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Assessment of Particulate Matter Concentration and Metal Content in an Urban Area of Makassar, Indonesia

Sattar Yunus[1]*, Ismail Marzuki[2], Mardiyyah Hasnawi[3], Muh. Ilham Anggamulia[1]

[1] Department of Environmental Engineering, Faculty of Engineering, Universitas Muslim Indonesia, Indonesia

[2] Department of Chemical Engineering, Faculty of Engineering, Universitas Fajar, Indonesia

[3] Department of Computer Science, Faculty of Computer Science, Universitas Muslim Indonesia, Indonesia

***Corresponding author:** sattar.teknik@umi.ac.id

Atmospheric particulate matter poses significant risks to the environment and human health, depending on its mass concentration and chemical composition. This study aims to quantify the mass concentrations of total suspended particles (TSP) and particulate matter with an aerodynamic diameter of less than 10 µm (PM_{10}), as well as to determine their elemental composition. Particulate samples were collected from three ambient air monitoring sites within the City of Makassar, the capital of South Sulawesi Province, during the peak dry season (May to September 2025). The measured concentrations of PM_{10} and TSP were evaluated against the Primary Impact Zone (PIA) standards of the Indonesian Air Quality (IAQ) guidelines. A high-volume air sampler (HVAS) was employed to collect particulate samples, and gravimetric analysis was conducted to determine their mass concentrations. The elemental composition of the particles was analyzed using scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS). The mean concentrations of PM_{10} and TSP were 34.20 µg/m^3 and 73.22 µg/m^3, respectively. The findings indicate that the mean mass concentrations of both TSP and PM_{10} were below the Indonesian regulatory standards, although temporal and spatial variations were observed. The identified elemental constituents included Al, Ca, K, Na, Rb, and Sr, suggesting contributions from crustal sources. These results provide valuable insights into the characteristics of particulate matter in residential areas of Makassar and support the development of improved, source-oriented air quality management strategies.

Keywords: particulate matter, ambient, metals, HVAS, SEM-EDS.

Introduction

Air pollution is a major global environmental issue affecting both developed and developing countries, driven by rapid urbanization, industrialization, and the expansion of transportation systems (Warmadewanthi et al., 2025; Zahra et al., 2024). In Asia, many developing countries are experiencing accelerated urban growth, which has intensified air pollution levels and increased associated health risks. The inhalation of particulate matter has been linked to lung inflammation, impaired pulmonary function, cardiovascular diseases, and premature mortality, particularly in densely populated urban environments (Manucci and Franchini, 2017; Saini et al., 2018; Sattar et al., 2020). Urbanization further increases reliance on personal and public transportation, leading to higher emissions and pollutant accumulation that may exceed the atmosphere's natural self-cleansing capacity (Bralewska, 2024; Manisalidis et al., 2020; Yunus et al., 2024; Chen et al., 2023). Particulate matter (PM), also known as atmospheric aerosols, consists of solid and liquid particles suspended in the air originating from both natural and anthropogenic sources. These particles may be directly emitted (primary particles) or formed through chemical transformations in the atmosphere (secondary particles) (Sattar et al., 2021). The health impact of particulate matter is strongly influenced by its chemical composition, particularly the presence of trace metals that can induce oxidative stress and inflammatory responses in human tissues. Therefore, understanding both the mass concentration and chemical composition of particulate matter is essential for accurately assessing environmental and health risks.

Despite the widespread implementation of air quality monitoring systems, most monitoring efforts primarily focus on measuring particulate mass concentrations, which limits the ability to identify pollution sources and evaluate associated risks comprehensively. Air quality data are also highly influenced by temporal and meteorological variations, such as climate conditions, which further complicate the interpretation of pollutant behavior (Sattar et al., 2021). Consequently, effective air pollution management requires not only concentration measurements but also detailed compositional analysis to enable accurate source identification and risk assessment.

A number of previous studies have identified high concentrations of particulate matter with different chemical characteristics in Makassar, a fast-growing urban area in Indonesia. These studies, however, have predominantly focused on specific components and only indirectly assessed particulate composition in residential areas where long-term human exposure plays the most important role. These constraints lead to a partial view of the sources and health impact of pollution in the Makassar city particulate-bound metals are also on the rise, and their contributions to urban air quality have emerged as a critical issue especially in areas with intensive industrial and transport activities. Apportioned by mobile and stationary sources, total suspended particles (TSP) and PM_{10} can carry different type of metal elements with diverse level of toxicity (Sattar et al., 2014; Lu et al., 2024). Although indicative studies relating particulate mass concentration with specific elemental composition in Makassar are much needed, these are still scarce, leading to a critical research gap.

Therefore, this study aims to characterize the mass concentrations and elemental composition of TSP and PM_{10} in urban residential areas of Makassar. This research integrates gravimetric analysis with Scanning Electron Microscopy–Energy Dispersive Spectroscopy (SEM–EDS) to provide a comprehensive assessment of particulate matter characteristics. The findings are expected to contribute to a better understanding of particulate sources, support evidence-based air quality management, and strengthen the development of targeted environmental policies in rapidly urbanizing regions.

