



# Meteorological baseline for air-quality assessment in a very wet tropical lowland

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## ABSTRACT

**Background:** Meteorological baselines are essential for interpreting ambient air-quality dynamics in humid tropical lowlands because rainfall, humidity, temperature, and wind jointly regulate wet deposition, pollutant dilution, atmospheric stagnation, and smoke transport. This study characterizes the climatic and dispersion-relevant meteorological setting of the PT X study area in Kapuas Regency, Central Kalimantan, Indonesia. **Methods:** Monthly meteorological data for 2011-2024 were compiled from the NASA POWER source-native dataset at -2.5486° latitude and 114.6967° longitude, approximately 5 m above sea level. Rainfall was classified using the Schmidt-Ferguson Q index, and rainfall, 2-m air temperature, relative humidity, wind direction, and wind speed were evaluated through descriptive climatological analysis. **Findings:** The study area had an average of 0.86 dry months, 0.64 humid months, and 10.50 wet months per year, producing a Q value of 8.16 and a Type A very wet climate. Mean annual rainfall was 2,878 mm, with the highest annual total in 2020 (3,865 mm) and the lowest in 2023 (2,245 mm). Mean annual air temperature was 26.5 °C, relative humidity averaged 88.4%, and monthly wind speeds were consistently very low, with a mean of 0.088 m s<sup>-1</sup>. Southeast and east winds dominated the monthly wind field. **Conclusion:** The site is persistently humid but still has a mid-year to early late-year rainfall minimum and weak atmospheric ventilation, conditions that can intensify pollutant accumulation when biomass burning, road dust, or operational emissions occur. **Novelty/Originality of this article:** The article provides a site-specific, meteorological baseline for air-quality assessment in a data-sparse tropical lowland by integrating Schmidt-Ferguson climate classification with dispersion-relevant humidity and wind metrics.

**KEYWORDS:** air quality assessment; meteorological baseline; Schmidt-Ferguson climate classification; tropical lowland meteorology; weak atmospheric ventilation.

## 1. Introduction

Air-quality assessment in tropical lowlands should be interpreted together with the meteorological conditions that regulate pollutant removal, transformation, and transport. Rainfall can promote wet scavenging of atmospheric particulate matter, although its effectiveness depends on rainfall intensity, duration, aerosol loading, and particle characteristics (Zeng et al., 2023). Relative humidity influences aerosol water uptake,

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particle growth, liquid-water content, and consequently particle properties and atmospheric behaviour (Prashanti et al., 2024; Wang & Wang, 2024). Wind speed and direction, together with atmospheric mixing and boundary-layer dynamics, regulate pollutant dispersion, dilution, and accumulation near the surface (Hasibuan & Mulyani, 2022). Consequently, pollutant concentrations measured under wet and well-ventilated conditions should not be interpreted in the same way as measurements obtained during relatively dry or stagnant periods. A meteorological baseline is therefore essential for providing the environmental context needed to interpret subsequent air-quality observations (Basri et al., 2020).

This requirement is particularly important in Central Kalimantan, where tropical rainfall variability interacts with peatland hydrology and recurrent fire risk. El Niño–Southern Oscillation (ENSO) can substantially modify hydroclimatic conditions in Central Kalimantan peatlands, with El Niño-related drought associated with reduced rainfall and substantial declines in peatland groundwater levels (Sulaiman et al., 2023; Treby et al., 2026). When hydrological drought develops, particularly in drained or degraded peatlands, declining water tables and reduced soil moisture increase the susceptibility of peat to fire (Goldstein et al., 2020; Horton et al., 2022; Mezbahuddin et al., 2023). Peat fires can transition from surface burning to prolonged subsurface smouldering, producing substantial particulate and gaseous emissions that contribute to regional smoke pollution (Graham et al., 2024; Horton et al., 2022; Yokelson et al., 2022). These regional processes make site-scale meteorological and hydrological interpretation particularly important for environmental monitoring in Kapuas Regency.

Kapuas Regency lies within the broader Central Kalimantan landscape in which peatlands, plantation activity, settlements, and seasonal fire occurrence can interact with local meteorology. Previous work has identified Kapuas among important peat-fire and haze areas in Central Kalimantan during El Niño-related events (Yulianti et al., 2020). For local air-quality management, the key meteorological questions are therefore when rainfall is least effective in removing particles, whether winds provide adequate ventilation, and which wind sectors may connect emission sources with sensitive receptors (Huang et al., 2015; Lee & Mak, 2021). Without this context, future pollutant measurements may be interpreted as isolated concentrations rather than as observations embedded in a seasonal dispersion regime (Istiana et al., 2023).

Rainfall is central to this interpretation because precipitation removes airborne particulate matter through wet deposition, and the efficiency of that process depends on rainfall characteristics (Wu et al., 2018). Relative rainfall minima can therefore create periods in which smoke, dust, or operational emissions persist longer than under wetter conditions. In Central Kalimantan and the wider Indonesian peatland region, drought and reduced rainfall have been associated with increased fire activity, smoke production, and peatland vulnerability (Field et al., 2016; Miettinen et al., 2017; Shi et al., 2023; Taufik et al., 2017). A local rainfall classification is consequently useful not only for climatology but also for identifying seasonal monitoring priorities.

Temperature and relative humidity provide additional information about the state of the lower atmosphere and land surface (Basri et al., 2017). Warm conditions can enhance evapotranspiration and surface drying during rainfall deficits, while high relative humidity can modify aerosol size and optical behavior through moisture uptake (Islam et al., 2023). These effects are especially relevant in smoke-affected environments because peat-fire aerosols contain complex mixtures of organic and inorganic material whose properties vary with ambient moisture (Jayarathne et al., 2018; Reddington et al., 2014; Stockwell et al., 2016). Considering temperature and humidity together with rainfall therefore provides a more realistic basis for interpreting fire-smoke vulnerability and pollutant persistence.

Wind conditions are equally important because they determine whether pollutants disperse, accumulate, or travel toward sensitive receptors. Low wind speed is commonly associated with weak atmospheric ventilation, whereas stronger winds can enhance dilution while also transporting pollutants over greater distances (Huang et al., 2015). Wind direction identifies potential transport pathways, but local roughness and source-receptor

geometry can substantially modify dispersion patterns (Lee & Mak, 2021; Li et al., 2022). Directional frequencies and wind-speed summaries are therefore useful screening indicators for locating monitoring stations and interpreting episodic concentration changes.

