



Health Risk Assessment of PM_{2.5} Exposure and Respiratory Symptoms among Residents Living Near a Stone Crushing Plant in Chonburi, Thailand

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Abstract

Background: Air pollution from industrial activities remains an environmental health concern among communities living near stone crushing plants. **Objective:** This study aimed to assess non-carcinogenic health risk using Hazard Quotient (HQ) based on PM_{2.5} exposure and identify factors associated with respiratory symptoms among residents living near a stone crushing plant in Chonburi Province, Thailand. **Methods;** A cross-sectional study was conducted among 368 residents from seven villages within a 5-km radius. PM_{2.5} concentrations were measured at two fixed-site air monitoring stations from 25–27 March 2026 using two low-volume air samplers operated continuously for 72 hours and analyzed by the gravimetric method. **Results:** The mean PM_{2.5} concentration was 28.06 µg/m³, and mean HQ was 0.96. Respiratory symptoms were reported by 57.9% of participants. Underlying medical conditions (AOR = 3.146, 95% CI: 1.393–7.105, p = 0.006), age <40 years (AOR = 2.065, 95% CI: 1.210–3.523, p = 0.008), opening windows all the time (AOR = 2.642, 95% CI: 1.335–5.229, p = 0.005) or during daytime only (AOR = 1.941, 95% CI: 1.010–3.733, p = 0.047), and low preventive behavior (AOR = 0.254, 95% CI: 0.076–0.843, p = 0.025) were significantly associated with respiratory symptoms. Although 47.3% of participants had HQ values ≥1, HQ was not significantly associated with respiratory symptoms. The HQ estimates were derived from short-term fixed-site PM_{2.5} monitoring and should be interpreted as preliminary estimates of community-level exposure. **Conclusion:** From a public health perspective, strengthening long-term environmental monitoring, respiratory health surveillance, community awareness, and effective dust

control measures may help reduce the health impacts of particulate matter exposure. Future studies should incorporate long-term environmental monitoring, exposure assessment, and respiratory health surveillance.

Keywords: PM_{2.5}; Health Risk Assessment; Hazard Quotient; Respiratory Symptoms; Stone Crushing Plant

What was Known

- Stone crushing activities increase particulate matter exposure.
- Particulate matter exposure is associated with respiratory health problems.

What's New and Next

- Respiratory symptoms were associated with individual and behavioral factors.
- Long-term monitoring is needed to improve community exposure assessment.

Introduction

Air pollution remains a major global environmental health problem, particularly in urban and industrial areas with intensive transportation and pollutant-emitting activities. The World Health Organization (WHO) reports that a large proportion of urban populations are exposed to air pollution levels exceeding recommended standards, contributing substantially to premature mortality worldwide ^(1,2).

Among air pollutants, particulate matter (PM), particularly PM_{2.5}, is considered highly harmful because of its ability to penetrate deeply into the respiratory tract and contribute to respiratory and cardiovascular diseases. Although stone crushing activities generate particulate matter across a broad size spectrum, including PM₁₀, respirable dust, and crystalline silica, PM_{2.5} was selected as the primary exposure indicator in this study because it can penetrate deeply into the alveolar region, remain suspended in the atmosphere for prolonged periods, and is widely recognized as an appropriate indicator for assessing long-term community exposure and non-carcinogenic health risk ⁽³⁻⁷⁾. In Thailand, PM_{2.5} pollution has become increasingly severe, especially in industrial and urban areas during the dry season ⁽⁸⁾. Health surveillance data have also shown increasing respiratory health problems associated with air pollution exposure ⁽⁹⁾.

Chonburi Province was selected as the study area because it is part of the Eastern Economic Corridor (EEC), where rapid industrial expansion has intensified environmental health concerns. The province contains a high concentration of stone crushing industries due to abundant limestone

resources. According to the Department of Primary Industries and Mines, Chonburi Province has 39 licensed stone crushing operations ⁽¹⁰⁾. Activities such as blasting, crushing, grinding, and transportation can generate substantial particulate matter emissions that may disperse into nearby residential communities and increase respiratory health risks among residents ^(11,12,13).

