

Impacts of PM2.5 Air Pollution on Migraine Outcomes in Northern Thailand: A Pilot Comparison Study of Polluted and Non-Polluted Periods

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Background: Emerging evidence suggests that air pollution, particularly fine particulate matter (PM2.5), may exacerbate migraine. Northern Thailand experiences severe seasonal air pollution, offering a unique context to investigate this association. This study aimed to evaluate the impact of seasonal PM2.5 exposure on migraine frequency, severity, emergency room (ER) visits, and medication use.

Methods: This retrospective observational study included 42 adult migraine patients attending a university hospital's headache clinic from 2021 to 2023 who completed monthly headache diaries. PM2.5 data were obtained from national monitoring networks. "Polluted months" (January–May) were compared with "non-polluted months" (June–December). Study outcomes included headache frequency (days/month), pain severity (mild/moderate/severe), ER visits, and medication use.

Results: Among 42 patients (mean age: 39.2 years; 57.1% female), headache frequency was higher during polluted months (6.4 vs 4.3 days/month, $P < 0.001$). All pain severity levels increased significantly during polluted periods. ER visits rose markedly (3.37 vs 0.65 visits/patient, $P < 0.001$). Use of both migraine-specific and non-specific medications per patient was significantly greater in polluted months.

Conclusion: PM2.5 exposure is associated with increased migraine burden. Seasonal air pollution may worsen headache frequency, severity, and healthcare utilization. Air quality should be considered in migraine management and environmental policy planning.

Keywords: migraine, PM2.5, air pollution, headache

Introduction

Air pollution, specifically fine particulate matter (PM2.5), represents a significant global health concern, linked extensively with cardiovascular, respiratory, and neurological diseases.^{1–4} PM2.5 particles, less than 2.5 micrometers in diameter, bypass the body's defences, infiltrating deep into the lungs and bloodstream. Exposure has notably been associated with heightened risks of neuroinflammation, cognitive decline, stroke, and Alzheimer's disease.^{5,6}

Migraine is a highly prevalent neurological disorder affecting approximately 12% of the global population and is a leading cause of disability worldwide, characterized by recurrent headaches, sensory hypersensitivity, nausea, and cognitive dysfunction, and ranking among the top contributors to years lived with disability in adults of working age.^{7,8} Its pathophysiology involves trigeminal nerve activation, cortical spreading depression, and vascular dysregulation, potentially influenced by environmental factors including air pollution.⁹ Recent studies indicate that air pollution may also contribute to migraine exacerbation.¹⁰ Proposed mechanisms by which PM2.5 may exacerbate migraine include systemic inflammation, oxidative stress, blood–brain barrier (BBB) disruption, and vascular dysregulation. Inhaled PM2.5 triggers pro-inflammatory cytokines such as interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF- α) and

increases reactive oxygen species (ROS), promoting neuroinflammation and sensitization of trigeminal pathways.¹¹ Resulting oxidative stress disrupts neuronal homeostasis and neurotransmitter balance, heightening cortical excitability.^{12,13} BBB impairment contributes to neurovascular dysfunction,¹⁴ while vasomotor instability and altered cerebral blood flow further aggravate migraine attacks.¹⁵ Environmental and epidemiological evidence links PM2.5 exposure with increased migraine frequency and severity, evidenced by higher medical visits and medication usage during pollution peaks.^{16,17} Despite these insights, the long-term effects of chronic PM2.5 exposure on migraine severity remain understudied, as current research predominantly addresses short-term pollution impacts.¹⁸ Recent systematic reviews have further synthesized this evidence, emphasizing the consistent association between air pollution and increased migraine burden across diverse populations. A comprehensive review also highlighted the methodological limitations and heterogeneity of prior studies, indicating the need for long-term analyses of migraine outcomes in high-pollution settings.¹⁹ Unlike previous studies that primarily assessed short-term pollution spikes or cross-sectional associations, the present study evaluates the longitudinal, cyclical impact of seasonal PM2.5 exposure on migraine outcomes across three consecutive years. This approach provides a more comprehensive view of how sustained environmental fluctuations influence migraine burden in a high-exposure region. However, causal inference in observational air-pollution studies remains challenging because of potential confounding factors, exposure misclassification, and temporal variability, which may limit interpretation of associations between PM2.5 and migraine.

Northern Thailand, particularly Chiang Mai Province, faces severe seasonal air pollution, mainly due to agricultural burning (slash-and-burn farming), vehicular emissions, and industrial activities.²⁰ The pollution season in Northern Thailand typically occurs from January to May, during which PM2.5 levels rise dramatically due to crop burning, forest fires, and stagnant air conditions.²¹ This seasonal phenomenon has caused Thailand to frequently rank among the most polluted countries in the world, with Chiang Mai often recording the worst air quality globally during this period.²² Reports from air quality monitoring agencies have shown that Chiang Mai has ranked as the world's most polluted city multiple times between January and May, with Air Quality Index (AQI) levels exceeding hazardous thresholds.²³

Given the growing burden of both air pollution and migraine, there remains a need for region-specific evidence linking PM2.5 exposure to migraine severity. This study aims to analyse migraine severity using headache frequency (days per month) and other clinical parameters, comparing patients' migraine burden during high-pollution and low-pollution periods in Northern Thailand. Understanding this relationship may provide critical insights into environmental risk factors for migraine exacerbation and inform public health policies to mitigate exposure risks.

