National Assessment on Acid Deposition in Indonesia

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Chapter 1. Basic Information on National Monitoring Activities

1.1 Outline

Indonesia initiated to participate in EANET activities since the preparatory phase. Acid deposition monitoring in Indonesia is implemented by observing wet and dry deposition, and attempted in assessing the impacts by monitoring soil, vegetation, and inland aquatic water. These tasks are conducted by various related national agencies which is Ministry of Environment and Forestry (MoEF) of Indonesia as National Focal Point (NFP), while Research and Development Center of Environmental Quality and Laboratory (P3KLL)/Environmental Management Center (EMC) - MoEF as the National Center (NC). The participating institutions are Meteorological Climatological and Geophysical Agency (BMKG), Center of Atmospheric Science and Technology - National Institute of Aeronautics and Space (PSTA-LAPAN) which then merged into National Research and Innovation Agency (BRIN) in 2021, and also Soil Research Institute (SRI)/BBSLDP - Ministry of Agriculture.

1.2. Monitoring program of acid deposition

Acid deposition monitoring program in 2020-2024 were performed to maintain the previous and current activities and further, and we plan to increase the number of EANET monitoring sites in Indonesia. Due to several alteration in the main task and function of the agencies, since 2015, EMC has undertaken the monitoring in all sites for ecological impact. However, no observation of annual vegetation monitoring during 2020-2024, as a result of technical and management issues.

Table 1. Monitoring sites in Indonesia

Location	Agencies	Monitoring interval
Serpong	EMC	WD: event, DD: biweekly (FP)
Bandung	BRIN	WD: event, DD: biweekly (FP, PS)

Jakarta	BMKG Jakarta	WD: weekly, DD: biweekly (FP, PS)
Kototabang	BMKG Jakarta	WD: weekly, DD: biweekly (PS)
Maros	BMKG Jakarta	WD: weekly
Situ Patengan	EMC	IA: 4 times a year
Situ Gunung	EMC	IA: 4 times a year
Bogor	SRI	S: every 5 years

Note: *WD = wet deposition, DD = dry deposition, FP = filter pack, PS = passive sampler, IA = inland aquatic, S = soil*

1.2.1 Wet and dry monitoring

During the Twentieth Senior Technical Managers' Meeting (STM20), Indonesia proposed two more rural wet deposition monitoring sites: station of Climatology Class II BMKG – Jembrana, Bali Province, located at 08º20'26.67" S 114º37'01.53" E and Station of Climatology Class I BMKG – Lombok Barat, West Nusa Tenggara Province, located at 08º38'10.4" S 116º10'15.0" E to complement the existing monitoring sites. Besides Serpong and Bandung, wet deposition monitoring sites were mostly carried out under responsibility of BMKG Jakarta, as the national agency, in which, one of their basic tasks and functions is to provide the information of rain water quality all over the country. Following EMC Serpong, BMKG Jakarta and BRIN Bandung established to monitor dry deposition using filter pack since April 2014. For ambient air quality, surface ozone observation in Bandung was implemented by BRIN since 2015 using Dasibi Ozone Analyzer. PM2.5 monitor was installed in BMKG Jakarta in 2016, however, there were some troubles on the equipment and PM2.5 data started to be reported in 2017. However, the measurement was terminated due to high-cost maintenance coupled with unreliable readings. Exploring lesson learned from the previous equipment, BMKG decided to deploy a new instrument using different method of observation on November 2021 in which the new instrument has been operating ever since.

Table 2. Information of monitoring sites in Indonesia

Site	Classification	Latitude	Longitude	Altitude (m)
Serpong	rural	06^{0}21'01,9" S	106^{0}40'04,07" E	64
Bandung	urban	06^{0}53'41,63" S	107^{0}35'11,31" E	753
Jakarta	urban	06^{0}09'21,51" S	106^{0}50'32,67" E	7
Kototabang	remote	0^{0}12'8.70" S	100^{0}19'4.50" E	845
Maros	Rural	04^0 59' 50.29' S	119^{0}34' 17.73" E	1
Jembrana	Rural	08º20'26.67" S	114º37'01.53" E	25
Lombok	Rural	08º38'10.4" S	116º10'15.0" E	55



Serpong



Bandung



Jakarta



Kototabang



Maros



Jembrana



Lombok Barat

Figure 1. Wet deposition monitoring sites

1.2.2 Ecological impact monitoring





(a) Situ Patengan, Bandung



(b) Situ Gunung, Sukabumi



Dramaga, Bogor

Figure 2. Ecological impact sites

The sampling sites selected for inland aquatic monitoring in Indonesia are Situ Patengan, Bandung and Situ Gunung, Sukabumi in West Java Province. Situ Patengan is located in West Bandung, about 214 km from EMC Serpong the southeast (SE) and 52,8 km from BRIN Bandung to the south west (SW). Situ Gunung is located in Sukabumi, about 135 km from EMC Serpong to the south southeast (SSE), while Dramaga Research Forest is 35 km to the south (S). Monitoring frequency was 4 times a year.

Soil site was located in Dramaga, Bogor and monitoring was conducted in every 5 years. Dramaga Research Forest which is covered an area of 60 ha was managed by the Center for Forest Research and Conservation, Ministry of Forestry. Vegetation monitoring also has been conducted in Dramaga Research Forest (block 12) Bogor (GPS located at 106 44'55.1" E and 6 33'7" S). The climate of the Dramaga Research Forest is typically humid tropical rainforest climate, fairly constant year-round averaging 24-27ºC, 80-90% humidity, and very high rainfall typically 3500-4500 mm per year.

