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Respiratory Health Risk Assessment of Deforestation in Kalimantan: Analysis of PM2.5 Exposure in Local Communities in Forest Fire Areas

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ABSTRACT

This study evaluated the association between exposure to fine particulate matter (PM2.5) due to deforestation and forest fires and the risk of respiratory disorders in local communities in Kalimantan, Indonesia. A mixed-methods design with an observational epidemiological approach was used to evaluate the impact of exposure to PM2.5 on acute respiratory infections (ARI), asthma exacerbations, and community lung function. A cross-sectional survey was conducted to assess the prevalence of respiratory diseases and socioeconomic factors influencing exposure levels. Field measurements of PM2.5 both indoors and outdoors were used to estimate population exposure based on time-activity and indoor/outdoor ratios. Results showed that outdoor workers had an average exposure of 156.3 g/m3-hour, significantly higher than indoor workers, and this difference was significant (p 0.001). Indoor workers had a mean exposure of 88.5 l/hr, and the difference was statistically significant. The regression model showed that every 10 m3 increase in PM2.5 increased the odds of ARI by 11% (OR=1.11, 95%CI: 1.06-1.17). This study emphasizes the importance of strengthening the air quality monitoring system, health early warning, and stricter land use regulations to improve community resilience to future recurring haze events.

Keywords: *Health Risks, Respiratory Disorders, PM 2.5*

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INTRODUCTION

Forest and peatland fires in tropical regions, especially in Kalimantan, have long been a critical issue in the context of land use change and climate change. One of the main challenges in studying air quality and health in this region is the high spatial and temporal variability of PM2.5 concentrations, which are influenced by wind direction, meteorological conditions, land cover type, and fire intensity. Additionally, measuring exposure in local communities faces structural constraints, such as the limited network of official monitoring stations, the use of low-cost sensors requiring regular calibration, and differences in household characteristics that affect particulate infiltration. This challenge often leads to uncertainty in exposure estimates at the individual level, making direct measurement-based research in local communities crucial for generating more accurate and relevant health risk assessments. Deforestation in Kalimantan intensifies forest fires, elevating PM2.5 levels that pose severe respiratory risks to local communities (Grosvenor et al., 2024). This study evaluates exposure in fire-affected areas to guide health interventions. Prolonged haze events reveal substantial health impacts from particulate matter inhalation (Graham et al., 2024).

Research on forest and peatland fires in tropical regions has become an important focus in the context of land-use change and climate change. Peatland fires, which frequently occur in areas such as Kalimantan, produce large emissions of fine particulate matter (PM2.5) that spread to the surrounding environment and potentially reach local communities and cross borders. As a major factor in air quality, PAP (particulate matter with a diameter of ≤2.5 μm) has been linked to a significant burden of disease at the global, regional, and local levels. For example, studies have found that peatland fires in Indonesia cause approximately 33,100 adults and 2,900 infants to die prematurely each year due to exposure to PM2.5 (Hein et al., 2022).

Fine particulate matter PM2.5 can penetrate the respiratory tract down to the alveoli and enter the systemic circulation; therefore, PM2.5 exposure is an important indicator of respiratory and cardiovascular health risks. International studies have shown a dose-response relationship between PM2.5 concentrations and increased morbidity and mortality, including visits to respiratory health services and chronic diseases (Sangkham et al., 2024). In this context, community groups exposed to haze from land fires are at high risk, especially when environmental protection and local health facilities are limited.

Specifically in Kalimantan, the characteristics of peatlands cleared through deforestation or drainage make them highly susceptible to prolonged fires (smouldering), which release high levels of PM2.5 and long durations. Land-use changes (such as forest conversion to plantations) and peatland drainage increase the intensity and frequency of fires, thereby expanding people's exposure to particulate matter (Haryanto et al., 2024). Thus, deforestation/land conversion is not only an environmental issue but also a significant source of air quality exposure.

While numerous regional studies have evaluated PM2.5 concentrations in fire-affected areas and estimated the health burden, there is a lack of research incorporating real-world exposure measurements in local communities, including indoor/outdoor ratios, time-to-activity ratios, and local household protective factors. For example, a study in Indonesia highlighted that PM2.5 concentrations during the dry season in some locations can significantly exceed WHO guidelines, but these were rarely directly linked to community health surveillance data (Graham et al., 2024). This methodological gap hinders accurate community exposure-based respiratory health risk estimates.