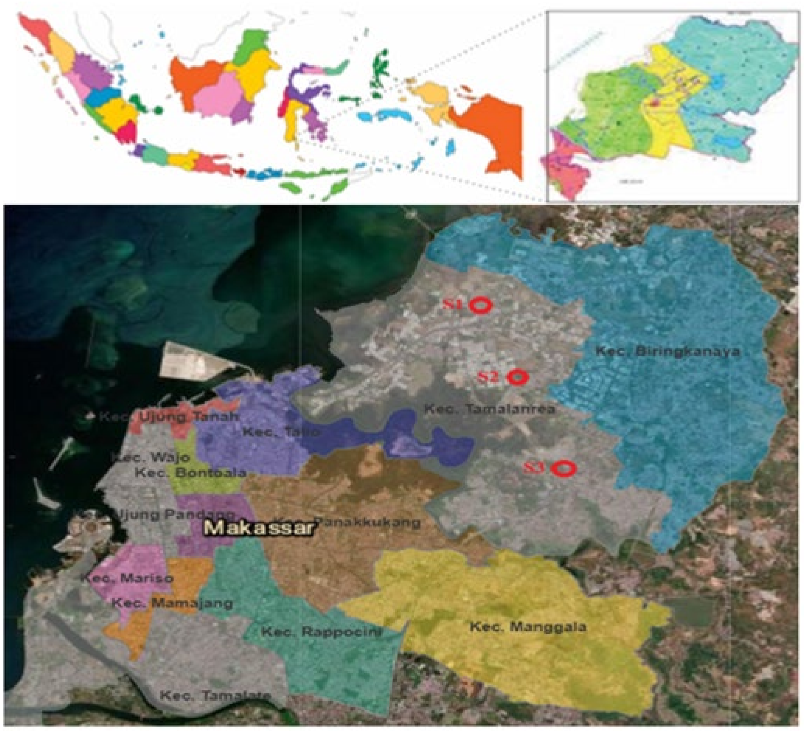
Materials and Methods

Sampling site description

Makassar City is the capital of South Sulawesi Province, Indonesia. As one of Indonesia's 38 provinces, South Sulawesi has Makassar as its administrative and economic center. Makassar City is bordered by Maros Regency to the north and east, the Makassar Strait to the west, and Gowa Regency to the south (Sattar et al., 2014). The city covers an area of 175.77 km^2 and is administratively divided into 15 districts. Makassar is one of the most densely populated and rapidly growing cities in Indonesia (Surya et al., 2021). As projected for 2024, the population is approximately 1.48 million inhabitants, reflecting a significant increase over recent years. Over the past five years, however, the compound annual growth rate (CAGR) has decreased to 0.65%, compared with 1.08% during the preceding five-year period. Makassar has the highest population among cities and regencies in South Sulawesi Province and is also the most populous city on Sulawesi Island. The city hosts approximately 145 industrial sectors, including basic metals, fabricated metal products, chemicals and chemical products, food and beverages, textiles and apparel, and wood and wood products, among others.

Rapid urban development and expanding industrial activity have contributed to deteriorating air quality in Makassar (Surya et al., 2021). Recent reports indicate a substantial increase in vehicle usage. In 2024, the total number of registered vehicles reached 2,110,601 units, among them 1,651,082 motorcycles, 100,364 buses, and 403 special-purpose vehicles (Sattar et al., 2014). The high volume of vehicles, combined with urbanization and industrialization, has resulted in persistent traffic congestion and increased vehicular emissions, which negatively affect urban air quality and public health. Personal vehicles (353,070 units) and freight vehicles (17,306 units) also contribute significantly to traffic density and emissions in the city. This study focused on urban residential areas located near major traffic corridors. Three sampling sites were selected: Citra Land Tallasa City (S1), Tamalanrea Bumi (S2), and Baruga Hills (S3). These locations are connected by Tarakan Street, an arterial road characterized by high traffic volume and considered one of the main transportation routes in Makassar City. Although three sampling sites may not fully represent the entire city's traffic conditions, the selected locations were considered representative of high vehicular emission exposure. All sampling sites are situated adjacent to densely populated residential areas, enabling assessment of particulate matter exposure in environments directly relevant to human health. The proximity of heavy traffic to residential zones allows for evaluation of the mass concentration and metallic constituents of ambient TSP and PM_{10} under real urban exposure conditions. The selected sampling points were designed to capture spatial variability along a high-activity urban corridor in Makassar City. The locations of the sampling sites are presented in *Fig. 1*.

Fig. 1. *Sampling sites in Makassar city*



Data collection

Sampling for TSP and PM_{10} was conducted over a six-month period, twice per week, from May to September 2025 in residential areas of the City of Makassar. Sampling was carried out on the same weekdays and the same weekend days each week to record and analyze potential differences in traffic volume and emissions between weekdays and weekends. The selected sampling days were intended to capture low, medium, and high levels of human activity and traffic flow in order to assess the possible effects of traffic variation on particulate concentrations. On each sampling day, 24-hour ambient air samples were collected. Each sampling period began at 08:00 and ended at 08:00 the following day to ensure consistency across all measurements. A High-Volume Air Sampler (HVAS) was installed at a height between 1.5 and 2.0 meters above ground level, corresponding to the typical human breathing zone. The HVAS was calibrated according to the manufacturer's recommendations prior to field deployment. The flow rate was checked before and after each sampling event to ensure stability and reliability.

