National Assessment on Acid Deposition in Lao PDR

by

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July 2026

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Abstract

This national assessment synthesizes a 24–year monitoring dataset (2002 to 2025) on atmospheric deposition and air quality in Lao PDR under the Acid Deposition Monitoring Network in East Asia (EANET). Results show that despite rapid urbanization in Vientiane Capital, rainwater remains buffered against severe acidification, maintaining a long-term average pH of 6.35 ± 0.52. This neutral state is maintained by crustal dust (Ca^{2+}) and agricultural ammonia (NH_4^+) scavenging acidic gases, though rising nitrate (NO_3^-) concentrations point to growing urban vehicular emissions. Particulate matter ($PM_{2.5}$) and dry deposition analysis reveal a severe seasonal "smog trap" during the dry season (November to April). Ambient $PM_{2.5}$ regularly peaks in March, exceeding 80 µg/m^3 due to boundary-layer inversions, stagnant pre-monsoon weather, and transboundary biomass burning, before southwest monsoons wash out pollutants to a baseline of 9 to 15 µg/m^3 in the summer.

In contrast to the buffered atmosphere, the aquatic environment at Nam Hum Lake presents an urgent warning signal. Between 2019 and 2024, the lake's pH dropped from a weakly alkaline 8.05 to a slightly acidic 6.41, while electrical conductivity surged tenfold from 3.4 to over 34 µS/cm. This rapid degradation is driven by the "monsoon flush" effect: accumulated dry-season atmospheric particulates and agricultural N-P-K fertilizer runoff are swept into the shallow lake basin during early rains, overwhelming its natural geological buffer.

Operational tracking remains hampered by equipment malfunctions and border customs bottlenecks that delay critical laboratory imports. Addressing these institutional gaps, establishing watershed buffer zones, initiating soil-vegetation monitoring, and drafting a dedicated clean air act are vital next steps to transition Lao PDR from passive environmental observation to active air quality management.

Keywords: Acid Deposition, EANET, Wet deposition, $PM_{2.5}$, Nam Hum Lake, Atmospheric Washout, Monsoon Flush, Lao PDR

1. Basic Information on National Monitoring Activities

1.1 Outline of the activities on acid deposition and national monitoring plan

Lao People's Democratic Republic (Lao PDR) is a landlocked, largely mountainous country whereas has the total area covering 236,800 km^2, and bordered by Myanmar, Cambodia, China, Thailand, and Viet Nam. However much of the terrains is rugged, the capital city is Vientiane which lies on a lowland plain. By the West, there is the Mekong River, which defines the border making the river an important, acting as a for transportation, communication for trade and connectivity with its neighboring countries. Parallelly, the Mekong River has 11 major-important vital tributaries flowing through Lao PRD, where playing a crucial role in the economy, agriculture, and hydroelectric power generation, including, Nam Tha, Nam Ou, Nam Beng, Nam Khan, Nam Ngum, Nam Sane, Nam Nghiep, Nam Kading, Xebangfai, Xedone, and Sekong.

The country has a tropical monsoon climate, characterized mainly by a rainy season (May to October) and dry season (November to April) and temperatures ranging from 5ºC to 40ºC depending on altitude. Humidity is generally high in the 70% to 80% range.

Acid Deposition issues are a fairly new phenomenon for Lao PDR and the interest in the prevention of this problem is still gaining momentum. There is lack of knowledge on various aspects of sulfur and nitrogen pollution including emissions, atmospheric transport and deposition, direct impacts of gases on human health, vegetation and corrosion of monuments and indirect impacts via changes in the soil.

Realizing the need to protect the country from the acid deposition problem, Lao PDR became one of the participating countries of EANET in November 2002. Since then, in order to ensure the monitoring activities of acid deposition in Lao PDR, the country has nominated the National Center for developed and implementing the nation monitoring plan as well as collecting the national monitoring data, promoting national QA/QC activities, public awareness raising through the acid deposition brochure and dealing with technical matters on the network activities in the country.

The national monitoring activities on acid deposition monitoring was established and started monitoring wet deposition in Vientiane capital city by collecting daily sample (during rainy season) and established the dry deposition monitoring at the same site of wet deposition monitoring. The activities also were surveyed the appropriate monitoring site for inland aquatic at the Nam Hum Lake and collected samples and analysis for observed data.

All activities were carried out by to Environment Quality Monitoring and Hazardous Chemical Center (EQMHCC), the National Center under Water Resources and Environment Research Institute (WERI) of Water Resources and Environment Administration (WREA) until 2011 was changed its name Environmental Laboratory (EL), under Natural Resources and Environment Research Institute (NRERI), Ministry of Natural Resources and Environment (MONRE). At the year of 2025, since the country has improved organizations for all nationwide by Lao government, so the current implement for all activities is under the Environment Quality Analysis Center (EQAC), Biotechnology and Ecology Institute (BEI), Ministry of Agriculture and Environment (MAE).

1.2 Monitoring program from 2002 to 2025

The national monitoring plan covers the generation of the relevant data and activities, operation and maintenance of field and laboratory facilities and conduct of QA/QC activities.

- For wet deposition monitoring to collecting daily sample and analyzed was conducted at the Department of Meteorological and hydrological stations. Ministry of Agriculture and Environment (MAE). Measurement parameters: Precipitation amount, pH and Electric Conductivity (EC). Anion: SO_4^{2-}, NO_3^-, Cl^- and Cation: Na^+, NH_4^+, K^+, Ca^{2+}, Mg^{2+} by using Ion Chromatography.
- For dry deposition monitoring, surveyed and established monitoring site at the Department of Meteorological and hydrological, Ministry of Natural Resources and Environment (MONRE) (2009 to 2024), and Ministry of Agriculture and Environment (MAE) (2025) in Vientiane and start to collect weekly sample (2010), and plan for monthly sample (from 2026). Measurements were done 12 parameters as follows: SO_2, HNO_3, HCl, NH_3, SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+} by using the Ion Chromatography.
- For ambient air quality monitoring established monitoring site at the Department of Meteorological and Hydrological, Ministry of Natural Resources and Environment (MONRE) (2013 to 2024), and Ministry of Agriculture and Environment (MAE) (2025) in Vientiane Capital and start to analyses by using the automated. Measurements were done 3 parameters: NO_x, PM_{10} and $PM_{2.5}$.
- For ambient air quality monitoring mobile unit established monitoring at prime minister ‘office (PMO) Ministry of Natural Resources and Environment (MONRE) (2014 to 2024), and Ministry of Agriculture and Environment (MAE) (2025). Measurement parameters: NO, NO_2, NO_x, PM_{10}, SO_2, O_3, CO and VOCs.
- For inland aquatic monitoring to survey monitoring site at Nam Hum Lake and collected sample and analyses follow the EANET manual parameters: pH, EC, Alkalinity. Anion: SO_4^{2-}, NO_3^-, Cl^-, PO_4^{3-} and cation: Na^+, NH_4^+, K^+, Ca^{2+}, Mg^{2+}, by using IC.
- For raising awareness and training on acid deposition to conducted national awareness workshop on acid deposition for relevant ministries and for the primary school teacher and student from National University of Laos (NUOL) especially Faculty of Science and Faculty of Environmental Science.
- To participant the activities analysis samples of Inter-laboratory comparison project on acid deposition: Wet and Dry deposition samples and Inland water.

1.3 Monitoring stations

The acid deposition station in Lao PDR

Table 1.1 Acid deposition monitoring sites in Lao PDR

Site category	Site classification	Location
Acid deposition monitoring Site: Wet deposition	Urban	Environment Quality Analysis Center (EQAC), Biotechnology and Ecology Institute (BEI), Ministry of Agriculture and Environment (MAE)
Acid deposition monitoring Site: Dry deposition	Urban	The same as the wet deposition monitoring site
Ambient Air Quality Monitoring Station	Urban	Vientiane capital (Department of Meteorological and Hydrological, Ministry of Agriculture and Environment (MAE)
Ambient Air Quality Monitoring Site: Mobile Unit	Urban	Environment Quality Analysis Center (EQAC), Biotechnology and Ecology Institute (BEI), Ministry of Agriculture and Environment (MAE)
Ecological survey site: Inland aquatic monitoring	Rural	Nam Hum Lake Vientiane capital
Ecological survey site: Soil and Vegetation monitoring	not start yet	

1.4 Sampling and measurements



Figure 1.1. Monitoring station for wet and dry deposition in Vientiane Capital (Environmental Quality Analysis Center, Ministry of Agriculture and Environment).



Figure 1.2. Ambient Air Quality Monitoring Mobile Unit.









Figure 1.3. Ambient Air Quality Monitoring Station | IES-200 Air Quality Monitor Sensor

2. State of Acid Deposition in Lao PDR

2.1 Atmospheric deposition

The global climate is changing. All witness changes are in average temperatures, shifts in seasons and an increasing intensity of extreme weather events. In Lao PDR, the effects of climate change are already visible and will become more evident in the future. Currently accurate predictions of the potential changes in climatic conditions and resulting adverse impact of such changes have not been developed nationally by the Lao PDR, but some indication can be taken from preliminary regional level predictions.

2.1.1. State of wet deposition

Wet deposition samples were collected in the Vientiane monitoring station and analyzed for pH, electrical conductivity, anion and cation concentrations (see, Table 2.1 to 2.2). As the shortage summary, precipitation chemistry acts as a direct mirror of both localized atmospheric pollution and regional meteorological influences. This report presents a rigorous geoscientific analysis of a 24–year precipitation monitoring dataset (2002 – 2025) compiled at the Vientiane Capital monitoring station.

By the way, the data of cation missing of some years (especially, the nearly year from 2024 – 2025) since our IC system has problem, it should be maintenance and the fee is quite high since the policy of the company authorize. With an unlucky we had ordered the new suppressors both anion and cation, including chemicals and standard solutions. When the shipping sends all items passes Thailand, we have a problem for Immigration tax afterward all items were sent back to the country of company.

Our core findings indicate that despite rapid urban expansion and motorization in Vientiane Capital over the past two decades, the rainwater quality remains largely buffered against severe acidification, exhibiting an average pH of 6.35 ± 0.52. This buffering is primarily driven by an abundant presence of crustal/soil-derived alkaline components (dominated by calcium ions, Ca^{2+}) and agricultural neutralizing agents (ammonium ions, NH_4^+).

Furthermore, we observe a pronounced dilution effect: as annual rainfall has steadily risen—climbing from historic lows of under 500 mm to recent highs exceeding 2,800 mm—there is a corresponding, statistically significant decrease in Electrical Conductivity (EC), indicating a highly efficient atmospheric washout of suspended particulates and soluble gases.