Methods

Study Design and Population

This retrospective, observational study was conducted at Maharaj Nakorn Chiang Mai Hospital, a tertiary, university-affiliated center in Northern Thailand. We included adults aged 20–65 years who were diagnosed with episodic or chronic migraine according to the International Classification of Headache Disorders, 3rd edition (ICHD-3), and who attended the specialized outpatient headache clinic between January 2021 and December 2023. To ensure sufficient longitudinal data, patients were required to have completed a headache diary documenting monthly migraine days for all 36 months of the study period. Complete headache diaries were defined as uninterrupted documentation of monthly headache-diary entries and clinic visit notes across the full 36-month period, verified at each follow-up appointment. Diary compliance was reviewed at each clinic visit by the attending neurologist and nursing staff and documented in the medical record using a standardized follow-up form. Patients recorded headache characteristics—including aura, nausea, vomiting, and other associated symptoms in their standardized headache diaries during routine clinical follow-up. Patients with missing diary months or incomplete clinical records were excluded. Collected variables included demographic information (age, sex, body mass index, educational level) and clinical characteristics such as age at migraine onset, migraine subtype (with or without aura), disease duration, comorbidities, and use of migraine-related medications. All patients received routine clinical care throughout the study period. Migraine treatments, including acute medications (eg, NSAIDs, triptans) and preventive therapies (eg, beta-blockers, antiepileptic drugs, flunarizine), were managed at the discretion of the attending neurologist according to standard clinical practice. Treatment adjustments were made only when

clinically indicated, such as inadequate symptom control, adverse effects, or changes in headache patterns. No protocol-driven treatment changes were mandated by the study, ensuring that observed differences between polluted and non-polluted months were not influenced by structured medication modifications.

Assessment of Pollution Exposure

Based on historical air quality patterns in Chiang Mai, pollution by the Pollution Control Department, Thailand's Air Quality and Situation Reports, and the Ministry of Natural Resources and Environment. The calendar year was divided into two distinct pollution phases: a high-pollution period from January to May and a low-pollution period from June to December. PM_{2.5} levels exceeding 50 µg/m³ were classified as high exposure, while levels below this threshold were considered low exposure, following the Thailand Pollution Control Department (PCD 2023) 24-hour standard, which exceeds the World Health Organization (WHO) air-quality guideline limit (15 µg/m³; WHO 2021). To facilitate comparisons, we defined "polluted months" as those occurring during the high-pollution period (January to May), when regional PM_{2.5} concentrations consistently exceeded safety thresholds, primarily due to seasonal agricultural burning and stagnant air conditions. Conversely, "non-polluted months" referred to the low-pollution period (June to December), when PM_{2.5} levels were generally lower and air quality was within acceptable limits. This classification was used throughout the study to analyze migraine severity in relation to differing air quality conditions.

Migraine Severity and Emergency Room Visit Assessment

The primary outcome of the study was the change in overall migraine frequency, measured as the number of headache days per month during polluted versus non-polluted periods. Secondary outcomes included the comparison of headache frequency between the two periods stratified by pain severity levels (mild, moderate, and severe), along with the frequency of ER visits and the use of acute migraine-specific and non-specific medications. Migraine severity was assessed using headache frequency, defined as the number of headache days per month, as recorded in patient-maintained headache diaries. In addition, pain severity was categorized according to the patient-recorded diary, which required patients to rate each headache as one of three grades: grade 1 (mild pain) referring to pain that does not interfere with regular activities; grade 2 (moderate pain) referring to pain that affects daily activities but does not require rest; and grade 3 (severe pain) referring to pain that prevents the patient from performing normal activities.²⁴ These definitions were reviewed with patients during clinic visits to ensure accurate diary completion. The use of acute medications, including migraine-specific and non-specific abortive medications, was also recorded as the number of days per month on which they were used. Acute medication use was quantified as the number of days per month in which patients reported taking migraine-specific or non-specific abortive medications, as recorded in their standardized headache diaries. Data were extracted from both electronic medical records and validated patient-reported headache diaries. Additionally, we extracted monthly data on ER visits for migraine-related complaints. All ER visits included in this analysis were migraine-specific encounters. Each visit was verified using the emergency department medical record, where the attending physician documented a diagnosis of migraine exacerbation. ER visit frequency was categorized by month, allowing for seasonal comparisons between polluted and non-polluted periods.

Statistical Analysis

Descriptive statistics were used to summarize demographic and clinical characteristics. Continuous variables were expressed as means with standard deviations (SD) or medians with interquartile ranges (IQR), depending on the data distribution. Categorical variables were presented as numbers and proportions. Comparisons of headache frequency, pain severity (mild, moderate, severe), medication use, and ER visits between polluted and non-polluted months were conducted using appropriate statistical tests based on data type and distribution. Paired t-tests were used for normally distributed data, while the Wilcoxon signed-rank test was applied for non-normally distributed or ordinal variables. Repeated measures analysis of variance (ANOVA) was used to evaluate within-subject changes in ER visit frequency across different pollution periods. A two-tailed p-value of less than 0.05 was considered statistically significant. For multiple pairwise comparisons, p-values were adjusted using Bonferroni correction, and 95% confidence intervals (95% CI) were calculated for the primary outcome measures. A retrospective sample-size calculation using paired comparisons ($\alpha = 0.05$, power = 0.80) and an

assumed moderate effect size (Cohen's $d_z = 0.50$) indicated that 34 participants would be required. The final sample of 42 exceeded this threshold. Statistical analyses were performed using licensed Stata Statistical Software version 16.1 (Stata Statistical Software: Release 16.1, Stata Corporation, College Station, TX, 2019). All figures were created using GraphPad Prism version 10.0 (GraphPad Software, San Diego, CA) and Microsoft Excel, with appropriate visualizations (eg, bar graphs, boxplots) to reflect comparative distributions between seasonal pollution phases.

Ethical Considerations

The study was conducted in accordance with the principles of the Declaration of Helsinki. This study was approved by the Chiang Mai University Institutional Review Board (IRB reference number: MED-2567-0386). As it was a retrospective observational study, data were collected as part of routine clinical care. All data were fully anonymized, and confidentiality was maintained prior to access. The requirement for individual patient informed consent was therefore waived by the IRB.