Previous studies have reported that stone quarrying and crushing activities are important sources of respirable particulate matter, including PM_{2.5}, PM₁₀, and respirable crystalline silica. These emissions may disperse beyond the workplace, resulting in elevated particulate concentrations and potential respiratory health risks among populations residing in surrounding communities ^(14,15). According to the Health Data Center (HDC), Ministry of Public Health, 157,164 patients with diseases monitored under the national air pollution surveillance system were recorded in Chonburi Province in 2025, including 72,876 patients with respiratory diseases. In communities located near stone crushing operations, 11,496 patients were recorded, of whom 6,487 had respiratory diseases, highlighting the importance of investigating respiratory health among residents living near stone crushing plants ⁽¹⁶⁾.

Hazard Quotient (HQ) is widely used to assess non-carcinogenic health risk from environmental exposure. HQ values ≥ 1 indicate that exposure exceeds the acceptable reference level and may pose potential health risks ⁽¹⁷⁾. However, previous studies have mainly focused on environmental monitoring without adequately examining respiratory health outcomes at the community level. Most existing studies have evaluated occupational exposure among workers or environmental particulate concentrations separately, whereas studies integrating PM_{2.5}-based health risk assessment using Hazard Quotient with respiratory symptom assessment among community residents living near stone crushing plants remain limited, particularly in Thailand. This knowledge gap highlights the need for an integrated assessment of environmental exposure and respiratory health among nearby communities. In addition, individual and behavioral factors, such as preventive practices and underlying medical conditions, may influence respiratory health responses ^(18,19).

Despite growing concerns regarding particulate emissions from stone crushing activities, evidence regarding community-level health risk and respiratory symptoms among nearby residents in Thailand remains limited. Therefore, this study aimed to: (1) assess non-carcinogenic health risk using HQ based on PM_{2.5} exposure and (2) identify factors associated with respiratory symptoms among residents living near a stone crushing plant in Chonburi Province, Thailand.

Materials and Methods

Study design and study area

This analytical cross-sectional study was conducted among residents living within a 5-km radius of a selected stone crushing plant in Huai Kapi Subdistrict, Mueang Chonburi District, Chonburi Province, Thailand. The selected stone crushing plant was purposively selected based on the following criteria: (1) it was a licensed stone crushing operation located within the study area; (2) it was situated in the closest proximity to residential communities among the licensed stone crushing plants in Huai Kapi Subdistrict and the surrounding area; and (3) crushing, screening, material handling, and transportation activities were conducted on a daily basis, providing a continuous source of particulate matter emissions throughout the study period.

Chonburi Province was selected because it is part of the Eastern Economic Corridor (EEC), where rapid industrial expansion and mining-related activities have increased environmental health concerns. According to the Department of Primary Industries and Mines, Chonburi Province contains 39 licensed stone crushing operations, with the highest concentration located in Mueang Chonburi and Ban Bueng districts⁽¹⁰⁾.

A 5-km buffer zone was established around the selected stone crushing plant to define the study area and identify communities potentially affected by particulate matter dispersion. The radius was determined based on the potential dispersion range of particulate matter from stone crushing activities reported in previous environmental health studies^(11,12,13).

Population and sample

The study population comprised 17,395 registered residents living in seven villages within Huai Kapi Subdistrict, Chonburi Province⁽²⁰⁾.

Sample size was calculated using Daniel's formula for cross-sectional studies⁽²¹⁾, based on a population size of 17,395, a 95% confidence level, a margin of error of 0.05, and an expected proportion of 0.33 obtained from a previous study⁽²²⁾. The minimum required sample size was 334 participants. After adding 10% to compensate for potential non-response, the final sample size was 368 participants.

The inclusion criteria were: (1) residing or working within the study area for at least one year; (2) aged 18–60 years; and (3) willingness to participate in the study. Individuals with communication difficulties, literacy impairment, or withdrawal during data collection were excluded from the study.

Sampling procedure

Stratified sampling was applied using seven villages within the 5-km buffer zone as strata. Proportional allocation was used to determine the number of participants recruited from each village according to population size to ensure representativeness of the study population. The numbers of participants recruited from each village were as follows: Village 1 (n = 52), Village 2 (n = 23), Village 3 (n = 27), Village 4 (n = 90), Village 5 (n = 88), Village 6 (n = 44), and Village 7 (n = 44). Simple random sampling was used to recruit eligible participants within each stratum to reduce selection bias. Eligible participants were randomly selected from the registered resident list provided by the local municipality for each village. Only residents who had lived or worked in the study area for at least one year and met the inclusion criteria were eligible for selection. To avoid clustering effects, only one eligible participant was selected from each household.

