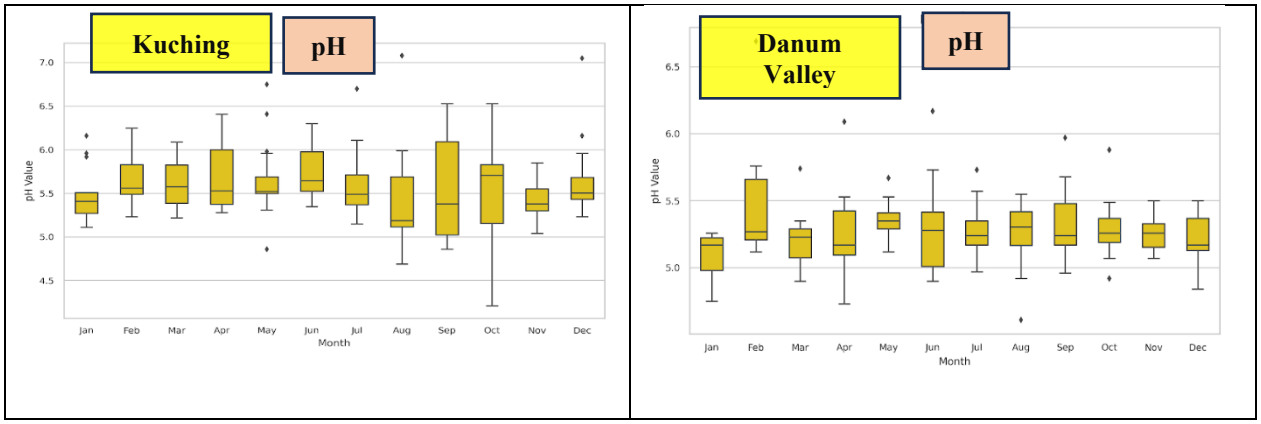


Figure 2.10. Monthly Box-Plot Distributions of pH Values from 2020 – 2024 for Cameron Highlands, Petaling Jaya, Kuching and Danum Valley.

The pH data reveals a clear **spatial gradient** in rainwater acidity across Malaysia:

Station	Classification	pH Range	Acidity Category	Primary Drivers
Petaling Jaya	Urban-Industrial	4.4–4.8	Acidic to Highly Acidic	Vehicle emissions, industry
Cameron Highlands	Rural High-Altitude	4.8–5.2	Moderately Acidic	Topographic trapping, agriculture
Kuching	Urban	5.2–5.7	Very Low Acidity	Marine influence, coastal location
Danum Valley	Remote Forest	5.2–5.4	Very Low Acidity	Pristine environment, no local sources

This gradient demonstrates that **urban-industrial activities** are the dominant driver of rainwater acidification in Malaysia, with Petaling Jaya exhibiting pH levels comparable to heavily industrialised cities in East Asia.

The monthly pH distributions (**Figure 2.10**) reveal **strong seasonal patterns** driven by the regional monsoon system:

- **Northeast Monsoon (November–February):** Characterised by elevated acidity across all stations, particularly in February. This period corresponds to enhanced transport of anthropogenic pollutants from continental Asia and the South China Sea.
- **Southwest Monsoon (May–September):** Associated with reduced acidity at most stations, except for Cameron Highlands where the July minimum represents a secondary acidity peak due to local topographic effects.
- **Inter-monsoon periods (March–April and October–November):** Transitional periods with variable acidity patterns, influenced by changing wind directions and the onset or cessation of monsoon systems. The sudden changes in pollutant concentrations during February and March are likely influenced by

shifting wind patterns from northeasterly to southwesterly flows as the monsoon trough progresses southwards across the South China Sea.