Table 2.1 Annual rainfall amount, pH and EC in Vientiane

Station	Year	Rainfall (mm y^{-1})	pH	EC (mS m^{-1})
Vientiane capital monitoring site	2002			
	2003	(88.6)	(6.51)	2.07
	2004	442	(5.65)	2.65
	2005	665	6.32	1.01
	2006	709	6.49	0.764
	2007	1399	5.67	0.396
	2008	1668	6.01	0.644
	2009	(181)	(5.48)	(0.534)
	2010	***	***	***
	2011	***	***	***
	2012	(1322)	(6.46)	(0.411)
	2013	***	***	***
	2014	1273	6.54	0.867
	2015	2147.9	6.18	1.943
	2016	1432.96	6.62	0.689
	2017	1337	*	*
	2018	829	*	*
	2019	700	*	*
	2020	1616.6	6.93	1.11
	2021	1702.4	7.41	0.680
	2022	1984.0	6.65	0.621
	2023	2448.32	6.93	0.897
	2024	2855	5.75	0.602
	2025	2836	6.40	0.683

***: No data or no measurement, *: The constituent was rejected or not measured although precipitation was not 0 mm., (): %PCL≤80% and/or %TP≤80%

As investigation of precipitation volume in Vientiane Capital (Table 2.1) exhibits intense inter-annual variability, paired with a distinct upward trend over the last decade as following:

The Long-term Hydrological Trends and Atmospheric Washout:

Precipitation volume growth: The minimum recorded annual rainfall was 88.6 mm in 2003 (indicating either an extremely dry localized cycle or incomplete monitoring/instrument outage), while the peak occurred in 2024 at 2,855 mm. The long-term average stands at 1,381.8 mm/year.

The dilution effect (EC vs. rainfall): Electrical conductivity (EC)—a proxy for the total concentration of dissolved inorganic ions—shows a clear inverse correlation with rainfall volume (r = - 0.35).

- During the hyper-dry years or early monsoon months (for an example, 2003 with 88.6 mm and 2004 with 442 mm, EC spiked to its highest recorded values of 2.07 mS/m and 2.65 mS/m respectively.
- Conversely**,** in high-rainfall years (such as 2024 – 2025 with rain > 2,800 mm, EC remained suppressed between 0.60 mS/m and 0.68 mS/m.
- Scientific interpretation: This demonstrates a classic atmospheric "washout" or scavenging process. Small volumes of rain scrub a relatively dirty boundary layer, concentrated with urban aerosols. Large, continuous rainfall events quickly deplete the atmospheric reservoir of these particulates, leading to a highly diluted, cleaner chemistry in subsequent rain events.

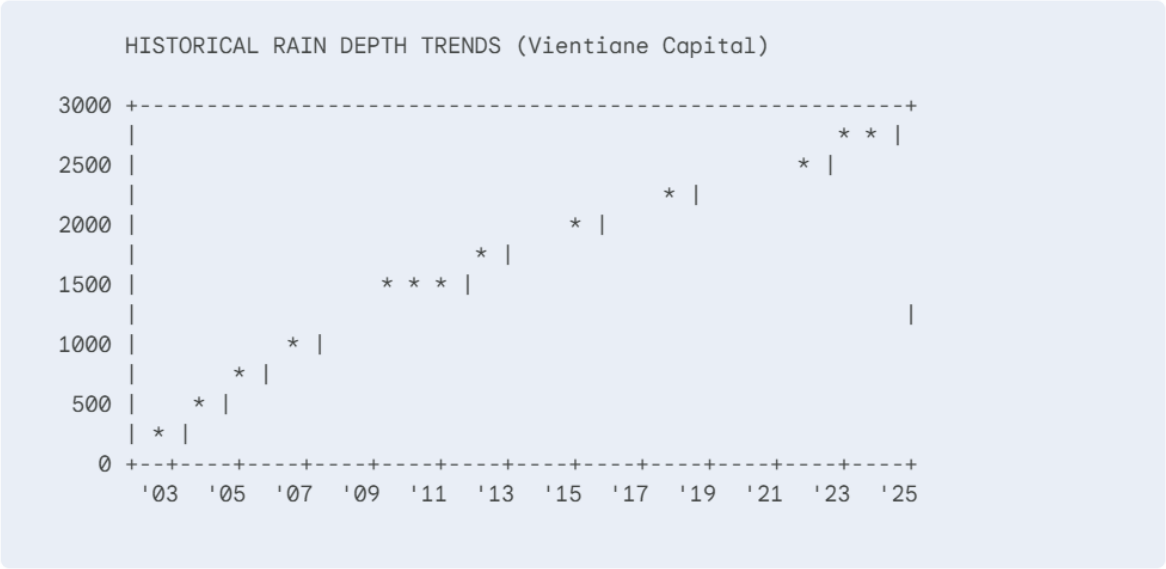


Figure 2.1. Historical rain depth trends (Vientiane Capital)

The investigation data (see, Table 2.1, and Figure 2.2 – 2.3) were clarified the clean, unpolluted water in equilibrium with atmospheric carbon dioxide (CO_2) possesses a theoretical pH of 5.6. Any precipitation value below this threshold is classified as acid rain.

The annual mean pH values were of the range 5.48 – 7.41 (23 years observation), and 5.75 – 7.41 (6 years, 2020 – 2025). The mean pH values were 6.35 ± 0.52 (well within the alkaline-buffered range). The minimum pH = 5.48 was observed in 2009, this is only monitored year where the annual mean slipped below 5.6 acid threshold, signaling, episodic acid precipitation events. The maximum annual average precipitation pH = 7.41 was observed in 2021, approaching a weakly alkaline state. There was no clear trend in the time series.

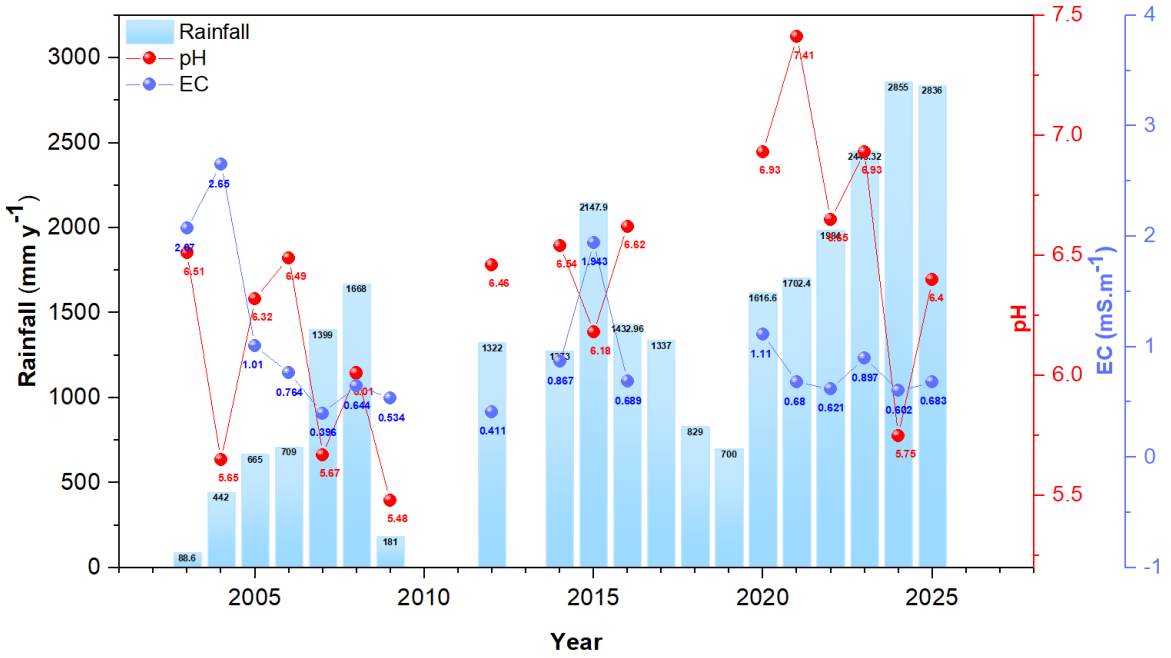


Figure 2.2. Annual variation of rainfall amount, pH and EC in Vientiane.

Acidity, Neutralization Dynamics, and the pH Profile:

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                        pH DISTRIBUTION

                [Acidic Rain]   |  [Naturally Buffered Rain]
                     < 5.6      |           >= 5.6
pH Range:       |-----------|-------------------------|
Vientiane Mean:                |         * (6.35)
Vientiane Min:  * (5.48)       |
Vientiane Max:                 |                    * (7.41)
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Figure 2.3. pH distribution

Despite regional coal combustion, biomass burning, and heavy vehicular traffic in the Mekong sub-region, Vientiane's rain does not exhibit chronic acid rain characteristics. This is explained by two primary chemical neutralization processes acting in the troposphere:

1. Crustal dust neutralization (Ca^{2+} and Mg^{2+}): Windblown Road dust, agricultural soils, and construction dust (calcite, calcium carbonate) are suspended in the local atmosphere. When rain droplets fall, they dissolve these alkaline minerals:

$$CaCO_{3(s)} + H^{+}_{(aq)} \longrightarrow Ca^{2+}_{(aq)} + HCO_3^{-}{}_{(aq)}$$

This reaction consumes free hydrogen ions (H^{+}), raising the pH. This is backed by the data: in 2021, when pH reached its peak of 7.41, we also observed a massive, corresponding spike in calcium concentrations to 18.96 µmol/L.

2. Agricultural ammonia neutralization (NH_4^+): Vientiane Capital is surrounded by extensive paddy fields and livestock farming, which release ammonia (NH_3) into the boundary layer. NH_3 is highly soluble in water droplets and acts as a powerful base:

$$NH_{3(g)} + H^+_{(aq)} \longrightarrow NH_4^+{}_{(aq)}$$

The data shows a strong negative correlation between NH_4^+ concentrations and pH (r = -0.81). When ammonium concentrations are high (e.g., 10.9 µmol/L in 2007 and 17.3 µmol/L in 2009), the acidity of the rain is rapidly neutralized, driving the free H^+ ions into bound ammonium forms, directly preventing acidification.