Research instrument

Questionnaire-based variables

Data were collected using a structured questionnaire consisting of four sections: personal characteristics, knowledge regarding particulate matter exposure, exposure-related behaviors, and preventive behavior. Knowledge regarding PM exposure was assessed using 20 true–false questions, with one point assigned for each correct answer and zero points for each incorrect answer, yielding a total score ranging from 0 to 20. Knowledge levels were categorized according to Bloom's criteria as low (<60%), moderate (60–79%), and high (80–100%)⁽²³⁾. Exposure-related behaviors were assessed using four questions describing participants' daily exposure characteristics, including time spent outdoors, primary outdoor activities, window–opening behavior, and smoking status, and were summarized using descriptive statistics. Preventive behavior was assessed using 15 items measured on a three–point Likert scale (3 = always, 2 = sometimes, 1 = never), with total scores ranging from 15 to 45. Preventive behavior was categorized as low (15–24), moderate (25–34), and good (35–45) according to Best's criteria⁽²⁴⁾.

Respiratory symptom assessment

Respiratory symptoms were assessed using self–reported responses regarding symptoms experienced during the previous 12 months, including cough, sore throat, sputum production, runny nose, and difficulty breathing. The symptom items and 12–month recall period were adapted from standardized respiratory health questionnaires commonly used in epidemiological studies^(25,26).

Participants reporting at least one symptom during the previous 12 months were classified as having respiratory symptoms for epidemiological analysis.

Questionnaire validity and reliability

The questionnaire was evaluated for content validity by three experts. The content validity index (CVI) for the knowledge, exposure-related behavior, and preventive behavior sections was 0.98, 0.83, and 0.97, respectively. Reliability was assessed using the KR-20 coefficient for the knowledge section (0.841) and Cronbach's alpha coefficient for the preventive behavior section (0.856), indicating acceptable internal consistency.

PM_{2.5} exposure assessment and Hazard Quotient

PM_{2.5} concentrations were measured at two fixed-site air monitoring stations located approximately 850 m and 1.0 km from the selected stone crushing plant. The stone crushing plant was located at 13°18'06.7"N, 100°58'44.4"E. Sampling Point 1 was located at 13°18'28.8"N, 100°58'49.2"E, approximately 850 m from the stone crushing plant, whereas Sampling Point 2 was located at 13°17'46.5"N, 100°58'27.1"E, approximately 1.0 km from the plant. Air sampling was conducted continuously for 72 hours during 25–27 March 2026 using two low-volume air samplers (TE-PM_{2.5}C), and PM_{2.5} concentrations were analyzed using the gravimetric method. The instruments were calibrated using a Delta Cal.DC 1 calibrator, and instrument performance was verified using the TE-Wilbur Calibration Worksheet before air sampling. Ambient temperature, relative humidity, and atmospheric pressure were monitored during sampling using calibrated thermo-hygrometer and barometric instruments. Meteorological conditions, including wind direction and wind speed, were also recorded throughout the sampling period to characterize atmospheric conditions during air sampling. Prevailing winds were predominantly from the south to southwest on 25 March 2026 and from the southwest on 26–27 March 2026, with wind speeds ranging from approximately 11 to 14 km/h⁽²⁷⁾. The average PM_{2.5} concentration from the two monitoring stations was used to estimate community level exposure among residents living within the 5-km buffer zone. The locations of the PM_{2.5} monitoring stations and air sampling setup are presented in Figure 1.

Although stone crushing activities primarily generate coarse particulate matter (PM₁₀), PM_{2.5} was used as a proxy indicator for inhalation exposure assessment because of its ability to penetrate deeply into the respiratory system and its established association with adverse respiratory health effects^(3–7). Inhalation exposure to PM_{2.5} was estimated using the following equation:

$$I = \frac{C \times IR \times ET \times EF \times ED}{BW \times AT}$$

where *I* represents inhalation exposure dose, *C* is the average PM_{2.5} concentration (28.06 µg/m³), *IR* is the inhalation rate (0.83 m³/h)⁽²⁸⁾, *ET* is exposure time (24 h/day), *EF* is exposure frequency (365 days/year), *ED* is exposure duration (years of residence), *BW* is body weight (kg), and *AT* is averaging time (*ED* × 365 days).