This situation is highly relevant within the national policy framework. Although Indonesia has established air quality standards and policies for managing land fires, the implementation of air quality monitoring in fire-affected areas, as well as public health response systems, remains uneven. Developing

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local evidence using a quantitative risk-exposure approach will strengthen the empirical foundation for mitigation policies and health services at the regional level (Maksum & Tarigan, 2022). With local evidence, local governments and health departments can design community-specific mitigation strategies.

In the context of local communities in Kalimantan, it is important to assess vulnerability factors that amplify respiratory health risks from PM2.5 exposure. Factors such as housing conditions (e.g., ventilation and building protection from outside smoke), access to health services, occupations that require outdoor activities during fires, and vulnerable groups (children, pregnant women, the elderly) need to be analyzed. Studies that map heterogeneity in exposure and health outcomes across communities will indicate where interventions are most effective.

In response to these issues, this study proposes to evaluate respiratory health risks in local communities in Kalimantan affected by fires through a series of approaches: (1) field measurements of PM2.5 both indoors and outdoors; (2) estimation of population exposure based on time-activity and indoor/outdoor ratios; (3) modeling the contribution of fires to PM2.5 concentrations; and (4) surveillance of clinical outcomes related to acute respiratory infections (ARI), asthma exacerbations, or community lung function. This multipronged approach is expected to produce more realistic and targeted risk estimates (Wellid et al., 2024).

This research is highly urgent, given the projected increase in peatland fires due to climate change and land-use pressures. The research results are expected to provide direct evidence to policymakers, provincial/district health offices, and community stakeholders to design mitigation strategies: risk zone mapping, health warning systems, increased housing protection, distribution of high-filtration masks, and land-use regulations that consider health aspects. Thus, this research contributes not only scientifically but also in the context of practical mitigation measures.

By closing the gap between regional exposure estimates and community-based health risks, this study is expected to strengthen the scientific basis and policy implementation in Indonesia. The combination of exposure data, community behavior, and health outcomes will provide a stronger foundation for integrated public health interventions and forest fire management.

METHODS

This research method uses a mixed design with an observational epidemiological approach to evaluate the relationship between exposure to fine particulate matter PM2.5 resulting from deforestation and forest fires and the risk of respiratory disorders in the local community in Kalimantan. A longitudinal approach was used to assess short-term changes in lung function and respiratory symptoms in a group of individuals who were monitored repeatedly, while cross-sectional surveys were used to measure the prevalence of respiratory disorders and sociodemographic factors influencing exposure levels. Data collection was conducted over a period of one year and included periods of both high and low fire intensity. The study locations include a number of communities with a history of fires in the last five years, purposively selected based on land type (peat and mineral) and the level of smoke exposure. The study population consists of the local community, with an emphasis on vulnerable groups such as children, the elderly, pregnant women, and outdoor workers. Respondent selection was conducted through stratified random sampling, involving 300–500 participants for the cross-sectional survey and 100–200 individuals for longitudinal monitoring.

Exposure to PM2.5 was measured using a combination of reference devices and low-cost sensors placed at community and household locations, with continuous measurements taken throughout the dry and rainy seasons and subsequently calculated as 24-hour averages. Calibration is performed

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through linear regression against reference data, including temperature and humidity correction. Meteorological data is obtained from local sensors and BMKG stations, while hotspot information is gathered from MODIS and VIIRS satellite imagery. Individual exposure was estimated using a seven-day activity-time diary to determine time spent indoors and outdoors, which was then used to calculate the infiltration factor and time-weighted exposure (µg·hour/m^3). Health data includes the incidence of upper respiratory tract infections (URTIs), asthma, and bronchitis obtained from health centre records and household questionnaires, as well as lung function parameters (FEV1 and FVC) measured using a portable spirometer. Covariates such as age, gender, smoking behaviour, home ventilation, and socioeconomic status were collected to be controlled for as confounding variables.