Ionic Fingerprint: Cations and Anions Characterization

By the data analysis in Table 2.1 to 2.2, Figure 2.2, and Figure 2.4 to 2.5 identified by Ionic Chromatography meter can certify the major chemical constituents in the rainwater can be classified by their origins: anthropogenic (combustion/urban), river (Mekong and Nam Ngum spray), and terrestrial (soils/agriculture), are following:

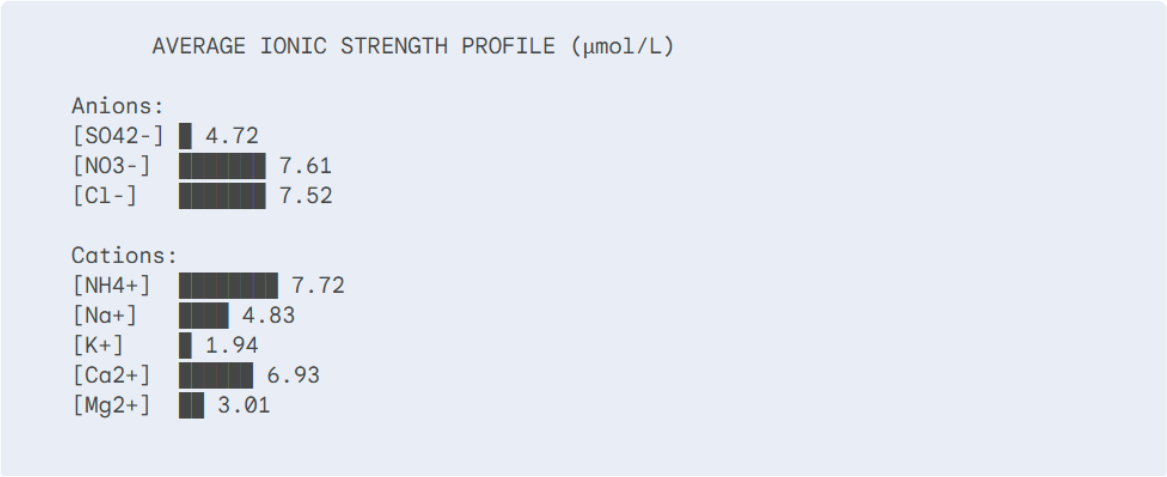


Figure 2.4. Average ionic strength profile (µmol/L)

(1) Anion chemistry (SO_4^{2-}, NO_3^-, Cl^-):

Nitrate (NO_3^-) is dominant: Averaging 7.61 µmol/L, nitrate frequently exceeds sulfate (4.72 µmol/L). Nitrate in rain originates from nitrogen oxides (NO_x) emitted by mobile sources (cars, motorbikes) and high-temperature industrial combustion. The ascendancy of nitrate over sulfate points to urban vehicular emissions as the dominant driver of atmospheric gaseous pollution in Vientiane Capital, rather than heavy sulfur-coal industrial plants.

Chloride (Cl^-): Averaging 7.52 µmol/L, Chloride is surprisingly active. While Vientiane Capital is landlocked and far from the sea, the elevated Cl^- cannot be attributed purely to sea spray (NaCl). Instead, it points to regional biomass burning (which releases significant organic chloride) and localized plastic/waste burning, a common practice in the outskirts of the capital.

(2) Cation chemistry (NH_4^+, Ca^{2+}, Na^+, Mg^{2+}, K^+):

The dominant cation duo: ammonium (NH_4^+: 7.72 µmol/L) and calcium (Ca^{2+}: 6.93 µmol/L) represent the primary cationic load, confirming that agricultural and crustal neutralizing pathways are the absolute governors of rainwater chemistry in the region.

Potassium (K^+): Averaging 1.94 µmol/L, potassium serves as an excellent tracer for biomass burning. The peak concentration of Potassium occurred in 2023 at 2.79 µmol/L, coinciding with intense regional agricultural residue burning and dry-season transboundary haze.

Table 2.2 The annual mean concentrations of anion and cation in Vientiane.

Year	SO_4^{2-} µmol.L^{-1}	NO_3^- µmol.L^{-1}	Cl^- µmol.L^{-1}	NH_4^+ µmol.L^{-1}	Na^+ µmol.L^{-1}	K^+ µmol.L^{-1}	Ca^{2+} µmol.L^{-1}	Mg^{2+} µmol.L^{-1}
2002								
2003	***	***	***	***	***	***	***	***
2004	***	***	***	***	***	***	***	***
2005	***	***	***	***	***	***	***	***
2006	(3.46)	(6.94)	(4.77)	(7.72)	(7.10)	(3.51)	(8.75)	(3.49)
2007	4.67	6.90	7.42	10.9	2.38	1.69	3.04	0.70
2008	5.06	5.96	7.41	8.39	2.91	1.69	5.77	1.31
2009	(4.05)	(9.73)	(6.19)	(17.3)	(9.14)	(0.93)	(5.50)	(0.72)
2010	***	***	***	***	***	***	***	***
2011	***	***	***	***	***	***	***	***
2012	(2.41)	(5.55)	(4.46)	***	***	***	***	***
2013	***	***	***	***	***	***	***	***
2014	***	***	***	***	***	***	***	***
2015	3.19	4.12	4.97	7.78	2.78	1.74	4.00	0.61
2016	(3.66)	(4.07)	(5.28)	(7.50)	(1.52)	(0.96)	(2.21)	(<0.3)
2017	*	*	*	*	*	*	*	*
2018	*	*	*	*	*	*	*	*
2019	*	*	*	*	*	*	*	*
2020	*	*	*	*	*	*	*	*
2021	6.99	4.38	12.98	0.28	6.33	2.16	18.96	1.69
2022	5.26	13.01	12.35	0.87	5.43	2.02	11.69	0.00
2023	5.75	11.95	6.40	8.73	5.84	2.79	2.45	18.43
2024	4.06	7.47	6.22	*	*	*	*	*
2025	8.10	11.29	11.79	*	*	*	*	*

***: No data or no measurement, *: The constituent was rejected or not measured although precipitation was not 0 mm., (): %PCL≤80% and/or %TP≤80%

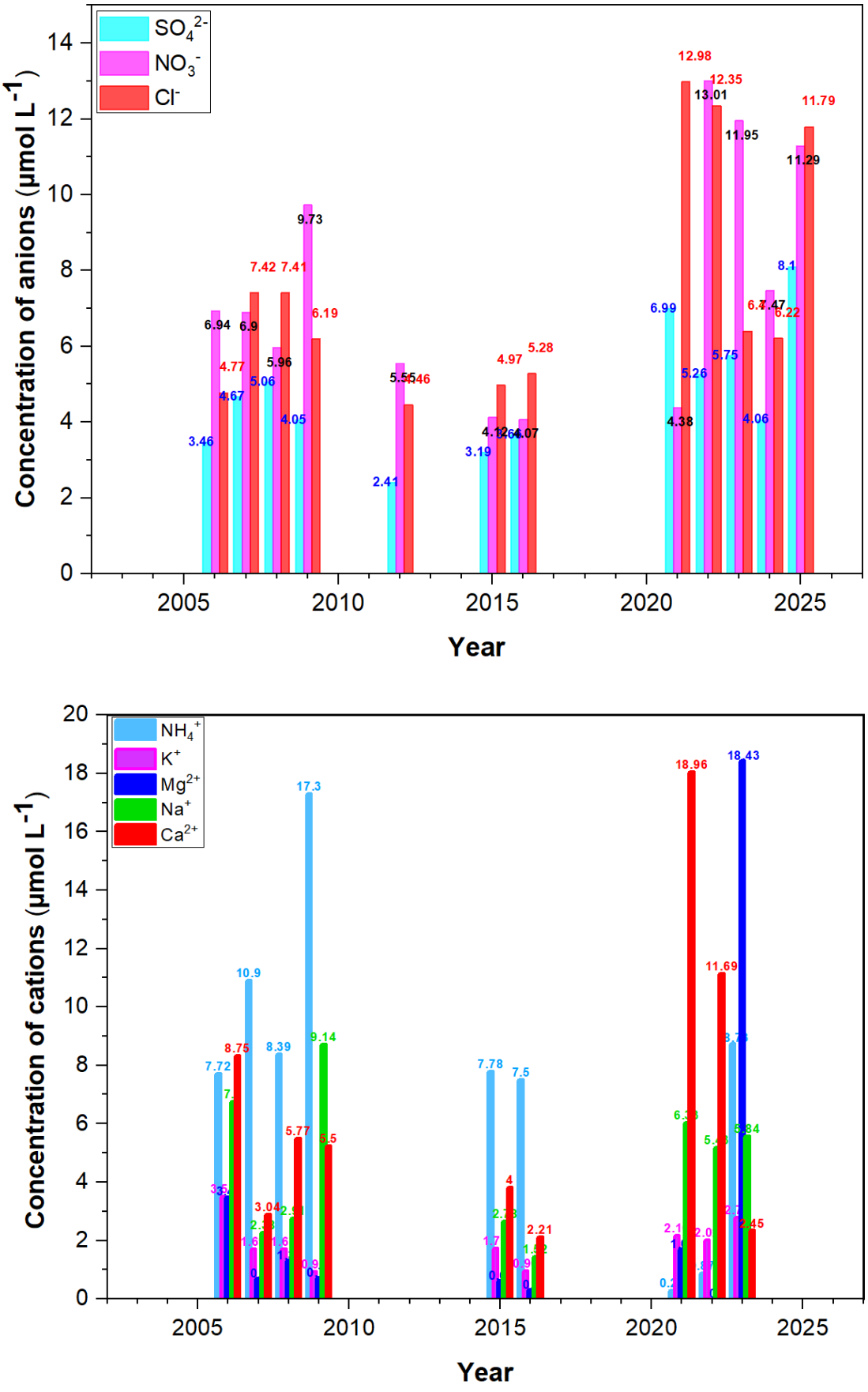


Figure 2.5. The values concentration of anions and cations during 2002 to 2025

Moreover, the precipitation acidity is ususally evaluated by the concentration diffrences between sum of non-seaslt anions (nss-SO_4^{2-}+NO_3^-) and sum of non-seasalt cations (nss-Ca^{2+}+NH_4^+) dissolved in rainwater. In the case in Vientian Capital, as the result calculated by using high quality data only, sum of non-seasalt cation concentration were usually higher than that of anion concentration. Therefore, it was considered that environmental acidification by precipitation was not significant at least in the monitoring period (see, Table 2.2 and Figure 2.4 to 2.5.).

The rain chemistry in Vientiane Capital presents a healthy, naturally buffered ecological status. The city is currently spared from the devastating impacts of acid rain (which damages forestry, leaches nutrients from soils, and corrodes concrete infrastructure) due to two lucky environmental shields: local alkaline soils and agricultural ammonia.

However, we must monitor the following trends closely:

(1) Rise in nitrate (NO_3^-): The high concentration of nitrates indicates that mobile source emissions (vehicles) are growing rapidly. If neutralizing agents (Ca^{2+} dust and agricultural NH_3) drop in the future due to paving over roads and shifting away from open-field farming, Vientiane Capital could quickly lose its alkaline buffer and transition into an acid-rain regime.

(2) Chloride (Cl^-) and potassium (K^+) spikes: The steady presence of these ions confirms that regional biomass burning and municipal solid waste combustion are actively contaminating the local air shed.

(3) Data quality control (QC): It is highly recommended that the monitoring agency addresses the data logging process. The appearance of negative ionic concentrations in official reporting represents a critical formatting error that should be resolved by enforcing strict instrumental detection limits (< LOD) rather than raw mathematical values.