1.3 Sampling and measurement

1.3.1 Wet deposition

Table 3. Measurement and analytical methods of wet deposition

Site	Parameters	Method	Instrument
Serpong	pH	Glass electrode	HORIBA F-22
	EC	Conductivity cell	HORIBA Navi DS-52
	SO_4^{2-}, NO_3^-, Cl^-	Ion Chromatography	DIONEX ICS5000
	Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}	Ion Chromatography	DIONEX ICS5000
Bandung	pH	Glass electrode	HORIBA F-51
	EC	Conductivity cell	WTW Inolab Cond Level 2
	SO_4^{2-}, NO_3^-, Cl^-	Ion Chromatography	DIONEX ICS 1500
	Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}	Ion Chromatography	DIONEX ICS 1600
Jakarta/ Kototabang/	pH	Glass electrode	THERMO Electron Corp. ORION 3 Star
Maros/ Jembrana/	EC	Conductivity cell	THERMO Electron Corp. ORION 3 Star
Lombok	SO_4^{2-}, NO_3^-, Cl^-	Ion Chromatography	DIONEX ICS 1600
	Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}	Ion Chromatography	DIONEX ICS 1600

Wet deposition sample was collected using wet-only sampler. In EMC Serpong and BRIN Bandung, rainwater was sampled on daily basis, and analyzed in laboratory. However, in BMKG

Kototabang and Maros based on weekly basis. They measure pH and EC on site, then remained sample was stored into polyethylene bottle. Samples were preserved with biocide before they sent to BMKG Jakarta for further analysis. BMKG Jakarta also collected sample on weekly basis.

1.3.2 Dry deposition

A four-stage filter pack method was mainly applied for dry deposition monitoring in Serpong, Bandung, and Jakarta. BMKG Jakarta conducted the sampling in Jakarta and sent the samples to EMC Serpong for filter pack analysis. Monitoring of SO_2 and NO_2 by passive sampler were also conducted in Bandung.

Table 4. Measurement and analytical methods of dry deposition

Site		Parameters	Method	Instrument
Serpong	FP	SO_4^{2-}, NO_3^-, Cl^-	Ion Chromatography	DIONEX ICS5000
		Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}	Ion Chromatography	DIONEX ICS5000
Bandung	FP	SO_4^{2-}, NO_3^-, Cl^-	Ion Chromatography	DIONEX ICS 1500
	FP	Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}	Ion Chromatography	DIONEX ICS 1600
	PS	SO_2	Ion Chromatography	DIONEX ICS 1500
	PS	NO_2	Spectrophotometry	Spectrophotometer
Jakarta*	FP	SO_4^{2-}, NO_3^-, Cl^-	Ion Chromatography	DIONEX ICS 5000
		Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}		
*analyzed by EMC				

1.3.3 Inland aquatic monitoring

Surface water were sampled directly by a clean polyethylene bucket every 4 times per year. Several physical and chemical parameters were measured on site using portable equipment, such as water temperature, water depth, clarity, water color, pH, EC, and DO. Since 2017, additional parameters were also conducted such as T-N, T-P, chlorophyll, and plankton identification.

Table 5. Measurement and analytical methods of inland aquatic

Site	Parameters	Method	Instrument
	pH	Glass electrode	HORIBA F-22
	EC	Conductivity cell	HORIBA Navi DS-52
Situ Patengan/	SO_4^{2-}, NO_3^-, Cl^-	Ion Chromatography	DIONEX ICS5000
Situ Gunung	Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}	Ion Chromatography	DIONEX ICS5000
	Alkalinity	Titrimetric	Burette, pH meter

1.3.4 Soil monitoring

Soil sample from Dramaga Research Forest, Bogor were analyzed once every 5 years with measurement of pH(H_2O), pH(KCl), ex-Na^+, ex-K^+, ex-Ca^{2+}, ex-Mg^{2+}, ex-acidity, ex-Al^{3+}, and ex-H^+. All procedures were performed based on Technical Manual for Soil Monitoring in East Asia.

1.4 Inter-laboratory comparison

Indonesia participated in the Inter–laboratory comparison (ILC) project on wet deposition, dry deposition, inland aquatic, and soil, which is involved 4 (four) laboratories. Water Research Center did not able to join the monitoring any longer due to internal policy.

Table 6. Inter Laboratory Comparison (ILC) Project in Indonesia

Agencies	Code	Type of ILC			
		Wet	Dry	IA	S
Research & Development Center of Environmental Quality & Laboratory/Environmental Management Center (EMC) – MoEF	ID01	√	√	√	√
Meteorological Climatological and Geophysical Agency (BMKG)	ID02	√			
National Institute of Aeronautics and Space (BRIN)	ID03	√	√		
Soil Research Institute (SRI)	ID05				√

In case of data submission, EMC is responsible to compile, validate, and submit the data from all respective agencies to the Network Center.

Chapter 2. State of Acid Deposition in Indonesia

2.1 Wet deposition

Wet deposition precipitation in Indonesia varied due to differences in the amount of annual rainfall. Figure 2. shows the total of annual precipitation ($mm.yr^{-1}$) in every monitoring site in 2020 to 2024. Jakarta, Jembrana and Lombok shared the lowest cumulative annual rainfall. The highest total annual average rainfall was in Maros (4,321 $mm.yr^{-1}$) on 2022, while the lowest one was in Jembrana (1,270 $mm.yr^{-1}$) on 2023.

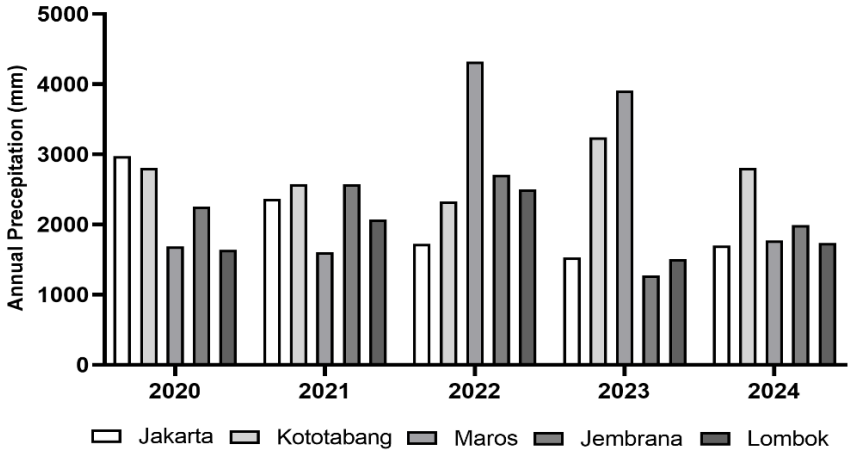


Figure 3. Annual precipitation of BMKG's sites in 2020-2024

Due to technical constraints and disruptions during the COVID-19 pandemic, data availability at the Serpong and Bandung sites was limited to a three-year period (2020–2022). The precipitation in Bandung were found to be much lower than Serpong every year.