Confounding variables are controlled by integrating these covariates into the statistical model to ensure that the estimated relationship between PM2.5 exposure and respiratory disorders is not influenced by other factors. In time series and cross-sectional analyses, stratification and multivariate adjustment were performed for age and sex by including both variables as confounders in the model. Socioeconomic status is controlled through proxies such as education level, income, and occupation, which are included as control variables. For individual data analysis, mixed-effects regression was used to address inter-individual and inter-group variability, while generalised additive models (GAMs) and distributed lag nonlinear models (DLNMs) were used to evaluate nonlinear and lagged effects simultaneously while controlling for covariates. All analyses were performed using R and Stata software, while spatial exposure mapping was done using QGIS.

RESULTS

Table 1. Sociodemographic and Environmental Characteristics of Respondents (n = 432)

Variables	Category	Frequency (n)	Percentage (%)
Gender	Man	213	49.3
	Woman	219	50.7
Age	< 20 years	42	9.7
	21–60 years	325	75.2
	> 60 years	65	15.1
Main job	Outdoor workers (farmers, laborers, fishermen)	124	28.6
	Indoor rkers (teachers, traders, clerks)	216	50.0
	Not working / other	92	21.4
Type of house	Wood / semi-permanent	275	63.7
	Concrete / permanent	157	36.3
Open ventilation without air filter	Yes	268	62.0
Use of masks during fire	Yes	147	34.0
Types of cooking fuel	Wood / charcoal	307	71.0

The majority of respondents live in wooden houses with open ventilation and no air filters. This indicates a high potential for wildfire smoke infiltration. Low mask use (34%) exacerbates the risk of direct exposure to fine airborne particulates.

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Table 2. PM2.5 Concentration in Ambient and Indoor Air

Location	Average PM2.5 (μg/m³)	Elementary School	Maximum	Indoor Average (μg/m³)	I/O Ratio	Finf
Pangkalanbun	213.4	78.5	421.0	82.1	0.42	0.62
Palangka	168.9	69.4	352.6	53.8	0.31	0.47
Ketapang	165.7	62.8	334.5	56.3	0.34	0.51
Overall average	**182.6**	**73.4**	**421.0**	**61.3**	**0.36**	**0.53**

PM2.5 concentrations during the fire season far exceeded the WHO safety limit (15 μg/m³), particularly in Pangkalanbun. The average I/O ratio of 0.36 indicates that approximately 36% of outdoor particulate matter enters homes. The infiltration factor was higher in non-permanent homes, indicating the effectiveness of the home structure against smoke penetration

Table 3. Estimated Individual Exposure Based on Activity and Type of Work

Activity Group	Average Exposure (μg/m³-hour)	Elementary School	Average Outdoor Duration (hours/day)	p-value
Outdoor workers	156.3	41.8	7.2	<0.001
Indoor workers	88.5	27.6	2.9	—
Not working / at home	74.2	31.5	1.6	—
Total average	**109.5**	**38.2**	**4.0**	—

Outdoor workers had nearly twice the level of PM2.5 exposure compared to indoor workers. The significant difference ($p < 0.001$) indicates that behavioral factors and daily activities were the primary determinants of actual exposure, not just environmental concentrations.

Table 4. Incidence of Respiratory Disorders During and Outside the Fire Season

Parameter	Non-Fire Season	Fire Season	Change (%)	p-value
ISPA cases per 1,000 population	98	144	+47.0	<0.001
Prevalence of cough (last 14 days)	21.4%	38.4%	+17.0	0.002
Prevalence of shortness of breath	11.2%	21.7%	+10.5	0.005
Mean FEV1 (% predicted)	92.6	86.8	−6.2	0.010
Average FVC (% predicted)	95.4	90.6	−4.8	0.015

There was a significant increase in all indicators of respiratory distress during the fire period. Decreases in lung function, measured through FEV1 and FVC, indicate a significant physiological effect of acute PM2.5 exposure. These findings are consistent with the pattern of increased ARI cases recorded at local health facilities.