Results

A total of 300 migraine patients attended the headache clinic between 2021 and 2023. Of these, 68 met the preliminary criterion of consistent clinic attendance and were screened for eligibility. Twenty-six patients were excluded (18 missing ≥ 1 diary month, 5 with incomplete clinical records, and 3 not meeting ICHD-3 criteria), resulting in a final analytic cohort of 42 patients with complete 36-month headache-diary datasets (Figure 1).

Monthly average PM_{2.5} levels in Chiang Mai from 2021 to 2023, demonstrating consistently elevated concentrations during January–May (“polluted months”) across all three years. Average PM_{2.5} concentrations were $46.2 \pm 25.2 \mu\text{g}/\text{m}^3$ (range 19–105 $\mu\text{g}/\text{m}^3$) during polluted months and $16.8 \pm 5.5 \mu\text{g}/\text{m}^3$ (range 11–31 $\mu\text{g}/\text{m}^3$) during non-polluted months (Figure 2). Detailed monthly PM_{2.5} values for all study years are provided in [Supplementary Table 1](#).

Demographic and clinical characteristics of the participants are listed in [Table 1](#). Forty-two patients with migraine (18 males and 24 females) were included in the study. The mean age at baseline was 39.2 ± 12.6 years, with a mean BMI of $25.8 \pm 4.0 \text{ kg}/\text{m}^2$. The average age of migraine onset was 24.2 ± 7.2 years. Educational attainment varied across participants: 6 (14.3%) held a master's degree, and 12 (28.6%) held a bachelor's degree. The remaining participants had education levels ranging from secondary school to below primary level. Visual aura was reported by 19 participants (45.2%), while 11 (26.2%) experienced sensory aura, 6 (14.3%) reported cognitive aura, and one patient (2.4%) reported atypical aura. Nausea was the most reported associated symptom, present in all patients (100%), followed by vomiting (97.6%), photophobia (59.5%), and phonophobia (50.0%).

All 42 participants included in the final analysis had complete data for all assessed outcomes, including headache frequency, pain severity ratings, aura subtype, acute medication use, and ER visit records. A summary of the primary and secondary migraine-related outcomes is presented in [Table 2](#). Across the three-year study period (2021–2023), total migraine frequency, severity stratifications, aura subtypes, ER visits, and medication use were compared between polluted and non-polluted months.

Migraine frequency was analyzed by severity level. The mean total migraine frequency was 6.4 days/month during polluted months and 4.3 days/month during non-polluted months, with a difference of 2.1 days/month ($P < 0.001$). Mild migraine frequency was 1.3 vs 1.0 days/month (difference 0.3 days/month, $P < 0.001$), moderate frequency was 2.1 vs 1.5 days/month (difference 0.6 days/month, $P < 0.001$), and severe frequency was 3.1 vs 1.8 days/month (difference 1.3 days/month, $P < 0.001$) (Figure 3).

Migraine frequency among patients with and without aura. In patients without aura, the frequency was 6.2 days/month during polluted months and 4.0 days/month during non-polluted months (difference 2.2 days/month, $P < 0.001$). In patients with aura, the frequency was 6.7 vs 4.6 days/month (difference 2.1 days/month, $P < 0.001$) (Figure 4).

Comparisons of ER visits and medication use. The average number of ER visits per patient was 3.37 during polluted months and 0.65 during non-polluted months, with a difference of 2.72 visits ($P < 0.001$). Migraine-specific medication use differed between periods ($P = 0.00014$), and non-migraine-specific medication use also showed a difference ($P = 0.042$) (Figure 5).

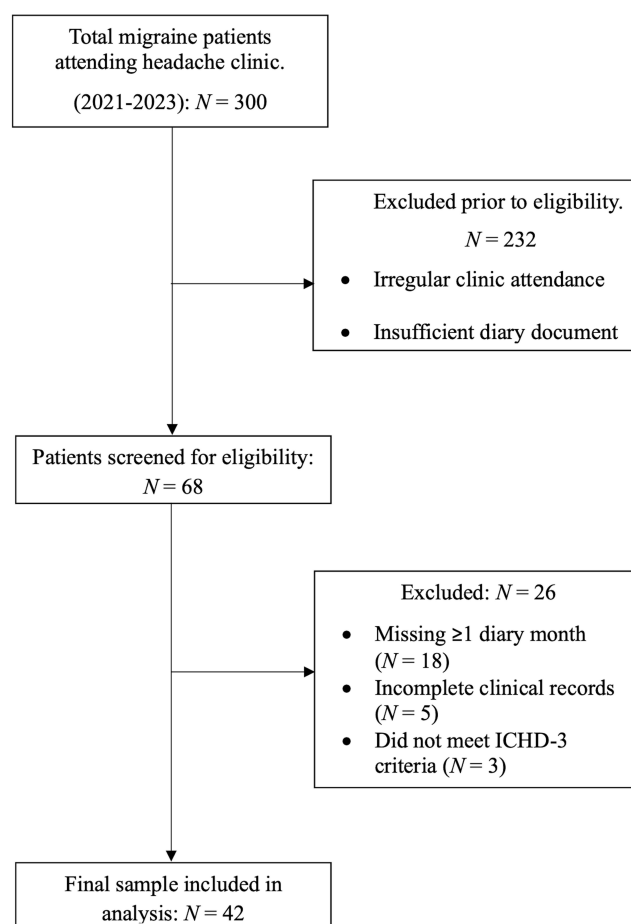


Figure 1 Study flowchart of patient selection and eligibility screening. This flowchart outlines the selection process for migraine patients included in the study. Of the 300 patients attending the headache clinic between 2021 and 2023, 232 were excluded before eligibility screening due to irregular clinic attendance or insufficient headache diary documentation. Sixty-eight patients met preliminary screening criteria and were evaluated for eligibility. Twenty-six patients were then excluded (18 missing ≥ 1 diary month, 5 with incomplete clinical records, and 3 not meeting ICHD-3 migraine diagnostic criteria). A total of 42 patients with complete 36-month headache diary datasets were included in the final analysis.