Prior to sampling, filter media were preconditioned and pre-weighed under controlled laboratory conditions. Gravimetric analysis was used to determine mass concentrations. All filter conditioning and weighing procedures were performed using calibrated analytical balances in a controlled laboratory environment to minimize measurement uncertainty. Ambient air samples for TSP and PM_{10} were collected using the HVAS and analyzed using the gravimetric method. All sampling procedures were conducted in accordance with Indonesian National Standards (SNI) for TSP and PM_{10} measurement. Heavy metal content in TSP and PM_{10} samples was analyzed using Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy (SEM-EDS). For SEM-EDS analysis, representative portions of each filter (approximately 1 cm × 1 cm) were cut and mounted onto aluminum stubs using conductive carbon tape. To prevent charging effects during imaging and elemental analysis, samples were coated with a thin conductive layer. The SEM-EDS system was calibrated using certified reference materials prior to analysis. Elemental analysis was conducted under high vacuum conditions, with an accelerating voltage of 15–20 kV and a working distance of approximately 10 mm. To ensure representative elemental characterization, multiple randomly selected fields of view were examined for each sample. Elemental composition was calculated in both weight and atomic percentages using built-in software with atomic number, absorption, and fluorescence (ZAF) correction. Only elements with spectral peaks clearly above background levels were interpreted. All laboratory analyses were conducted by qualified personnel in a university laboratory accredited for environmental monitoring.

Statistical analysis

To evaluate differences in particulate concentrations among the three sampling sites (S1, S2, and S3), one-way analysis of variance (ANOVA) was performed at a 95% confidence level ($\alpha = 0.05$). Prior to ANOVA, assumptions of normality and homogeneity of variance were tested using the Shapiro–Wilk test and Levene's test, respectively. If the assumption of normality was violated, the nonparametric Kruskal–Wallis test was applied as an alternative. A p-value ≤ 0.05 was considered statistically significant. All statistical analyses were conducted using IBM SPSS Statistics version 27. OriginPro software was used for data processing and graphical presentation.

Results and Discussion

Results

Table 1 presents the TSP and PM_{10} concentrations collected from the ambient air at Tallasa City Street, Perintis Kemerdekaan Street, and Dokter Leimena Street. The table also includes spatial meteorological parameters recorded during the sampling period from May to September 2025. *Fig. 2* illustrates the data distribution.

TSP concentrations ranged from 62.40 to 126.00 μg/m^3, with a mean value of 73.39 μg/m^3 (see *Fig. 2*). These

Table 1. *Descriptive statistics of particulate concentrations and meteorological parameters for all sites in Makassar (May–September 2025)*

Parameter	Mean	SD	Minimum	Maximum
TSP (μg/m^3)	73.39	85.60	62.40	126.00
PM_{10} (μg/m^3)	34.20	16.90	20.60	85.72
Relative Humidity (%)	77.30	18.30	56.10	91.30
Temperature (°C)	31.13	5.40	27.60	33.70
Wind speed (m/s)	2.60	0.90	0.00	7.07

variations likely reflect differences in anthropogenic activities across sampling locations. PM_{10} had a mean concentration of 34.20 µg/m^3 and a maximum value of 85.72 µg/m^3 (see *Fig. 2*). The maximum value exceeded the Indonesian 24-hour ambient air quality standard of 75 µg/m^3, as stipulated in Government Regulation No. 22/2021. This comparison is valid because all samples were collected over 24-hour periods. According to the World Health Organization (WHO) Air Quality Guidelines, the recommended 24-hour mean limit for PM_{10} is ≤ 45 µg/m^3 (WHO, 2021). Thus, the observed peak concentration exceeded both national and international standards, indicating potential health risks during high pollution events. Although the mean PM_{10} concentration remained below regulatory limits, these exceedances suggest episodic air quality deterioration. The mean relative humidity was 77.3%, and the temperature ranged from 27.6 to 33.7°C, reflecting typical tropical conditions. The mean wind speed was 2.6 m/s (see *Fig. 2*), indicating limited dispersion capacity, while higher wind speeds (up to 7.07 m/s) may have enhanced pollutant dispersion at certain times. Overall, particulate matter concentrations were influenced by both anthropogenic activities and meteorological conditions, particularly wind speed, which regulates pollutant accumulation and dispersion (Krishan et al., 2019).

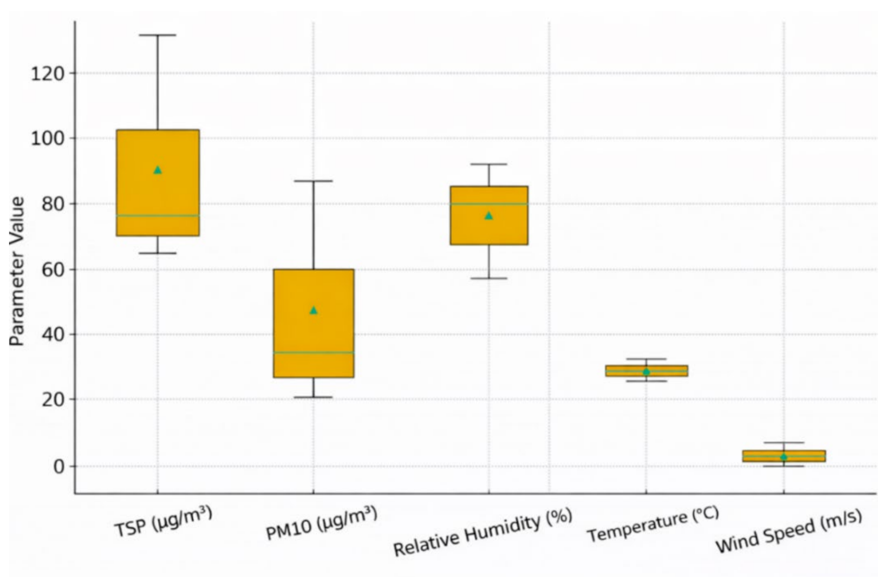
SEM-EDS analysis was conducted on TSP samples collected at sampling locations S1, S2, and S3. The mean concentrations of detected elements are presented in *Table 2*.