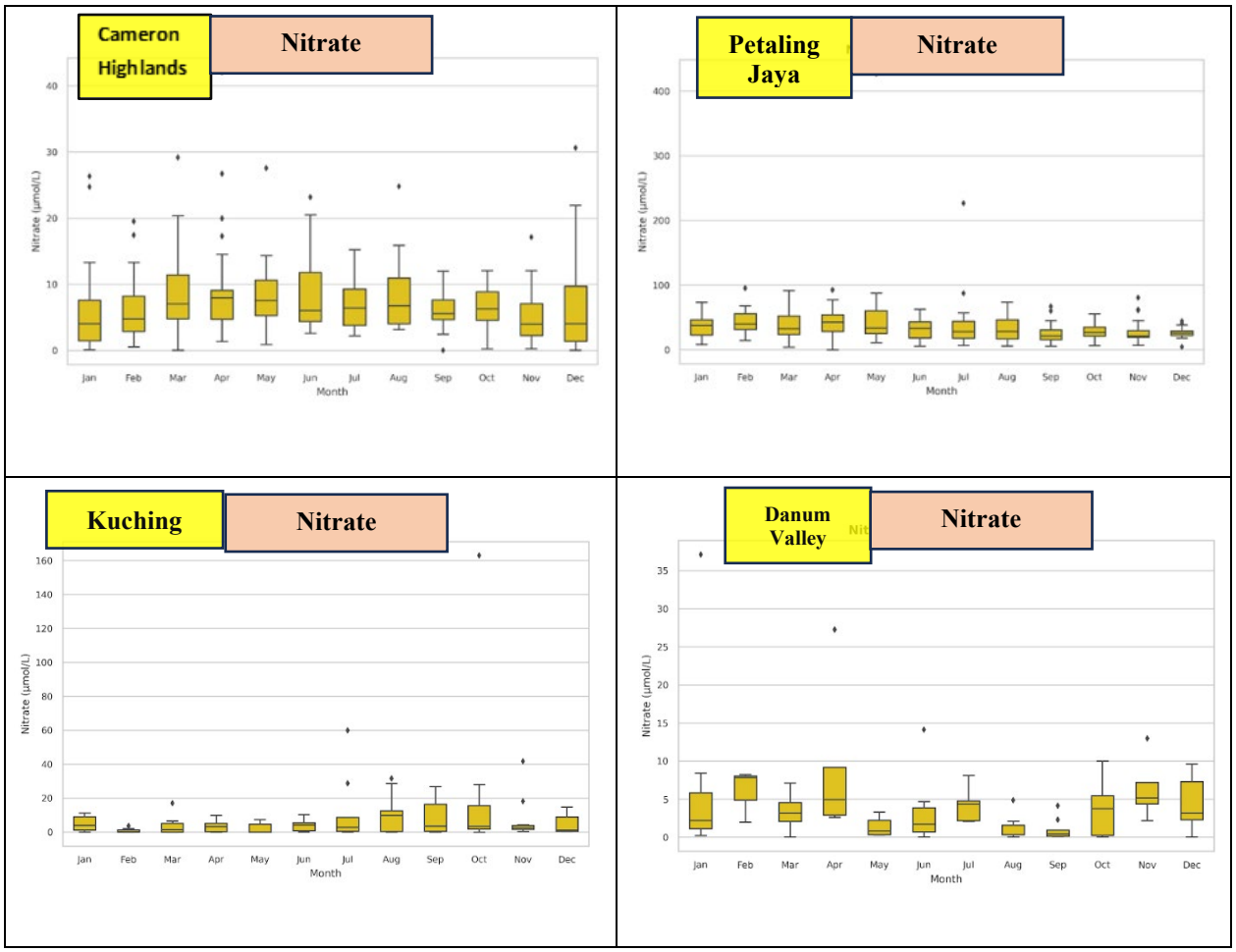


Figure 2.11. Monthly Box-Plot Distributions of Nitrate Concentrations (µmol/L) from 2020 –2024 for Cameron Highlands, Petaling Jaya, Kuching and Danum Valley.

Nitrate (NO_3^-) and Sulphate (SO_4^{2-}) represent the two primary acidifying anions in wet deposition, originating predominantly from anthropogenic emissions of nitrogen oxides (NO_x) and sulphur dioxide (SO_2) through fossil fuel combustion in vehicles, power generation, and industrial activities. Once deposited, these ions contribute significantly to the acidification of soils and freshwater ecosystems, posing risks to both environmental and public health. As part of the Acid Deposition Monitoring Network in East Asia (EANET), Malaysia systematically measures both nitrate and sulphate concentrations (**Figure 2.11 & Figure 2.12**) in wet deposition across four strategically classified stations: Petaling Jaya (urban-industrial), Cameron Highlands (rural high-altitude), Kuching (urban coastal), and Danum Valley (remote forest reserve).

The box-plot analysis of Nitrate Concentrations (2020-2024) (**Figure 2.11**) shows that Petaling Jaya exhibits **extremely elevated nitrate concentrations** that are orders of magnitude higher than all other stations, with values extending up to approximately **350–400 µmol/L** during peak months. This extraordinary magnitude reflects the station's location within Malaysia's most densely industrialised and traffic-congested region, the Klang Valley.

Monthly Distribution:

- **Maximum concentrations** are observed in **February**, coinciding with the Northeast Monsoon period when regional air masses transport pollutants from continental sources.
- A **secondary elevated period** occurs between **October and November**, corresponding to the inter-monsoon transition.
- **Minimum concentrations** are recorded in **June**, during the Southwest Monsoon when maritime air masses dominate.
- The data exhibit **substantial inter-monthly variability**, with box-plot ranges indicating significant fluctuations in nitrate loading throughout the year.

The sustained high nitrate levels at Petaling Jaya are characteristic of its urban-industrial setting. Vehicle emissions remain the dominant source, with road transport accounting for approximately 24% of NO_2 emissions nationwide. The February peak reflects the combined influence of local emissions and enhanced long-range transport during the Northeast Monsoon. The June minimum corresponds to the Southwest Monsoon period, which brings cleaner marine air from the South China Sea, facilitating pollutant dispersion and atmospheric scavenging.