In many data-sparse tropical lowland areas, continuous on-site meteorological observations are unavailable during the early stages of environmental assessment. The NASA Prediction of Worldwide Energy Resources (NASA POWER) dataset provides a practical source of model- and satellite-based meteorological information with consistent temporal coverage (Marzouk, 2021). NASA POWER products have been evaluated against station observations in several applications, although local validation remains important when the data are used for site-specific operational decisions (Rodrigues & Braga, 2021). For a baseline study, the principal value of the dataset is its standardized multi-year coverage (Basri et al., 2017).

The objectives are to classify the local climate using the Schmidt-Ferguson method, describe monthly and annual rainfall behavior during 2011-2024, summarize temperature and relative humidity baselines, characterize wind direction and wind speed, and interpret the implications of these meteorological features for air-quality monitoring and sustainable environmental management. The study contributes a site-focused integration of rainfall classification and dispersion-relevant meteorological parameters for a very wet, data-sparse tropical lowland environment.

Temporal representativeness is another reason why a meteorological baseline is needed before pollutant data are evaluated. Short monitoring campaigns are common in project-level assessments, but their findings may be misleading if the sampling window is not linked to rainfall, wind, and humidity conditions. A low concentration recorded during a high-rainfall month could reflect strong wet scavenging rather than low emissions, while a high concentration during a calm rainfall-minimum period could reflect both emission intensity and unfavorable dispersion. Establishing the baseline first allows later measurements to be positioned within the seasonal envelope of the site.

## 2. Methods

### 2.1 Research design and analytical scope

This study used a descriptive climatological baseline design to characterize the meteorological setting of the PT X study area in Kapuas Regency, Central Kalimantan. The design was selected because the purpose was not to test a causal hypothesis regarding pollutant concentration, but to establish the environmental conditions needed to interpret future air-quality observations. The analysis therefore focused on defining normal seasonal patterns, identifying periods of elevated meteorological sensitivity, and assessing whether prevailing conditions are more favorable to pollutant removal, transport, or stagnation.

The analytical scope was limited to meteorological variables directly relevant to air-quality interpretation. Rainfall was used to indicate wet-scavenging potential and seasonal dryness; temperature to describe thermal conditions and drying pressure; relative humidity to characterize atmospheric moisture and its influence on particles; and wind direction and wind speed to assess transport pathways and ventilation (Huang et al., 2015; Istiana et al., 2023). This scope allows the manuscript to function as a meteorological reference for later monitoring of particulate and gaseous pollutants.

### 2.2 Study area and environmental setting

The study area is located within Kapuas Regency, Central Kalimantan Province, Indonesia, and is associated with the PT X environmental baseline area. The coordinate used for meteorological extraction was  $-2.5486^{\circ}$  latitude and  $114.6967^{\circ}$  longitude, at approximately 5 m above sea level. This coordinate represents a tropical lowland setting in which rainfall, humidity, and near-surface winds are environmentally important because

they influence peat drying, smoke persistence, and pollutant transport (Shi et al., 2023; Yulianti et al., 2020).

Kapuas Regency is part of a wider lowland landscape where plantation activity, peatland hydrology, seasonal fire risk, and rural settlement exposure may intersect. For that reason, a project-level meteorological baseline is more useful than a broad provincial description. The selected coordinate was treated as the reference point for describing the immediate meteorological context of the study area, while recognizing that micro-scale variation may occur because of vegetation cover, canals, land clearing, surface roughness, and local operational activities.

2.3 Data source, period, and meteorological variables

Monthly meteorological data were compiled from the NASA POWER source-native dataset for the period 2011-2024. The 14-year period was selected to capture recent interannual variability while remaining relevant to current environmental management needs. NASA POWER was used because gridded model- and satellite-derived products provide consistent meteorological coverage where continuous local observations are unavailable (Marzouk, 2021; Rodrigues & Braga, 2021).

According to NASA POWER documentation, the meteorological products used in this study are provided at a native spatial resolution of 0.5° latitude × 0.625° longitude, corresponding to the MERRA-2 meteorological grid (NASA POWER, n.d.). The value extracted at the study coordinate therefore represents the corresponding model grid cell rather than a point-scale observation at the exact project site. Monthly values were used to characterize multi-year climatic patterns and seasonal dispersion conditions, not short-term or microscale meteorological variability.

The variables extracted and analyzed were monthly rainfall, 2-m air temperature, relative humidity, wind direction, and wind speed. Rainfall was expressed in millimeters per month and summarized as annual totals and monthly climatology. Air temperature was summarized as mean 2-m temperature, relative humidity as percentage, wind direction as compass-sector frequency, and wind speed as monthly and overall values. Together, these variables describe the climatic and dispersion-relevant conditions used in the baseline analysis.

Table 1. Dataset and analytical procedures used in this study

| Component                  | Description                                                                                                                                                               |
|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Location                   | Kapuas Regency, Central Kalimantan, Indonesia; -2.5486° latitude and 114.6967° longitude; approximately 5 m a.s.l.                                                        |
| Period                     | Monthly meteorological data from 2011 to 2024.                                                                                                                            |
| Spatial resolution         | 0.5° latitude × 0.625° longitude for meteorological products (NASA POWER native MERRA-2 grid).                                                                            |
| Parameters                 | Rainfall, 2-m air temperature, relative humidity, wind direction, and wind speed.                                                                                         |
| Climate classification     | Schmidt-Ferguson Q index based on dry months (< 60 mm), humid months (60-100 mm), and wet months (> 100 mm).                                                              |
| Descriptive analysis       | Annual rainfall totals, monthly climatology, 2024 rainfall comparison, temperature-humidity summaries, wind-sector frequencies, and wind-speed interpretation.            |
| Air-quality interpretation | Baseline interpretation for wet deposition, humidity effects, weak ventilation, pollutant stagnation, smoke vulnerability, receptor planning, and sustainable management. |

2.4 Schmidt-Ferguson climate classification

Rainfall was classified using the Schmidt-Ferguson method, a rainfall-ratio approach that is commonly applied in Indonesian climate characterization. Each monthly rainfall value was assigned to one of three categories; 1) dry month when rainfall was below 60

mm, 2) humid month when rainfall was 60-100 mm, and 3) wet month when rainfall was above 100 mm. For each year in the 2011-2024 series, the number of dry, humid, and wet months was counted to describe the annual distribution of rainfall categories.