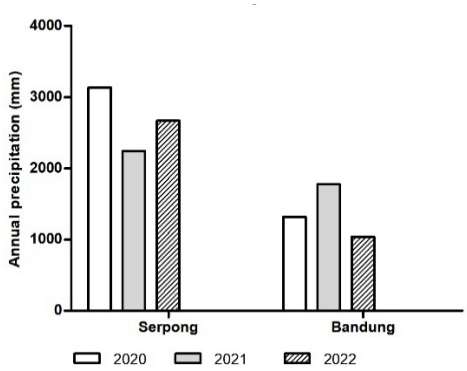
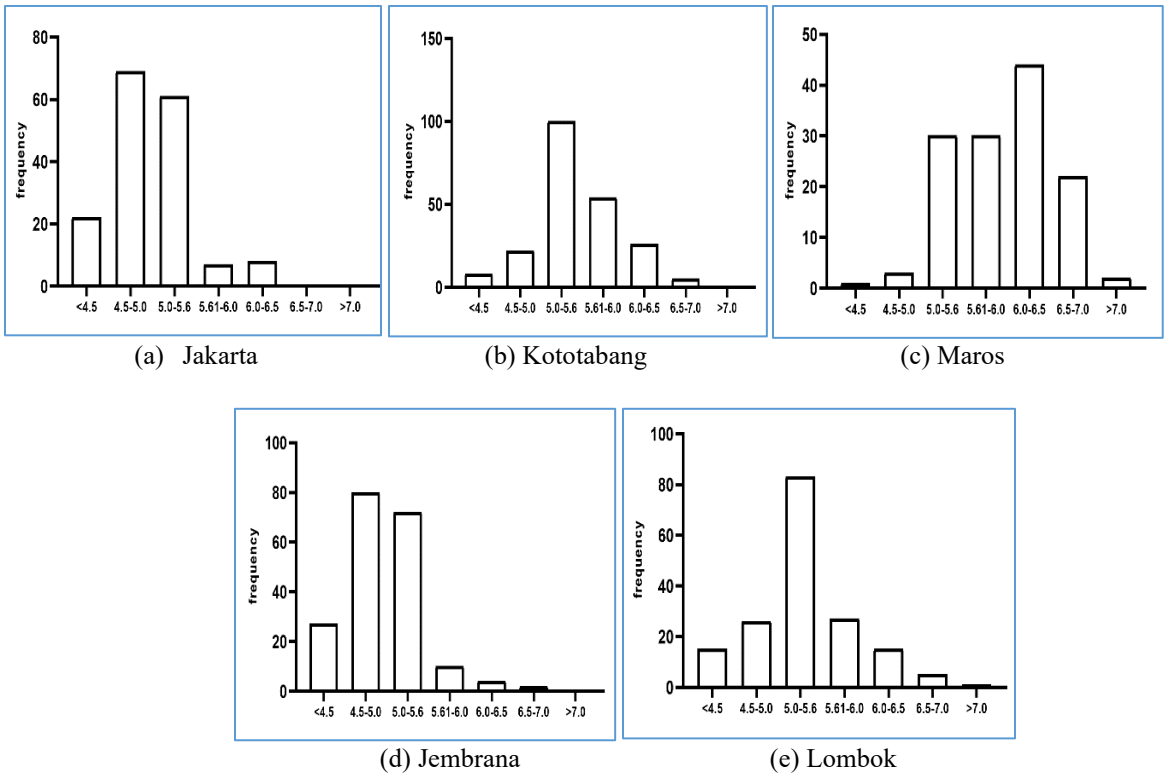


Figure 4. Annual precipitation in 2020-2022

Table 7. Annual Average of pH in 2020-2024

Site	2020	2021	2022	2023	2024
Jakarta	5.14	4.91	4.92	4.79	5.28
Kototabang	5.40	5.68	5.73	5.58	5.02
Maros	5.57	6.35	6.25	5.90	5.64
Jembrana	5.24	4.98	4.97	5.10	4.73
Lombok	5.46	5.35	5.42	5.44	4.86
Serpong	5.13	5.47	5.12	-	-
Bandung	5.97	5.49	5.62	-	-

The average weighted pH for the period of 2020 to 2024 was shown in Table 7. The annual average pH in Indonesia were between 4.73 – 6.35. Jakarta and Jembrana had low pH values throughout the years as opposed to Maros. Kototabang and Lombok demonstrated high pH particularly on 2020-2023 and low pH on 2024. Low pH indicated increased acidity in a solution. Table 8 depicted the annual average of electrical conductivity (EC) in all of the sites. The average values ranged from 0.35 – 3.77 mS m^{-1}. Lombok experienced the largest value while Kototabang showed the lowest one in 2022. Jakarta, Jembrana and Lombok indicated more polluted rainwater than other sites. Serpong has the lowest pH value in 2020 and 2022 compared to Bandung.