Meanwhile Cameron Highlands exhibits **low to moderate nitrate concentrations**, typically ranging between **0 and 20 µmol/L**, with occasional elevated readings extending to approximately **35 µmol/L**.

Monthly Distribution:

- **Maximum concentrations** are observed in **March** and **July**, representing two distinct annual peaks.
- **Minimum concentrations** occur in **January**, coinciding with the period of lowest atmospheric acidity.
- The box-plot distributions reveal **moderate variability**, with the interquartile range (Q1–Q3) generally spanning 5–15 µmol/L across most months.

The double-cyclic nitrate pattern at Cameron Highlands mirrors the bimodal acidity cycle observed in pH measurements. The March and July peaks correspond to periods of enhanced agricultural activity—particularly fertiliser application—combined with the topographical trapping effects of the high-altitude valley setting. The thermal inversion layers that frequently form in this region prevent pollutant dispersion, concentrating local emissions from agricultural machinery, transport, and fertiliser volatilisation. The January minimum reflects reduced agricultural activity and more favourable dispersion conditions during the Northeast Monsoon.

Kuching demonstrates **low nitrate concentrations**, with values typically remaining below **20 µmol/L** and occasional outliers extending to approximately **40 µmol/L** during certain months.

Monthly Distribution:

- **Maximum concentrations** are observed in **September**, during the Southwest Monsoon period when regional air masses transport pollutants from Kalimantan.
- **Minimum concentrations** occur in **January**, during the Northeast Monsoon when maritime air masses dominate.
- A **clear seasonal pattern** is evident, with nitrate levels elevated from **August to October** and reduced from **December to February**.

The relatively clean nitrate profile at Kuching reflects its coastal location, which benefits from marine air masses and effective pollutant dispersion in the absence of topographical confinement. The September peak aligns with the Southwest Monsoon, during which transboundary transport from biomass burning in Kalimantan can influence air quality. The January minimum coincides with the Northeast Monsoon, bringing cleaner air from the South China Sea. The overall low nitrate levels indicate that local urban emissions—while present—are substantially lower than those in the Klang Valley.

Danum Valley maintains **very low nitrate concentrations**, with values consistently below **10 µmol/L** throughout the year and minimal monthly variation.

Monthly Distribution:

- **Maximum concentrations** are observed in **February** and **April**, with values typically remaining below 10 µmol/L.
- **Minimum concentrations** occur in **January**, reflecting background atmospheric conditions.
- The box-plot distributions demonstrate **remarkable stability**, with narrow interquartile ranges and

The pristine nitrate profile at Danum Valley underscores the effectiveness of the surrounding forest reserve in maintaining atmospheric quality. Located at 427 metres above sea level within the Danum Valley Forest Conservation area, the station is surrounded by tropical rainforest with no significant local pollution sources. The February–April elevation reflects the influence of long-range pollutant transport during the Northeast Monsoon transition, while the January minimum represents true background conditions. Notably, nitrate concentrations at Danum Valley are substantially lower than those observed at the other three stations, confirming the remote and unpolluted nature of this site.

The nitrate data reveals a **pronounced spatial gradient** across Malaysia's monitoring stations:

Station	Classification	Nitrate Range (µmol/L)	Primary Sources	Seasonal Pattern
Petaling Jaya	Urban-Industrial	0–400	Vehicle emissions, industry	NE Monsoon peak (Feb)
Cameron Highlands	Rural High-Altitude	0–35	Agriculture, trapped local emissions	Bimodal (Mar, Jul)
Kuching	Urban Coastal	0–40	Urban emissions, transboundary	SW Monsoon peak (Sep)
Danum Valley	Remote Forest	0–10	Long-range transport	Minimal variation

This gradient demonstrates that **urban-industrial activities** are the dominant driver of nitrate deposition in Malaysia, with Petaling Jaya exhibiting concentrations comparable to heavily industrialised cities in East Asia. The contrast between Petaling Jaya and the other stations is particularly striking, with nitrate levels in

the urban-industrial site exceeding those at Danum Valley by factors of 40 to 400.

The monthly nitrate distributions reveal **strong seasonal patterns** driven by the regional monsoon system:

- **Northeast Monsoon (November–February):** Characterised by elevated nitrate concentrations at Petaling Jaya and Danum Valley. This period corresponds to enhanced transport of anthropogenic pollutants from continental Asia and the South China Sea. At Petaling Jaya, the February maximum represents the annual peak in nitrate loading.
- **Southwest Monsoon (May–September):** Associated with elevated nitrate concentrations at Kuching and Cameron Highlands. The September peak at Kuching reflects transboundary transport from biomass burning in Kalimantan, while the July peak at Cameron Highlands corresponds to local agricultural emissions trapped by topographical conditions.
- **Inter-monsoon periods (March–April and October–November):** Transitional periods with variable nitrate patterns. The March peak at Cameron Highlands and the October–November elevation at Petaling Jaya reflect changing wind directions and the onset or cessation of monsoon systems.

