Original Article

A decreased impact of air pollution on hospital pneumonia visits during COVID-19 outbreak in northeastern Thailand

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Background: The coronavirus disease 2019 (COVID-19) pandemic had effects on changes in people, society, and pollutant sources. This was a unique research opportunity to assess the effects on the risk of pneumonia resulted from the changes in air pollution and personal hygiene regarding city lockdown.

Methods: This study, we estimated time-series relative risks (RRs) of pneumonia (n=94,288) associated with PM_{10}, $PM_{2.5}$, NO_2, and O_3 in Khon Kaen province and its vicinity, using Poison regression with generalized additive model and compared air pollutant-associated risk of pneumonia before *vs.* during the COVID-19 outbreak [2018–2021].

Results: During the COVID-19 period, pneumonia cases, $PM_{2.5}$, PM_{10}, and NO_2 levels were lower than those before the COVID-19 but the O_3 level was significantly higher. The single-pollutant analyses showed that the increase in PM_{10}, $PM_{2.5}$, and NO_2 were significantly associated with pneumonia risks at single-day lag 0 in the earlier two years (2018–2019). For multi-pollutant analyses, there were higher RRs in $PM_{2.5}$ at lag 0 [RR =1.078, 95% confidence interval (CI): 1.004 to 1.157], lag 4 (RR =1.054, 95% CI: 1.011 to 1.098) and lag 5 (RR =1.090, 95% CI: 1.021 to 1.165) and for all cumulative-day lags, greatest was at lag 0–5 (RR =1.314, 95% CI: 1.200 to 1.439) before the COVID-19 period while there were lower pneumonia RRs of a 10-$\mu g/m^3$ increase in $PM_{2.5}$ at single-day lag 1 (RR =1.064, 95% CI: 1.002 to 1.130) and for all cumulative-day lags, greatest was at lag 0–5 (RR =1.201, 95% CI: 1.073 to 1.344) during the COVID-19 outbreak. Multi-pollutant of NO_2 significantly increased pneumonia risk in cumulative day exposure before the COVID-19 outbreak at lag 0–3 (RR =1.050, 95% CI: 1.001 to 1.100). It was significantly greater than that risk during the outbreak.

Conclusions: This study revealed that the lockdown measures to control COVID-19 were effective in improving air quality and lowering associated pneumonia risk. These findings would help raise awareness about measures and policies to preserve the air quality to increase respiratory health benefits.

Keywords: Air pollutant; pneumonia; coronavirus disease 2019 (COVID-19); generalized additive model (GAM)

Submitted Jul 04, 2023. Accepted for publication Nov 24, 2023. Published online Jan 16, 2024.
doi: 10.21037/jtd-23-1051
View this article at: https://dx.doi.org/10.21037/jtd-23-1051

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Introduction

Background

Respiratory diseases affect the lives of more than one billion people worldwide and are the principal cause of mortality and morbidity. Clinical pneumonia is usually caused by various infectious agents (viruses, bacteria, and other pathogens) but the etiology of pneumonia states that it is a complex disease caused by a combination of host, infection, and environmental factors (1). Other than the meteorological factors, such as temperature, humidity, sunshine, and wind speed, the study of Lam *et al.* [2018] have linked air pollutants to pneumonia (2). Many cities had serious air pollution situations that reported the effect of fine particulate matter ($PM_{2.5}$) and O_3 on hospital visits for pneumonia (3-5).

When coronavirus disease 2019 (COVID-19) started spreading in late 2019, it brought about changes in people's behaviors, healthcare, and the environment. There was an increase in active protective measures and some of the regulations such as lockdowns, work from home, and the suspension of events had a direct impact on public health in many cities. Especially, the impact of lockdown periods significantly reduced hospital admissions, emergency department visits, and Intensive care unit (ICU) admission of many diseases (6,7). Moreover, in countries imposing lockdowns, a better quality of air pollutants along with particulate matter (PM_{10} and $PM_{2.5}$) and gaseous pollutants (NO_2, SO_2, CO) was significantly witnessed (8,9). The positive effect of the environmental changes on human health during the COVID-19 pandemic has also been seen in many cities. The improvements in air quality since the lockdown may be an actual cause of the reduction in admissions of asthma and chronic obstructive pulmonary disease (COPD) (10,11). Additionally, Ambika *et al.* [2021] observed that a significant decrease in particulate matter and health risk (cancer risk, acute, and chronic health index) during the lockdown is due to a corresponding decrement in air pollution in India (12).