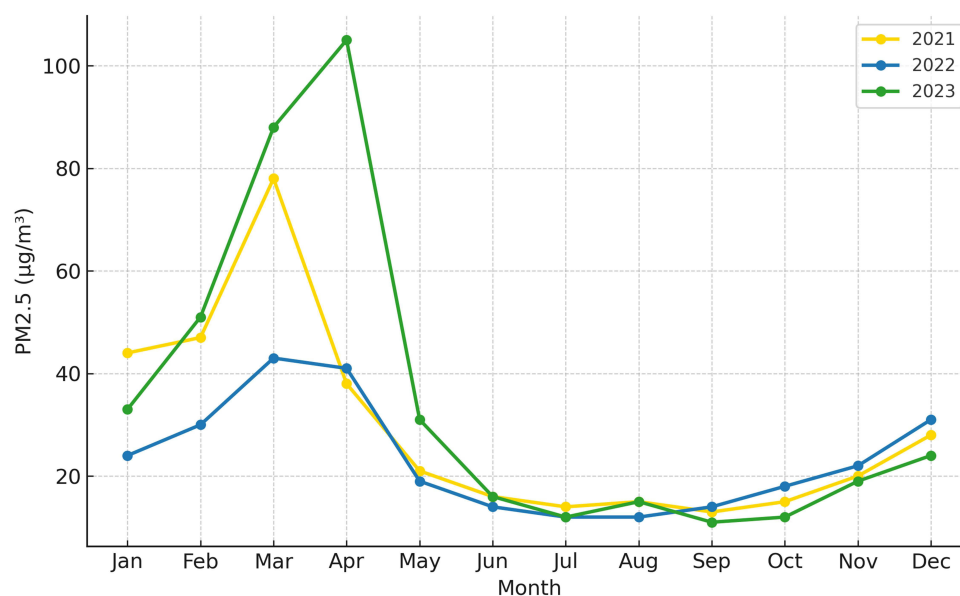


Figure 2 Monthly average PM_{2.5} levels in Chiang Mai from 2021 to 2023. This figure presents the monthly mean PM_{2.5} concentrations for the years 2021 (yellow), 2022 (blue), and 2023 (green), showing the month-to-month variation in ambient air pollution across the three-year study period.

Table 1 Demographic and Clinical Characteristics of the Study Population

Age, Years – Mean (SD)	39.2 (12.6)
Female Sex – no. (%)	24 (57.1)
BMI, kg/m ² – mean (SD)	25.8 (4.0)
Education – no. (%)	
– Below Primary School	5 (11.9)
– Primary School	5 (11.9)
– Secondary School	10 (23.8)
– Diploma	4 (9.5)
– Bachelor	12 (28.6)
– Master	6 (14.3)
Age of onset, years – mean (SD)	24.2 (7.2)
Aura – no. (%)	19 (45.2)
– Visual Aura	11 (26.2)
– Sensory Aura	6 (14.3)
– Cognitive Aura	1 (2.4)
– Atypical Aura	1 (2.4)
Associated symptoms – no. (%)	
– Nausea	42 (100.0)
– Vomiting	41 (97.6)
– Photophobia	25 (59.5)
– Phonophobia	21 (50.0)

Abbreviations: BMI, body mass index; kg, kilogram; m², square meter; No, number; SD, standard deviation.

Table 2 Summary of Migraine Outcomes During Polluted months vs Non-Polluted months

Outcomes	Polluted Months (Days/Month)	Non-Polluted Months (Days/Month)	Difference (Days/Month)	Statistical Test	P value
Total migraine frequency (days/month)	6.4 ± 2.2	4.3 ± 1.8	2.1	Paired t-test (t = 6.8)	< 0.001
Mild migraine frequency (days/month)	1.3 ± 0.9	1.0 ± 0.8	0.3	Wilcoxon (z = 5.2)	< 0.001
Moderate migraine frequency (days/month)	2.1 ± 1.0	1.5 ± 0.9	0.6	Wilcoxon (z = 5.4)	< 0.001
Severe migraine frequency (days/month)	3.1 ± 1.7	1.8 ± 1.2	1.3	Wilcoxon (z = 5.8)	< 0.001
Migraine without aura frequency (days/month)	6.2 ± 2.0	4.0 ± 1.7	2.2	Paired t-test (t = 6.8)	< 0.001
Migraine with aura frequency (days/month)	6.7 ± 2.3	4.6 ± 1.9	2.1	Paired t-test (t = 6.2)	< 0.001
ER visits (average per patient)	3.37 ± 1.2	0.65 ± 0.5	2.72	Paired t-test (t = 13)	< 0.001
Migraine-specific medication (total medication uses per patient)	26.7 ± 25.9	20.2 ± 25.9	6.7	Wilcoxon (z = 4.1)	< 0.001

(Continued)

Table 2 (Continued).

Outcomes	Polluted Months (Days/Month)	Non-Polluted Months (Days/Month)	Difference (Days/Month)	Statistical Test	P value
Non-migraine-specific medication (total medication uses per patient)	51.0 ± 39.3	42.7 ± 46.7	8.3	Wilcoxon (z = 2.0)	0.042

Notes: Values are presented as mean ± SD for normally distributed variables and as total medication uses per patient for medication-related outcomes. P-values were obtained using paired t-tests or Wilcoxon signed-rank tests as appropriate.

Abbreviation: ER, emergency room.