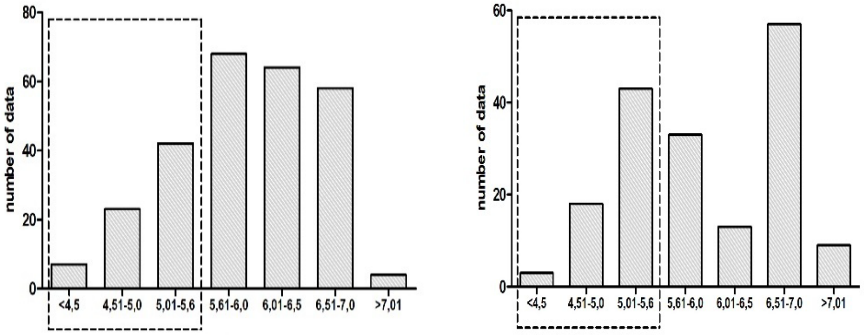


(a) Jakarta (b) Kototabang (c) Maros

(d) Jembrana (e) Lombok

Figure 5. pH distribution in Jakarta, Kototabang, Maros, Jembrana and Lombok during 2020-2024

Sampling periode: biweekly (data source: BMKG Jakarta)



(a) Serpong (b) Bandung

Figure 6. pH distribution in Serpong and Bandung during 2020-2022
Sampling periode: event (data source: EMC and BRIN)

Figure 5 showed the frequency distribution of pH in all sites. Jakarta and Jembrana had quite similar patterns which were more skewed to the left meaning that the pH values were dominated in lower pH magnitudes (4.5 – 5.0). Kototabang and Lombok also exhibited comparable frequency distribution patterns posing a Normal-like distribution where it peaked at higher pH values (5.0 – 5.6). Unlike the other sites, Maros showed the highest frequency occurred in the 6.0–6.5 range, indicating even higher pH magnitudes of rainwater.

Table 8. Annual Average of Electrical Conductivity in 2020-2024

Site	2020	2021	2022	2023	2024
Jakarta	1.27	1.81	1.71	1.74	2.02
Kototabang	0.50	0.51	0.35	0.61	1.02
Maros	0.69	0.66	0.56	0.88	0.72
Jembrana	1.99	1.79	1.29	1.37	1.85
Lombok	1.03	0.97	3.77	1.64	1.49
Serpong	2.03	2.00	1.98	-	-
Bandung	1.96	1.59	1.92	-	-

The following chart (Figure 7) highlights the annual average of EC in all sites during 2020-2024. Jakarta and Jembrana maintained a steady and higher baseline of EC, while Lombok experienced dramatic peak on 2022. Representing a remote site, Kototabang had low EC during 2020-2023 and elevated on 2024.

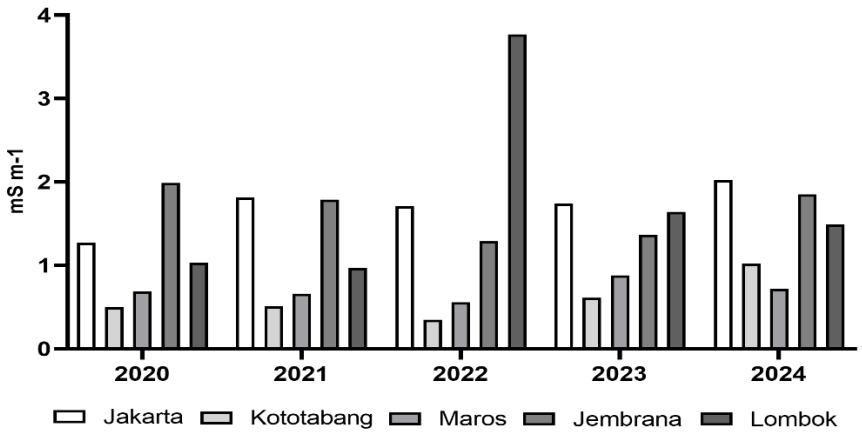


Figure 7. Annual average of EC in Jakarta, Kototabang, Maros, Jembrana and Lombok during 2020-2024

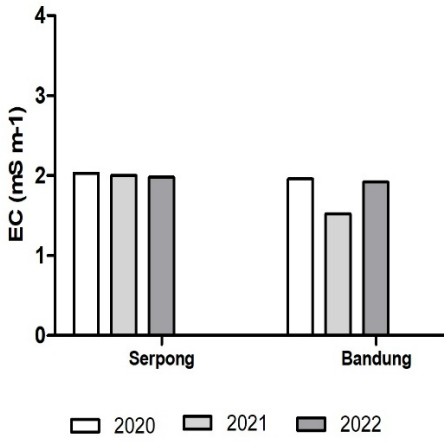
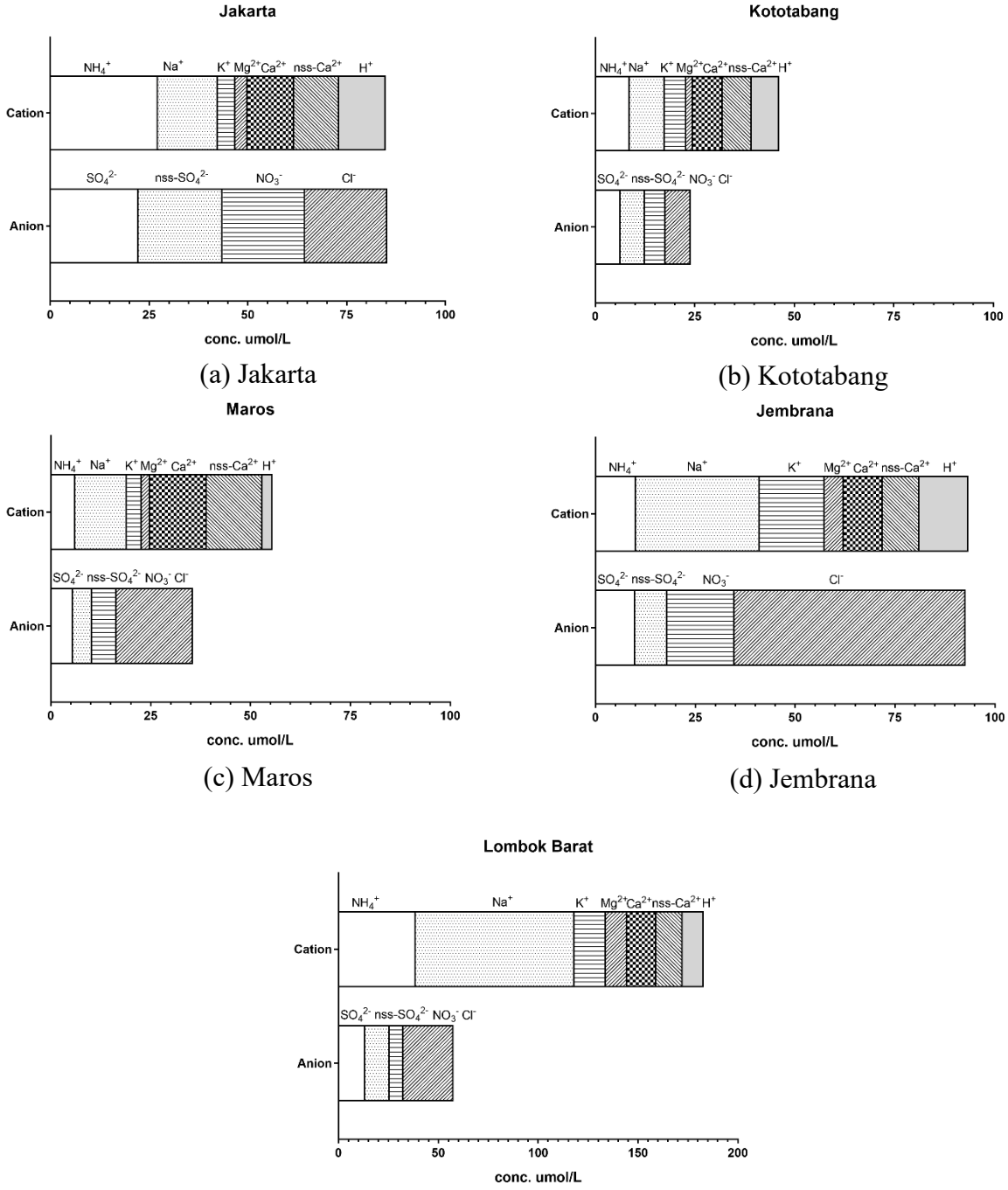