2.1.2. State of dry deposition

Atmospheric dry deposition represents a vital pathway for the removal of gaseous and particulate pollutants from the atmosphere, directly influencing soil chemistry, vegetation health, and aquatic ecosystems in Vientiane Capital, Lao PDR. Under the auspices of the Acid Deposition Monitoring Network in East Asia (EANET), the dry deposition monitoring station in Vientiane Capital (co-located with the wet deposition site) was designed to establish a critical baseline for atmospheric load in the region at the end of 2009 and started collecting sample and analyses in 2010.

Therefore, this report provides an analysis of the gaseous and particulate dry deposition data successfully captured during the 2016 monitoring campaign. It details the seasonal behavior of acidic and alkaline precursors, examines the stoichiometric relationships between anions and cations in particulate matter, and analyzes the mechanical and chemical pathways that define dry deposition in Vientiane Capital's tropical monsoon environment. Furthermore, this document recounts the operational history of the monitoring program, documenting the technical challenges associated with the Ion Chromatography (IC) systems from 2010 to 2014, the post-2016 human resource constraints, and the ongoing initiatives to modernize laboratory systems and train a new generation of technical staff.

The Center has recently initiated a comprehensive recovery and stabilization program:

(1) New operational work team: A newly formed technical team has been assigned specifically to manage the dry deposition filter pack sampling network.

(2) Technical capacity-building: The new team is undergoing structured training on EANET standard operating procedures for filter pack preparation, sampling rates, sample extraction, and contamination prevention.

(3) IC system modernization: The Center is actively upgrading the Ion Chromatography system with new columns, new suppressors both anion and cation and advanced software. However, with unlucky we had ordered the new suppressors both anion and cation, including chemicals and standard solutions. When the shipping sends all items passes Thailand, we have a problem for Immigration tax afterward all items were sent back to the country of company.

(4) Expert mission: The Center requires technical assistance from EANET and ACAP experts to resolve an ongoing issue with our Ion Chromatography (IC) system. Specifically, we need guidance on troubleshooting and correcting the auto-sampling functionality, which is currently failing to operate.

Therefore, by the investigation dry deposition data (see, Table 2.3 and Figure 2.6) certified of gaseous atmospheric pollutants (SO_2, HNO_3, HCl, and NH_3) observed at the Vientiane Capital monitoring station during 2016. The values demonstrate a pronounced seasonal signal driven by the tropical monsoon cycle (dry season: November to April; wet season: May to October).

Table 2.3 The mean concentrations of Gas and Particle for 2016

in Vientiane Capital monitoring station

	Gas (ppb)				Particle (μg m^{-3})							
	SO_2	HNO_3	HCl	NH_3	SO_4^{2-}	NO_3^-	Cl^-	NH_4^+	Na^+	K^+	Mg^{2+}	Ca^{2+}
Jan	0.5	<0.1	0.4	3.2	5.73	0.38	0.02	1.57	0.31	0.83	0.06	0.31
Feb	0.6	0.3	0.3	3.7	5.20	0.65	0.03	1.58	0.22	0.78	0.08	0.23
Mar	0.5	0.6	0.4	3.8	6.30	0.51	0.05	1.90	0.51	0.70	0.09	0.28
Apr	0.4	0.4	0.4	3.3	3.85	0.12	0.06	1.21	0.17	0.40	0.03	0.14
May	0.4	0.2	0.3	2.3	3.19	0.83	0.07	0.77	0.27	0.16	0.06	0.18
Jun	0.6	0.1	0.2	2.6	1.06	0.47	0.18	0.29	0.21	0.11	0.03	0.28
Jul	0.2	0.2	0.1	1.8	1.90	0.58	0.07	0.58	0.25	0.08	0.05	0.31
Aug	0.2	0.1	0.1	2.0	1.92	0.43	0.08	0.55	0.24	0.10	0.04	0.22
Sep	0.3	0.2	0.1	1.9	1.05	0.27	0.07	0.38	0.10	0.16	0.02	0.10
Oct	0.2	0.1	0.2	2.1	3.42	0.11	0.01	1.18	0.22	0.18	0.03	0.13
Nov	0.5	0.3	0.3	2.9	4.50	0.28	0.02	1.42	0.27	0.43	0.04	0.15
Dec	0.2	0.2	0.2	2.6	7.13	0.22	0.03	1.99	0.24	0.33	0.05	0.31
Annual	0.4	0.2	0.2	2.7	3.77	0.40	0.06	1.12	0.25	0.36	0.05	0.22

Gaseous Phase Analysis

(1) Ammonia (NH_3) dominance: The most striking feature of the gas-phase chemistry is the overwhelming dominance of ammonia (NH_3), which exhibits an annual average of 2.7 ppb—nearly an order of magnitude higher than all other gaseous species combined. This indicates

a heavily neutralized atmospheric boundary layer. The peak concentrations of NH_3 occur during the dry season, specifically from January to April (3.2 to 3.8 ppb). This seasonality is attributed to:

- Agricultural activities: High agricultural fertilizer application and livestock emissions in the rural periphery of Vientiane Capital.
- Biomass burning: Widespread open-field burning and slash-and-burn practices common in northern and central Laos during the dry transition (February–April).
- Meteorological inversions: Low boundary layer heights and minimal wet scavenging during the dry winter months, trapping ground-level emissions.

(2) Sulfur dioxide (SO_2) and acidic precursors: The concentration of SO_2 remains low throughout the year, averaging 0.4 ppb (with a peak of 0.6 ppb in February and June). This reflects the lack of heavy coal-fired industrial development in the immediate vicinity of Vientiane Capital compared to other regional capitals. The HNO_3 and HCl concentrations are similarly low, averaging 0.2 ppb each. Nitric acid (HNO_3) peaks in March (0.6 ppb), matching the period of high photochemistry and local biomass combustion, which generates NOx precursors that subsequently oxidize into HNO_3.

(3) Particulate matter ionic chemistry: Anion and cation profiles: Particulate-phase dry deposition species extracted from the filter pack systems are summarized in Table 2.3, and Figure 2.6. These water-soluble inorganic ions (SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Mg^{2+}, and Ca^{2+}) represent the fine and coarse aerosol fractions.

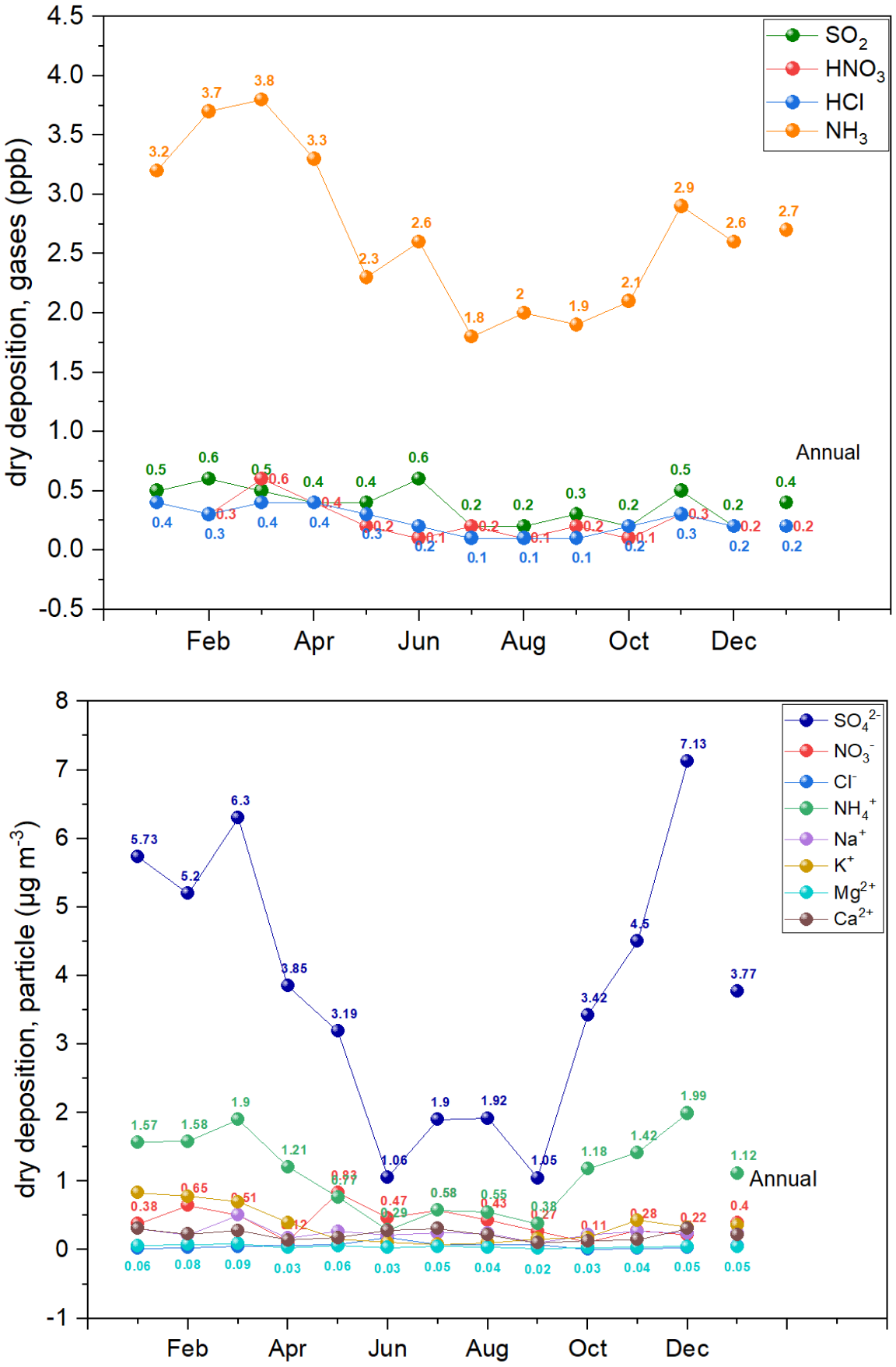


Figure 2.6. Technically seasonal atmospheric components (dry deposition) in Vientiane, 2016