The Schmidt-Ferguson Q index was calculated as  $Q = (M_d/M_w) \times 100$ , where  $M_d$  represents the mean number of dry months per year and  $M_w$  represents the mean number of wet months per year. Dry months were defined as rainfall below 60 mm, humid months as 60-100 mm, and wet months as above 100 mm. The resulting Q value was interpreted using the original Schmidt-Ferguson classification, in which Type A represents a very wet climate when Q is below 14.3, with progressively higher Q values representing drier climate classes (Schmidt & Ferguson, 1951).

The classification was used as a climatic frame rather than as a substitute for seasonal analysis. Type A result indicates that wet months dominate the annual cycle, but it does not imply that short dry spells or rainfall-minimum periods are absent. The Q index was therefore interpreted together with monthly rainfall climatology and the 2024 sequence to avoid overgeneralizing the climatic condition of the site (Schmidt & Ferguson, 1951).

## 2.5 Descriptive statistical and temporal analysis

Descriptive statistical analysis was conducted at annual and monthly scales. Annual rainfall totals were summarized to identify the mean, standard deviation, wettest year, driest year, and the position of 2024 relative to the 2011-2024 baseline. Monthly rainfall climatology was calculated to identify the wettest and driest months in the long-term monthly cycle. The 2024 monthly rainfall sequence was then analyzed separately to show how the most recent year compared with the multi-year pattern.

Temperature and relative humidity were summarized as annual and monthly averages. The 2-m air-temperature analysis focused on the annual mean, interannual range, monthly minimum, and monthly maximum, while the relative-humidity analysis focused on the annual mean, interannual range, and seasonal decline during the rainfall-minimum period. These summaries were interpreted in relation to drying pressure, aerosol moisture response, visibility, and potential fire-weather sensitivity.

Wind direction and wind speed were analyzed as dispersion-relevant variables (Lee & Mak, 2021). Wind direction was converted into compass-sector frequencies for the full 2011-2024 monthly dataset and for 2024, while wind speed was summarized through monthly values and the overall mean. The wind analysis was used to identify prevailing directional tendencies, weak-ventilation conditions, and implications for downwind receptor selection. A polar wind rose was generated from the eight compass-sector frequencies. Because wind speed was available only as monthly aggregate values, the figure reports the observed wind-speed range and overall mean alongside the directional-frequency rose rather than assigning unsupported speed classes to individual sectors.

## 2.6 Air-quality interpretation framework and limitations

The meteorological results were interpreted through an air-quality framework linking rainfall, humidity, temperature, and wind to pollutant behavior. Rainfall was treated as a control on wet scavenging (Wu et al., 2018), relative humidity as a modifier of aerosol properties (Islam et al., 2023), temperature as a contributor to drying pressure during rainfall deficits, and wind speed and direction as indicators of ventilation and transport pathways (Huang et al., 2015; Lee & Mak, 2021).

Results were organized into climate classification and annual rainfall context, monthly rainfall regime and 2024 pattern, temperature and relative humidity baseline, and wind direction, wind speed, and integrated indicators. The discussion was aligned with the same pattern to ensure that each empirical result was followed by a directly corresponding interpretation. Figures and tables were retained as author-processed outputs from NASA POWER source-native data and the supplied baseline data.

Several methodological limitations were considered. NASA POWER is a gridded product and can smooth local-scale variability, particularly for near-surface wind speed and direction. Monthly aggregation also cannot resolve short-duration rainfall events, diurnal variability, hourly calm periods, or transient smoke plumes. In addition, the study does not include direct measurements of PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>, NO<sub>2</sub>, CO, or O<sub>3</sub>. The findings should therefore be interpreted as a meteorological screening baseline and as guidance for future field monitoring rather than as evidence of pollutant concentration (Rodrigues & Braga, 2021).

Because the analysis uses gridded monthly data, several scale-related limitations apply. Spatially, grid-cell values can smooth microclimatic differences associated with vegetation cover, canals, open land, surface roughness, and other local characteristics. Temporally, monthly aggregation suppresses diurnal cycles, short-duration rainfall events, wind gusts, calm episodes, and rapid wind-direction shifts that can strongly influence pollutant transport and dispersion. These limitations are particularly important for near-surface wind variables, which are sensitive to local surface conditions and may differ from the gridded regional signal.

Local meteorological validation was not performed in this study because a collocated, quality-controlled site-station time series was not available within the dataset assembled for the 2011–2024 baseline. Consequently, the NASA POWER fields were not bias-corrected against local observations. The results should therefore be interpreted as a regional-to-site screening baseline rather than a substitute for on-site meteorological measurements. Future monitoring should include temporary or permanent station measurements at representative receptor height to evaluate local bias and refine wind, rainfall, temperature, and humidity estimates.

### 3. Results and Discussion

#### 3.1. Results

##### 3.1.1 Climate classification and annual rainfall context

The Schmidt–Ferguson analysis classified the study area as a Type A climate (very wet). During 2011–2024, the average numbers of dry, humid, and wet months were 0.86, 0.64, and 10.50 months yr<sup>-1</sup>, respectively. The resulting Q index was 8.16, below the threshold of 14.3 for Type A climate, indicating that wet months strongly dominated the annual rainfall cycle, whereas dry months were uncommon. This pattern is consistent with the generally humid hydroclimatic conditions of the Indonesian Maritime Continent, although rainfall remains influenced by seasonal circulation and large-scale ocean–atmosphere variability (Chen et al., 2023).

The Type A classification represents the long-term climatic background and should not be interpreted as an absence of seasonal environmental variability. Because the Schmidt–Ferguson index summarizes the relative occurrence of dry and wet months, it does not capture the intensity or duration of individual rainfall deficits. Monthly rainfall characteristics are therefore necessary to identify shorter periods during which wet scavenging, surface moisture, and hydrological conditions may decline. This distinction is particularly relevant in the Indonesian Maritime Continent, where ENSO and the Indian Ocean Dipole can modify rainfall extremes, with the magnitude and timing of these effects varying spatially and seasonally (Chen et al., 2023; Kurniadi et al., 2021).

Mean annual rainfall during 2011–2024 was 2,878 mm yr<sup>-1</sup>, with a standard deviation of 451 mm. The highest annual rainfall occurred in 2020 (3,865 mm), whereas the lowest occurred in 2023 (2,245 mm), producing a difference of 1,620 mm between the wettest and driest years. The coefficient of variation was approximately 15.7%, indicating that rainfall was consistently abundant but still exhibited meaningful interannual variability. Such variability is relevant for environmental interpretation because rainfall fluctuations can influence surface moisture and atmospheric pollutant removal. In Central Kalimantan,

changes in rainfall are also associated with peatland hydrological responses; Sulaiman et al. (2023) reported substantial groundwater-level declines during major dry climatic anomalies, demonstrating that rainfall variability can have important implications for peatland environmental conditions.