Figure 8. Annual average of EC in Serpong and Bandung during 2020-2022



(a) Jakarta

(b) Kototabang

(c) Maros

(d) Jembrana

(e) Lombok

Figure 9. Chemical composition of rainwater in Jakarta, Kototabang, Maros, Jembrana and Lombok during 2020-2024

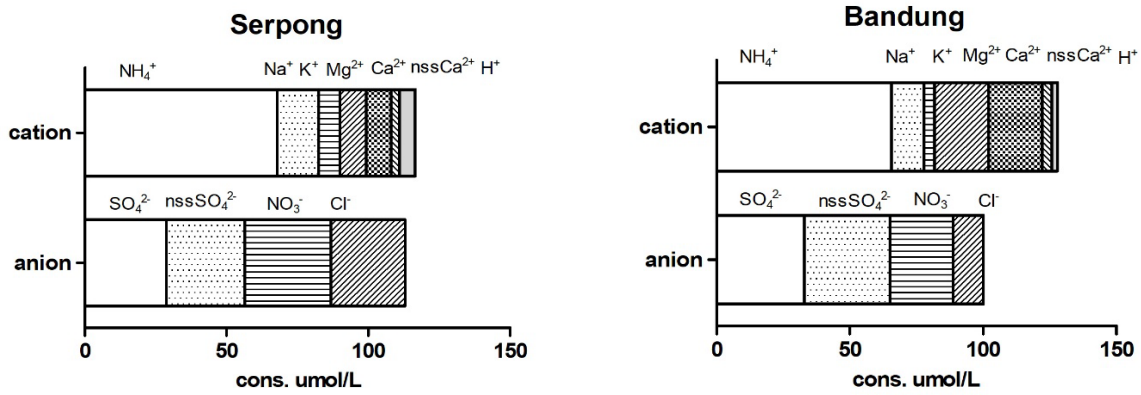


Figure 10. Chemical composition of rainwater in Serpong and Bandung during 2020-2022

Figure 9. and Figure 10. shows the characteristic of chemical rainwater in several sites based on average annual data for each parameter from 2020 to 2024. In Jakarta, NH_4^+ was the most significant cation while NO_3^- was the most dominant anion. In addition, SO_4^{2-} was also found quite comparable to the two species. Similar cases occurred in Serpong and Bandung for NH_4^+. The proportion of anions were almost equal in Serpong, while in Bandung was mostly dominated by SO_4^{2-} and nss-SO_4^{2-}. Kototabang had almost comparable portion cation, except for K^+, and anion. Meanwhile, the most dominant cation in Maros was Ca^{2+} followed by Na^+, and the most significant anion was Cl^-. Lastly, Na^+ was the major cation while Cl^- had the largest portion of anion in Jembrana and Lombok.

2.2 Dry deposition

Dry deposition monitoring in Indonesia was conducted at three locations: Serpong, Jakarta, and Bandung, using the filter pack method. This monitoring covered gases and particles. Gas compounds included SO_2, HNO_3, HCl, and NH_3, while particles included SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Mg^{2+}, and Ca^{2+}.