Stoichiometry and Ionic Relationships

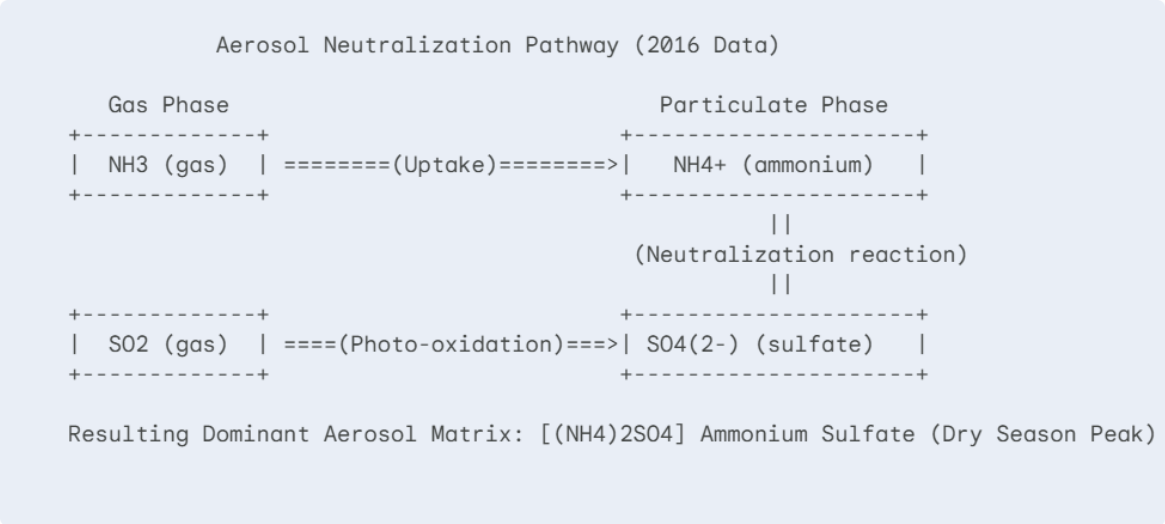


Figure 2.7. Aerosol neutralization pathway (2016 data)

(1) Sulfate (SO_4^{2-}) and ammonium (NH_4^+) Association: Particulate sulfate (SO_4^{2-}) is the single largest ionic component of the aerosol mass, with an annual average of 3.77 µg m^{-3}. It is followed by ammonium (NH_4^+) at 1.12 µg m^{-3}. The ratio of NH_4^+ to SO_4^{2-} equivalents is approximately 0.79. This implies that while there is an abundance of gaseous ammonia (NH_3) to act as a neutralizing agent, the particulate phase consists of a mixture of highly stable ammonium sulfate ($(NH_4)_2SO_4$) and ammonium bisulfate (NH_4HSO_4). The persistent presence of these compounds, especially in the dry winter months (December: 7.13 µg m^{-3} SO_4^{2-}, 1.99 µg m^{-3} NH_4^+), reflects transboundary accumulation and regional fine particulate transport rather than purely local primary emissions.

(2) Biomass burning tracer (potassium, K^+): Particulate potassium (K^+) is a widely recognized tracer for biomass burning. Its seasonal profile in Vientiane is highly pronounced:

- Dry/burning season (November–March): K^+ ranges between 0.43 µg m^{-3} and 0.83 µg m^{-3}.
- Wet/monsoon season (June–August): K^+ drops precipitously to 0.08 - 0.11 µg m^{-3}. This sharp variation confirms that active agricultural residues, forest fires, and charcoal combustion during the dry season are major drivers of Vientiane's ambient air quality. This activity also drives up secondary organic aerosols and fine particulate concentrations.

(3) Crustal and marine contributions (Ca^{2+}, Mg^{2+}, Na^+, Cl^-): * Calcium (Ca^{2+}): Exhibits an annual average of 0.22 µg m^{-3}. Unlike agricultural indicators, calcium remains relatively steady throughout the year (fluctuating between 0.10 and 0.31 µg m^{-3}). This is a result of mechanical resuspension of road dust and construction dust, which are consistent urban activities in Vientiane Capital.

- Sodium (Na^+) and chloride (Cl^-): These marine tracers are low, confirming Vientiane Capital's continental inland location. The annual mean of Cl^- is only 0.06 µg m^{-3}

interestingly, Cl^- spikes slightly during the wet summer monsoon (June: 0.18 µg m^{-3}), which is consistent with the landward transport of marine air masses from the Gulf of Tonkin or the Andaman Sea.

Gaseous vs. Particulate Dry Deposition Pathways: Seasonality

The physical dry deposition flux is a function of ambient concentration (*C)* and the deposition velocity (V_d), which varies based on the physical state of the chemical species (gases vs. particles).

During the dry season (November–April)**,** the combination of elevated ambient concentrations (due to open burning, low planetary boundary layer heights, and dry air) and dry, high-surface-roughness canopies creates a highly efficient dry deposition regime.

Conversely, during the wet season (May–October)**,** atmospheric dry deposition velocities are significantly lower because:

- Wet scavenging (rainout and washout): Soluble gases like NH_3 and particulates like SO_4^{2-} are rapidly scavenged by precipitation. This shifts the dominant deposition pathway from dry to wet deposition (as reflected in the corresponding wet deposition rainwater data).
- Relative humidity effects: High relative humidity causes hygroscopic growth of aerosols, altering their size distribution and increasing their gravitational settling velocity close to sources, while limiting far-field transport.

Table 2.4 Seasonal variation of $PM_{2.5}$ concentration in Vientian Capital (µg m^{-3})

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2018	***	***	***	***	***	***	***	***	***	***	30	32	31
2019	44	55	80	44	22	13	12	9	23	25	30	44	32
2020	***	***	***	***	***	***	***	***	14.06	19.42	29.45	36.82	24.94
2021	50.77	44.12	54.41	32.08	19.26	11.43	11.22	13.24	10.72	17.56	26.42	39.94	27.60
2022	41.00	38.11	41.96	38.11	41.96	37.11	17.50	12.55	11.25	12.28	21.66	36.39	26.98
2023	47.70	50.45	66.51	***	***	***	***	15.42	12.61	22.70	31.76	39.822	36.87
2024	30.12	41.51	***	***	***	***	***	***	***	***	***	***	35.82
2025	106.03[s]	61.8[s]	89.36[s]	55.03[s]	26.12[s]	20.20[s]	14.84[s]	20.41[s]	17.43[s]	24.57[s]	38.31[s]	52.66[s]	43.90

***: No data or no measurement, *: The constituent was rejected or not measured although precipitation was not 0 mm, [s]: local IES-200 air quality monitor sensor (Koala).

By the investigation of fine particulate matter ($PM_{2.5}$) and atmospheric deposition dynamics (see, Table 2.4, and Figure 2.7) has been started in 2018 in Vientiane Capital. Utilizing long-term monitoring data from the local EANET station in Lao PDR, we examine the seasonal behavior of $PM_{2.5}$ from 2018 to 2025. By the beginging of 2024, air quality monitoring station was errored, and we are rere fund for maintenance. Parallelly this, the monitoring station experienced recurrent electrical instability attributed to insufficient UPS capacity and elevated humidity levels, which led to subsequent data loss. Consequently, the 2025 $PM_{2.5}$ dataset was investigated and supplemented using a localized IES-200 air quality monitoring sensor (Koala). Annual mean concentration in 2019 was 32 µg m^{-3} in Vientiane Capital with seasonal variation in which high and low concentrations were observed from the end of year to March and in summertime (from June to August). In 2025,

the annual mean $PM_{2.5}$ concentration was 43.90 µg m^{-3}, with a peak maximum concentration of 106.03 µg m^{-3} recorded in January.