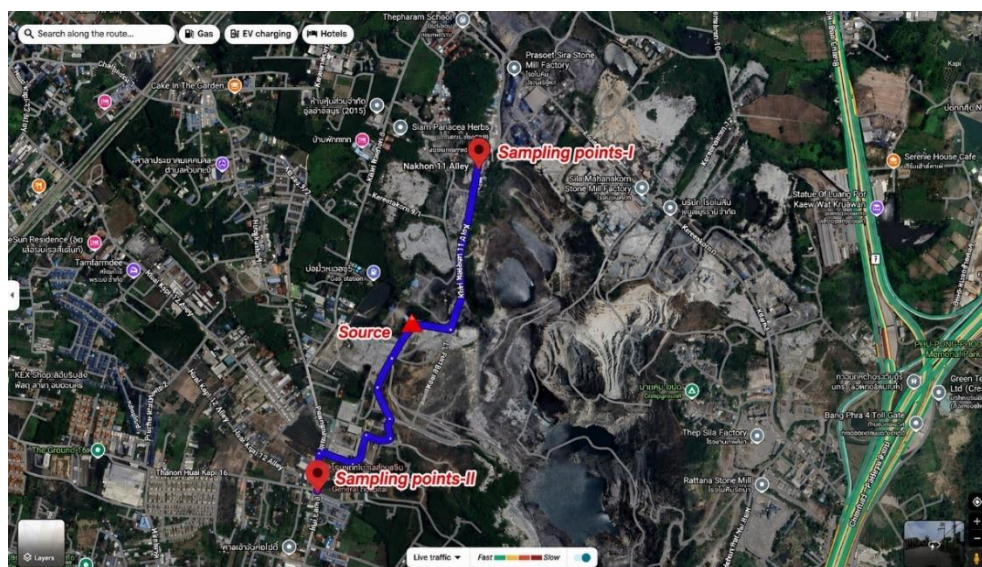


Figure 1 Study area and locations of the stone crushing plant and PM_{2.5} monitoring stations.

Source: Adapted from Google Maps and field survey data.

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The reference dose (RfD) used for HQ calculation was 0.005 mg/kg/day, adopted from the Guidelines for Surveillance of Air Pollution Risk Areas: Fine Particulate Matter (PM₁₀ and PM_{2.5}) published by the Department of Health, Ministry of Public Health, Thailand ⁽²⁹⁾. Hazard Quotient (HQ) was calculated using the following equation:

$$HQ = \frac{I}{RfD}$$

HQ ≥ 1 indicated that the estimated exposure dose exceeded the selected reference dose, suggesting a potential non-carcinogenic health concern, whereas HQ < 1 indicated that the estimated exposure dose did not exceed the selected reference dose.

Due to the absence of personal and long-term exposure monitoring data, the average PM_{2.5} concentration from the two monitoring stations was used as a common community-level exposure estimate for all participants. Although the PM_{2.5} concentration was identical for all participants, individual HQ values varied because the exposure assessment incorporated participant-specific parameters, including body weight (BW), duration of residence (ED), and the corresponding averaging time (AT).

Data collection

Data were collected from 1–31 March 2026 using face-to-face interviews conducted by the principal researcher and trained research assistants. Permission was obtained from the local administrative organization, and village health volunteers assisted with participant recruitment. All participants were informed regarding the study objectives, procedures, benefits, and potential risks before providing written informed consent.

Statistical analysis

Descriptive statistics were used to summarize participant characteristics. Chi-square tests were performed to examine associations between independent variables and respiratory symptoms. Variables with p-values < 0.25 in the bivariate analysis were entered simultaneously into the multivariable logistic regression model using the Enter method, as recommended by Hosmer et al. ⁽³⁰⁾ Multicollinearity among the independent variables was assessed using tolerance values and variance inflation factors (VIF) before model fitting. No evidence of problematic multicollinearity was observed (tolerance = 0.886–0.987; VIF = 1.013–1.129). Adjusted odds ratios (AORs) and 95% confidence intervals (CIs) were reported. Model fit was evaluated using the Hosmer–Lemeshow goodness-of-fit test. Statistical significance was set at $p < 0.05$. All analyses were performed using SPSS version 26.

Results

Participant characteristics

A total of 368 participants were included in the study. Most participants were female (54.3%), aged ≥ 40 years (70.9%), and worked in agriculture or daily labor occupations (54.9%). The mean age was 46.00 ± 10.59 years, and the mean body weight was 64.55 ± 11.45 kg. Most participants reported no underlying medical conditions (88.6%), while 57.9% reported respiratory symptoms during the previous 12 months. Most participants engaged in outdoor activities during daytime (77.7%), primarily for work-related activities (61.1%), and 91.3% were never smokers. In addition, 61.1% demonstrated good preventive behavior. Participants had lived in the study area for 25.00 ± 11.59 years, and the mean distance from their residence to the stone crushing plant was 3.40 ± 1.52 km. Detailed participant characteristics are presented in Table 1.