Highlight box

Key findings

- The effect of $PM_{2.5}$ and NO_2 modeled significantly related to pneumonia. The $PM_{2.5}$ model showed that the pneumonia risks from air pollution displayed declined and RRs of pneumonia and NO_2 decreased significantly during the coronavirus disease 2019 (COVID-19) period.

What is known and what is new?

- The results suggested that the decreased relative risk (RR) of pneumonia could be achieved with reduced air pollutants.
- Air pollutant improvements and public health policies during the COVID-19 outbreak were evidence to support the risk reduction of respiratory illness.

What is the implication, and what should change now?

- This study's result reinforces the current knowledge that air pollution has damaged human health, which could support air quality policies and measures to reduce respiratory health illnesses as witnessed during the COVID-19 period.

Rationale and knowledge gap

Changes in the ambient air pollutants provided a rare opportunity to investigate the change in health risk. Interestingly, no study has evaluated the air pollution effect on respiratory diseases, especially pneumonia before and during the COVID-19 outbreak in Thailand. Khon Kaen is a province to keep an eye on in Thailand. This province and its vicinity have had air pollution problems and a high level of $PM_{2.5}$ during harvesting season every year. Between 2018 and 2019, the annual average of $PM_{2.5}$ was higher than Bangkok (capital) and Chiang Mai (13). Parallel to the incidence of pneumonia in this province, pneumonia incidence was in the top five leading rates in Thailand from 2017–2019 (14). Therefore, this was a unique research opportunity to assess the effects on the risk of pneumonia resulted from the changes in air pollution before *vs.* during the COVID-19 outbreak.

Objective

The aim of this study is to evaluate the association between short-term exposure to air pollutants and the count of hospital visits with pneumonia through the generalized additive model (GAM) method. We comprehensively explained the changes in air pollutants during the COVID-19 outbreak in 2020–2021 compared to those before the outbreak in 2018–2019 and estimated the relative risk (RR) attributable to the air pollutant variation in Khon Kaen, one of the most polluted provinces in Thailand. The findings of this study provided details on the dangers of air pollution and can be utilized as epidemiological evidence to demonstrate the risk factors for respiratory ailments. We present this article in accordance with the STROBE reporting checklist (available at https://jtd.amegroups.com/article/view/10.21037/jtd-23-1051/rc).

Methods

Study area

Khon Kaen, a center of the mid-northeastern region of Thailand, is connected to 9 provinces with an area of 10,886 sq.km. In 2021, its population was 1.79 million, with a higher proportion of females than males (50.9% *vs.* 49.1%). Classifications of age group were as follows: 0–12 years old (12.8%), 13–24 years old (14.6%), 25–44 years old (29.5%), 45–64 years old (30.2%), and above 65 years old (12.9%). The province is known as a great educational province surrounded by business districts resulting in the traffic congestion in large areas. The major industries were found in the non-metallic, metal, food, and transportation. There were some air pollution sources from productions of power, ethanol, natural gas, industrial rock, mineral deposit extraction, and a center for the distribution of fuel and gas for northeastern region of Thailand. Moreover, this city has a large agricultural industry with an agricultural area of 6,752 km^2 (62% of the total area). There have been problems with burning agricultural waste. Therefore, the province has had air pollution problems and high level of $PM_{2.5}$ during harvesting season for decades (13). Overall, the area of this study covered 50 kilometers around a selected air quality monitoring station as shown in *Figure 1*. People who stayed within 50 km of 14 districts in Khon Kaen province and 4 districts in Maha Sarakham province around the station were enrolled in this study.