The shifting wind patterns during February and March—from northeasterly to southwesterly flows as the monsoon trough progresses southwards—significantly influence transboundary and regional pollutant transport into both Peninsular and East Malaysia.

The box-plot analysis of Sulphate Concentrations (2020-2024) (**Figure 2.12**) shows that Petaling Jaya exhibits elevated sulphate concentrations relative to other stations, with values typically ranging between approximately 5 and 50 μmol/L, and occasional outliers extending higher. Maximum concentrations are observed in February, coinciding with the Northeast Monsoon period when regional air masses transport pollutants from continental sources, while a secondary elevated period occurs between October and November, corresponding to the inter-monsoon transition. Minimum concentrations are recorded in June, during the Southwest Monsoon when maritime air masses dominate. The data exhibit substantial inter-monthly variability, with box-plot ranges indicating significant fluctuations in sulphate loading throughout the year. The sustained elevated sulphate levels at Petaling Jaya are characteristic of its urban-industrial setting, where industrial activities, particularly manufacturing and power generation, remain the dominant sources of SO_2 emissions. The February peak reflects the combined influence of local emissions and enhanced long-range transport during the Northeast Monsoon, while the June minimum corresponds to the Southwest Monsoon period, which brings cleaner marine air from the South China Sea. The 2022–2023 annual peak at approximately 15 μmol/L, declining to 12.5 μmol/L by 2024, indicates recent improvements likely attributable to the nationwide transition to cleaner fuel standards (RON 95) and stricter industrial emission regulations implemented over the past decade.

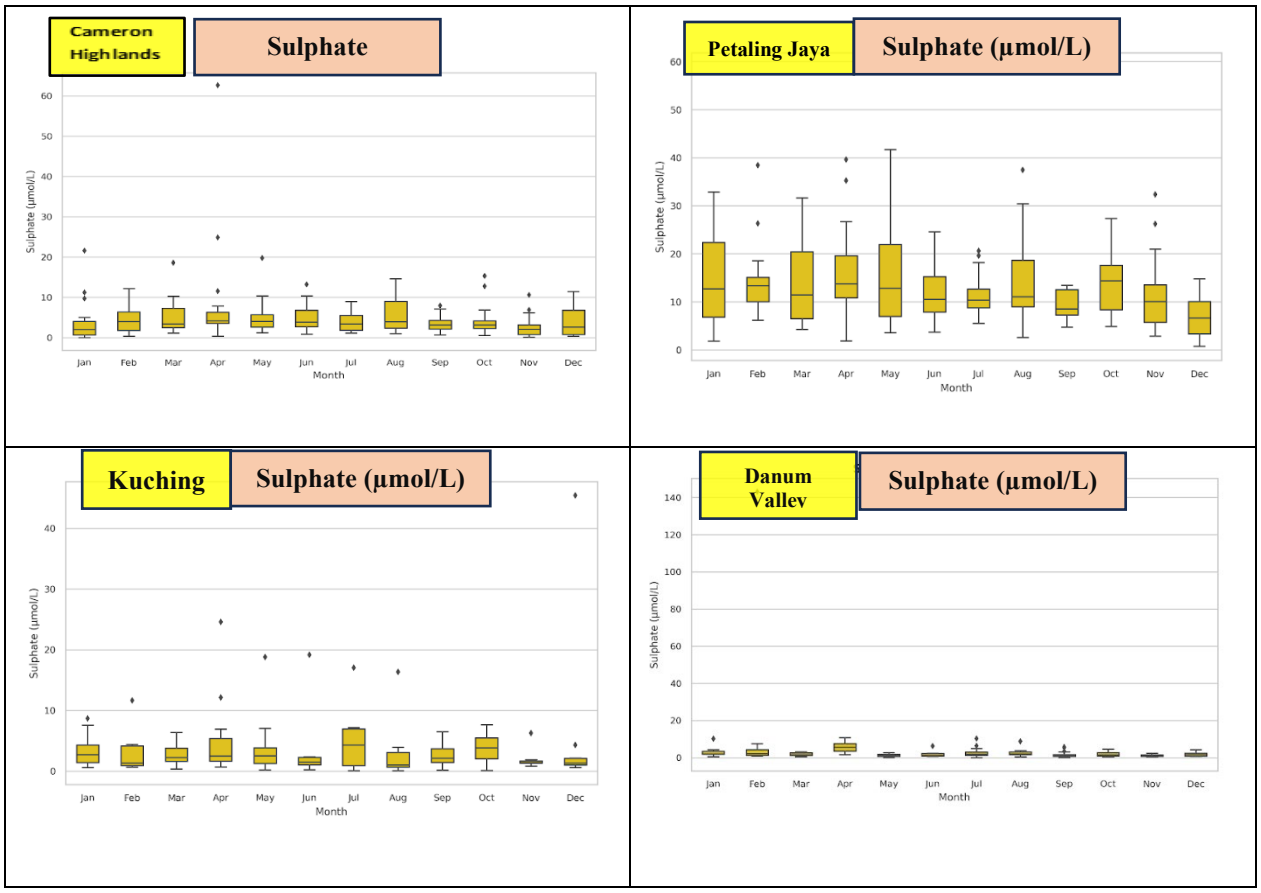


Figure 2.12. Monthly Box-Plot Distributions of Sulphate Concentrations (µmol/L) from 2020 – 2024 for Cameron Highlands, Petaling Jaya, Kuching and Danum Valley.