Moreover, the monitoring reveals a highly predictable, severe seasonal pattern: Vientiane experiences a prolonged "smog season" from November to April, culminating in hazardous spikes during March. Chemical tracer analysis identifies agricultural biomass burning, forest fires, and secondary inorganic aerosol formation (driven by high ammonia emissions reacting with combustion-derived oxides) as the dominant sources of this pollution. During the wet season (May to October), intense monsoon precipitation acts as a vital environmental cleanser, scavenging suspended particles and reducing ambient concentrations by up to 85% relative to dry season peaks.

```
VIENTIANE SEASONAL AIR QUALITY MANAGEMENT

   DRY SEASON (Nov - Apr)                WET SEASON (May - Oct)
==============================        ============================
[ Agriculture & Biomass Burning ]     [ Monsoon Rain Washout ]
                |                                 |
                ▼                                 ▼
• Establish Open Burning Ban          • Atmospheric Self-Cleaning
• Deploy Low-Cost Sensor Grid         • Vehicle Fleet Maintenance
• Thermal Inversion Alerts            • Soil/Runoff Monitoring
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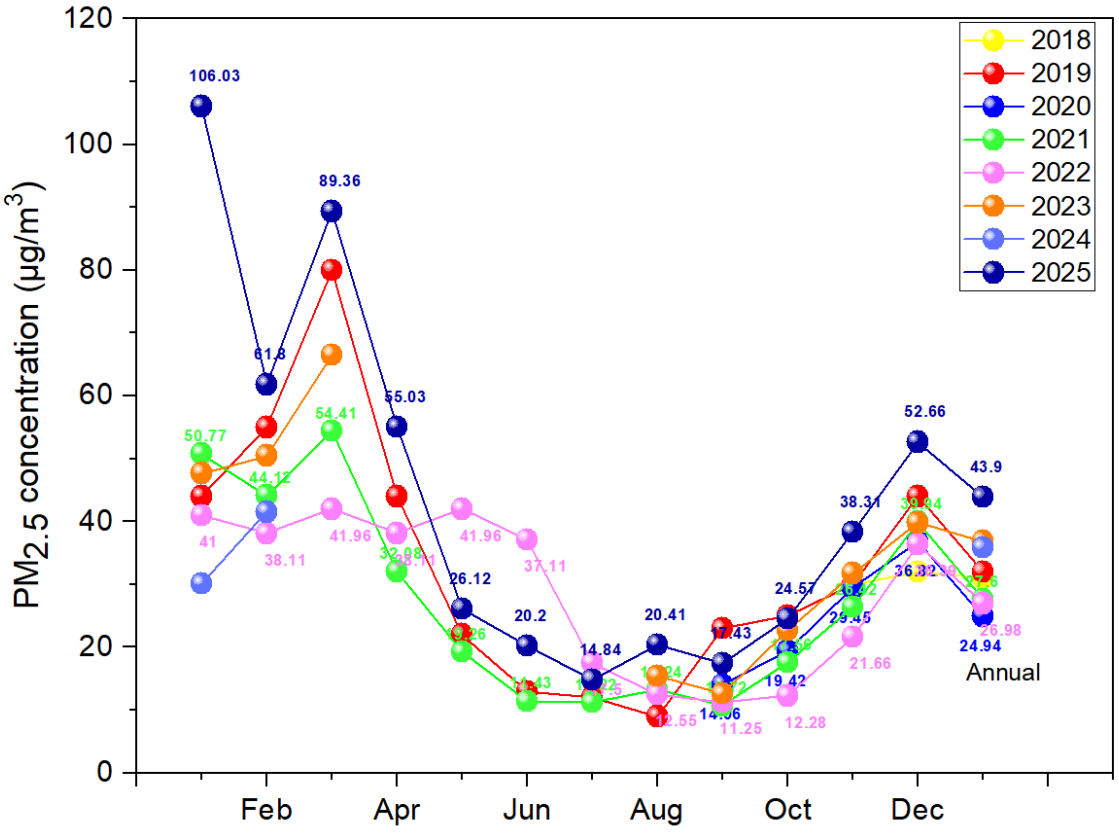


Figure 2.7. Annual variation of $PM_{2.5}$ concentration in Vientian Capital (2018 to 2025)

(1) The dry season atmospheric trap (November to April): during the cool dry season (November to February), Vientiane Capital's atmospheric boundary layer shrinks significantly due to reduced solar radiation and nighttime radiation cooling. This leads to frequent temperature inversions, trapping localized vehicular emissions, dust, and domestic cooking smoke close to the surface.

(2) The March flare-up (the peak of the haze): every year, March stands out as the most polluted month, with concentrations peaking at 80.00 μg m^{-3} in 2019 and 89.36 μg m^{-3} in 2025. This spike is driven by a critical transition in regional activities:

- Agricultural residue burning: farmers clear rice straw and prepare crop fields for the upcoming monsoon planting cycle.
- Transboundary haze: high-temperature agricultural burning and forest fires across the Mekong basin (including neighboring Northern Thailand, Myanmar, and Western Vietnam) release massive plumes of fine smoke. Regional wind patterns transport these air masses into the low-lying Vientiane plain, where they accumulate.
- Low wind speeds and high temperatures: pre-monsoon weather in March is characterized by stagnant air and high ambient temperatures, which accelerate secondary photochemical reactions in the air, creating a dense chemical smog.

(3) The wet season cleansing (May to October): by June and July, the prevailing southwest monsoon brings consistent, heavy precipitation. Ambient $PM_{2.5}$ drops to its annual minimums, routinely hovering between 9.00 and 15.00 μg m^{-3}. These concentrations easily satisfy the historical national standard and align closely with the World Health Organization's (WHO) updated annual guideline of 5.00 μg m^{-3}.

2.2. State of inland aquatic environment



Figure 2.8. View of Nam Hum Lake monitoring site.

Following initial candidate site surveys in 2005 and baseline data analysis in 2009, Nam Hum Lake in Vientiane Capital was designated as Lao PDR's monitoring site for inland aquatic environments. Although sample collection and analysis under the EANET manual began in 2010, data collection was disrupted between 2010 and 2013 due to poor deionized water quality and Ion Chromatography System malfunctions.

Table 2.5 Result of annual inland aquatic environmental monitoring in Nam Hum Lake

	Unit	2019	2020	2021	2022	2023	2024	2025
Transparency	*m*	0.6	***	***	0.4	0.5	0.6	0.5
Temp	*°C*	28.4	***	***	28.29	28.50	26.65	27.15
pH	-	8.05	***	***	7.69	7.44	6.41	7.37
EC	*µS/cm*	3.37	***	***	3.54	38.96	34	42.4
DO	*mg/L*	8.7	***	***	6.5	8.04	7.57	6.7
COD	*mg/L*	19.4	***	***	14.89	26.29	17.61	3.08
Alk	*meq/L*	0.34	***	***	0.35	0.98	0.74	0.54
SO_4^{2-}	*mg/L*	3.65	***	***	1.17	0.52	1.6	0.78
NO_3^-	*mg/L*	0.01	***	***	0.87	0.23	0.16	0.39
Cl^-	*mg/L*	0.40	***	***	0.86	1.01	1.92	1.34
NO_2^-	*mg/L*	0	***	***	0	0	1.25	0.005
PO_4^{3-}	*mg/L*	0.01	***	***	0.01	0.01	0.001	0.0005
NH_4^+	*mg/L*	***	***	***	0.01	0.02	0.04	0.025
Na	*mg/L*	***	***	***	2.37	0.71	5.04	2.16
K	*mg/L*	***	***	***	1.21	1.78	1.73	2.09
Ca	*mg/L*	***	***	***	4.38	7.32	8.26	10.36
Mg	*mg/L*	***	***	***	2.12	1.12	1.11	1.36
Mn	*mg/L*	***	***	***	***	***	0	0.31
Fe	*mg/L*	***	***	***	***	***	0	0.1
T-N	*mg/L*	***	***	***	***	***	2.27	3.35
T-P	*mg/L*	***	***	***	***	***	0.02	0.04

***: No data or no measurement, *: The constituent was rejected or not measured although precipitation was not 0 mm., (): %PCL≤80% and/or %TP≤80%

This report provides a comprehensive diagnostic analysis of Nam Hum Lake's water quality trends over a six-year period (2019 to 2024). By evaluating physical, chemical, and organic parameters, we characterize the shifting baseline of this vital freshwater resource.

The analysis reveals two critical trends: gradual basin acidification, with pH declining from 8.05 to 6.41, and a ten-fold expansion in electrical conductivity (EC) starting in 2023 (see, Table 2.5, and Figure 2.9 to 2.10). By cross-referencing regional atmospheric data—specifically rain chemistry and $PM_{2.5}$ concentrations—we establish a highly probable link between these aquatic shifts, seasonal atmospheric deposition, and localized agricultural or urban runoff.

To ensure a rigorous interpretation, it is crucial to clarify the structural changes in the monitoring schedule over the observation window:

- Active monitoring years (2019, 2022, 2023, 2024): * From 2019 to 2023, sampling was conducted four times annually to capture seasonal variations (Winter, Transition, Wet, and Dry seasons).
    - In 2024, the protocol was streamlined to two key seasonal samplings targeting the extremes: the peak dry season and the peak wet season.
    - The values reported in this assessment represent the annual arithmetic means of these seasonal runs to smooth out short-term meteorological anomalies.
- Data gaps (2020 – 2021): No field data was recorded during these two years. This gap coincides with the COVID-19 pandemic, during which regional lockdowns and field resource constraints temporarily suspended routine aquatic monitoring programs.

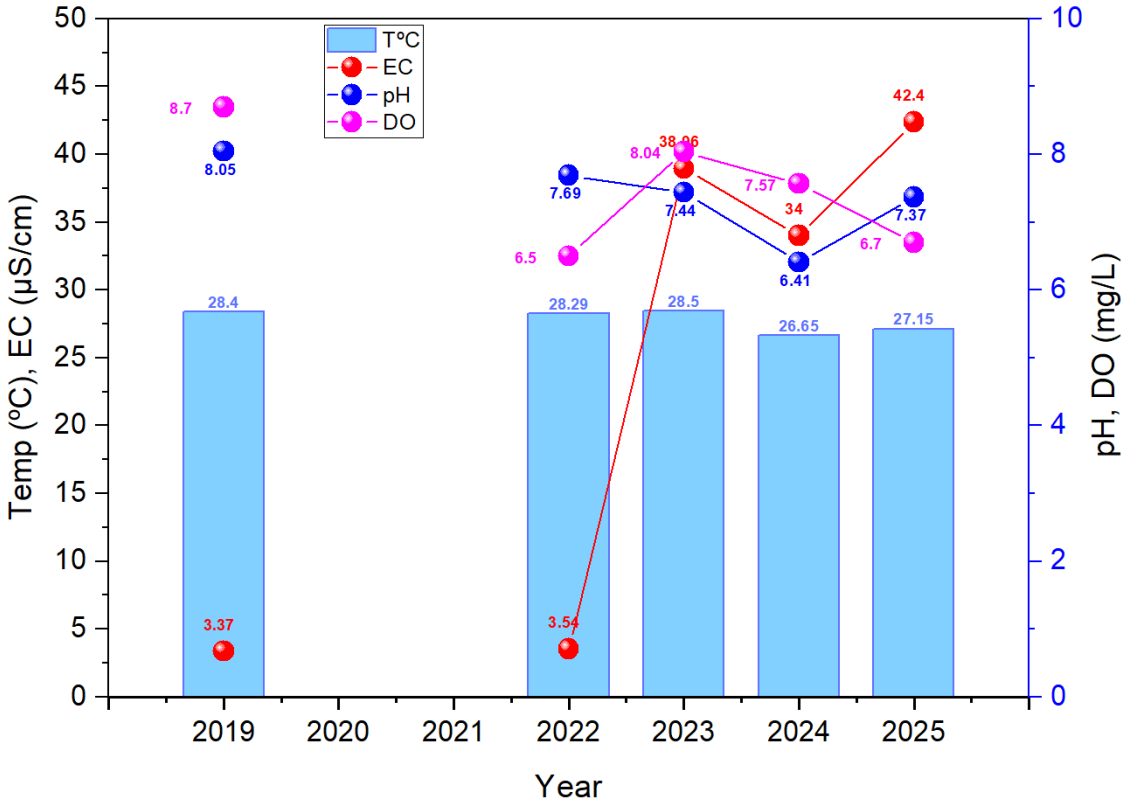


Figure 2.8. Result of annual physical parameters for inland aquatic of Nam Hum Lake

The Acidification Signal (pH Trends)

Perhaps the most striking trend in Nam Hum Lake is the steady decline in pH:

pH 8.05 (2019) ⟶ pH 7.69 (2022) ⟶ pH 7.44 (2023) ⟶ pH 6.41 (2024)

Nam Hum Lake has shifted from a weakly alkaline/buffered system to a slightly acidic one. This acidification can be explained by two compounding factors:

(1) Atmospheric deposition (acid rain): Long-term regional rainfall monitoring in Vientiane consistently exhibits a sub-neutral pH baseline. Historically, rainfall events record pH values ranging between 5.48 and 6.01 (highly influenced by dissolved gaseous SO_2 and HNO_3). The cumulative impact of acidic rainfall directly reduces the buffering capacity of relatively shallow, low-alkalinity inland water bodies like Nam Hum.

(2) Organic matter decomposition: The elevated chemical oxygen demand (COD) indicates a steady input of oxidizable organic compounds. The microbial breakdown of this organic material releases carbon dioxide (CO_2), which dissolves to form weak carbonic acid, further pulling the pH downward.