Discussion

This study provides evidence that higher PM_{2.5} levels are associated with increased migraine burden among patients living in Northern Thailand. We observed that headache frequency, pain severity, acute medication use, and ER visits were all higher during months with elevated PM_{2.5} concentrations. A notable aspect of this study is the use of headache frequency (days per month) as a practical and globally applicable indicator of migraine severity. This metric is widely recognized in both clinical and epidemiological settings and aligns with classification systems such as the ICHD-3. Unlike migraine severity scoring systems that rely on questionnaire-based tools, such as the Migraine Disability Assessment (MIDAS) or Headache Impact Test (HIT-6), which depend on subjective self-reporting and are susceptible to recall bias, headache frequency provides a more objective, accessible, and easy-to-apply measure in both clinical

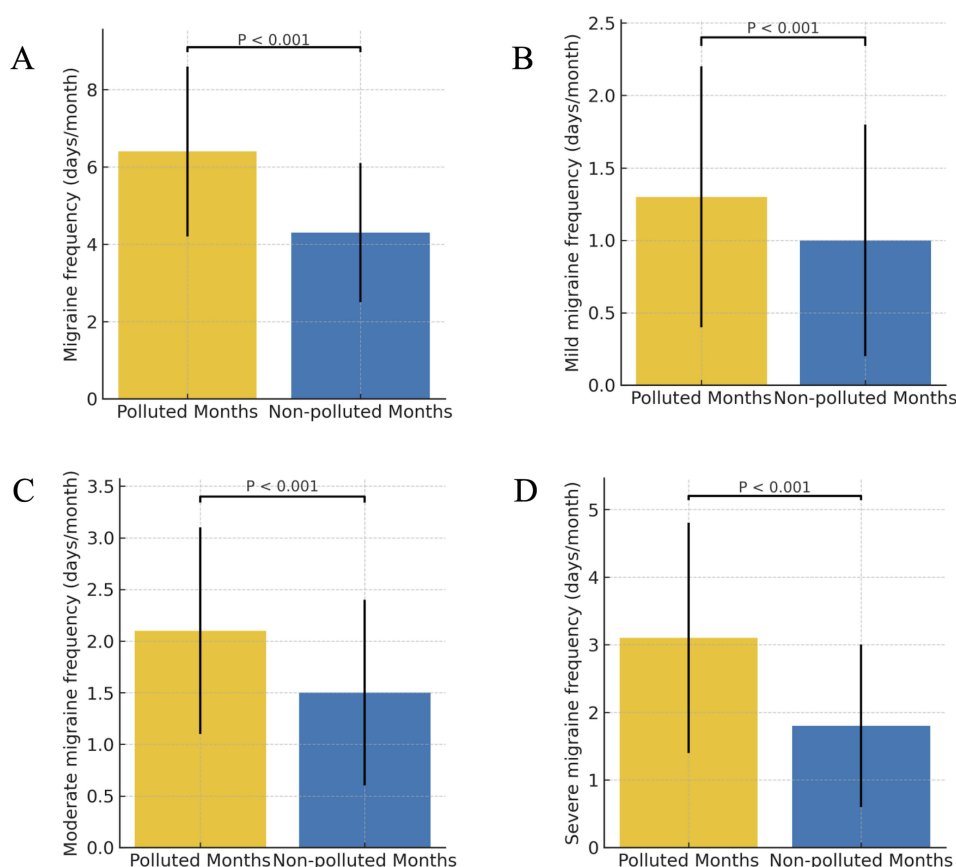


Figure 3 Comparison of migraine frequency (days/month) by severity during polluted and non-polluted months. (A) Mean migraine frequency was 6.4 days/month during polluted months and 4.3 days/month during non-polluted months, with a difference of 2.1 days/month (P < 0.001). (B) Mild migraine occurred at a frequency of 1.3 days/month in polluted months and 1.0 days/month in non-polluted months, with a difference of 0.3 days/month (P < 0.001). (C) Moderate migraine frequency was 2.1 days/month in polluted months and 1.5 days/month in non-polluted months, with a difference of 0.6 days/month (P < 0.001). (D) Severe migraine frequency was 3.1 days/month during polluted months and 1.8 days/month during non-polluted months, with a difference of 1.3 days/month (P < 0.001).

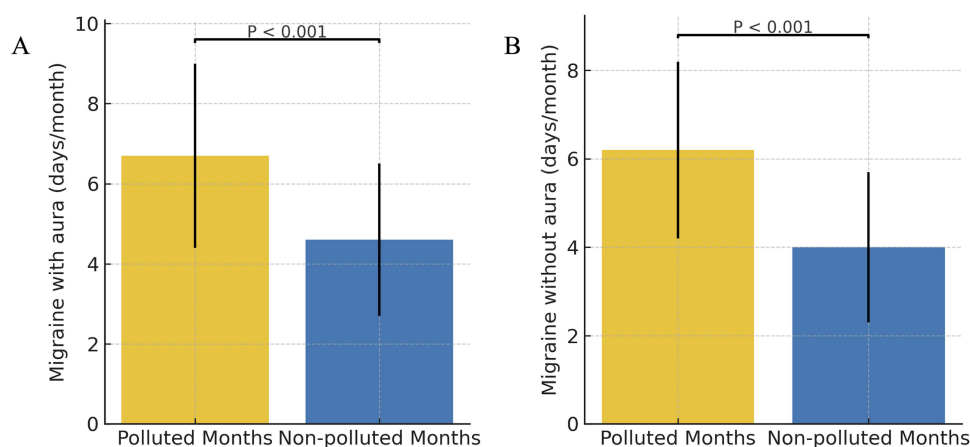


Figure 4 Comparison of migraine frequency (days/month) with and without aura during polluted and non-polluted months. **(A)** For patients without aura, mean migraine frequency was 6.2 days/month during polluted months and 4.0 days/month during non-polluted months, with a difference of 2.2 days/month ($P < 0.001$). **(B)** For patients with aura, mean migraine frequency was 6.7 days/month during polluted months and 4.6 days/month during non-polluted months, with a difference of 2.1 days/month ($P < 0.001$).