The 2024 annual rainfall total was 2,880 mm yr<sup>-1</sup>, almost identical to the 2011–2024 mean of 2,878 mm yr<sup>-1</sup>, differing by only approximately 0.07%. Thus, 2024 represents a near-average rainfall year and provides a useful recent reference period for subsequent environmental monitoring. However, the near-average annual total does not imply uniform rainfall throughout the year; the observed seasonal minimum indicates that short-term meteorological conditions may differ substantially from the annual average. Accordingly, interpretation of air-quality observations should consider monthly rainfall distribution and seasonal meteorological conditions, rather than relying solely on annual rainfall totals. This approach is particularly important when assessing periods of reduced wet scavenging or changing surface and peat moisture conditions.

Table 2. Schmidt-Ferguson climate classification results for the study area, 2011-2024

| Metric                        | Value             | Interpretation                           |
|-------------------------------|-------------------|------------------------------------------|
| Mean dry months (< 60 mm)     | 0.86 months yr-1  | Very limited dry-month occurrence        |
| Mean humid months (60-100 mm) | 0.64 months yr-1  | Short transitional rainfall condition    |
| Mean wet months (> 100 mm)    | 10.50 months yr-1 | Wet condition dominates most of the year |
| Q index                       | 8.16              | Q < 14.3                                 |
| Climate class                 | Type A            | Very wet climate                         |

3.1.2 Monthly rainfall regime and 2024 pattern

The monthly rainfall climatology shows high rainfall at the beginning and end of the year and lower rainfall during the mid-year to early late-year period. March had the highest mean monthly rainfall at 351 mm month<sup>-1</sup>, while January and December each recorded 349 mm month<sup>-1</sup>. The lowest long-term monthly average occurred in September at 111 mm month<sup>-1</sup>. Although this September value still exceeds the Schmidt-Ferguson wet-month threshold of 100 mm, it is much lower than the wettest months and therefore represents the period when wet scavenging is likely to be least effective.

The seasonal rainfall contrast has direct implications for air-quality interpretation because precipitation is an important pathway for particulate removal through wet scavenging. However, the effectiveness of rainfall depends on rainfall characteristics, including event duration and intensity. Evidence from tropical Southeast Asia is particularly relevant: a study in Metro Manila found that PM concentrations did not necessarily decline during the wet season because short-duration rainfall events were inefficient at scavenging particles, whereas longer rainfall events produced more effective removal (Hilario et al., 2022). Similarly, rainfall-PM<sub>10</sub> analysis has demonstrated measurable wet-scavenging effects but substantial temporal variation in deposition efficiency. Therefore, the July–October rainfall minimum, particularly the September minimum identified in this dataset, represents an appropriate seasonal window for intensified air-quality monitoring, rather than evidence by itself of elevated pollution.

The 2024 rainfall pattern broadly reproduced the long-term seasonal structure, with rainfall peaking at 446 mm month<sup>-1</sup> in January, declining through the middle of the year, reaching a minimum of 77 mm month<sup>-1</sup> in September, and increasing again to 362 mm month<sup>-1</sup> in November. The September 2024 value was within the Schmidt-Ferguson humid-month category, despite the annual rainfall total being almost identical to the 2011–2024 mean. This contrast demonstrates why annual rainfall totals can conceal short periods of substantially reduced precipitation. The implication is particularly relevant to Central Kalimantan, where rainfall deficits can interact with peatland hydrology and fire susceptibility. Studies of Indonesian peatlands have shown that drought and groundwater

decline are important controls on peat-fire risk, while Central Kalimantan observations demonstrate strong interactions among rainfall, groundwater levels, and large-scale climate variability (Mezbahuddin et al., 2023; Sulaiman et al., 2023).

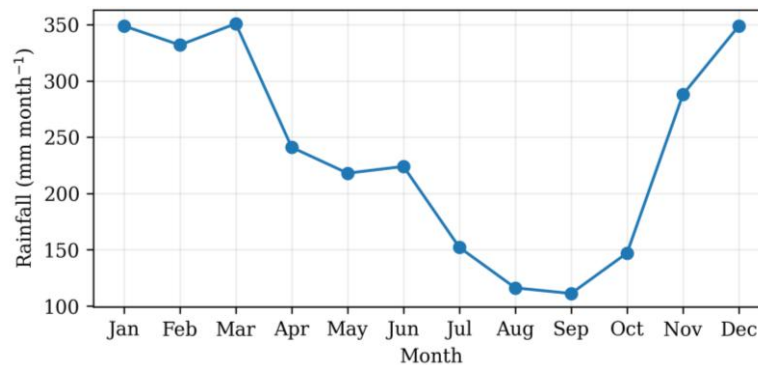


Fig. 1. Mean monthly rainfall in the study area during 2011-2024

The dataset further demonstrates that extreme monthly rainfall deficits can occur within an overall very wet climate. September 2015 recorded 0 mm rainfall, showing that the Type A classification does not preclude episodic severe rainfall deficits. This finding is particularly relevant to Central Kalimantan, where fire activity has been strongly associated with dry-season rainfall anomalies. Long-term fire-weather analysis for Central Kalimantan identified August–October as the principal fire period and showed that major fire years were associated with exceptionally low rainfall during these months; the 2015 El Niño year was particularly extreme (Hein et al., 2022; Horton et al., 2022). Consequently, the Type A classification should be interpreted as the prevailing climatic background, not as an assurance against anomalously dry conditions. For environmental management, the results support maintaining routine monitoring under the generally wet regime while increasing air-quality and fire-risk surveillance during rainfall-minimum periods and, especially, during anomalous departures from the established monthly climatology (Kurniadi et al., 2021).