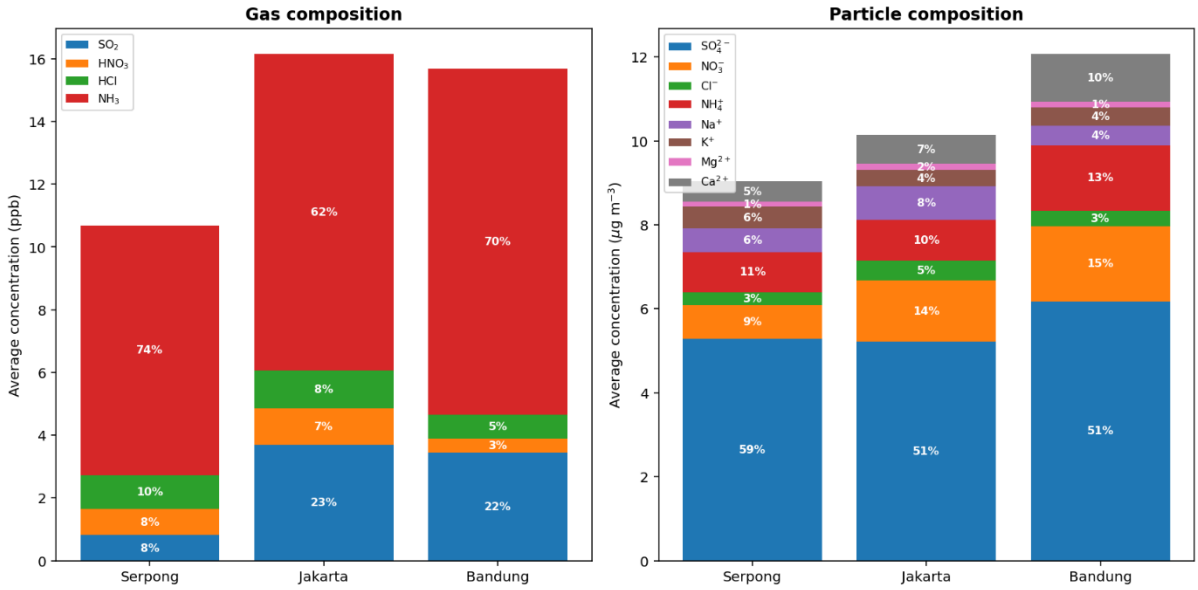


Figure 11. Gas and particle composition in Serpong, Jakarta and Bandung from 2020 – 2022

The results of dry deposition monitoring from 2020 to 2021 for both gas and particulate matter are shown in Figure 2X. This figure presents a comparison of the chemical composition of the gas and particle phases at the three observation locations: Serpong, Jakarta, and Bandung. In the gas phase, NH_3 (ammonia) consistently dominated at all locations. The highest contributions were approximately 74% in Serpong, 62% in Jakarta, and 70% in Bandung. This indicates that ammonia emissions, which generally originate from agricultural activities, waste, and other anthropogenic sources, are a major component of regional atmospheric chemistry. Meanwhile, SO_2 contributions were relatively higher in Jakarta (23%) and Bandung (22%) compared to Serpong (8%). This indicates the strong influence of urban and industrial activities. HNO_3 and HCl contributed less, but still played a role in the formation of secondary aerosols.

In the particle phase, sulfate (SO_4^{2-}) dominated the composition at all locations. Contributions were 59% in Serpong, 51% in Jakarta, and 51% in Bandung. This suggests that the oxidation of SO_2 to

sulfate is the primary mechanism for fine particle formation in these areas. The second largest component was nitrate (NO_3^-). Nitrate increased from Serpong (9%) to Bandung (15%), indicating the important role of gas-particle reactions involving NOx in urban areas. Ammonium (NH_4^+) also contributed significantly (10–13%). This confirms its role in neutralizing acidic aerosols through the formation of ammonium salts such as ammonium sulfate and ammonium nitrate.

Overall, the dominant combination of NH_3 in the gas phase and SO_4^{2-} and NO_3^- in the particle phase indicates that the formation of secondary inorganic aerosols (SIA) is very strong at all three locations. This is mainly influenced by the interaction between precursor gas emissions (SO_2, NOx, and NH_3) and local atmospheric conditions. The differences in composition between locations reflect variations in emission sources and environmental characteristics. Jakarta and Bandung are more influenced by urban and industrial activities than Serpong.

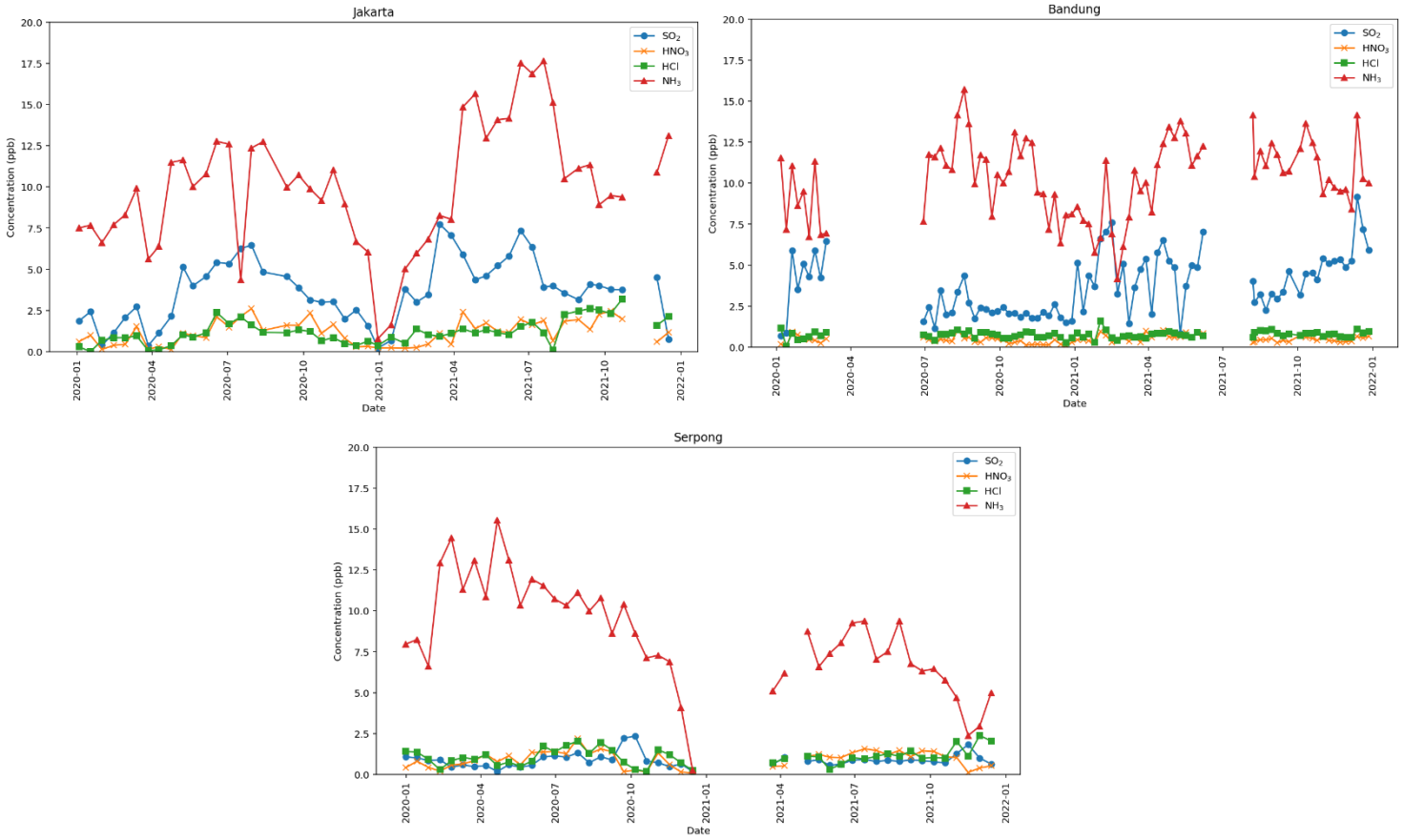


Figure 12. Trend of Gas Composition in Serpong, Jakarta, and Bandung from 2020 - 2022