Table 2. *Mean concentration of metal elements detected in TSP*

Elements	S1 (µg/m^3)	S2 (µg/m^3)	S3 (µg/m^3)
TSP	72.28	75.55	71.82
Al	0.8264	0.8536	0.8319
Ca	0.7153	0.8214	0.7834
K	0.8328	0.9162	0.0851
Na	0.8533	0.8926	0.7138
Rb	0.0546	0.0945	0.0838
Sr	0.0623	0.0824	0.0782

The logarithmic bar chart illustrates the variation in TSP and elemental concentrations (aluminum (Al), calcium (Ca), potassium (K), sodium (Na), rubidium (Rb), and strontium (Sr)) across the three sampling sites. TSP concentrations ranged from approximately 71 to 76 µg/m^3, which is consistent with typical urban ambient levels reported in similar studies (Zhang et al., 2025). Although TSP levels were relatively uniform across sites, S2 exhibited a slightly higher mean concentration

Fig. 2. *Distribution of particulate matter (TSP and PM_{10}) and meteorological parameters across sampling sites*



(75.55 μg/m^3), suggesting stronger anthropogenic influence or localized emission sources (Petrov et al., 2023). In contrast, elemental concentrations were substantially lower than total TSP levels. Major elements (Al, Ca, K, Na) ranged between approximately 0.7 and 0.9 μg/m^3, while trace elements (Rb and Sr) were below 0.1 μg/m^3. Site-specific differences were observed. Potassium (K) levels were notably higher at S2, potentially indicating contributions from biomass burning or vehicular emissions (Li et al., 2021). Sodium (Na) concentrations were higher at S1 and S2, suggesting influences from marine aerosols and resuspended road dust (Galatioto et al., 2022). Aluminum (Al) and calcium (Ca) showed relatively consistent concentrations across sites, indicating a dominant crustal origin.

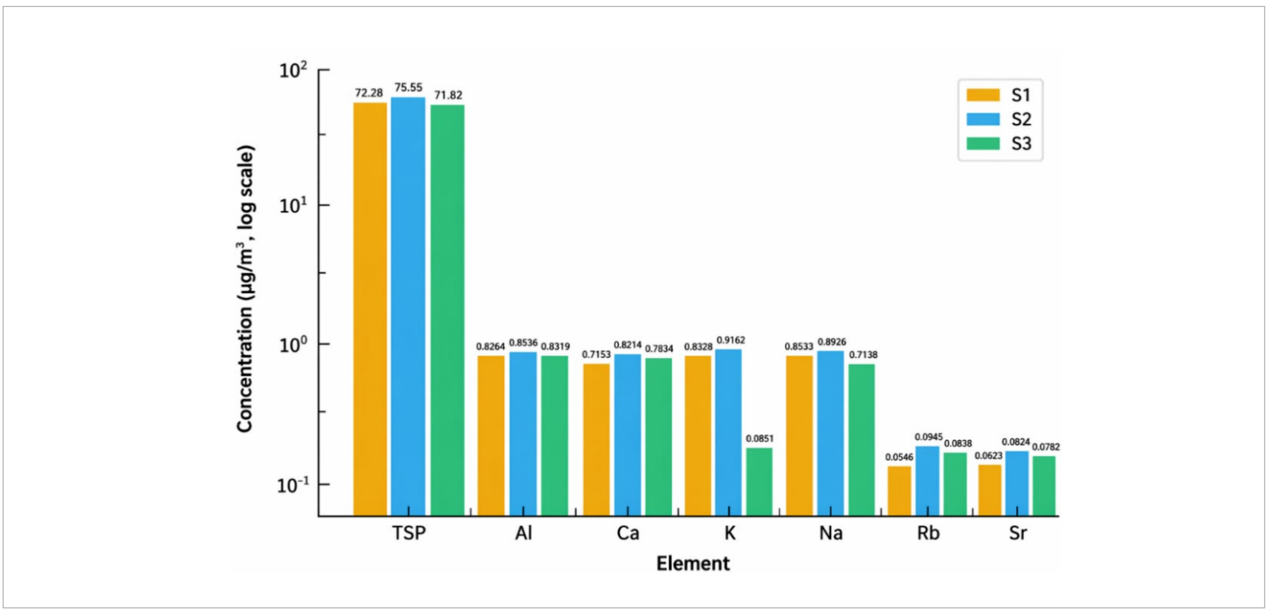
Fig. 3 shows that, for most parameters, S2 exhibited the highest values, suggesting the presence of a localized source that may explain the elevated particulate concentrations in this area. The use of a logarithmic scale was essential to distinguish between the bulk concentrations of TSP and the trace elements. This emphasizes the importance of investigating not only total particulate matter but also its chemical constituents for accurate source apportionment and health risk assessment. The EDS (energy dispersive spectroscopy) analyses conducted on all PM_{10} samples collected from sampling sites S1, S2, and S3 are presented in *Table 3*, showing the mean concentration of the detected elements per sample.