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Table 5. Analysis of the Relationship between PM2.5 Exposure and the Risk of ARI

Analysis Model	Exposure Variables	Estimated Value	95% CI	p-value
Mixed-effects logistic regression	PM2.5 (per 10 μg/m³)	OR = 1.11	1.06–1.17	<0.001
Time-series Poisson model	Lag 0 days	RR = 1.05	1.01–1.09	0.021
	2 days lag	RR = 1.08	1.03–1.13	0.002
GAM (non-linear)	>100 μg/m³	RR = 1.24	1.15–1.36	<0.001
PAF (population attributable fraction)	—	32.1%	—	—

A 10 μg/m³ increase in PM2.5 increases the odds of ARI by 11% after controlling for covariates. The exposure effect shows a 2-day delay after the PM2.5 increase, with the sharpest increase in risk at concentrations above 100 μg/m³. Approximately one-third of ARI cases can be directly attributed to exposure to particulate matter from forest fires.

Table 6. Relationship between House Characteristics and PM2.5 Infiltration (Finf)

Type of House	Finf (mean ± SD)	p-value
Wood / semi-permanent	0.61 ± 0.09	0.013
Concrete / permanent	0.47 ± 0.08	—

Wooden houses exhibit higher infiltration factor (Finf) values, meaning outside air more readily enters, carrying particulate matter. This underscores the importance of structural interventions such as improving airtightness or using filters to reduce indoor exposure.

DISCUSSION

1. Sociodemographic and Environmental Characteristics of Respondents

The majority of respondents lived in wooden or semi-permanent houses (63.7%), with open ventilation without air filters (62%), and low mask use (34%). This situation suggests that social and physical environmental factors play a significant role in determining PM2.5 exposure levels. According to the theory of environmental exposure determinants, house design and ventilation are the main mediators influencing the infiltration of particulate matter from outdoors into indoor spaces. Recent research by Simatupang et al. (2024) found that unfiltered ventilation increased indoor particulate concentrations by up to twofold compared to closed ventilation (Simatupang et al., 2024).

Wooden houses with open ventilation and the use of solid fuels (such as wood or charcoal) increase the potential for multiple exposures from both indoor and outdoor sources. Furthermore, low mask use reflects limited access to effective personal protective equipment in rural areas, which is assumed to contribute to increased respiratory health risks during fire periods.

The findings in this section are potentially influenced by information bias because the condition of the homes and protective behaviours were self-reported by the respondents. Additionally, the sample size for homes with closed ventilation is very small, which limits generalisability. Disturbing factors such as passive smoking and the use of respiratory medications cannot be fully controlled in the analysis.

2. PM2.5 Concentration in Ambient and Indoor Air

The average PM2.5 concentration during the fire season reached 182.6 μg/m^3, or more than 12 times the WHO threshold (15 μg/m^3). An I/O ratio of 0.36 and an infiltration factor (Finf) of 0.53 indicate the high ability of particles to penetrate household buildings. This supports the passive infiltration theory of fine particulates, which states that particles measuring ≤ 2.5 μm can penetrate ventilation gaps even in closed buildings (Zhang & Kang, 2022).

Variations in Finf values between locations are caused by differences in building materials and tropical air humidity, which accelerate particle deposition. Researchers also assume that houses in areas with low vegetation density (the result of deforestation) are more exposed to exposure because they are no longer protected by natural barriers (tree canopies).

PM2.5 measurements rely on a combination of reference instruments and low-cost sensors, which still carries the risk of measurement bias even after calibration. Spatial variability between houses is not fully captured due to the limited number of sampling points, so the results may not fully represent the micro-environmental variation across the community.

3. Estimation of Individual Exposure Based on Activity and Type of Work

Outdoor workers had an average exposure of 156.3 μg/m^3-hour, significantly higher than indoor workers (88.5 μg/m^3-hour), and this difference was significant ($p < 0.001$). This is in line with the time–activity exposure model, which states that the duration of exposure and the location of daily activities determine the internal dose more than the average environmental concentration (Carter et al., 2023). A study of firefighters in Thailand also found that high outdoor exposure to PM2.5 was associated with decreased lung function (Panumasvivat et al., 2024).

The duration of outdoor activity is the most dominant variable in determining cumulative exposure, especially for farmers working in open, unprotected areas. Researchers also assume that fire risk awareness is low, resulting in reactive, rather than preventative, self-protection efforts.

Individual exposure estimates depend on time-activity diaries, which are prone to recall bias, especially for short or mobile activities. The duration spent indoors/outdoors is also not verified with personal sensors. Additionally, confounding factors such as mask use can actually increase or decrease the actual dose, but cannot be modelled precisely.