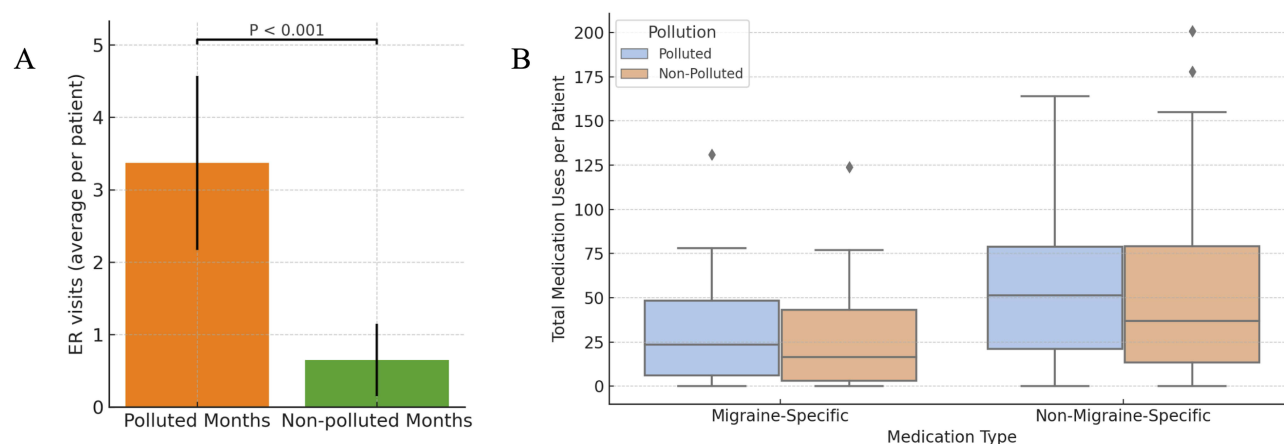


Figure 5 Emergency room visits and medication use during polluted and non-polluted months. **(A)** Mean number of migraine-related emergency room (ER) visits per patient was 3.37 during polluted months and 0.65 during non-polluted months, with a difference of 2.72 visits ($P < 0.001$). **(B)** Migraine-specific medication use differed between polluted and non-polluted months ($P < 0.001$), and non-migraine-specific medication use also showed a difference ($P = 0.042$).

practice and research.^{25,26} This approach enhances comparability across studies and populations and supports the integration of environmental exposure research into routine migraine monitoring and management worldwide.

Based on the analysis of total migraine frequency, the observed increase of 2.1 headache days per month during polluted months is clinically relevant and aligns with earlier work suggesting that even short-term exposure to PM_{2.5} can trigger more frequent migraine attacks.^{27,28} This supports the idea that air pollution may contribute to increased migraine incidence and may aggravate ongoing symptoms in patients with chronic or episodic migraine. When examining the severity stratification, mild, moderate, and severe migraine days all increased during polluted periods. This gradient reinforces the dose-response nature of pollution's effects on the nervous system. Several biological mechanisms may help explain the increased migraine frequency and severity observed during polluted months. PM_{2.5} has been shown in experimental studies to induce systemic and neuroinflammatory responses, including elevations of cytokines such as IL-6 and TNF- α , which may sensitize trigeminal pathways and lower the threshold for migraine attacks. Oxidative stress and mitochondrial dysfunction induced by particulate exposure may further heighten cortical excitability, potentially contributing to the greater number of moderate and severe headache days observed in our cohort.^{29–31} In addition, air-pollution-related vascular dysregulation and endothelial dysfunction may influence cerebral blood flow, which could exacerbate more severe

attacks and partially explain the increased ER utilization during high-pollution periods.³² These pathways collectively provide plausible biological explanations consistent with the clinical patterns identified in this study.

Interestingly, the increase in migraine frequency was similar across aura subtypes, with both aura-positive and aura-negative patients showing more than 2 additional headache days per month during polluted months. This may suggest a shared environmental sensitivity across migraine phenotypes. While few studies have examined aura-specific effects, a study also noted pollution-related increases in migraine visits regardless of aura status, suggesting a broad triggering mechanism via vascular and neurochemical pathways.¹⁸

Our findings on ER utilization are consistent with the possibility that higher pollution levels may be associated with greater clinical severity. Patients visited the ER an average of 3.37 times during polluted months compared to 0.65 times during non-polluted months, emphasizing that the increase in frequency and pain is not only statistically evident but also leads to greater healthcare utilization. This echoes prior population-level studies linking air quality to increased ER visits for neurological complaints.^{17,33} We also observed elevated use of migraine-specific and non-migraine-specific medications during polluted months. This likely reflects both increased symptom burden and the need for more aggressive or frequent acute treatment. These trends align with findings from prior studies reporting higher analgesic use during pollution events.²³

Importantly, our data provide insight into a real-world, seasonal model of pollution exposure. Unlike studies based solely on short-term or event-based spikes in PM_{2.5}, this study leveraged Chiang Mai's predictable annual pollution pattern, offering a unique opportunity to examine cumulative environmental effects. This adds to the literature by emphasizing the longitudinal, cyclical nature of air pollution's impact on migraine. While the biological mechanisms linking PM_{2.5} to migraine remain complex, our findings reinforce several plausible pathways. In addition to neuroinflammation and oxidative stress, vascular dysregulation—including changes in endothelial function and cerebral blood flow—may contribute to migraine worsening.^{15,34} Moreover, air pollution-induced activation of the hypothalamic–pituitary–adrenal (HPA) axis has been implicated in stress-related headache worsening, providing another possible mechanism for environmental sensitivity in migraine patients.³⁵