Table 3. *Mean concentration of metal elements detected in* PM_{10}

Elements	S1 (μg/m^3)	S2 (μg/m^3)	S3 (μg/m^3)
PM_{10}	35.26	34.23	33.12
Al	0.5207	0.4133	0.3628
Ca	0.5821	0.5512	0.4865
K	0.6219	0.6118	0.4552
Na	0.3153	0.2916	0.2865
Rb	0.0773	0.0226	0.0545
Sr	0.0524	0.0423	0.0393

The distribution of PM_{10} and its elemental constituents (Al, Ca, K, Na, Rb, and Sr) was evaluated across three sampling sites and is presented in the logarithmic bar graph. PM_{10} was the dominant component, ranging from 33 to 36 μg/m^3. These values are consistent with previously reported PM_{10} concentrations in urban environments near the sampling locations (Pongpiachan et al., 2017; Rapalis et al., 2021). Although PM_{10} concentrations were relatively similar across the three sites, variations were observed in the elemental composition. Major elements (Al, Ca, K, and Na) were generally below 1 μg/m^3, while trace elements (Rb and Sr)

Fig. 3. *Mean concentration of elements at sampling sites (log scale)*



were below 0.1 μg/m^3. Ca and K were the dominant elements at S1 and S2, likely associated with soil dust resuspension or fuel combustion processes (Zhu et al., 2024; Das et al., 2024). Na concentrations were relatively uniform across all three sites, suggesting a regional source such as marine aerosols or long-range transport of urban dust (Chianese et al., 2022; Liu et al., 2025). The consistently elevated Al concentrations across all sites indicate a predominantly natural origin, most likely derived from soil particles (Boreddy et al., 2021; Spencer et al., 2022). The logarithmic scale clearly illustrates the substantial difference between the dominant PM_{10} mass and the minor elemental constituents, such as Rb and Sr, which would be obscured on a linear scale. These compositional characteristics provide the basis for source apportionment analysis and for evaluating potential environmental and health risks associated with exposure to PM_{10} (Borlaza et al., 2021; Liniauskiene and Klik et al., 2024).

Discussion

This study analyzes the levels of TSP and PM_{10} at three specific sites in Makassar, including Jalan Tallasa, Jalan Perintis Kemerdekaan, and Jalan Dokter Leimena, along with concurrent measurements of relevant meteorological variables from May to September 2025. These sites were selected to represent residential areas located near major traffic corridors and areas characterized by different patterns of urban activity. The study period corresponds to the dry season, which is particularly important for understanding pollutant behavior. During this period, pollutants are more likely to accumulate due to limited precipitation and relatively stable atmospheric conditions, allowing for clearer observation of their concentration patterns.

Variability in particulate concentrations and the influence of human activity

The TSP concentration ranged from 62.4 μg/m^3 to 126 μg/m^3, with a mean value of 73.39 μg/m^3. This wide range indicates substantial variability in pollutant concentrations, likely influenced by local anthropogenic activities such as vehicular traffic, construction activities, and road dust resuspension. Previous studies (Kumar et al., 2024) similarly reported that TSP concentrations are strongly correlated with human activities and meteorological conditions that promote pollutant accumulation. For the respirable fraction (PM_{10}), the mean concentration was 34.20 μg/m^3, with a maximum value of 85.72 μg/m^3. While the mean concentration suggests moderate pollution levels, the maximum value indicates the occurrence of short-term episodic pollution events. Although the mean PM_{10} concentration complies with the Indonesian 24-hour standard of 75 μg/m^3 (Government Regulation No. 22/2021), the recorded maximum exceeds both the national standard and the more stringent WHO 2021 24-hour guideline of 45 μg/m^3. This finding suggests that while long-term mean concentrations meet national regulatory limits, episodic peaks pose potential health risks according to international health-based standards.

Similar research has reported that up to 87% of TSP may consist of PM_{10} and smaller particle fractions during episodic pollution events (Zioła and Słaby, 2020), highlighting the dominance of anthropogenic sources. The combination of high TSP variability and episodic PM_{10} spikes reflects two key characteristics of air pollution in the study area. First, there is a persistent baseline concentration driven by continuous emissions. Second, there are short-term peaks caused by episodic sources that temporarily elevate pollutant levels before returning to baseline conditions. From an air quality management perspective, these findings suggest that mitigation strategies should address both continuous emission sources and episodic pollution events (Kusuma et al., 2024). While long-term control measures should focus on reducing steady emissions, targeted interventions are also necessary to manage episodic sources such as heavy traffic congestion, open burning, demolition activities, and other short-duration emission events. Continuous on-site monitoring is essential to detect and respond promptly to such episodes.

The role of meteorological influence

The mean relative humidity at the study location was 77.3%, while air temperatures ranged from 27.6 to 33.7°C throughout the observation period, indicating relatively stable tropical climatic conditions. The mean wind speed was 2.6 m/s, with a maximum of 7.07 m/s. These conditions suggest generally limited atmospheric dispersion, as low wind speeds reduce mixing processes and favor pollutant accumulation. Consistent with previous studies, lower wind speeds are associated with higher particulate concentrations due to restricted horizontal and vertical transport (Parra et al., 2024; Xu et al., 2023). In contrast, higher wind speeds enhance pollutant dispersion, as reflected in the observed maximum wind speed (7.07 m/s), which likely contributed to short-term reductions in particulate concentrations. In addition, high humidity and stable temperature conditions may promote hygroscopic growth of particles, increasing their size and residence time in the atmosphere. This process further supports the persistence of particulate matter under tropical conditions. Overall, the combination of low wind speed, high humidity, and stable temperature creates favorable conditions for particulate accumulation in the study area. These findings indicate that meteorological factors play a critical role in regulating pollutant variability and should be considered alongside emission sources in air quality management.