Data collection

Air pollution data were retrieved from the Thai Pollution Control Department (PCD). The daily average calculation, hourly measurements of each pollutant must be available more than 75% each day for the whole 4-year period of analysis otherwise it was excluded. Estimated daily air pollutant concentrations of PM_{10}, $PM_{2.5}$, and NO_2 were calculated for the 24-hour mean and daily O_3 was calculated for the maximum 8-hour rolling mean regarding PCD standard metrics. The ambient temperature and relative humidity were provided by Thai Meteorological Department, and the station is located in Khon Kaen center as shown in *Figure 1*. Their daily averages were also used for statistical analysis to control weather effects. Lastly, daily pneumonia hospital admitted cases were obtained from the Information and Communication Technology Center, Ministry of Public Health from 1st January 2017 to 31st December 2021. The diagnosis of pneumonia was mainly based on codes of International Classification of Disease, 10th edition (ICD-10: J10-18) together with the demographic information of gender, address, date of birth, and date of diagnosis.

Statistical analysis

Descriptive analysis and regression models were used to test different hypotheses. To characterize cases and exposure, Mann-Whitney *U* test was used to compare differences of variables of hospital visits with pneumonia together with air pollution concentration and meteorological factors before the COVID-19 outbreak and during the COVID-19 outbreak. Spearman's correlation was used to present the degree of correlation between air pollutants and meteorological variables.

Poison with GAM was employed to examine the association between the counts Y_t of hospitalization for pneumonia and a vector X_t of air pollution variables pertaining to each day *t* (15). The confounder control time strata in the model specifications, nonlinear independent variables (temperature, humidity, and time) were fitted by smoothing spline function to control seasonality and long-term effects [temperature (3 degrees of freedom; df), relative humidity (3 df), and time (7 df per year)]. Also, a day of the week (DOW) and public holidays were the dummy variable to control for the short-term trend. A specified regression model and df to control the time-varying covariates, each variable was set in accordance with previous literature (3,5).

First, the single-pollutant model was performed to include one pollutant (PM_{10}, $PM_{2.5}$, NO_2, and O_3) as a predictor in the model for the hospital visits with pneumonia.

Second, as for effects of co-pollutants, to adjust for the potential confounding effect of interactions among air pollutants on pneumonia, the multi-pollutant model used the same model as the single-pollutant models to control the influence effect modification of various pollutants.

Third, to determine the acute, delay, and potential prolonged effects between the increase in air pollution and hospital visits with pneumonia, the models with different lag structures, including both single-day lag (e.g., lag 0 was the same day of air pollutant concentration and hospital visit, lag 1 was air pollutant concentration of the day before hospital visit) and cumulative-day lag (e.g., lag 0–1 was the 2-day averages of current and previous day concentrations of air pollutants) were fitted in both single- and multi-pollutant models. The results were expressed in terms of RR and 95% confidence interval (95% CI) with a 10 $\mu g/m^3$ increase in the concentrations of air pollutants.