Table 1 Demographic, health, exposure-related, and preventive behavior characteristics of study participants (n = 368)

Characteristics	n (%)
Demographic characteristics	
Sex	
Male	168 (45.7)
Female	200 (54.3)
Age (years), mean $\pm$ SD	46.00 ± 10.59
<40 years	107 (29.1)
≥ 40 years	261 (70.9)
Body weight (kg), mean $\pm$ SD	64.55 ± 11.45
Duration of residence (years), mean $\pm$ SD	25.00 ± 11.59
Distance from residence to the stone crushing plant (km), mean $\pm$ SD	3.40 ± 1.52
Marital status	
Single	107 (29.1)
Married	187 (50.8)
Widowed	52 (14.1)
Divorced	22 (6.0)

Table 1 Demographic, health, exposure-related, and preventive behavior characteristics of study participants (n = 368) (Cont.)

Characteristics	n (%)
Education level	
Primary education	136 (37.0)
Secondary education	127 (34.5)
Diploma	44 (12.0)
Bachelor's degree	61 (16.5)
Occupation	
Agriculture/daily labor	202 (54.9)
Self-employed/business owner	75 (20.4)
Company employee/government officer	44 (11.9)
Unemployed	47 (12.8)
Income (THB), mean ± SD	12,350.41 ± 6,971.74
3,000–11,000 THB	191 (51.9)
11,001–13,000 THB	34 (9.2)
≥13,001 THB	143 (38.9)
Health characteristics	
Underlying medical conditions	
No	326 (88.6)
Yes	42 (11.4)
Respiratory symptoms	
No	155 (42.1)
Yes	213 (57.9)
Exposure-related behaviors	
Time spent outdoors	
Daytime (06:00–18:00)	286 (77.7)
Nighttime (18:00–06:00)	82 (22.3)
Primary outdoor activities	
Work	225 (61.1)
Exercise/market/social activities	143 (38.9)

Table 1 Demographic, health, exposure-related, and preventive behavior characteristics of study participants (n = 368) (Cont.)

Characteristics	n (%)
Window-opening behavior	
Open all the time	91 (24.7)
Open during daytime	90 (24.5)
Open during nighttime	92 (25.0)
Do not open	95 (25.8)
Smoking status	
Current smoker	9 (2.5)
Occasional smoker	13 (3.5)
Former smoker	10 (2.7)
Never smoke	336 (91.3)
Preventive behavior	
Preventive behavior, mean ± SD (range)	35.79 ± 5.94 (19–45)
Low	18 (4.9)
Moderate	125 (34.0)
Good	225 (61.1)

PM_{2.5} concentration and Hazard Quotient (HQ)

PM_{2.5} concentrations measured during 25–27 March 2026 ranged from 21.57 to 35.07 µg/m³ across the two monitoring stations. The overall average PM_{2.5} concentration was 28.06 µg/m³, and the mean HQ among participants was 0.96 (SD = 0.50). Overall, 47.3% of participants had HQ values ≥1, indicating potential non–carcinogenic health risk. Detailed PM_{2.5} concentrations and HQ values are presented in Table 2.

Factors associated with respiratory symptoms

Bivariate analysis identified age, occupation, underlying medical conditions, window–opening behavior, and preventive behavior as significantly associated with respiratory symptoms. Variables with p–values <0.25 were subsequently entered into the multivariable logistic regression model using the Enter method. Detailed results of the bivariate analysis are presented in Table 3.

Table 2 PM_{2.5} concentration and Hazard Quotient among participants

Monitoring station	Sampling date	PM _{2.5} concentration (µg/m ³)
Station 1	25 March 2026	32.51
	26 March 2026	26.72
	27 March 2026	28.45
Station 2	25 March 2026	24.08
	26 March 2026	21.57
	27 March 2026	35.07
Variable	Mean ± SD	
PM _{2.5} concentration (µg/m ³)	28.06 ± 4.89	
Hazard Quotient (HQ)	0.96 ± 0.50	
HQ category	n (%)	
HQ <1	194 (52.7)	
HQ ≥1	174 (47.3)	