The Conductivity Surge (EC) and Dissolved Minerals

Electrical Conductivity (EC), which measures the water's ability to conduct electricity via dissolved ions, remained extremely low and stable during the initial baseline years:

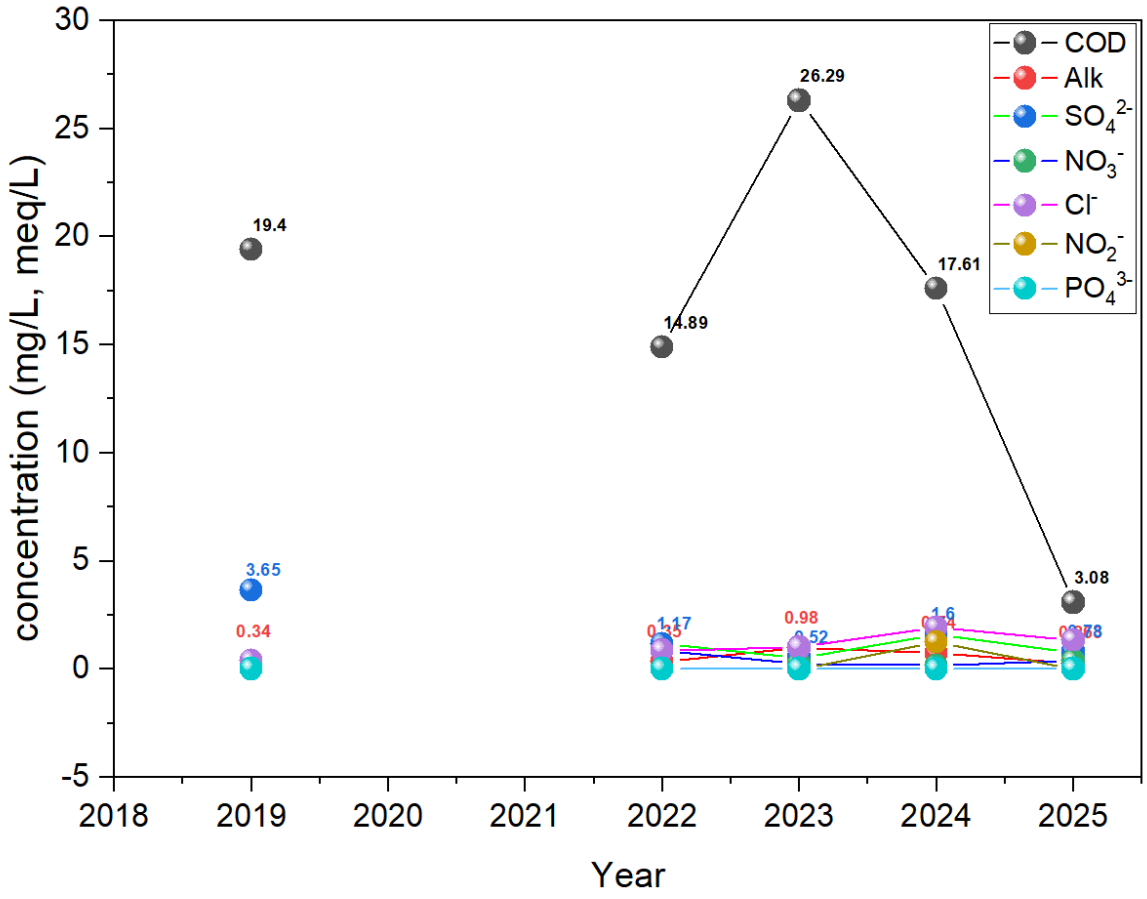
2019: 3.37 *µS/cm* vs. 2022: 3.54 *µS/cm*

However, in 2023 and 2024, EC surged by an order of magnitude, stabilizing at 38.96 and 34.00 µS/cm, respectively.

- Erosion and runoff: This surge points directly to a major influx of dissolved inorganic ions. Looking at the mineral breakdown between 2022 and 2023, we see calcium (Ca^{2+}) increasing from 4.38 mg/L to 7.32 mg/L**,** and potassium (K^+) climbing from 1.21 mg/L to 1.78 mg/L.
- The Anthropogenic connection: The increase in potassium, combined with elevated nitrate (NO_3^-) post-2022, strongly implies that agricultural fertilizer runoff (commonly containing N-P-K complexes) has breached the lake's buffer zones.

Organic Loading and Oxygen Dynamics (COD and DO)

- Dissolved oxygen (DO): DO levels remain highly reassuring, hovering between 6.50 mg/L (2022) and 8.04 mg/L (2023). These concentrations are well within healthy thresholds for warm-water tropical fisheries and aquatic biota, suggesting that Nam Hum Lake has a high physical aeration rate, likely driven by wind-induced mixing and seasonal inflows.
- Chemical oxygen demand (COD): COD peaks in 2023 at 26.29 mg/L before retreating to 17.61 mg/L in 2024. A COD range of 15–26 mg/L indicates a mild-to-moderate organic loading. Because phosphorus remains exceptionally low and stable ($PO4^{3-} \approx 0.01$ mg/L), the lake is currently protected from runaway run away algal blooms (eutrophication), but the organic organic baseline must be carefully watched.



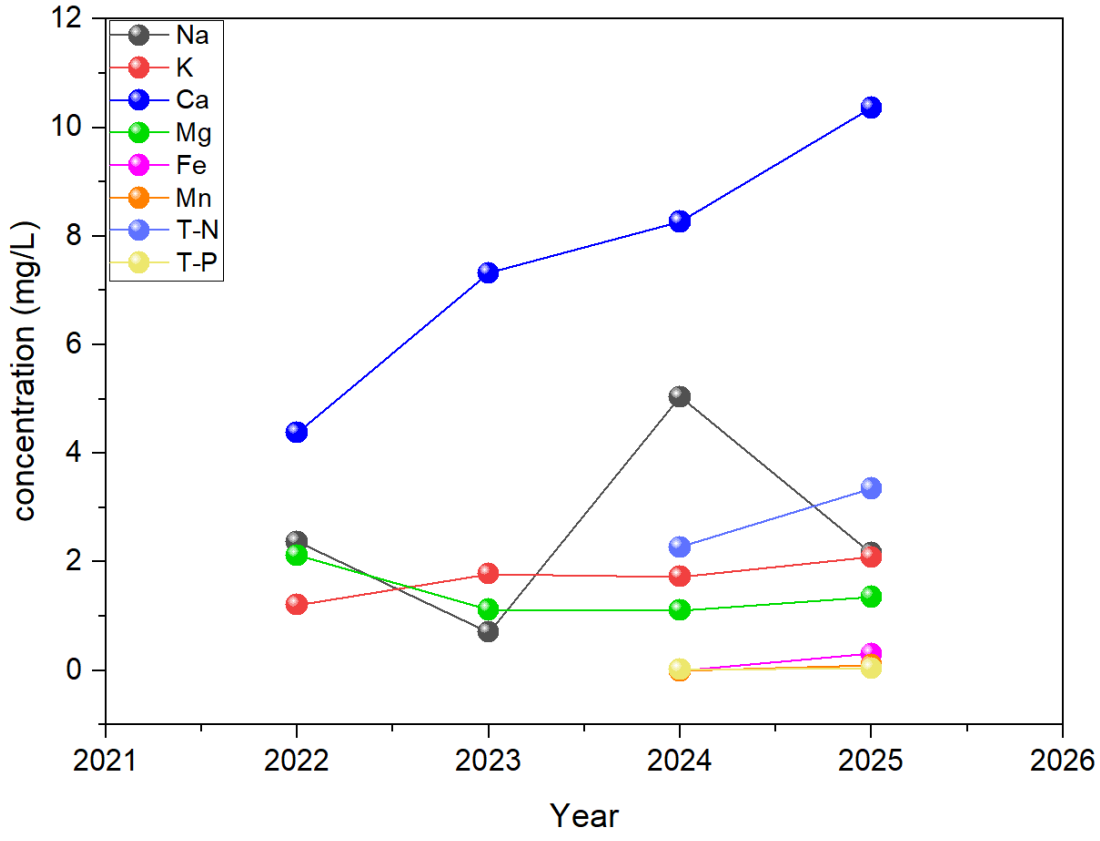
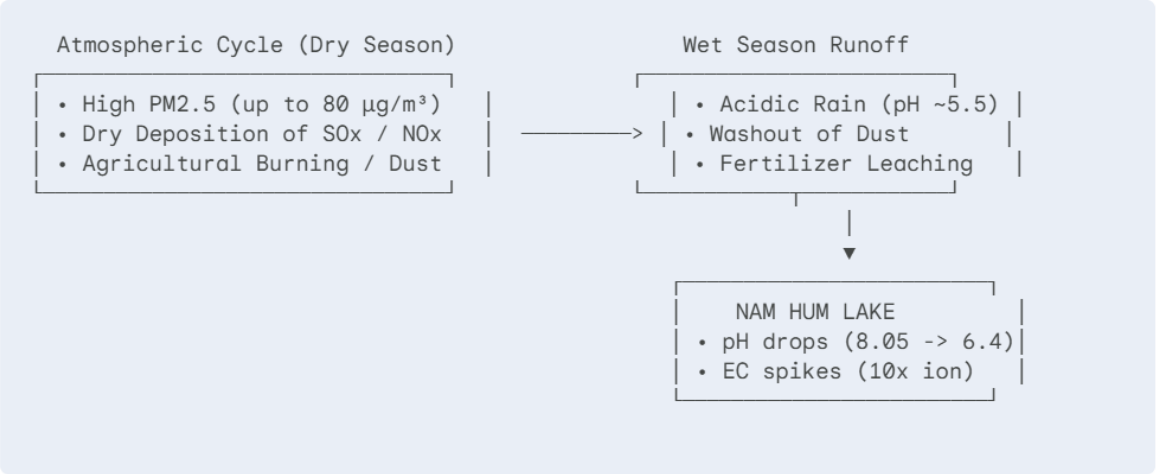


Figure 2.9. Result of annual chemical parameters for inland aquatic of Nam Hum Lake

By the regional particulate and meteorological files paint a clear picture of seasonal transport:



(1) Seasonal $PM_{2.5}$ deposition: Regional air quality data shows severe seasonal spike patterns. During dry winter and pre-monsoon months (January–March), Vientiane's $PM_{2.5}$ averages routinely exceed 45–80 µg m^{-3}, heavily loaded with dry-deposited particles rich in sulfate, nitrate, ammonium, and calcium.

(2) The monsoon "Flush" effect: Throughout the prolonged dry months, these dry-deposition particulates settle on the lake's catchment basin. When the heavy rainy season starts, the initial precipitation (which is inherently acidic) flushes this highly concentrated chemical crust directly into Nam Hum Lake. This explains why, despite receiving massive volumes of diluting rainwater, the lake's electrical conductivity and mineral ions actually spiked dramatically in the latter years.

2.3. State of soil and vegetation

Lao PDR has not yet decided for soil and vegetation monitoring activities at this time due to constraints for instruments and capacity building. However, the national center will consider conducting soil and vegetation monitoring in the future.

3. Air Quality Management

3.1. Legislation and Mandate

There is no specific air pollution control act or law that provides a legal framework for air quality management in the country. Article 27 of the Lao PDR's Constitution (2013) has a provision for Lao National Environmental Standard as the basis for the environmental monitoring and pollution control on water, soil, air and noise. "all organizations and citizens must protect the environment and the natural resources: land, underground, forests, fauna, water sources and the atmosphere"

In addition to the Constitution, the Environmental Protection Law (EPL) 2013 is the main environmental legislation relevant to Lao PDR at the national level. The EPL mandates the Ministry of Natural Resources and Environment (MONRE, presently is MAE) responsible for environmental protection. Nevertheless, MAE and MPWT still have the decree and implemented some programs below to protect environment:

- Decree on the National Environmental Standard No. 2734/PMO.WREA dated 7 December 2009
- Decree on The Vehicles Technical Standard and Vehicles Accessory, Permit, import to register in Lao PDR No. 4312/MPWT dated 11 November 2002
- Decree on The Protection and Vehicles Facilitation No. 12302/ MPWT dated 7 September 2009

3.2. Ambient Air Quality standards

Lao PDR has not adopted ambient AQ standards but monitoring results are often compared with some standards which are much more lenient than WHO guidelines (see Table 3.1).

Table 3.1 Ambient AQ standards used for comparison with monitoring results in Lao PDR Pollutant

Parameter	Lao National Environmental Standard	WHO Standard	USEPA
PM_{10}, 24-hr	0.12 mg/m^3	0.05 mg/m^3 (WHO, 2005)	0.15 mg/m^3
NO_2, 24-hr	-	-	-
NO_2, 1 Year	-	-	0.053 mg/m^3

3.3. Management of Mobile Sources

There is no specific regulation that controls the emissions of pollutants from mobile sources. The EPL also does not stipulate any specific provisions on this sector. The Transport Policy however of the Ministry of Public works and Transport (MPWT) has also set forth policy objectives and statements strongly supporting cleaner transport technology and mode shifting to more sustainable modes. The main environmental objectives of the MPWT include reduction of emissions from vehicles, reduction of noise as well as reduction of accidents. The MPWT also has adopted the following strategies (Table 3.2):

Table 3.2 MPWT transport strategies

Area	Strategy
Non-motorised transport	Promotion of non-motorised transport
	Improve safety and security
Public transport	Improve comfort
	Reduce walking distances to public transport
	Decrease travel times
	Increase service frequency
	Improve reliability and punctuality
	Provide customer information systems
	Introduce convenient fare systems

	Introduce high-capacity vehicles, where appropriate
	Integrate public transport fully with other modes
	Use cleaner fuels for public transport
	Integrate land-use and public transport planning
	Establish appropriate institutional structures for managing public transport
Private vehicle restriction measures	Provide priority for public transport in road space
	Reduce private vehicle usage through internalisation of impacts
	Introduce greater parking restrictions
	Examine potential for higher vehicle import taxation and petrol taxation

Although there is a vehicle registration system in place in Lao PDR, compliance with any emissions standards does not seem to be a legislated requirement.

Considering that the fuel for automobile use in the country is imported, it is highly probable that the automotive gasoline in use in Lao PDR is lead-free.

3.4. Management of Stationary Sources

Although Lao PDR does not have a large number of large industries, industrial air pollution from stationary sources is also managed by Ministry of Agriculture and Environment and the Ministry of Industry and Commerce. Stack monitoring of industries such as cement factories are also being conducted to ensure that these industries do not pollute the atmospheric environment of the country.

The environmental impact assessment (EIA) system requirements of the country for industries and establishments also are a way to monitor and regulate air pollution from the industry. The EIA system utilized in Lao PDR however is still informal and ad hoc in nature (Tan, 1998).