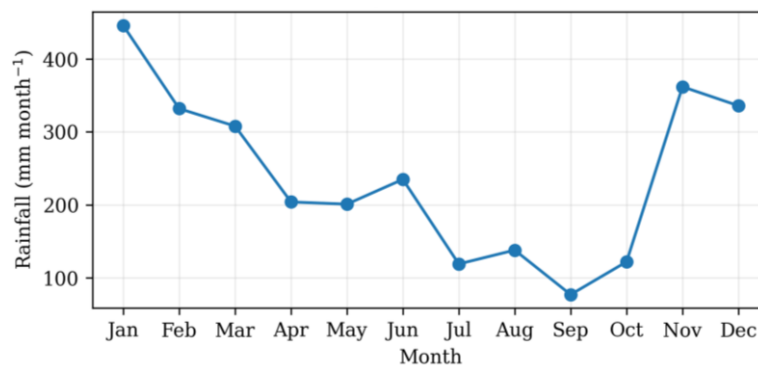


Fig. 2. Monthly rainfall in 2024 at the study coordinate

### 3.1.3 Temperature and relative humidity baseline

The 2-m air temperature regime was thermally stable. Mean annual temperature was 26.5 °C, with annual values ranging from 26.0 °C in 2011 to 27.2 °C in 2024. The narrow range indicates a typical humid tropical thermal environment with limited interannual variability compared with rainfall. At the monthly scale, the lowest mean temperature occurred in July at 25.8 °C, while the highest mean values occurred in October and November at 27.0 °C. This pattern places the warmest conditions after the rainfall minimum, a sequence that may contribute to drying pressure when rainfall is anomalously low.

The temperature baseline is relevant because air-quality risk in fire-prone tropical landscapes is often shaped by combinations of meteorological conditions rather than by temperature alone. Warm temperatures can increase evapotranspiration and accelerate drying of surface materials during periods of rainfall deficit. In a very wet climate, this effect may be modest during normal years, but it can become more important when rainfall is suppressed by regional climate variability. The October-November temperature peak, following the August-September rainfall minimum, therefore deserves attention in any seasonal fire-smoke preparedness framework.

Relative humidity was persistently high across the study period. Mean annual relative humidity was 88.4%, with interannual values ranging from 86.4% in 2015 to 89.5% in 2017 and 2021. Monthly humidity was highest in June at 90.2% and lowest in October at 84.9%. Even the lowest monthly mean remained high in absolute terms, confirming that the site is characterized by a moist near-surface atmosphere. This persistent humidity is consistent with the Type A climate classification and the high annual rainfall baseline.

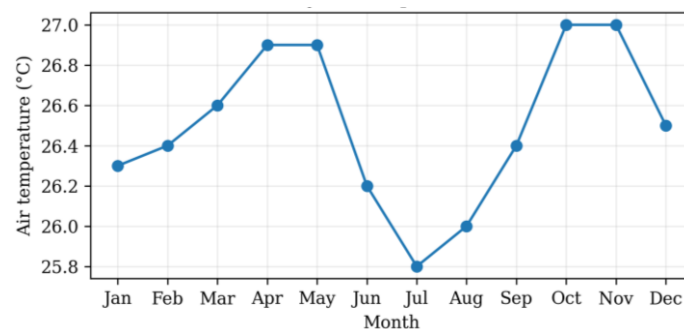


Fig. 3. Mean monthly 2-m air temperature in the study area during 2011-2024

The monthly humidity pattern complements the rainfall and temperature results. Humidity remained especially high from January to July, when rainfall was generally abundant and temperatures were moderate. It declined from August to October, coinciding with the rainfall minimum and the subsequent temperature peak. The October minimum in relative humidity, combined with high temperature, suggests a period when atmospheric and surface drying pressure may be relatively elevated. This does not necessarily mean that severe drying occurs every year, but it identifies the season in which rainfall anomalies could have stronger environmental consequences.

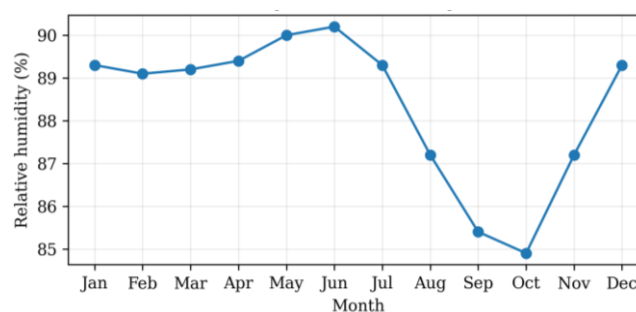


Fig. 4. Mean monthly relative humidity in the study area during 2011-2024

### 3.1.4 Wind direction, wind speed, and integrated indicators

Wind direction was dominated by the southeast and east sectors. For the full 2011-2024 monthly record, southeast winds accounted for 45.8% of observations and east winds accounted for 25.6%. Together, these two sectors represented 71.4% of monthly wind-direction records. In 2024, the concentration in these sectors was even stronger: southeast winds accounted for 50.0% and east winds for 33.3%, giving a combined share of 83.3%. This directional dominance is important for future monitoring because it indicates the

prevailing pathways along which smoke or local emissions may move under the gridded wind regime.

Wind speed was consistently very low. Monthly values ranged from 0.04 to 0.13 m s<sup>-1</sup>, with an overall mean of 0.088 m s<sup>-1</sup>. Such conditions indicate weak horizontal ventilation and may increase the persistence of locally emitted pollutants when atmospheric mixing is limited (Huang et al., 2015). Because near-surface dispersion is also sensitive to local roughness and source-receptor configuration, site-scale measurements are needed before the gridded values are used for detailed dispersion assessment (Lee & Mak, 2021).

The combined wind-direction and wind-speed results produce a clear air-quality baseline message. Directional dominance provides information about likely transport pathways, but the very low speed indicates that dilution may be limited. Therefore, future monitoring should not assume that pollutants will disperse rapidly away from sources. Instead, monitoring design should consider both upwind and downwind receptors, local activity zones, roads, settlement boundaries, and the possibility of stagnant episodes during the rainfall-minimum season. The wind baseline is especially important because gridded low-level winds can differ from local measurements; a site station would be needed to refine these findings. Figure 5 presents the directional distribution as a polar wind rose and places the reported monthly wind-speed statistics (0.04–0.13 m s<sup>-1</sup>; mean 0.088 m s<sup>-1</sup>) beside the rose, making the dominant southeast–east transport tendency and weak ventilation regime visually explicit.