Cameron Highlands exhibits low to moderate sulphate concentrations, typically ranging between approximately 3 and 20 µmol/L, with occasional elevated readings extending to approximately 30–35 µmol/L. Maximum concentrations are observed in March and July, representing two distinct annual peaks, while minimum concentrations occur in January, coinciding with the period of lowest atmospheric acidity. The box-plot distributions reveal moderate variability, with the interquartile range generally spanning 5–15 µmol/L across most months. The double-cyclic sulphate pattern at Cameron Highlands mirrors the bimodal acidity cycle observed in pH measurements. The March and July peaks correspond to periods of enhanced agricultural activity and tourism-related emissions, combined with the topographical trapping effects of the high-altitude valley setting. The thermal inversion layers that frequently form in this region prevent pollutant dispersion, concentrating local emissions from agricultural machinery, transport, and other sources. The January minimum reflects reduced activity and more favourable dispersion conditions during the Northeast Monsoon.

Kuching demonstrates low sulphate concentrations, with values typically remaining below approximately 15–20 µmol/L, and occasional outliers extending to approximately 35 µmol/L during certain months. Maximum concentrations are observed in August, during the Southwest Monsoon period when regional air masses transport pollutants from Kalimantan, while minimum concentrations occur in December, during the Northeast Monsoon when maritime air masses dominate. A clear seasonal pattern is evident, with sulphate levels elevated from August to October and reduced from December to February. The relatively clean sulphate profile at Kuching reflects its coastal location, which benefits from marine air masses and effective

pollutant dispersion in the absence of topographical confinement. The August peak aligns with the Southwest Monsoon, during which transboundary transport from biomass burning and coal-fired power generation in Kalimantan can influence air quality. The December minimum coincides with the Northeast Monsoon, bringing cleaner air from the South China Sea. Notably, the sulphate seasonal pattern at Kuching differs from nitrate, indicating distinct source contributions and transport pathways for these two acidifying species.

Danum Valley maintains very low sulphate concentrations under normal conditions, with values consistently below approximately 5 μmol/L throughout most of the year. However, the station exhibited a remarkable sulphate anomaly in 2020, reaching approximately 17.5 μmol/L, before returning to baseline levels well below 2.5 μmol/L through 2024. Maximum concentrations are observed in February, coinciding with elevated pollutant transport during the Northeast Monsoon, while minimum concentrations occur in March, following the decline of monsoon-driven pollutant transport. The box-plot distributions demonstrate remarkable stability under normal conditions, with narrow interquartile ranges and minimal outliers, except for the 2020 anomaly. The pristine sulphate profile at Danum Valley underscores the effectiveness of the surrounding forest reserve in maintaining atmospheric quality. The February peak reflects the influence of long-range pollutant transport during the Northeast Monsoon, while the March recovery indicates the cessation of this transport pathway. The dramatic, isolated spike in sulphate at Danum Valley in 2020—completely decoupled from its historical baseline—is highly characteristic of a localised, short-term event, likely driven by transient biomass burning (forest fires) upwind or transboundary haze active during that specific dry season. This anomaly fully resolved by 2021, with levels remaining well below 2.5 μmol/L through 2024.

The sulphate data reveals a pronounced spatial gradient across Malaysia's monitoring stations, confirming that urban-industrial activities are the dominant driver of sulphate deposition. Petaling Jaya exhibits elevated concentrations (5–50 μmol/L) driven by industrial emissions and power generation with a Northeast Monsoon peak in February. Cameron Highlands shows low to moderate levels (3–35 μmol/L) influenced by trapped local emissions and agriculture with a bimodal pattern in March and July. Kuching maintains low levels (5–35 μmol/L) affected by urban emissions and transboundary transport with a Southwest Monsoon peak in August. Danum Valley preserves pristine conditions (2–5 μmol/L normally, 17.5 μmol/L during the 2020 anomaly) with minimal variation and episodic anomalies driven by long-range transport. The contrast between Petaling Jaya and Danum Valley under normal conditions is striking, with sulphate levels in the urban-industrial site exceeding those at the remote forest site by factors of 5 to 10.

The monthly distributions of both nitrate and sulphate reveal strong seasonal patterns driven by the regional monsoon system. During the Northeast Monsoon (November–February), elevated concentrations of both ions are observed at Petaling Jaya and Danum Valley, corresponding to enhanced transport of anthropogenic pollutants from continental Asia and the South China Sea. The February maximum at Petaling Jaya represents the annual peak for both species, while Danum Valley exhibits concurrent elevations reflecting long-range transport. During the Southwest Monsoon (May–September), elevated concentrations are observed at Kuching and Cameron Highlands. The August–September peaks at Kuching for both species reflect transboundary transport from biomass burning and industrial activities in Kalimantan, while the July peaks at Cameron Highlands correspond to local emissions trapped by topographical conditions.