Chemical composition of particulate matter and sampling location characteristics

EDS analysis showed that all three sampling sites within the TSP fraction shared a consistent pattern of crustal elements. Aluminium (Al) and calcium (Ca) dominated the TSP composition across all sites. These findings indicate that crustal and soil dust materials are major contributors to the area's coarse particulate matter. Previous literature suggests that the proportion of crustal materials within aerosol samples increases in regions with high dust resuspension (e.g., Zhang et al., 2025). This supports the hypothesis that traffic activity and wind-induced resuspension are primary drivers of TSP variability. In contrast, elevated potassium (K) levels at site S2 suggest additional anthropogenic contributions, such as biomass burning or vehicular emissions. Potassium is widely recognized as a tracer for biomass or vegetation burning in air quality studies and supports the assumption that S2 is influenced by anthropogenic activity rather than solely natural crustal sources. Furthermore, the enrichment of K in TSP at S2 may indicate that crustal materials are being disturbed and resuspended due to local human activities. Meanwhile, the relatively high concentrations of sodium (Na) observed across the sampling sites indicate contributions from both road dust and marine aerosols. Previous studies have identified Na as a tracer for sea salt aerosols in coastal regions (Wu et al., 2024).

Compared to TSP, the major elemental concentrations in the respirable PM_{10} fraction were below 1 μg/m^3 but exhibited greater spatial variability. Elevated levels of Ca and K at S1 and S2 further support the hypothesis that, in addition to soil dust resuspension, local biomass burning and heavy vehicle movement influence PM_{10} variability. These findings align with prior research indicating that fine particles are more compositionally sensitive to human activities and local environmental characteristics than coarse particles. Sodium concentrations in PM_{10} were relatively uniform across the sampling sites, suggesting a regional rather than local source. This uniformity may reflect widespread transport of marine aerosols across the study area. Additionally, high aluminium concentrations further confirm that a substantial proportion of particulate matter originates from crustal sources. Overall, the measured chemical constituents indicate that particulate matter in the study area results from two primary processes: (1) natural sources, including soil dust and crustal material resuspension, and (2) intermittent anthropogenic sources, such as biomass burning and heavy vehicle activity, which particularly influence PM_{10} levels. These findings suggest that air quality management strategies should not focus solely on controlling anthropogenic emissions. Dust resuspension processes and natural contributions must also be considered as integral components of the total particulate load (Nuryoto et al., 2025). Future research should incorporate quantitative source apportionment modeling to examine the relationships between elemental tracers (K, Ca, Al, Na), emission sources (e.g., construction activities, traffic, biomass burning), and local meteorological conditions (e.g., wind patterns, humidity, atmospheric stability, and deposition processes).

Implications for air quality and health risks

Higher TSP and PM_{10} concentrations at the S2 site suggest that it was subjected to stronger sources of emissions in close proximity. While the overall PM_{10} mean concentration (34.20 μg/m^3) was below that of Indonesian 24-hour standards (>75 μg/m^3), S2 maximum concentrations (85.72 μg/m^3) exceeded national and WHO guideline values (45 μg/m^3) which indicates short-term pollution episodes having possible adverse health effects. Such exceedances indicate that episodic peaks may pose an acute exposure risk even if mean conditions are acceptable, especially in most residential areas with a high density of population. The presence of high levels of PM_{10} is correlated with increased stress on the respiratory and cardiovascular systems for sensitive populations, including infants, the elderly, and those with existing health issues. This study provides a screening-level assessment based on concentration comparisons with regulatory standards. However, no quantitative health risk assessment (e.g., hazard quotient or exposure dose estimation) was conducted; therefore, the findings should be interpreted as indicative of potential risk rather than definitive evidence of health impact. The observed particulate characteristics suggest contributions from multiple sources, including vehicular emissions, re-suspended road dust, and episodic activities such as biomass burning. Although the detected elemental concentrations were relatively low, the combined influence of these sources may contribute to cumulative exposure risks over time. From a management perspective, these findings emphasize the need to address both continuous emissions and episodic pollution sources. Targeted measures such as traffic emission control, dust management, and short-term air quality advisories are essential to reduce exposure during high-concentration events. Integrating air quality management with meteorological forecasting may further enhance the effectiveness of mitigation strategies in urban environments such as Makassar.

Conclusion

The analysis of TSP samples revealed mean concentrations ranging from 71 to 76 μg/m^3. The S2 site exhibited the highest mean TSP concentration (75.55 μg/m^3), which is likely attributable to its proximity to emission sources near the sampling location. The dominant elements identified across sampling sites were Al, Ca, K, and Na, which are primarily associated with crustal sources. Elevated potassium (K) concentrations observed at the S2 site suggest contributions from biomass burning and vehicular emissions. Increased sodium (Na) levels at both S1 and S2 are likely associated with marine aerosols and/or resuspended road dust. The elemental distribution of PM_{10} and TSP samples was generally comparable across sites; however, variations in Ca and K concentrations between S1 and S2 indicate additional inputs from soil dust and combustion-related materials. A key contribution of this study is the integration of gravimetric analysis with scanning electron SEM-EDS to distinguish between crustal and anthropogenic particle sources in Makassar, a rapidly urbanizing tropical city. The findings indicate that air pollution in Makassar arises from a combination of natural sources (e.g., marine aerosols and crustal materials) and anthropogenic activities, rather than from a single dominant source. From a policy perspective, effective air quality management should emphasize source-oriented control strategies, including mitigation of resuspended road dust and the integration of meteorological forecasting into pollution management planning. Urban air quality monitoring systems should prioritize source identification and support the development of air quality alert systems to protect vulnerable populations. Future research should address existing gaps, including seasonal variation analysis, $PM_{2.5}$ exposure pathway modeling, and Hazard Quotient (HQ) assessments to improve long-term public health risk quantification.