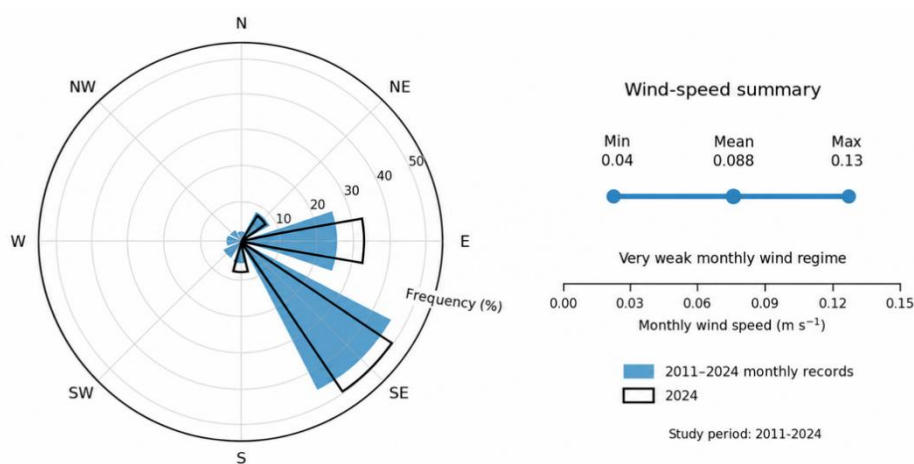


Fig. 5. Wind rose showing the frequency of monthly wind directions for 2011–2024, with the 2024 distribution overlaid, and a companion summary of monthly wind speed (range 0.04–0.13 m s<sup>-1</sup>; mean 0.088 m s<sup>-1</sup>). Radial values are frequency (%)

The monthly meteorological summary in Table 3 identifies a coherent seasonal transition: rainfall declines during August–September, temperature rises toward October–November, and relative humidity reaches its minimum in October. Rather than representing independent signals, these changes jointly define the period in which wet removal is weaker and drying pressure is relatively greater. This seasonal window should therefore receive particular attention in future air-quality sampling.

Table 3. Summary of monthly meteorological baseline values, 2011–2024

| Month     | Rainfall (mm) | Air temperature (°C) | Relative humidity (%) |
|-----------|---------------|----------------------|-----------------------|
| January   | 349           | 26.3                 | 89.3                  |
| February  | 332           | 26.4                 | 89.1                  |
| March     | 351           | 26.6                 | 89.2                  |
| April     | 241           | 26.9                 | 89.4                  |
| May       | 218           | 26.9                 | 90.0                  |
| June      | 224           | 26.2                 | 90.2                  |
| July      | 152           | 25.8                 | 89.3                  |
| August    | 116           | 26.0                 | 87.2                  |
| September | 111           | 26.4                 | 85.4                  |

|          |     |      |      |
|----------|-----|------|------|
| October  | 147 | 27.0 | 84.9 |
| November | 288 | 27.0 | 87.2 |
| December | 349 | 26.5 | 89.3 |

(NASA POWER, n.d.)

Table 4 translates the meteorological findings into air-quality implications. The very wet climate suggests frequent wet removal of particles, but the September rainfall minimum indicates a period of reduced scavenging. The mean annual temperature confirms warm tropical conditions that can contribute to drying during rainfall deficits. The high relative humidity can modify particulate behavior and visibility. The very low wind speed indicates weak ventilation, and the dominant southeast-eastern wind sectors identify directions that should be considered when selecting monitoring locations. Collectively, these indicators show that the site is not simply wet; it is wet, humid, warm, and poorly ventilated, with a recurring seasonal window of lower rainfall.

Table 4. Key meteorological indicators relevant to air-quality interpretation

| Indicator               | Result                                                  | Air-quality implication                                                                           |
|-------------------------|---------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Climate type            | Type A; very wet (Q = 8.16)                             | Frequent rainfall supports wet removal of particles but does not remove episodic dry-season risk. |
| Mean annual rainfall    | 2,878 mm yr <sup>-1</sup>                               | High annual rainfall indicates generally humid baseline conditions.                               |
| Rainfall minimum        | September; 111 mm month-1 long-term mean; 77 mm in 2024 | Lower wet scavenging and potentially greater smoke/dust persistence.                              |
| Mean annual temperature | 26.5 °C                                                 | Warm tropical conditions may increase drying pressure during rainfall deficits.                   |
| Mean relative humidity  | 88.4%                                                   | High humidity can influence particle growth and visibility reduction.                             |
| Mean wind speed         | 0.088 m s <sup>-1</sup>                                 | Weak ventilation may favor near-surface pollutant accumulation.                                   |
| Dominant wind sectors   | SE 45.8% and E 25.6% of monthly records                 | Direction of potential pollutant transport should be considered in future monitoring design.      |

The numerical separation between dry, humid, and wet months also confirms that the site has a strongly asymmetric rainfall regime. Dry months represent a small fraction of the record, while wet months dominate most annual cycles. This pattern means that water availability is generally high, but it also makes the few low-rainfall months disproportionately important for environmental interpretation. When rare dry or humid months occur, they represent departures from the prevailing wet background and may produce air-quality conditions that differ sharply from the annual average.

Interannual rainfall variability is also relevant for baseline assessment. The difference between the wettest year, 2020, and the driest year, 2023, was 1,620 mm. This difference is larger than the annual rainfall total in many drier regions and shows that the site can move between very wet and comparatively less wet annual states while remaining within a humid tropical category. For environmental monitoring, such variability means that a single year of observation should not be treated as fully representative without comparison to a multi-year baseline.

The monthly sequence in 2024 demonstrates why annual totals alone are insufficient for environmental interpretation. Although annual rainfall was close to the long-term mean, a distinct September minimum remained evident. This contrast supports sampling designs

that compare high-rainfall conditions with the rainfall-minimum season instead of relying on a single annual monitoring campaign.

The integrated timing of rainfall, temperature, and humidity points to August-October as the most important seasonal window for future air-quality assessment. During this period, rainfall is near its annual minimum, relative humidity declines, and temperature rises toward its annual peak. These variables do not operate independently. Reduced rainfall lowers wet deposition, lower humidity changes aerosol water uptake, and warmer conditions can intensify drying pressure. When combined with weak winds, these conditions provide a plausible meteorological setting for greater pollutant persistence.

### 3.2 Discussion

#### 3.2.1 Climate classification and annual rainfall context

The Type A Schmidt-Ferguson classification is best interpreted as a description of the long-term rainfall regime, rather than as evidence that short periods of atmospheric or landscape stress are unlikely. This distinction is particularly important in Central Kalimantan. Susilo et al. (2013), using a longer rainfall record from tropical peatland areas in the province, showed that ENSO significantly modifies rainfall characteristics and that El Niño exerts a stronger influence on rainfall reduction than La Niña. The present baseline therefore complements, rather than contradicts, earlier regional studies; a location can remain climatologically very wet while still experiencing episodic rainfall anomalies that are environmentally important.