This study also has important clinical and public health implications. First, clinicians should consider air quality as a relevant factor when evaluating seasonal patterns in migraine exacerbation. Second, preventive strategies, such as recommending that patients avoid outdoor activity during high-PM periods, using air purifiers, or wearing masks, may reduce the symptom burden. Third, policymakers should recognize migraine as one of the many chronic conditions influenced by environmental quality, warranting stronger air pollution control efforts. In addition, personal exposure to PM_{2.5} is influenced by indoor environments and protective behaviours. In Northern Thailand, many individuals use air purifiers, keep indoor spaces closed during pollution peaks, and routinely wear masks, all of which can substantially reduce actual exposure compared with outdoor PM_{2.5} measurements. Because our study did not capture data on indoor air quality, ventilation, air filtration, or mask use, the influence of these factors on migraine outcomes remains uncertain. Future studies incorporating indoor exposure data and protective behaviours would help clarify their modifying effects on pollution–migraine relationships. However, we acknowledge several limitations of our study. As a retrospective observational design, causal conclusions cannot be drawn, and although the retrospective sample-size calculation indicated that our final sample exceeded the estimated requirement, the overall sample size remains modest and should be considered when interpreting the findings. While headache diaries provide valuable clinical insight, they rely on self-reporting and patient compliance, which may introduce reporting bias. Additionally, we did not account for other potentially influential variables, such as ambient temperature, humidity, sleep quality, menstrual cycle, medication adjustments, or psychological stress levels, which may co-occur with high-pollution periods and contribute to migraine exacerbation. Future studies with prospective designs and broader variable control are warranted to better account for these factors. Lastly, the study population was limited to a single geographic region, which may restrict the generalizability of our findings to other populations with different environmental exposures or healthcare contexts.

Future research should explore whether migraine prophylaxis strategies can be adjusted according to seasonal pollution patterns and whether biomarkers of inflammation, oxidative stress, or vascular dysfunction correlate with pollution-related migraine exacerbations. Additionally, prospective studies with real-time environmental monitoring and wearable sensor data could help disentangle the effects of co-existing variables, which may act as independent or synergistic migraine triggers during high-pollution periods. Furthermore, expanding to multi-center or multi-regional cohorts with diverse demographic and environmental profiles would enhance the generalizability of findings and help identify vulnerable subpopulations.

Conclusions

This pilot study identifies an association between higher PM_{2.5} levels and increased migraine burden in Northern Thailand, reflected by higher headache frequency, pain severity, medication use, and ER visits during high-pollution months. Using headache frequency as a practical index of migraine severity, these findings provide preliminary insight into how seasonal fluctuations in air quality may relate to migraine patterns in this population. Given the modest sample size and exploratory nature of the study, the findings should be interpreted cautiously. Larger, prospective, multi-center studies are needed to confirm and extend these preliminary observations.

Data Sharing Statement

All the datasets generated during the study are available upon reasonable request from the corresponding author.

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Author Contributions

All authors made a significant contribution to the work reported, whether in the conception, study design, execution, acquisition of data, analysis, and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Zanobetti A, Dominici F, Wang Y, Schwartz JD. A national case-crossover analysis of the short-term effect of PM_{2.5} on hospitalizations and mortality in subjects with diabetes and neurological disorders. *Environ Health*. 2014;13(1):38. doi:10.1186/1476-069X-13-38
2. Thangavel P, Park D, Lee YC. Recent insights into particulate matter (PM_{2.5})-mediated toxicity in humans: an overview. *Int J Environ Res Public Health*. 2022;19(12):7511. doi:10.3390/ijerph19127511
3. Peters R, Ee N, Peters J, Booth A, Mudway I, Anstey KJ. Air pollution and dementia: a systematic review. *J Alzheimers Dis*. 2019;70(s1):S145–s63. doi:10.3233/JAD-180631
4. Liu Q, Xu C, Ji G, et al. Effect of exposure to ambient PM_{2.5} pollution on the risk of respiratory tract diseases: a meta-analysis of cohort studies. *J Biomed Res*. 2017;31(2):130–142. doi:10.7555/JBR.31.20160071
5. Cristaldi A, Fiore M, Oliveri Conti G, et al. Possible association between PM_{2.5} and neurodegenerative diseases: a systematic review. *Environ Res*. 2022;208:112581. doi:10.1016/j.envres.2021.112581
6. Genc S, Zadeoglulari Z, Fuss SH, Genc K. The adverse effects of air pollution on the nervous system. *J Toxicol*. 2012;2012:782462. doi:10.1155/2012/782462
7. Khan J, Asoom LIA, Sunni AA, et al. Genetics, pathophysiology, diagnosis, treatment, management, and prevention of migraine. *Biomed Pharmacother*. 2021;139:111557. doi:10.1016/j.biopha.2021.111557
8. Stovner LJ, Nichols E, Steiner TJ. Global, regional, and national burden of migraine and tension-type headache, 1990–2016: a systematic analysis for the global burden of disease study 2016. *Lancet Neurol*. 2018;17(11):954–976. doi:10.1016/S1474-4422(18)30322-3
9. Goadsby PJ, Holland PR, Martins-Oliveira M, Hoffmann J, Schankin C, Akerman S. Pathophysiology of migraine: a disorder of sensory processing. *Physiol Rev*. 2017;97(2):553–622. doi:10.1152/physrev.00034.2015
10. Costa LG, Cole TB, Dao K, Chang Y-C, Garrick JM. Developmental impact of air pollution on brain function. *Neurochem Int*. 2019;131:104580. doi:10.1016/j.neuint.2019.104580
11. Basith S, Manavalan B, Shin TH, et al. The impact of fine particulate matter 2.5 on the cardiovascular system: a review of the invisible killer. *Nanomaterials*. 2022;12(15):2656. doi:10.3390/nano12152656
12. Li Q, Zheng J, Xu S, et al. The neurotoxicity induced by PM 2.5 might be strongly related to changes of the hippocampal tissue structure and neurotransmitter levels. *Toxicol Res*. 2018;7(6):1144–1152. doi:10.1039/C8TX00093J