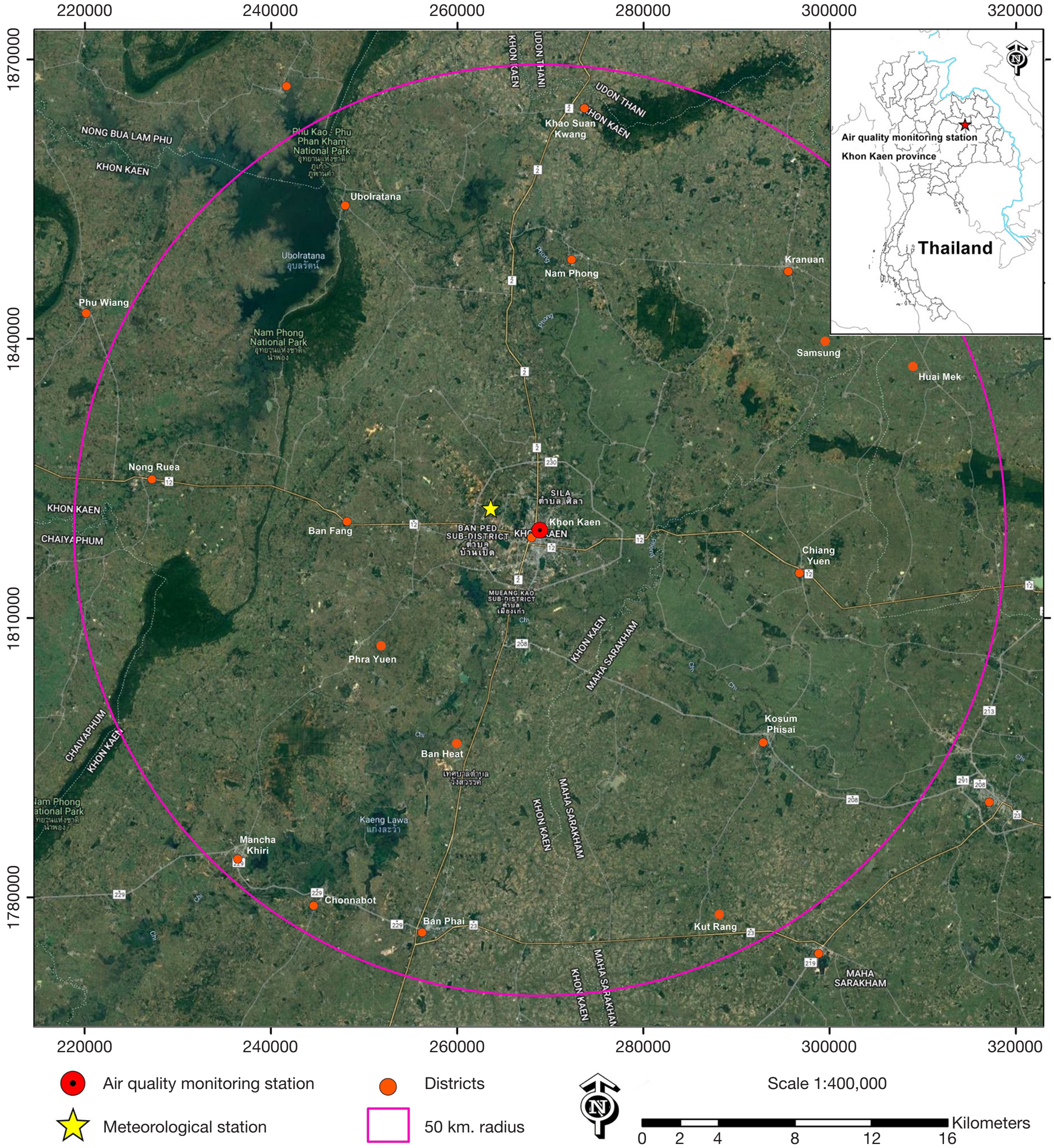


Figure 1 Study area covering 18 districts and showing the location of weather and air quality monitoring stations.

Finally, this study used the Z-test to compare the RR of pneumonia associated with air pollution before *vs.* during the COVID-19 outbreak for lockdown interaction testing (16). The mathematical was explained by $z = \frac{(Q_1 - Q_2)}{\sqrt{SE_1^2 + SE_2^2}}$, where Q_1 and Q_2 are natural logarithms of RRs before and during the COVID-19 outbreak, and SE_1 and SE_2 are their respective standard errors. All the analyses were conducted using mgcv, dlnm, and splines packages in R 4.1.3 (R Foundation for Statistical Computing, Vienna, Austria).

Table 1 Statistic summary of data on daily pneumonia, meteorological factors, and ambient air pollutants before the COVID-19 and during the COVID-19 outbreak, respectively

Variables	Before COVID-19 outbreak				During COVID-19 outbreak				P value†
	Mean (SD)	Min	Median	Max	Mean (SD)	Min	Median	Max	
Air pollutants (μg/m^3)									
PM_{10} (24-hour mean)	55.59 (26.09)	17.17	48.62	163.67	54.71 (24.62)	19.30	48.24	137.79	0.630
$PM_{2.5}$ (24-hour mean)	32.61 (17.75)	10.33	26.83	109.29	29.44 (15.99)	9.042	24.23	87.50	<0.001
NO_2 (24-hour mean)	18.24 (10.22)	2.22	16.69	68.97	17.63 (9.68)	2.32	15.53	61.69	0.373
O_3 (8-hour mean)	78.15 (59.60)	3.27	64.75	242.21	103.25 (38.47)	34.78	101.84	192.39	<0.001
Meteorological factors									
Temperature (℃)	27.43 (2.57)	17.54	27.66	34.20	27.14 (2.93)	14.84	27.35	34.08	0.452
Relative humidity (%)	70.09 (11.72)	30.50	70.10	99.12	70.87 (11.92)	38.62	70.38	96.46	0.292
Total pneumonia (cases/day)	68.81 (23.01)	15	68	165	60.27 (25.26)	15	57	150	<0.001
Sex									
Male	37.12 (12.67)	8	37	86	33.53 (13.64)	9	32	87	<0.001
Female	31.71 (11.86)	7	30	79	26.75 (12.99)	4	25	74	<0.001
Age (years)									
0–17	18.69 (8.37)	1	18	63	9.53 (7.88)	0	8	51	<0.001
18–64	23.89 (9.47)	2	24	60	26.61 (15.97)	4	23	100	0.759
≥65	26.25 (9.64)	2	26	55	24.15 (9.56)	5	23	64	<0.001