The relevance of these rainfall anomalies becomes clearer when rainfall deficits are considered together with peatland hydrology and fire processes. (Field et al., 2009; Yokelson et al., 2022) found a nonlinear relationship between dry-season precipitation and Indonesian fire activity and smoke pollution, with fire and pollution increasing rapidly when prolonged dry-season precipitation fell below approximately 4 mm day<sup>-1</sup>; the sensitivity was particularly evident over Kalimantan. Taufik et al. (2017) further demonstrated that hydrological drought amplified wildfire area in the humid tropics of Borneo, highlighting the importance of subsurface hydrological processes in addition to meteorological drought indicators. More recent modelling by Mezbahuddin et al. (2023) showed that incorporating soil-moisture and water-table dynamics substantially improved fire-activity predictions compared with weather variables alone, indicating that meteorological conditions do not fully represent the hydrological controls on tropical fire susceptibility. Thus, the environmental consequence of a rainfall deficit depends not only on the amount of precipitation received, but also on antecedent hydrological conditions, soil and peat moisture, water-table dynamics, land management, and the persistence of dry conditions.

Compared with these event-based and process-oriented studies, the contribution of the present analysis is to define the meteorological envelope within which such environmentally sensitive conditions may emerge at the study site. The results do not demonstrate that drought, fire, or elevated pollutant concentrations occurred whenever rainfall declined; rather, they identify departures from the dominant wet background that warrant greater attention in subsequent environmental monitoring. This distinction is important because climate classification, meteorological drought, hydrological drought, fire occurrence, and air-pollution responses operate at different temporal and spatial scales. The need to distinguish meteorological conditions from hydrological responses is supported by Mezbahuddin et al. (2023), who showed that water-table depth and near-surface soil moisture provide information that cannot be fully captured by weather variables alone. Similarly, Sulaiman et al. (2023) demonstrated that peatland groundwater dynamics in Central Kalimantan exhibit temporal relationships with ENSO and positive Indian ocean dipole (IOD) events, further indicating that rainfall anomalies should be interpreted within a broader hydroclimatic system.

For environmental assessment, this means that a single annual rainfall total or climate-class label should not be used as the sole meteorological context for interpreting air-quality measurements. Future assessments would be more robust if pollutant concentrations were interpreted together with seasonal rainfall anomalies, ENSO conditions, and, where possible, peat-water-table or soil-moisture information. Such an approach would allow the baseline to function as a risk-stratification framework rather than as a deterministic predictor of air quality.

### *3.2.2 Monthly rainfall regime and 2024 pattern*

The main significance of the monthly rainfall pattern is not simply the occurrence of a lower-rainfall period, but the concentration of reduced wet-scavenging potential within an otherwise humid annual regime. Precipitation is an important atmospheric removal pathway for particulate matter, although its effectiveness depends on rainfall amount, frequency, intensity, duration, particle characteristics, and the prevailing aerosol burden (Ge et al., 2021; Huang et al., 2015). Evidence from tropical and subtropical environments further indicates that rainfall seasonality can substantially modify the efficiency of particulate removal, while short or weak rainfall events may produce limited scavenging despite relatively high seasonal rainfall totals (Kurniadi et al., 2021; Plocoste et al., 2023; Susilo et al., 2013). This seasonal sensitivity is particularly relevant to Central Kalimantan because Indonesian fire activity and smoke pollution have demonstrated strong sensitivity to prolonged dry conditions, especially during El Niño-associated droughts (Field et al., 2016, 2009). In Central Kalimantan specifically, Yulianti et al. (2020) reported that high hotspot densities during the 2006–2019 period were concentrated in several peatland areas, including Kapuas, while the severe 2015 fire episode was accompanied by substantial deterioration in visibility and PM<sub>10</sub>-related air pollution. The agreement between these regional observations and the seasonal rainfall structure identified in the present baseline gives the rainfall-minimum period greater relevance for local air-quality monitoring, although it does not establish that elevated pollution occurred at the study site during every rainfall-minimum month.

Reduced rainfall can influence air quality through at least two interacting pathways. First, fewer or less effective rainfall events can reduce wet removal of suspended particles from the atmosphere, thereby potentially increasing particle persistence when emissions are present (Ge et al., 2021; Huang et al., 2015). Second, prolonged rainfall deficits can reduce landscape moisture and increase the susceptibility of combustible surface materials and peat to drying, thereby increasing the potential for biomass-burning emissions when ignition sources are present. Field et al. (2009) demonstrated a nonlinear response of Indonesian fire activity and smoke pollution to prolonged dry-season conditions, particularly over Kalimantan, while Taufik et al. (2017) showed that hydrological drought amplified wildfire area in the humid tropics of Borneo. The latter finding is particularly important because meteorological rainfall deficits do not immediately translate into equivalent hydrological stress; antecedent moisture conditions and subsurface water storage can influence how long the landscape remains susceptible after rainfall declines. Thus, the rainfall minimum identified in the present study should be understood as a meteorologically sensitive period, rather than as a direct measure of fire danger or pollutant concentration.

The 2024 rainfall sequence is useful primarily because it illustrates a scale problem; an annual rainfall total close to the multi-year mean can coexist with a substantially drier seasonal interval. Such temporal aggregation can obscure short periods during which atmospheric removal conditions differ markedly from the annual background. Evidence from aerosol–precipitation studies shows that wet-scavenging efficiency varies substantially with rainfall characteristics and season, meaning that the occurrence of rainfall alone does not necessarily imply efficient particulate removal (Kurniadi et al., 2021; Plocoste et al., 2023; Susilo et al., 2013). This supports the use of seasonal rather than annual-only sampling strategies when the objective is to characterize meteorological

controls on air quality. At the same time, the present study does not contain synchronized PM, fire-hotspot, or smoke observations for 2024; consequently, the rainfall minimum should be interpreted as a period of increased meteorological susceptibility, rather than as evidence that pollutant concentrations were necessarily elevated during that year. This distinction is essential because the relationship between rainfall and observed PM can be non-linear and depends on both atmospheric removal and contemporaneous emission processes (Kurniadi et al., 2021; Ridahwati, 2021; Wang & Hocke, 2022).