However, notable differences exist between the seasonal patterns of nitrate and sulphate. At Kuching, nitrate peaks in September while sulphate peaks in August, suggesting distinct source contributions and transport

efficiencies for these two species. At Cameron Highlands, the double-cyclic pattern is driven by both ions, with nitrate being the main driver during certain months and sulphate being the main driver during others. At Petaling Jaya, the significant drop in acidity from October to December is mainly driven by a reduction in sulphate concentration, while nitrate remains a more consistent contributor throughout the year.

The 2020 Danum Valley sulphate anomaly—reaching approximately 17.5 µmol/L—represents a critical observation that distinguishes sulphate from nitrate at this remote site. While nitrate concentrations remained within normal background levels, sulphate exhibited an isolated spike completely decoupled from its historical baseline. This pattern strongly indicates episodic transboundary pollutant transport driven by regional monsoonal wind systems and highlights the vulnerability of even remote ecosystems to biomass burning and haze from Kalimantan. The fact that this anomaly was not observed in nitrate suggests that the event was dominated by sulphur-containing emissions, characteristic of biomass burning and coal combustion sources.

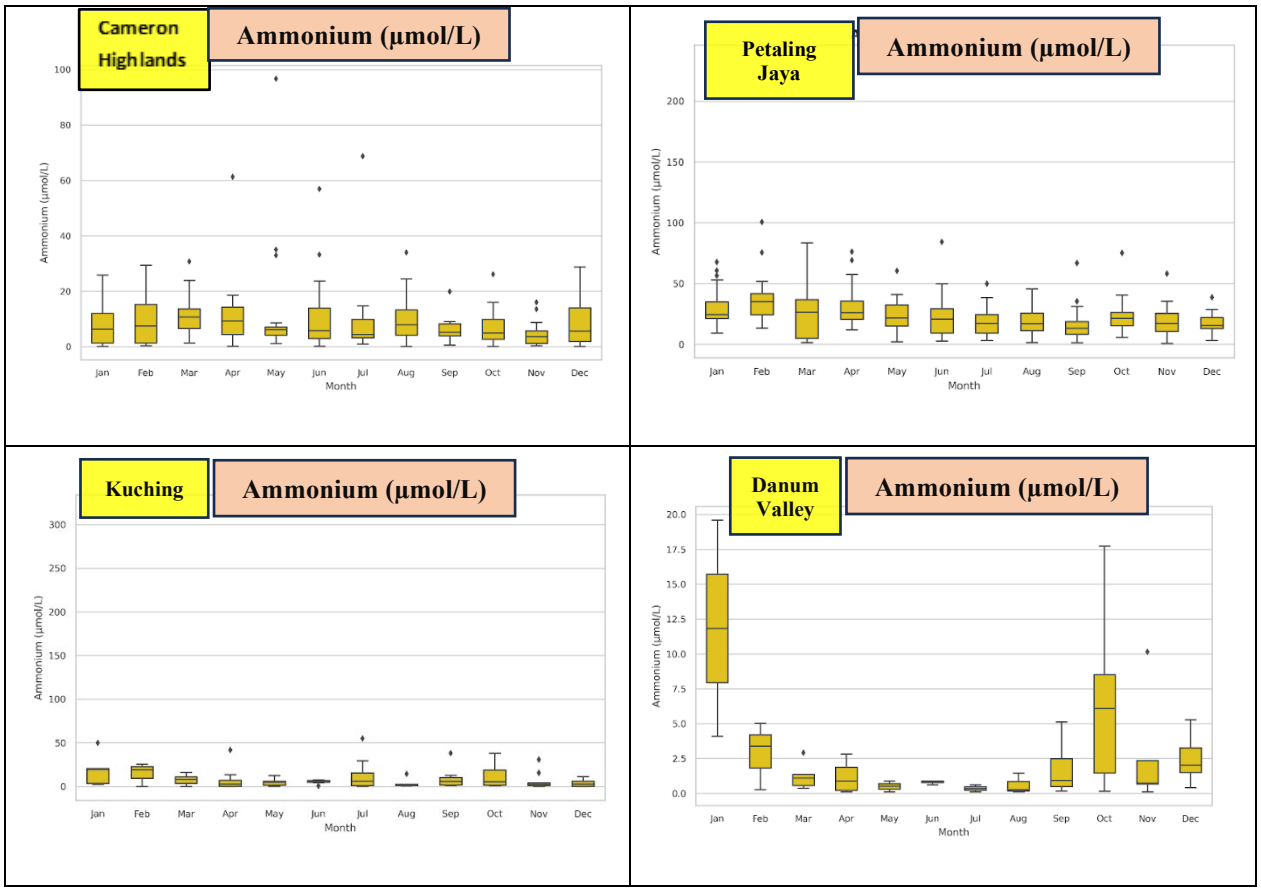


Figure 2.13. Monthly Box-Plot Distributions of Ammonium Concentrations (µmol/L) from 2020 – 2024 for Cameron Highlands, Petaling Jaya, Kuching and Danum Valley.