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References

Ahmed F., Bayazid A. Z. M., Islam M. M., Rahaman M. Z., and Al Muntasir M. F. (2024) The terrible air pollution in D*haka city is getting worse. GSC Advanced Research and Reviews 19(1): 42–52. Available at: https://doi.org/10.30574/gscarr.2024.19.1.0133*

Boreddy S. K., Hegde P., and Aswini A. R. (2021) Geochemical characteristics of trace elements in size-resolved coastal urban aerosols associated with distinct air masses over tropical peninsular India: size distributions and source apportionment. *Science of The Total Environment* 763: 142967. Available at: https://doi.org/10.1016/j.scitotenv.2020.142967

Borlaza L. J. S., Weber S., Jaffrezo J. L., Houdier S., Slama R., Rieux C., Albinet A., Micallef S., Trébluchon C., and Uzu G. (2021)

Disparities in particulate matter (PM_{10}) origins and oxidative potential at a city scale (Grenoble, France)–Part 2: sources of PM_{10} oxidative potential using multiple linear regression analysis and predictive applicability of multilayer perceptron neural network analysis. *Atmospheric Chemistry and Physics* 21(12): 9719–9739. Available at: https://doi.org/10.5194/acp-21-5415-2021

Bralewska K. (2024) Air pollution inside fire stations: state-of-the-art and future challenges. *International Journal of Hygiene and Environmental Health* 255: 114289. Available at: https://doi.org/10.1016/j.ijheh.2023.114289

Chen F., Zhang W., Mfarrej M. F. B., Saleem M. H., Khan K. A., Ma J., and Han H. (2024) Breathing in danger: understanding the multifaceted impact of air pollution on health impacts. *Ecotoxicology and Environmental Safety* 280: 116532. Available at: https://doi.org/10.1016/j.ecoenv.2024.116532

Chianese E., Tirimberio G., Dinoi A., Cesari D., Contini D., Bonasoni P., Marinoni A., Andreoli V., Mannarino V., Moretti S., and Naccarato A. (2022) Particulate matter ionic and elemental composition during the winter season: a comparative study among rural, urban and remote sites in southern Italy. *Atmosphere* 13(2): 356. Available at: https://doi.org/10.3390/atmos13020356

Das S., Teinilä K., Timonen H., Ikonen E., and Laurila T. (2024) Real-time measurement of metals in submicron aerosols with particle-into-liquid sampler combined with micro-discharge optical emission spectroscopy. *Environmental Monitoring and Assessment* 196(11): 1128. Available at: https://doi.org/10.1007/s10661-024-13298-3

Government of Indonesia (2021) Peraturan Pemerintah Republik Indonesia Nomor 22 Tahun 2021 tentang Penyelenggaraan Perlindungan dan Pengelolaan Lingkungan Hidup (Government Regulation of the Republic of Indonesia No. 22/2021 on the Implementation of Environmental Protection and Management) [in Indonesian]. Jakarta: Government of Indonesia.

Krishan M., Jha S., Das J., Singh A., Goyal M. K., and Sekar C. (2019) Air quality modelling using long short-term memory (LSTM) over NCT-Delhi, India. *Air Quality, Atmosphere & Health* 12: 899–908. Available at: https://doi.org/10.1007/s11869-019-00696-7

Kumar P., Garg A., Sharma K., Nadeem U., Sarma K., Gupta N. C., Kumar A., and Pandey A. K. (2024) Seasonal and spatial variations in particulate matter, black carbon and metals in Delhi, India's megacity. Available at: https://doi.org/10.3390/urbansci8030101

Kusuma M. N., Handriyono R. E., Pramestyawati T. N., Sari A. N., Listyaningsih D., and El Hafizah N. (2024) Mitigation of CO_2 emissions based on aboveground biomass assessment in tropical regions (case study: Gresik City, East Java, Indonesia). *Journal of Environmental Research, Engineering and Management* 80(4): 48–59. Available at: https://doi.org/10.5755/j01.erem.80.4.35259

Li W., Ge P., Chen M., Tang J., Cao M., Cui Y., Hu K., and Nie D. (2021) Tracers from biomass burning emissions and identification of biomass burning. *Atmosphere* 12(11): 1401. Available at: https://doi.org/10.3390/atmos12111401

Liniauskiene E. and Klik B. (2024) Scientific Reports 14: 16732. Available at: https://doi.org/10.1038/s41598-024-67576-8

Liu X., Zhang X., Jin B., Wang T., Qian S., Zou J., Dinh V. N. T., Jaffrezo J. L., Uzu G., Dominutti P., and Darfeuil S. (2025) Source apportionment of PM_{10} based on offline chemical speciation data at 24 European sites. *npj Climate and Atmospheric Science* 8(1): 255. Available at: https://doi.org/10.1038/s41612-025-01097-7

Lu Y., Nie L., Guo X., Pan T., Chen R., Liu X., Li X., Li T., and Liu F. (2024) Rapid assessment of heavy metal accumulation capability of Sedum alfredii using hyperspectral imaging and deep learning. *Ecotoxicology and Environmental Safety* 282: 116704. Available at: https://doi.org/10.1016/j.ecoenv.2024.116704

Manisalidis I., Stavropoulou E., Stavropoulos A., and Bezirtzoglou E. (2020) Environmental and health impacts of air pollution: a review. *Frontiers in Public Health* 8: 1–13. Available at: https://doi.org/10.3389/fpubh.2020.00014

Manucci P. M. and Franchini M. (2017) Health effects of ambient air pollution in developing countries. *International Journal of Environmental Research and Public Health* 14: 1048. Available at: https://doi.org/10.3390/ijerph14091048

Nuryoto N., Heriyanto H., Rahmavetty R., Nawwari R. Z., Harrisma S. F., and Bagaskara R. N. T. (2025) Strategy for maintaining environmental stability: synthesis of CO_2 emission gases into sodium carbonate. *Journal of Environmental Research, Engineering and Management* 81(4): 120–130. Available at: https://doi.org/10.5755/j01.erem.81.4.39917