The data indicate distinctive monthly patterns in the concentrations of SO_2, HNO_3, HCl, and NH_3 across Jakarta, Bandung, and Serpong from 2020 to 2022. In Jakarta, SO_2 and NH_3 concentrations exhibit significant peaks during specific months, particularly in June and July 2021, suggesting seasonal influences such as increased industrial or vehicular emissions. NH_3 demonstrates the most pronounced fluctuations, with sharp increases in October 2020 and March 2021, which may be associated with agricultural activities or waste management practices. HNO_3 and HCl concentrations remain stable throughout the year, without notable spikes. In Bandung, similar patterns are evident, with SO_2 concentrations rising in mid-2021 and NH_3 peaking in July and October 2021, aligning with seasonal variations. HNO_3 and HCl remain consistently low during the observed period.

In Serpong, a comparable trend is observed, with NH_3 concentrations steadily increasing during August 2021 and January 2022, indicating ongoing sources from agriculture or waste-related activities. SO_2 levels in Serpong peaked in June 2021, which likely reflects increased industrial activity during that period. The consistently stable levels of HNO_3 and HCl across all regions suggest minimal variation in their emissions. These seasonal trends emphasize the influence of both environmental and anthropogenic factors, such as industrial emissions, agricultural practices, and seasonal weather conditions, on pollutant concentrations. SO_2 and NH_3 are identified as the most variable gases across the regions. These findings underscore the necessity of monitoring air quality with consideration for seasonal variations to inform more effective control measures.

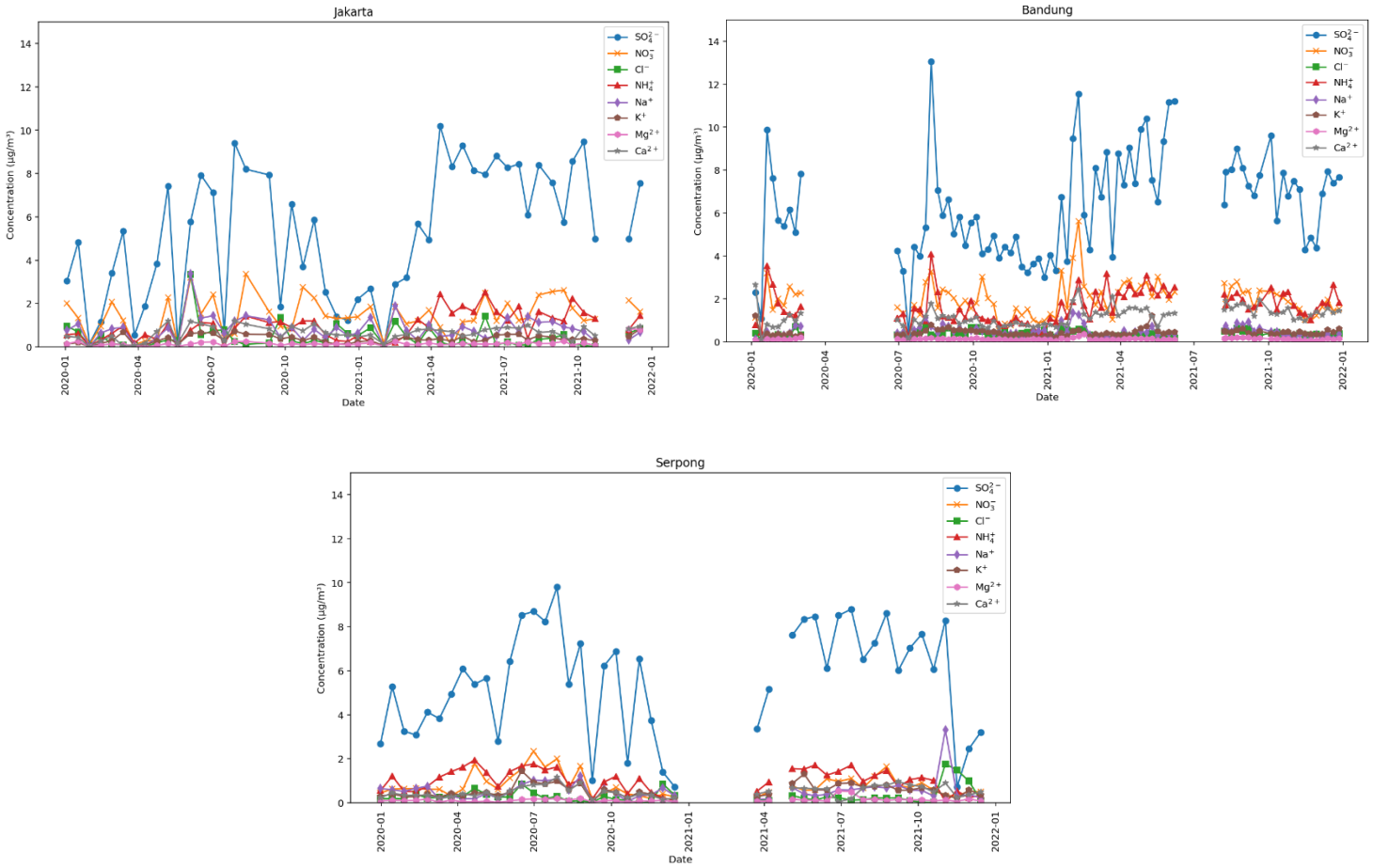


Figure 13. Trend of Particle Composition in Serpong, Jakarta and Bandung from 2020 - 2022