Ammonium (NH_4^+) is a critical cationic species in wet deposition, serving both as a nutrient and as a neutralizing agent for acidic anions such as nitrate and sulphate. Its primary sources include agricultural activities (particularly fertiliser application and livestock operations), biomass burning, industrial emissions, and vehicular exhaust. Unlike the acidifying anions, ammonium plays a complex dual role: it can neutralise acidity in rainwater through the formation of ammonium salts, yet elevated ammonium deposition contributes to nitrogen saturation in ecosystems, leading to soil acidification, nutrient imbalances, and eutrophication of freshwater systems.

The box-plot analysis of Ammonium Concentrations (2020-2024) (**Figure 2.13**) shows that Petaling Jaya exhibits **substantially elevated ammonium concentrations** relative to other stations, with values extending up to approximately **150–200 µmol/L** during peak months. This elevated magnitude reflects the station's location within Malaysia's most densely populated and industrialised region, the Klang Valley, where anthropogenic ammonium sources—including vehicular emissions, industrial activities, and waste management—are concentrated.

Maximum concentrations are observed in **February**, representing the annual peak in ammonium loading. Following this peak, a consistent decreasing trend is observed for the next four months, leading to minimum concentrations in **June**. A secondary minimum is observed during **November**, though concentrations in June and November are not readily distinguishable. The data exhibit substantial inter-monthly variability, with box-plot ranges indicating significant fluctuations in ammonium loading throughout the year.
The sustained elevated ammonium levels at Petaling Jaya are characteristic of its urban-industrial setting, where multiple anthropogenic sources contribute to atmospheric ammonium. The February maximum coincides with the Northeast Monsoon period, when regional air masses transport pollutants from continental sources, combined with local emissions. The subsequent decline from February to June corresponds to the transition from the Northeast Monsoon to the Southwest Monsoon, with the June minimum reflecting the influence of cleaner maritime air masses and enhanced atmospheric scavenging during the inter-monsoon period. The November secondary minimum likely reflects reduced agricultural and industrial activity during the inter-monsoon transition, combined with more efficient pollutant dispersion.

Cameron Highlands exhibits moderate ammonium concentrations, with values typically ranging between approximately 5 and 30 µmol/L, and occasional elevated readings extending to approximately 60–70 µmol/L during certain months. This reflects the station's location within Malaysia's primary high-altitude agricultural region, where fertiliser application is intensive.

As for the monthly distribution, the highest concentrations are observed in February and June, with values reaching approximately 32 µmol/L and 58 µmol/L respectively. The lowest concentrations occur in September (8 µmol/L) and November (15 µmol/L). The box-plot distributions reveal a pattern driven by regular three-monthly cycles annually, with the interquartile range generally spanning 5–15 µmol/L across most months.

The ammonium pattern at Cameron Highlands is closely linked to agricultural activity cycles. The February peak corresponds to periods of enhanced fertiliser application at the onset of the growing season, combined with the topographical trapping effects of the high-altitude valley setting at 1,545 metres above sea level. The June peak, while elevated, represents a secondary maximum associated with continued agricultural activity. The thermal inversion layers that frequently form in this region prevent pollutant dispersion, concentrating local emissions from fertiliser volatilisation, agricultural machinery, and livestock operations. The September minimum reflects reduced agricultural activity and more favourable dispersion conditions during the inter-monsoon period. A 2023 study confirmed that pH in Cameron Highlands shows a strong positive correlation with NH_4^+, Na^+, K^+, and Ca^{2+}, attributed to atmospheric neutralisation reactions between acids (HNO_3 and H_2SO_4) and alkaline compounds present in suspended fine particles.

Kuching (Urban Coastal Station) demonstrates low to moderate ammonium concentrations, with values

typically ranging between approximately 5 and 30 µmol/L and occasional outliers extending to approximately 45–50 µmol/L during certain months. The station exhibits a distinct seasonal pattern with significantly higher concentrations from August to October compared to the rest of the year.

The highest concentrations are observed in September and October, with median values reaching approximately 30–35 µmol/L. Lowest concentrations occur in January, with median values of approximately 10 µmol/L. A clear seasonal pattern is evident, with ammonium levels elevated from August to October and reduced from December to February.

The relatively clean ammonium profile at Kuching reflects its coastal location, which benefits from marine air masses and effective pollutant dispersion in the absence of topographical confinement. The August–October peak aligns with the Southwest Monsoon, during which transboundary transport from biomass burning and agricultural activities in Kalimantan can influence air quality. The September–October maximum coincides with the peak of the dry season in Kalimantan, when agricultural burning is most prevalent. The January minimum coincides with the Northeast Monsoon, bringing cleaner air from the South China Sea. The overall moderate ammonium levels indicate that local urban emissions—while present—are substantially lower than those in the Klang Valley, and that transboundary sources play a significant role in shaping the seasonal ammonium pattern.