Parra J. C., Gómez M., Salas H. D., Botero B. A., Piñeros J. G., Tavera J., and Velásquez M. P. (2024) Linking meteorological variables and particulate matter PM2.5 in the Aburrá Valley, Colombia. Available at: https://doi.org/10.3390/su162310250

Petrov M., Nikolaeva Z., and Dimitrov A. (2023) The impact of anthropogenic activity on the global environment. *Science Business Society* 8(2). Available at: https://stumejournals.com/journals/sbs/2023/2/59.full.pdf

Pongpiachan S., Liu S., Huang R., Zhao Z., Palakun J., Kositanont C., and Cao J. (2017) Variation in day-of-week and seasonal concentrations of atmospheric PM2.5-bound metals and associated health risks in Bangkok, Thailand. *Archives of Environmental Contamination and Toxicology* 72(3): 364–379. Available at: https://doi.org/10.1007/s00244-017-0382-0

Rapalis P., Zinkutė R., Lazareva N., Suzdalev S., and Taraškevičius R. (2021) Geochemistry of the dust collected by passive samplers as a tool for search of pollution sources: the case of Klaipėda Port, Lithuania. *Applied Sciences* 11(23): 11157. Available at: https://doi.org/10.3390/app112311157

Saini M., Rusdi N., Sattar Y., and Ibrahim (2018) The influence of throat length and vacuum pressure on air pollutant filtration using ejectors. *AIP Conference Proceedings*. Available at: https://doi.org/10.1063/1.5042939

Sattar Y., Rashid M., Ramli M., and Sabariah B. (2014) Black carbon and elemental concentration of ambient particulate matter in Makassar, Indonesia. *IOP Conference Series: Earth and Environmental Science* 18: 012099. Available at: https://doi.org/10.1088/1755-1315/18/1/012099

Sattar Y., Makmur S., Rizal S., Rusdi N., and Ibrahim (2020) The effect of ejectors on reduction of indoor air pollution in the welding room. *Nature Environment and Pollution Technology* 19(4): 1695–1699. Available at: https://doi.org/10.46488/NEPT.2020.v19i04.039

Sattar Y., Fitri A., Nani A., Ramdiana M., and Syarifuddin A. (2021) Total suspended particulate matter and PM_{10} concentrations related to meteorological conditions in Daya, Makassar. *Indian Journal of Environmental Protection* 41(7): 790–795

Spencer C. J., Davies N. S., Gernon T. M., Wang X., McMahon W. J., Morrell T. R. I., Hincks T., Pufahl P. K., Brasier A., Seraine M., and Lu G. M. (2022) Composition of continental crust altered by the emergence of land plants. *Nature Geoscience* 15(9): 735–740. Available at: https://doi.org/10.1038/s41561-022-00995-2

Surya B., Salim A., Hernita H., Suriani S., Menne F., and Rasyidi E. S. (2021) Land use change, urban agglomeration, and urban sprawl: a sustainable development perspective of Makassar City, Indonesia. *Land* 10: 556. Available at: https://doi.org/10.3390/land10060556

Warmadewanthi I. D. A. A., Ikhlas N., Ramadan B. S., Winora F. R., Zuhdi M. W., Puspita A. S., and Kataja K. (2025) Single-use plastics (SUPs) ban: supermarkets responses in the implementation of the SUPs ban policy in Surabaya City. *Journal of Material Cycles and Waste Management*. Available at: https://doi.org/10.1007/s10163-025-02456-5

WHO (World Health Organization) (2021) WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization. Available at: https://doi.org/10.1016/j.envint.2021.106719

Wu X., Kong Q., Lan Y., Sng J., and Yu L. E. (2024) Refined sea salt markers for coastal cities facilitating quantification of aerosol aging and PM2.5 apportionment. Available at: https://doi.org/10.1021/acs.est.3c10142

Xu M., Yang J., Li M., Chen X., Lv Q., Yao Q., and Gao B. (2023) The role of temporal scales in extracting dominant meteorological drivers of major airborne pollutants. Available at: https://doi.org/10.5194/acp-23-14065-2023

Yunus S., Kamil K., Angraini N., Muis R., and Zainal Z. (2024) Measurement of carbon monoxide concentrations during the community activities restrictions enforcement level 4 in the COVID-19 pandemic in Makassar City, Indonesia. *AIP Conference Proceedings* 2838(1). Available at: https://doi.org/10.1063/5.0180776

Zahra Abd Saleh., Hassan A. A., Idan I. J., Al-Isawi R. H. K., and Al Saleh H. A. A. (2024) Peanut shell as a natural adsorbent for the removal of acid blue 25 from aqueous solution. *Environmental Research, Engineering and Management* 80(1): 21–31. Available at: https://doi.org/10.5755/j01.erem.80.1.34614

Zhang H., Wang S., Dong Z., Li X., and Zhang R. (2025) Measurement report: crustal materials play an increasing role in elevating particle pH – insights from 12-year records in a typical inland city of China. Available at: https://doi.org/10.5194/egusphere-2024-2869

Zhu Y., Liu C., Huo J., Li H., Chen J., Duan Y., and Huang K. (2024) A novel calibration method for continuous airborne metal measurements: implications for aerosol source apportionment. *Science of The Total Environment*. Available at: https://doi.org/10.1016/j.scitotenv.2023.168274

Zioła N. and Słaby K. (2020) The content of selected heavy metals and polycyclic aromatic hydrocarbons (PAHs) in PM_{10} in urban-industrial area. Available at: https://doi.org/10.3390/su12135284