SD, standard deviation

Multivariable analysis of factors associated with respiratory symptoms

Binary logistic regression analysis showed that participants with underlying medical conditions had significantly higher odds of reporting respiratory symptoms than those without underlying medical conditions (AOR = 3.146, 95% CI: 1.393–7.105, $p = 0.006$). Participants aged <40 years were also more likely to report respiratory symptoms than those aged ≥40 years (AOR = 2.065, 95% CI: 1.210–3.523, $p = 0.008$). Compared with participants who did not open their windows, those who reported opening windows all the time (AOR = 2.642, 95% CI: 1.335–5.229, $p = 0.005$) or during daytime only (AOR = 1.941, 95% CI: 1.010–3.733, $p = 0.047$) had significantly higher odds of respiratory symptoms. Compared with participants reporting good preventive behavior, low preventive behavior remained significantly associated with respiratory symptoms (AOR = 0.254, 95% CI: 0.076–0.843, $p = 0.025$). The logistic regression model was statistically significant ($\chi^2 = 59.786$, $df = 18$, $p < 0.001$), and the Hosmer–Lemeshow goodness-of-fit test indicated an acceptable model fit ($\chi^2 = 7.736$, $df = 8$, $p = 0.460$). Detailed results are presented in Table 4.

Table 3 Bivariate analysis of factors associated with respiratory symptoms (n = 368)

Variables	Respiratory symptoms		p-value ^a
	Yes n (%)	No n (%)	
Sex			0.269
Male	64 (38.1)	104 (61.9)	
Female	91 (45.5)	109 (54.5)	
Age			0.005
<40 years	74 (69.2)	33 (30.8)	
≥40 years	139 (53.3)	122 (46.7)	
Marital status			0.332
Single	46 (43.0)	61 (57.0)	
Married	73 (39.0)	114 (61.0)	
Widowed	23 (44.2)	29 (55.8)	
Divorced	13 (59.1)	9 (40.9)	
Education level			0.519
Primary education	61 (44.9)	75 (55.1)	
Secondary education	56 (44.1)	71 (55.9)	
Diploma	15 (34.1)	29 (65.9)	
Bachelor's degree	23 (37.7)	38 (62.3)	
Occupation			0.044
Agriculture/daily labor	127 (62.9)	75 (37.1)	
Self-employed/business owner	35 (46.7)	40 (53.3)	
Company employee/government officer	28 (63.6)	16 (36.4)	
Unemployed	23 (48.9)	24 (51.1)	
Income			0.552
3,000–11,000 THB	81 (42.4)	110 (57.6)	
11,001–13,000 THB	17 (50.0)	17 (50.0)	
≥13,001 THB	57 (39.9)	86 (60.1)	

Table 3 Bivariate analysis of factors associated with respiratory symptoms (n = 368) (Cont.)

Variables	Respiratory symptoms		<i>p</i> -value ^a
	Yes n (%)	No n (%)	
Underlying medical conditions			0.004
No	180 (55.2)	146 (44.8)	
Yes	33 (78.6)	9 (21.4)	
Window-opening behavior			0.014
Open all the time	62 (68.1)	29 (31.9)	
Open during daytime	58 (64.4)	32 (35.6)	
Open during nighttime	46 (50.0)	46 (50.0)	
Do not open	47 (49.5)	48 (50.5)	
Preventive behavior			0.022
Low	5 (27.8)	13 (72.2)	
Moderate	71 (56.8)	54 (43.2)	
Good	137 (60.9)	88 (39.1)	
Hazard Quotient			0.212
HQ <1	108 (55.7)	86 (44.3)	
HQ ≥1	105 (60.3)	69 (39.7)	

^a Pearson's chi-square test; *p* < 0.05 indicates statistical significance.

Discussion

This study found that nearly half of the participants had Hazard Quotient (HQ) values ≥1, indicating a potential non-carcinogenic health risk based on the estimated PM_{2.5} exposure. These findings are consistent with previous studies reporting elevated particulate matter exposure and environmental health risks among populations living near industrial emission sources^(12,13,31).