4. Occurrence of Respiratory Disorders During and Outside the Fire Season

Data show a 47% increase in ARI during the fire season compared to non-fire seasons, as well as a 6.2% decrease in FEV1 and 4.8% decrease in FVC on average. This strong association between exposure and outcome aligns with the results of a systematic review highlighting an increased risk of respiratory infections due to exposure to air pollution during natural disasters or fires (Burhan & Mukminin, 2023). The theory states that exposure to fine particles triggers airway inflammation, asthma exacerbations, and decreased lung function.

The increase in ARI cases is not only caused by direct exposure, but also by indirect effects such as oxidative stress, decreased immunity, and overcrowding during times of sheltering indoors. Researchers assume physiological effects may persist for several weeks after peak exposure.

The increased incidence of ARI and decreased lung function may be influenced by seasonal factors, exposure to other pollutants (e.g., O_3, CO), and comorbidities that are not fully recorded. Because the survey was conducted over a specific period, these results do not yet reflect the long-term effects or progression of chronic diseases due to PM2.5 exposure.

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5. Analysis of the Relationship between PM2.5 Exposure and the Risk of ISPA

The regression model showed that every 10 μg/m^3 increase in PM2.5 increased the odds of ARI by 11% (OR=1.11, 95%CI: 1.06–1.17). The two-day delayed effect (RR=1.08) and non-linear effects increased sharply above 100 μg/m^3, and the PAF was around 32.1%. These results support the construction of the exposure-response theory and the risk increases non-linearly when exposure is extreme (Siregar et al., 2022). The mechanism of the delayed effect occurs due to the accumulation of particulate matter in lung tissue before triggering an acute inflammatory response. Researchers also assume that fluctuating daily exposure with extreme peaks is more dangerous than moderate but stable exposure.

Although the regression model controls for many covariates, there is still the possibility of residual confounding, including the quality of home ventilation, housing density, and exposure to cigarette smoke. The observational design does not allow researchers to fully infer causal relationships, and daily PM2.5 variability is not always continuously recorded at every location.

6. Relationship between House Characteristics and PM2.5 Infiltration

Wooden houses have a higher infiltration factor (Finf) (0.61 ± 0.09) than concrete houses (0.47 ± 0.08; p = 0.013). The physical characteristics of the building such as construction materials, ventilation systems, and airtightness levels significantly influence the infiltration of particles from outside into the living space. Dense and airtight building materials tend to reduce the rate of particle infiltration, because strong physical barriers make it difficult for particles to penetrate. Conversely, poor ventilation or an open ventilation system can make it easier for particles from outside to enter the room, because the air from outside carrying pollutants flows in (Fauzi et al., 2025).

Building materials and roof type are important determinants of infiltration, and increased humidity due to low rainfall during the dry season also accelerates the spread of particulate matter indoors. Researchers also hypothesize that simple interventions such as covering vents with a wet cloth or using a portable air purifier could significantly reduce Finf values.

Finf measurements in certain home categories have a limited number of observations, which restricts the precision of the estimates, especially for concrete homes, which are fewer in number. Other structural factors such as roof type, density of surrounding vegetation, and wind direction were not included in the model and could potentially be confounding factors.

CONCLUSIONS

This study shows that exposure to PM2.5 from deforestation and forest fires in Kalimantan has a significant impact on increasing ARI incidence, reducing lung function, and increasing the risk of respiratory health problems, especially among vulnerable groups and outdoor workers. Variations in house characteristics, ventilation, and protective behaviours have been shown to play a role in determining the magnitude of particulate infiltration and actual exposure at the individual level.

These findings underscore the need for further research integrating personal exposure data, longitudinal health data, and spatial air quality models to gain a more comprehensive understanding of long-term risks. In addition, the development of community based mitigation strategies, such as improving home airtightness, providing clean rooms, and distributing high filtration masks, needs to be prioritised, especially in communities most vulnerable to forest fires.

This study also emphasises the importance of strengthening evidence-based air quality control policies and integrating public health interventions at the local level to reduce health risks from PM2.5 exposure due to forest fires and deforestation. Strengthening the air quality monitoring system, health

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early warning, and stricter land use regulations are urgently needed to improve community resilience to future recurring haze events.

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