The graph presents concentration trend of several particulate ions (SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Mg^{2+}, Ca^{2+}) across Jakarta, Bandung, and Serpong from 2020 to 2022. In Jakarta, SO_4^{2-} and NO_3^- exhibit pronounced peaks, particularly during mid-2021, which may indicate increased industrial activity. NH_4^+, Na^+, and K^+ concentrations display seasonal fluctuations, with notable peaks in May and October 2021. Bandung demonstrates comparable patterns, with SO_4^{2-} and NO_3^- reaching maximum concentrations in July 2021, and NH_4^+ peaking in January 2021. Other ions in Bandung show moderate variation throughout the study period. Serpong reflects these trends, with SO_4^{2-} and NO_3^- concentrations increasing in April and May 2021, respectively, alongside fluctuations in NH_4^+, Na^+, and Ca^{2+}.

These findings underscore the significant influence of industrial emissions and vehicular activity on particulate pollution in these regions. The recurring peaks in SO_4^{2-} and NO_3^- concentrations suggest that industrial processes and traffic are primary sources. In contrast, the localized and seasonal variability of NH_4^+ and other ions indicates contributions from additional sources, including agricultural activities. The observed seasonal fluctuations highlight the necessity for targeted air quality management strategies during peak periods to effectively reduce pollution from industrial, vehicular, and agricultural sources.

Passive Sample

The bar chart presents monthly concentrations of SO_2, NO_2, O_3, and NH_3 in Bandung, based on passive sampler measurements in 2020. The results indicate distinct monthly fluctuations for each gas. NO_2 exhibits the highest concentrations, particularly in February, July, and November. SO_2 and NH_3 also display notable peaks during these months. In contrast, O_3 concentrations remain relatively low, with a modest increase observed in November. These seasonal variations suggest that specific local sources and seasonal activities significantly influence air quality in Bandung.

The primary sources of air pollution in Bandung come from motor vehicle emissions and agricultural activities. The high concentrations of NO_3 and NH_3 present an opportunity for the formation of secondary pollutants, such as ammonium nitrate, which is related to the formation of PM2.5. Further research is needed to understand the formation of secondary pollutants and their relationship to PM2.5 concentrations in Bandung, which would provide valuable insights into managing air quality and reducing particulate matter that affects public health.

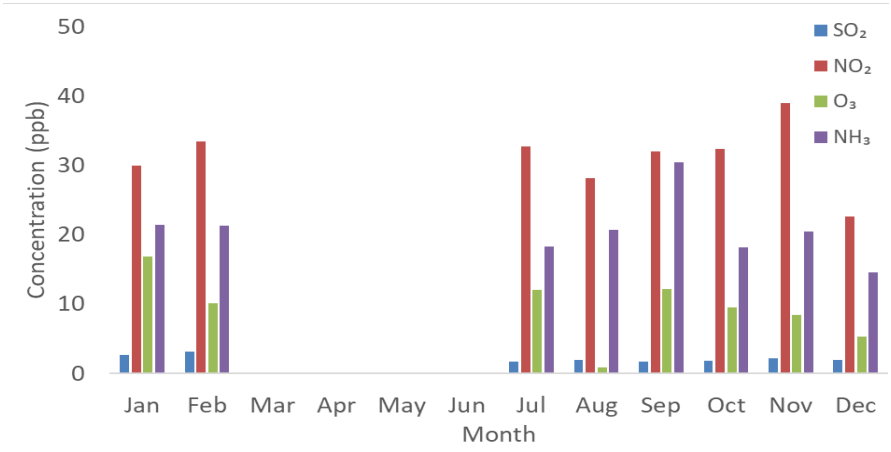


Figure 14. Passive Sampler Monitoring in Bandung (2020)

2.3 Ecological Impact Monitoring

In response to revisions in the institutional mandates and responsibilities of the relevant agencies, EMC assumed responsibility for monitoring this criterion across all sites between 2015 and 2019. Monitoring activities were suspended during the COVID-19 pandemic, and as a result, no ecological impact monitoring data were collected from 2020 to 2024.

Chapter 3. Review of National Air Quality Management including Acid Deposition

The Ministry of Environment and Forestry supported the grand design of air pollution control by regulating the stationary and mobile sources. Regulations related to air pollution control are mostly based on Government Regulation No 41/1999 for Control of Air Pollution and State Minister of Environmental Decree No 13/1995 for Stationary Sources. In 2021, the regulation about ambient air were updated into Government Regulation No. 22 of 2021, in which a regulation concerning the Implementation of Environmental Protection and Management in Indonesia. It covers various environmental aspects, including environmental approvals, management of water, air, and marine quality, pollution and environmental damage control, management of hazardous and non-hazardous waste, environmental information systems, and environmental supervision and administrative sanctions. This regulation was issued as a derivative regulation of the Job Creation Law and came into effect on 2 February 2021.

Based on the Ministry of Environment and Forestry of Indonesia Strategic Plan (Renstra KLHK) 2020–2024, the following are its main programs of air pollution control. Blue Sky Program (Program Langit Biru) is the program to control and to prevent of air pollution from stationary sources (industries) and mobile sources (motor vehicles). During the 2020–2024 period, the program continued to be implemented as part of air pollution control and environmental quality improvement efforts, including reducing vehicle emissions, promoting more environmentally friendly fuels, conducting emission tests, supporting sustainable transportation, and improving urban air quality. In 2020, PT Pertamina (Persero) – Indonesian State-Owned Oil and Gas Corporation. with support from Ministry of Environment and Forestry, implemented the Blue Sky Program to encourage the use of higher-octane fuel and reduce vehicle emissions. On the other hand, emission technical approval**,** a technical management related to industrial emissions is widely introduced. Development of the Air Pollutant Standard Index (ISPU) is also applied to enhance of Indonesia’s ambient air quality information system.

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