†, Mann-Whitney *U* test. COVID-19, coronavirus disease 2019; SD, standard deviation.

Ethical statement

The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). This study was reviewed by the graduate program, Faculty of Science, Chulalongkorn University, and was considered exempt from institutional review board approval, since this study used secondary data without any personal identifiers and did not contain confidential patient data. For this type of study, informed consent from the subjects is not required.

Results

Statistic summary of data

Total pneumonia cases, air pollutant levels, and meteorological variables were characterized in *Table 1*. For the air pollutant status, we noticed that during the outbreak, concentrations of PM_{10}, $PM_{2.5}$, and NO_2 were lower as compared to those before the COVID-19 period. Especially $PM_{2.5}$ was decreased significantly (P<0.001). Nevertheless, the 8-hour running average of O_3 was quite higher during the COVID-19 outbreak (103.25 μg/m^3) than before the outbreak (78.15 μg/m^3) (P<0.001). The weather conditions were comparable in two periods, with the daily mean temperature and the relative humidity before the outbreak *vs.* during the outbreak (27.43 *vs.* 27.14 ℃ and 70.09% *vs.* 70.87% respectively). Both of the weather variables were no significant difference between the two periods. The daily average number of pneumonia cases was about 69 cases/day within a range of 15–165 cases/day. During the outbreak, it decreased to 60 [15–150] cases/day. Compared with that before the COVID-19 period, the average daily pneumonia case was significantly lower during the COVID-19 outbreak (P<0.001). However, in the adult group (18–64 years old), it increased during the outbreak period.

Spearman correlation coefficient

Considering the correlation between air pollutants and weather measurements, in *Figure 2* we found a strong