13. Lin C-H, Nicol CJB, Wan C, Chen S-J, Huang R-N, Chiang M-C. Exposure to PM_{2.5} induces neurotoxicity, mitochondrial dysfunction, oxidative stress and inflammation in human SH-SY5Y neuronal cells. *Neurotoxicology*. 2022;88:25–35. doi:10.1016/j.neuro.2021.10.009
14. Yang Y, Rosenberg GA. Blood–brain barrier breakdown in acute and chronic cerebrovascular disease. *Stroke*. 2011;42(11):3323–3328. doi:10.1161/STROKEAHA.110.608257
15. Hansen JM, Schankin CJ. Cerebral hemodynamics in the different phases of migraine and cluster headache. *J Cereb Blood Flow Metab*. 2019;39(4):595–609. doi:10.1177/0271678X17729783
16. Portt AE, Orchard C, Chen H, Ge E, Lay C, Smith PM. Migraine and air pollution: a systematic review. *Headache*. 2023;63(9):1203–1219. doi:10.1111/head.14632
17. Lukina AO, Burstein B, Szyszkowicz M, Aherne J. Urban air pollution and emergency department visits related to central nervous system diseases. *PLoS One*. 2022;17(6):e0270459. doi:10.1371/journal.pone.0270459
18. Lee H, Myung W, Cheong H-K, et al. Ambient air pollution exposure and risk of migraine: synergistic effect with high temperature. *Environ Int*. 2018;121(Pt 1):383–391. doi:10.1016/j.envint.2018.09.022
19. Dong H-J, Ran P, Liao D-Q, et al. Long-term exposure to air pollutants and new-onset migraine: a large prospective cohort study. *Ecotoxicol Environ Saf*. 2024;273:116163. doi:10.1016/j.ecoenv.2024.116163
20. Suriyawong P, Chuettor S, Samae H, et al. Airborne particulate matter from biomass burning in Thailand: recent issues, challenges, and options. *Heliyon*. 2023;9(3):e14261. doi:10.1016/j.heliyon.2023.e14261
21. Supasri T, Gheewala SH, Macatangay R, Chakpor A, Sedpho S. Association between ambient air particulate matter and human health impacts in northern Thailand. *Sci Rep*. 2023;13(1):12753. doi:10.1038/s41598-023-39930-9
22. Chansuebsri S, Kolar P, Kraissititkul P, et al. Chemical composition and origins of PM_{2.5} in Chiang Mai (Thailand) by integrated source apportionment and potential source areas. *Atmos Environ*. 2024;327:120517. doi:10.1016/j.atmosenv.2024.120517
23. Pothirat C, Chaiwong W, Liwsrisakun C, et al. Acute effects of air pollutants on daily mortality and hospitalizations due to cardiovascular and respiratory diseases. *J Thorac Dis*. 2019;11(7):3070–3083. doi:10.21037/jtd.2019.07.37
24. Stewart WF, Lipton RB. Epidemiologic clues and the classification of primary headaches. *Cephalalgia*. 1994;14(2):77. doi:10.1046/j.1468-2982.1994.1402076.x
25. Stewart WF, Lipton RB, Kolodner KB, Sawyer J, Lee C, Liberman JN. Validity of the migraine disability assessment (MIDAS) score in comparison to a diary-based measure in a population sample of migraine sufferers. *Pain*. 2000;88(1):41–52. doi:10.1016/S0304-3959(00)00305-5
26. Kosinski M, Bayliss MS, Bjorner JB, et al. A six-item short-form survey for measuring headache impact: the HIT-6. *Qual Life Res*. 2003;12(8):963–974. doi:10.1023/A:1026119331193
27. Sabour S, Harzand-Jadidi S, Jafari-Khounigh A, Zarea Gavgani V, Sedaghat Z, Alavi N. The association between ambient air pollution and migraine: a systematic review. *Environ Monit Assess*. 2024;196(3):271. doi:10.1007/s10661-024-12376-w
28. Szyszkowicz M, Stieb DM, Rowe BH. Air pollution and daily ED visits for migraine and headache in Edmonton, Canada. *Am J Emerg Med*. 2009;27(4):391–396. doi:10.1016/j.ajem.2008.03.013
29. Calderón-Garcidueñas L, Reed W, Maronpot RR, et al. Brain inflammation and Alzheimer's-like pathology in individuals exposed to severe air pollution. *Toxicol Pathol*. 2004;32(6):650–658. doi:10.1080/01926230490520232
30. Oberdörster G, Sharp Z, Atudorei V, et al. Translocation of inhaled ultrafine particles to the brain. *Inhal Toxicol*. 2004;16(6–7):437–445. doi:10.1080/08958370490439597
31. Li T, Hu R, Chen Z, et al. Fine particulate matter (PM_{2.5}): the culprit for chronic lung diseases in China. *Chronic Dis Transl Med*. 2018;4(3):176–186. doi:10.1016/j.cdtm.2018.07.002
32. Block ML, Calderón-Garcidueñas L. Air pollution: mechanisms of neuroinflammation and CNS disease. *Trends Neurosci*. 2009;32(9):506–516. doi:10.1016/j.tins.2009.05.009
33. Szyszkowicz M, Kaplan GG, Grafstein E, Rowe BH. Emergency department visits for migraine and headache: a multi-city study. *Int J Occup Med Environ Health*. 2009;22(3):235–242. doi:10.2478/v10001-009-0024-5
34. Weichenthal S, Bai L, Hatzopoulou M, et al. Long-term exposure to ambient ultrafine particles and respiratory disease incidence in Toronto, Canada: a cohort study. *Environ Health*. 2017;16(1):64. doi:10.1186/s12940-017-0276-7
35. Friedman DI, De Ver Dye T. Migraine and the environment. *Headache*. 2009;49(6):941–952. doi:10.1111/j.1526-4610.2009.01443.x