Consistent with the present findings, studies conducted in developing countries have reported that communities residing near industrial areas were exposed to particulate matter concentrations exceeding recommended standards, which may contribute to increased respiratory health risks^(32,33). Studies among stone quarry workers in India also reported impaired pulmonary function among

Table 4 Multivariable binary logistic regression analysis of factors associated with respiratory symptoms (n = 368)

Variables	Category	AOR	95% CI	p-value
Age				
	≥40 years	Ref		
	<40 years	2.065	1.210–3.523	0.008
Occupation				
	Unemployed	Ref		
	Agriculture/daily labor	1.729	0.855–3.496	0.127
	Self-employed/business owner	0.849	0.375–1.920	0.694
	Company employee/government officer	1.837	0.724–4.662	0.201
Underlying medical conditions				
	No	Ref		
	Yes	3.146	1.393–7.105	0.006
Window-opening behavior				
	Do not open	Ref		
	Open all the time	2.642	1.335–5.229	0.005
	Open during daytime	1.941	1.010–3.733	0.047
	Open during nighttime	1.225	0.639–2.348	0.542
Preventive behavior				
	Good	Ref		
	Moderate	0.910	0.530–1.564	0.733
	Low	0.254	0.076–0.843	0.025
Hazard Quotient				
	HQ <1	Ref		
	HQ ≥1	1.010	0.637–1.603	0.966

AOR, adjusted odds ratio; CI, confidence interval; Ref, reference group

p < 0.05 indicates statistical significance.

workers with prolonged occupational dust exposure⁽³⁴⁾. In Thailand, residents living near stone crushing industries were reported to have higher non-carcinogenic health risks, particularly during dry seasons and periods of increased particulate dispersion⁽³⁵⁾.

However, no statistically significant association was observed between HQ and respiratory symptoms despite elevated HQ levels. This non-significant association is an important finding, suggesting that the estimated community-level PM_{2.5} exposure alone may not adequately explain the occurrence of respiratory symptoms in this population. This finding may be explained by exposure misclassification related to the use of fixed-site monitoring stations, limited exposure variability within the study area, and the short PM_{2.5} monitoring period, which may not represent seasonal variation in particulate concentrations^(2,18). Therefore, the estimated HQ values should be interpreted cautiously because they were derived from short-term fixed-site ambient PM_{2.5} monitoring rather than long-term individual exposure assessment. In addition, meteorological conditions, particularly wind direction and wind speed during the sampling period, may have influenced the spatial distribution of PM_{2.5} concentrations across the study area. A previous study conducted in Samut Prakan Province, Thailand, demonstrated that meteorological factors, including ventilation conditions and wind patterns, can substantially influence PM_{2.5} variability and particulate dispersion characteristics⁽³⁶⁾. Therefore, the use of only two fixed-site monitoring stations within the 5-km buffer zone may not fully reflect variations in particulate dispersion among different residential locations.

These findings are generally consistent with a previous study conducted in stone crushing areas in Saraburi Province, Thailand, which reported that particulate matter exposure and associated health risks may vary according to meteorological conditions, seasonal variation, and residential location relative to stone crushing activities⁽³⁷⁾. These findings further support the importance of considering spatial and temporal variability when assessing community-level particulate matter exposure. Previous studies have also emphasized the importance of long-term environmental monitoring and effective dust control measures to reduce health risks among nearby communities⁽³⁷⁾.

Although stone crushing activities primarily generate coarse particulate matter (PM₁₀), the ambient PM_{2.5} concentrations measured in this study may also have been influenced by other emission sources, including road traffic, biomass burning, household activities, and nearby industrial emissions^(38,39). Therefore, PM_{2.5} was used as a proxy indicator of community-level air pollution rather than a direct measure of exposure attributable solely to stone crushing activities because of its ability

to penetrate deeply into the respiratory tract and contribute to adverse respiratory effects^(5,32). Previous evidence has also demonstrated that mechanically generated dust contains substantial fine particle fractions capable of affecting respiratory health⁽⁴⁰⁾. In addition, stone crushing operations generate a complex mixture of airborne particles, including PM₁₀, coarse dust, respirable dust, and silica-containing dust, which were not evaluated in the present study. Therefore, the observed respiratory outcomes should be interpreted in the context of multiple potential particulate exposures rather than PM_{2.5} alone.

Underlying medical conditions were significantly associated with respiratory symptoms, which is consistent with previous studies indicating that individuals with pre-existing diseases are more vulnerable to particulate matter exposure^(4,7). Similar findings have been reported in communities located near industrial and traffic-related pollution sources⁽⁴¹⁾. Individuals with underlying respiratory or chronic diseases may be more susceptible to the adverse effects of air pollution because of impaired physiological defense mechanisms and increased sensitivity to inhaled particulate matter^(4,7).