A stronger monitoring design would therefore use contrast-based seasonal sampling, with measurements collected during both high-rainfall and rainfall-minimum conditions and interpreted alongside contemporaneous rainfall, wind speed and direction, relative humidity, and relevant source activity. Such an approach would help distinguish whether changes in pollutant concentrations arise primarily from variations in emissions, atmospheric removal, dispersion, or a combination of these processes. The importance of this integrated approach is supported by evidence that rainfall characteristics control wet scavenging while hydrological conditions influence fire susceptibility at longer temporal scales (Braud et al., 2013; Niemczynowicz, 1999; Treby et al., 2026). In Central Kalimantan, where fire-related smoke episodes have historically coincided with pronounced dry-season anomalies, incorporating seasonal rainfall indicators with fire and air-quality observations would provide a more informative basis for environmental assessment than relying on annual rainfall totals alone. Seasonal pairing would therefore provide a more defensible basis for environmental management while avoiding the unsupported assumption that every rainfall-minimum period necessarily produces elevated air pollution.

### *3.2.3 Temperature and relative humidity baseline*

The relatively narrow temperature range observed in the present baseline indicates that temperature alone is unlikely to explain major temporal changes in air-quality susceptibility at the study site. Its interpretive value lies instead in its seasonal timing relative to rainfall and relative humidity. Warmer conditions occurring after the rainfall minimum may increase evaporative demand and contribute to surface drying when water availability is reduced, while the concurrent decline in relative humidity indicates a transition away from the persistently moist atmospheric background. In tropical peatland environments, the environmental significance of such meteorological combinations is greater when rainfall deficits are sufficiently prolonged to influence soil and groundwater conditions, rather than being inferred from temperature alone (Sulaiman et al., 2023; Taufik et al., 2017). Therefore, the August–October transition identified in the present baseline is more appropriately interpreted as a meteorologically sensitive period for fire-smoke preparedness than as evidence that the absolute temperature maximum itself creates elevated fire or pollution risk.

Previous field studies in Central Kalimantan also show why humidity should be interpreted in relation to aerosol composition rather than as a simple indicator of pollution intensity. Stockwell et al. (2016) documented complex trace-gas and aerosol emissions from peat fires during the 2015 El Niño, and Jayarathne et al. (2018) found that peat-fire PM<sub>2.5</sub> was dominated by organic carbon with a large water-insoluble fraction. These findings imply that the response of smoke particles to ambient moisture can vary with composition; consequently, high relative humidity should not be assumed to produce a uniform change in particulate mass or visibility.

The present monthly analysis therefore provides a climatic context for aerosol behavior but cannot resolve the short-term processes that determine exposure. In a different Indonesian setting, Istiana et al. (2023) showed that PM<sub>2.5</sub>-meteorology relationships in Jakarta varied with hour-specific atmospheric conditions, including early-morning thermal inversion. Although the source environment differs from Kapuas, that study demonstrates the importance of temporal resolution and reinforces that monthly temperature and humidity means are more suitable for baseline screening than for explaining individual pollution episodes.

Future monitoring should combine hourly or sub-hourly temperature and relative-humidity measurements with PM<sub>2.5</sub>, PM<sub>10</sub>, visibility, and, where feasible, aerosol composition. This would make it possible to test whether the August-October meteorological transition identified here is accompanied by changes in particle concentration, optical properties, or smoke persistence. The current results identify when such targeted observations would be most informative, but they do not substitute for direct aerosol measurements.

### *3.2.4 Wind direction, wind speed, and integrated indicators*

The most important implication of the wind analysis is the indication of weak background ventilation, but the absolute gridded wind-speed values should be interpreted cautiously. Near-surface wind is highly sensitive to roughness, vegetation, canals, clearings, buildings, and source-receptor geometry, whereas NASA POWER represents conditions over a much larger grid cell and the present analysis uses monthly aggregation. The wind results are therefore more reliable as indicators of a generally low-ventilation regime than as precise estimates of wind speed at individual receptors.

This scale dependence is consistent with Lee & Mak (2021), who showed that changes in incident wind direction and local physical configuration can substantially alter low-wind zones and pollutant dispersion. Their urban building setting differs from the plantation-lowland environment considered here, but the underlying implication is transferable: local geometry can modify the regional wind signal. Accordingly, the southeast-east directional dominance identified in the present study is useful for initial receptor placement, but it should not be treated as a fixed site-scale transport pathway without local validation.

The interaction between weak ventilation and rainfall seasonality is more informative than either parameter considered alone. During wetter periods, rainfall can provide an important particle-removal pathway even when horizontal dispersion is limited. During the rainfall minimum, that compensating removal mechanism weakens, so local emissions or transported smoke may persist longer if atmospheric mixing also remains weak. This interpretation is consistent with regional studies showing substantial particulate contributions from vegetation and peat fires in Southeast Asia (Reddington et al., 2014) and with in-situ evidence of high PM<sub>2.5</sub> emissions from Central Kalimantan peat combustion (Jayarathne et al., 2018).

The combined evidence supports a monitoring strategy that pairs on-site wind measurements with upwind and downwind pollutant observations, source-activity records, and fire-hotspot information. Such data would help distinguish local accumulation from regional smoke transport and would test whether the gridded southeast-east pattern persists at receptor height. Until that validation is available, the present wind baseline should be regarded as a screening tool for monitoring design rather than as a dispersion model or predictor of receptor-level concentrations.

## **4. Conclusions**

The PT X study area in Kapuas Regency is characterized by a Type A very wet climate according to the Schmidt-Ferguson method, with a Q index of 8.16, mean annual rainfall of approximately 2,878 mm, persistently high relative humidity, warm tropical temperatures, and very weak wind speeds. The results show that abundant rainfall supports wet removal of particles during much of the year, but the July to October rainfall minimum, particularly September, represents a seasonal window when wet scavenging is reduced. The October-November temperature peak and the August-October humidity decline further indicate a period of relatively higher drying pressure. At the same time, the mean wind speed of 0.088 m s<sup>-1</sup> suggests limited atmospheric ventilation and a potential for near-surface pollutant accumulation. These findings provide a site-specific meteorological baseline for designing future air-quality monitoring, selecting sampling periods, positioning receptors, and interpreting pollutant measurements in a humid tropical lowland. Future work should

integrate direct pollutant monitoring, on-site meteorological validation, emission inventories, land-cover analysis, and peat hydrology indicators to strengthen environmental assessment and sustainable management.

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### **Author Contribution**

Conceptualization, W.A.; methodology, L.S.; formal analysis, N.U. and N.S.; data curation, N.S.; writing - original draft preparation, A.A.; writing - review and editing, L.S. and N.U.; visualization, N.S.; supervision, W.A.; project administration, W.A. All authors have read and agreed to the submitted version of the manuscript.

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