4. Conclusion

4.1. Synthesis of Environmental Status and Trends

The 24–year monitoring dataset (2002 – 2025) presents a complex, dual-faceted picture of Lao PDR's atmospheric and aquatic health. While the country has historically been spared from severe acid rain due to natural planetary and local buffering mechanisms, alarming developmental and ecological pressures are rapidly emerging.

*(1) **Atmospheric Deposition and Air Quality Dynamics:***

- Wet Deposition: Vientiane's precipitation exhibits relative resilience against chronic acidification, maintaining a long-term average pH of 6.35 ± 0.52. This stability is governed by strong neutralization pathways: crustal dust (Ca^{2+}, Mg^{2+}) and agricultural ammonia (NH_4^+). However, the growing dominance of Nitrate (NO_3^-) over Sulfate (SO_4^{2-}) points to urban mobile sources (vehicular emissions) as a rising atmospheric threat.

- Dry Deposition and $PM_{2.5}$: Atmospheric particulate matter shows a severe seasonal "smog trap." During the dry season (November to April), transboundary haze, biomass clearing, and thermal inversions cause $PM_{2.5}$ concentrations to spike dramatically, peaking in March (exceeding 60 – 89 µg/m^3). Monsoon rains provide a highly efficient washout effect, reducing wet-season $PM_{2.5}$ to healthy baselines (9 – 15 µg/m^3 but the winter concentrations pose chronic public health and deposition risks.

(2) ***The Inland Aquatic Warning Signal:*** Unlike the buffered atmospheric baseline, the ecological health of Nam Hum Lake reveals a highly concerning trend of rapid degradation:

- Acidification: The lake's pH has steadily dropped from a weakly alkaline 8.05 in 2019 to a slightly acidic 6.41 in 2024.
- Ion Accumulation: Electrical Conductivity (EC) surged tenfold from a baseline of 3.4 µS/cm (2019 – 2022) to over 34 – 42 µS/cm in the 2023 – 2025 window.
- This aquatic shift is a direct physical indicator of catchment flushing. Particulates deposited dry during the winter months, combined with agricultural N-P-K fertilizer runoff, are washed into the shallow lake basin during the early monsoon, overwhelming its natural geological buffering capacity.

(3) ***Inland Soil and Vegetation Gaps:*** Due to systemic resource and technical limitations, ecological monitoring of soil and vegetation has not yet commenced. This remains a critical blind spot, as the acidification trend observed in Nam Hum Lake suggests that surrounding forest soils may already be undergoing nutrient leaching.

4.2. Institutional and Operational Challenges

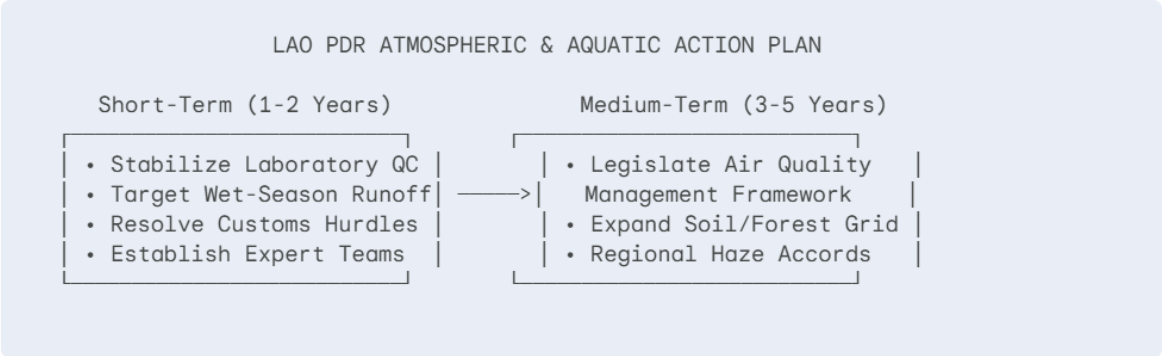
The technical and structural history of Lao PDR's EANET activities highlights a persistent gap between policy intent and operational reality:

- Institutional restructuring: The transition of operations to the Environment Quality Analysis Center (EQAC) under the Biotechnology and Ecology Institute (BEI) of the Ministry of Agriculture and Environment (MAE) in 2025 represents an opportunity to centralize and streamline environmental tracking.
- Laboratory and equipment malfunctions: Essential instrumentation has faced persistent bottlenecks. The $PM_{2.5}$ monitoring grid suffered severe failures in early 2024, and the dry deposition tracking systems have historically suffered from deionized water impurities and automated sampler breakdowns.
- Logistical and customs barriers: Crucial laboratory modernization has been hindered by administrative hurdles. For example, the import of essential Ion Chromatography (IC) suppressors, standard solutions, and chemicals was blocked and returned at the border due to complex transit customs and immigration taxes. Resolving these logistical pathways is crucial for maintaining data continuity.
- Data quality control: Formatting and data-logging errors—such as the reporting of mathematical negative values instead of working within strict instrumental Limits of

Detection (<LOD)—highlight a pressing need for ongoing training in EANET-compliant QA/QC protocols.

4.3. Strategic Recommendations and Policy Action Plan

To transition from passive environmental observation to active air quality and watershed management, the Government of Lao PDR, led by MAE, should implement the following targeted initiatives:



(1) Short-Term Technical Stabilization (1–2 Years):

- Re-establish laboratory integrity: Secure dedicated operational funding to maintain the $PM_{2.5}$ automated sensors. Coordinate an EANET/ACAP technical expert mission to Vientiane to troubleshoot the auto-sampling functionality of the EQAC Ion Chromatography systems.
- Mitigate customs bottlenecks: Establish a formal ministerial protocol between the MAE, Ministry of Finance, and customs authorities to grant tax-exempt fast-track status to certified scientific equipment, standard solutions, and consumables imported for national public health and network activities.
- Address watershed runoff: Introduce community-level buffer management zones around Nam Hum Lake to limit direct, untreated agricultural runoff and fertilizer leaching, protecting the basin from further acidification and ionic loading.

(2) Medium-Term Policy Integration (3–5 Years):

- Draft a dedicated clean air act: Transition from the broad provisions of the Environmental Protection Law (EPL) 2013 to a specific regulatory framework for air quality control. This must include updating national ambient air quality standards to align more closely with protective WHO guidelines, replacing lenient historical standards.
- Establish an emissions inventory: Move beyond ad-hoc research projects to build a permanent, national emissions inventory. This system must quantify the exact contributions of mobile sources (urban vehicle fleet) and stationary sources (cement plants, regional industries).

- Expand monitoring to soil and vegetation: Build technical capacity through EANET-sponsored training to start baseline soil chemistry and forestry health assessments, closing the current ecological data gap.
- Strengthen regional transboundary cooperation: Leverage Lao PDR's position within the ASEAN Agreement on Transboundary Haze Pollution and EANET to implement joint agricultural burning bans, coordinate fire-risk warnings, and manage regional pre-monsoon smog.

Author contribution

Sitthideth Nonthaxay* and Soukthakhane Singsonesack*: writing the original draft, data analysis, and graphic design. Soukthakhane Singsonesack, Ketsana Buaphavong, Thilakhone Sisouphanh, Sommack Souksavath: acid deposition monitoring and ambient air quality monitoring. Keophoungeun Kanmany, Nout Kanyaphim, Soukthakhane Singsonesack, Ketsana Buaphavong, Sommack Souksavath: inland aquatic environmental monitoring, laboratory analysis, and data reports. Khamsene Ounekham* and Sitthideth Nonthaxay*: reviewer, and editor.

Acknowledgments

This work was financially supported by the Lao government, Ministry of Agriculture and Environment (MAE); technical and some equipment supported by Acid Deposition Monitoring Network in East Asia (EANET), especially the Asia Center for Air Pollution Research (ACAP), Japan. The authors acknowledge the use of equipment, scientific and technical assistance of the Environmental Quality Analysis Center (EQAC) for laboratory experiment. Thank given the Department of Meteorological and Hydrological (DMH) for placing the ambient air monitoring site.

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Notes: The authors declare no competing financial interest.

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