Participants aged <40 years were more likely to report respiratory symptoms than those aged ≥40 years. This association may reflect differences in occupational activities, time spent outdoors, or other unmeasured exposure patterns among younger participants. However, because of the cross-sectional study design, age should be interpreted as a potential marker of exposure rather than a direct causal factor. Similar observations have been reported in previous environmental exposure studies^(12,35).

Participants who reported opening windows all the time or during daytime only were more likely to report respiratory symptoms. This association may reflect differences in indoor-outdoor air exchange and opportunities for ambient particulate matter infiltration into indoor environments. However, unmeasured environmental and behavioral factors may also have contributed to this observed association. Previous studies have reported that household ventilation behavior may affect indoor pollutant concentrations depending on outdoor air quality conditions⁽¹⁹⁾.

Preventive behavior was significantly associated with respiratory symptoms. Compared with participants reporting good preventive behavior, those with low preventive behavior had significantly lower odds of respiratory symptoms. This inverse association should be interpreted cautiously. Therefore, this finding should not be interpreted as evidence that low preventive behavior reduces the risk of respiratory symptoms. One possible explanation is reverse causation, whereby individuals

experiencing respiratory symptoms may subsequently adopt preventive practices such as mask use or reducing outdoor activities. Similar interpretations have been proposed in previous environmental and occupational health studies⁽⁴²⁾.

These findings highlight the importance of integrated environmental and behavioral interventions in communities affected by stone crushing activities. In addition to emission control measures, community health education, promotion of appropriate preventive practices, and increased public awareness may contribute to reducing potential respiratory health risks. Environmental management strategies should also consider meteorological conditions and seasonal variation, which may influence particulate dispersion patterns⁽³⁷⁾.

This study has several strengths, including the integration of environmental health risk assessment and epidemiological analysis, as well as the inclusion of behavioral and individual factors. However, several limitations should be acknowledged. The cross-sectional design limits causal interpretation. In addition, PM_{2.5} monitoring was conducted over a short 72-hour period during March 2026 and may not adequately represent seasonal or annual variation in particulate matter concentrations. Therefore, the calculated HQ values should be interpreted as preliminary estimates of potential chronic health risk rather than definitive long-term exposure assessments. Furthermore, the use of fixed-site monitoring stations may not fully capture individual exposure variability. In addition, respiratory symptoms were assessed using self-reported information covering the previous 12 months, which may be subject to recall bias. The broad definition of self-reported respiratory symptoms may also have resulted in outcome misclassification because these symptoms are non-specific and may arise from various respiratory conditions.

Conclusion

This study found that nearly half of the participants had Hazard Quotient (HQ) values ≥ 1 , indicating a potential non-carcinogenic health risk based on the estimated community-level PM_{2.5} exposure. Although HQ was not significantly associated with respiratory symptoms, this finding suggests that estimated community-level PM_{2.5} exposure alone may not adequately explain the occurrence of respiratory symptoms in this population. Underlying medical conditions, younger age, window-opening behavior, and preventive behavior were significantly associated with respiratory symptoms. However, these associations should be interpreted cautiously because of the cross-sectional study design and the potential influence of residual confounding, unmeasured exposure patterns, and reverse causation.

These findings suggest that respiratory health among communities living near stone crushing activities may be influenced by multiple environmental, individual, and behavioral factors. However, the estimated HQ values should be regarded as preliminary estimates derived from short-term fixed-site PM_{2.5} monitoring rather than definitive measures of long-term individual exposure. Integrating environmental control measures with community-based health education and appropriate preventive practices, together with improved environmental monitoring, may contribute to reducing potential respiratory health risks in high-exposure areas.

From a public health perspective, strengthening long-term environmental monitoring, respiratory health surveillance, community awareness, and effective dust control measures may help reduce the health impacts of particulate matter exposure. Future studies should incorporate long-term and seasonal air quality monitoring, personal exposure assessment, prospective study designs, and objective respiratory health measurements to improve exposure characterization and strengthen causal interpretation.

Ethical Approval Statement

This study was approved by the Human Research Ethics Committee of Mahasarakham University (Approval No. 081-012/2569; 29 January 2026). Written informed consent was obtained from all participants, and confidentiality of participant information was strictly maintained throughout the study.

Author Contributions

JM conceived and designed the study. Guidance on the research methodology, sampling procedure, data collection instruments, and data analysis was provided by JW, WT, and TB. The manuscript was drafted by JM with academic guidance from all co-authors. The manuscript was critically reviewed and revised by JW. All authors read and approved the final version of the manuscript and agreed to take responsibility for the accuracy and integrity of the research work.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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