Danum Valley (Remote Forest Station) maintains very low ammonium concentrations, with values typically below approximately 15 µmol/L throughout most of the year and minimal monthly variation. The station exhibits a distinct seasonal pattern with significantly higher concentrations from May to September compared to the rest of the year.

Highest concentrations are observed in August, with median values of approximately 1.5 µmol/L and maximum values reaching 15.5 µmol/L. Lowest concentrations occur in February, with median values of approximately 3.5 µmol/L and minimum values approaching detection limits (0.5–0.2 µmol/L). The box-plot distributions demonstrate remarkable stability, with narrow interquartile ranges and minimal outliers. Occasional outliers are observed in January (2.5 µmol/L), February (2.8 µmol/L), March (2.5 µmol/L), October (10.0 µmol/L), and December (0.2 µmol/L).

The pristine ammonium profile at Danum Valley underscores the effectiveness of the surrounding forest reserve in maintaining atmospheric quality. Located at 427 metres above sea level within the Danum Valley Forest Conservation area, the station is surrounded by tropical rainforest with no significant local pollution sources. The May–September elevation reflects the influence of long-range pollutant transport during the Southwest Monsoon, when biomass burning in Kalimantan can transport ammonium-containing aerosols to the region. The August peak coincides with the peak of the dry season in Kalimantan. The February minimum represents true background conditions, with concentrations approaching the analytical detection limit. The October outlier (10.0 µmol/L) may represent an episodic event associated with regional biomass burning or other transient sources. Notably, ammonium concentrations at Danum Valley are substantially lower than those observed at the other three stations, confirming the remote and unpolluted nature of this site.

The ammonium data reveals a **pronounced spatial gradient** across Malaysia's monitoring stations:

Station	Classification	Ammonium Range (μmol/L)	Primary Sources	Seasonal Pattern
Petaling Jaya	Urban-Industrial	5–200	Vehicle emissions, industry, waste	NE Monsoon peak (Feb)
Cameron Highlands	Rural High-Altitude	5–70	Agriculture (fertiliser), livestock	Bimodal (Feb, Jun)
Kuching	Urban Coastal	5–50	Urban emissions, transboundary	SW Monsoon peak (Sep–Oct)
Danum Valley	Remote Forest	0.2–15.5	Long-range transport, biomass burning	SW Monsoon peak (Aug)

This gradient demonstrates that **urban-industrial and agricultural activities** are the dominant drivers of ammonium deposition in Malaysia, with Petaling Jaya exhibiting concentrations substantially higher than all other stations. The contrast between Petaling Jaya and Danum Valley is particularly striking, with ammonium levels in the urban-industrial site exceeding those at the remote forest site by factors of 10 to 400. This gradient underscores the significant anthropogenic influence on atmospheric ammonium concentrations in Malaysia's urban and agricultural regions.

Seasonal Drivers and Monsoon Influence

The monthly distributions of all measured parameters reveal strong seasonal patterns driven by the regional monsoon system. The Northeast Monsoon (November–February) is characterised by elevated concentrations of all species at Petaling Jaya and Danum Valley, corresponding to enhanced transport of anthropogenic pollutants from continental Asia. The Southwest Monsoon (May–September) is associated with elevated concentrations at Kuching and Cameron Highlands, reflecting transboundary transport from biomass burning and agricultural activities in Kalimantan. The inter-monsoon periods (March–April and October–November) represent transitional periods with variable patterns.

Public Health and Environmental Implications

The elevated concentrations of nitrate, sulphate, and ammonium observed at Petaling Jaya represent a significant public health burden. These ions are major constituents of fine particulate matter ($PM_{2.5}$), which has been significantly associated with mortality and morbidity from cardiovascular and respiratory diseases. The *Lancet Countdown 2025* report attributed over 22,500 deaths in Malaysia in 2022 to anthropogenic $PM_{2.5}$ pollution, with 61% linked to fossil fuel use.

Environmentally, the deposition of nitrate and sulphate contributes to soil and freshwater acidification,

reducing nutrient availability, affecting plant growth, and threatening aquatic ecosystems. The 2020 Danum Valley sulphate anomaly highlights the ongoing threat of transboundary pollution to even the most pristine ecosystems in Malaysia.

References

Liu, L. *et al*, 2016: Characteristics of atmospheric single particles during haze periods in a typical urban area of Beijing: A case study in October, 2014. *J Environ Sci (China)*, 40, pp: 145 - 153

Luo, Li *et al*, 2019: Spatial Distributions and Sources of Inorganic Chlorine in PM2.5 across China in Winter. *Atmosphere*, 10, pp: 505

Swee, L. K., 2017: The Story of Sarawak Energy, Sarawak Energy and Taiwan SmartGrid Exchange Symposium