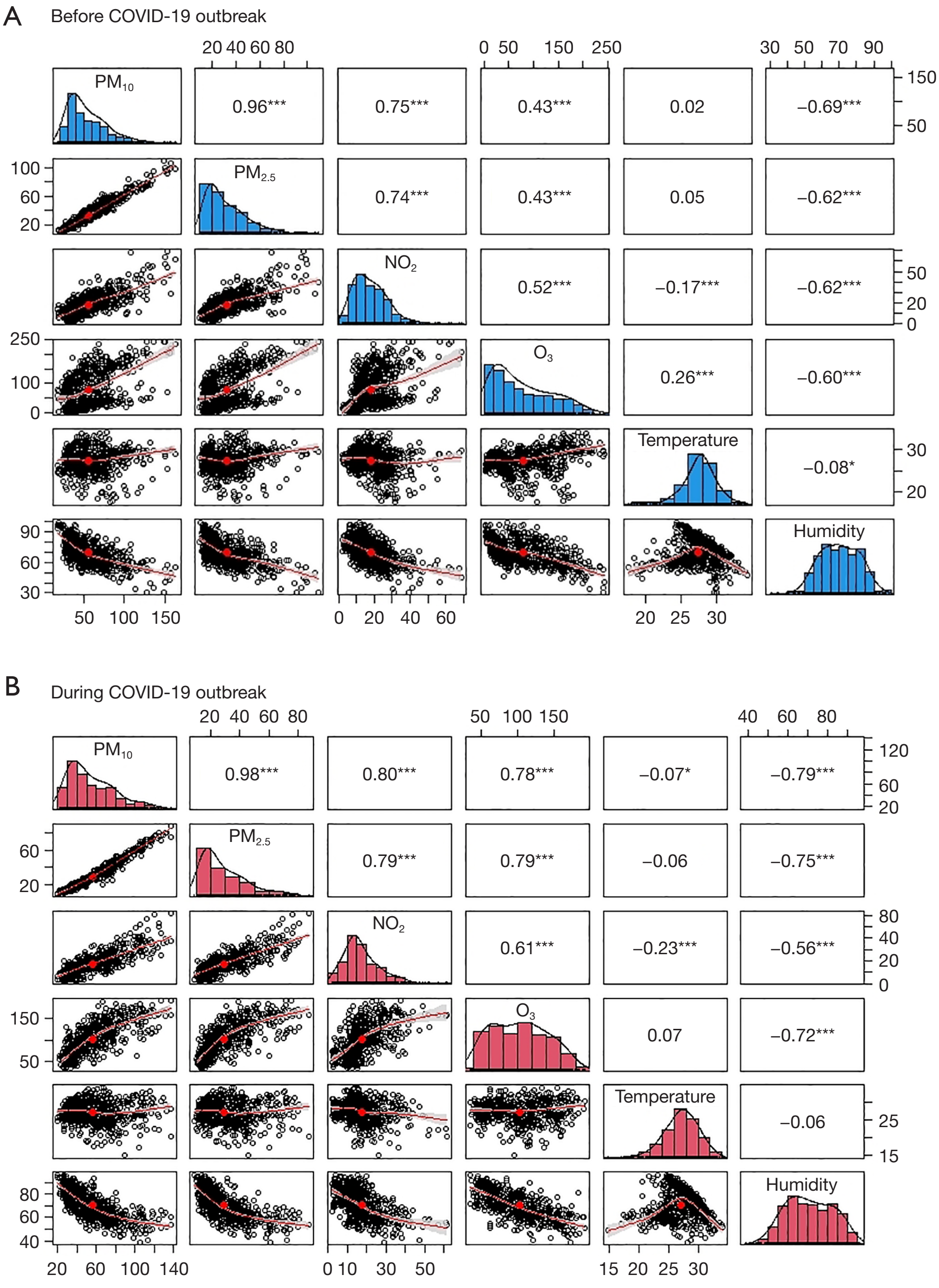


Figure 2 Spearman correlation coefficient for air pollutants concentration and meteorological factors, the data from 2018–2019 (before the COVID-19 outbreak) (A) and 2020–2021 (during the COVID-19 outbreak) (B). *, P<0.05; ***, P<0.001. COVID-19, coronavirus disease 2019.

correlation among PM_{10}, $PM_{2.5}$ and NO_2 in both two periods. Spearman corresponding coefficients of PM_{10} and $PM_{2.5}$ (r=0.98), PM_{10} and NO_2 (r=0.80), NO_2 and $PM_{2.5}$ (r=0.79) during the COVID-19 outbreak were slightly higher than those before the COVID-19 period (r=0.96, 0.75, and 0.74, respectively). Moreover, less active emission sources and fuel change during the outbreak regarding changes in transportation mode and industry plants made PM_{10}, $PM_{2.5}$ and NO_2 correlations with O_3 greater positive levels (r=0.78, 0.79, and 0.61 respectively

(P<0.001).

Single-pollutant analysis

With single-pollutant model analysis, a 10-μg/m^3 increase in PM_{10}, $PM_{2.5}$, and NO_2 except O_3 showed increases in pneumonia effect in the period before the outbreak, and it was noticeable that their RRs were all significant as early as at single-day lag 0, RR =1.016 (95% CI: 1.003 to 1.030), RR =1.036 (95% CI: 1.014 to 1.058), and RR =1.046 (95% CI: 1.015 to 1.078), respectively (*Figure 3A*). No association was found during the outbreak. A similar result was seen with cumulative-day exposure lag as no increased air pollutants-pneumonia association was found during the outbreak (*Figure 3B*). However, PM_{10}, $PM_{2.5}$, and NO_2 except O_3 showed increasingly pronounced risks detected through all cumulative-day lags. RRs kept increasing from lag 0–1 to lag 0–5 then dropping at lag 0–6 (P<0.05) only in the period before the outbreak. The greatest pneumonia effect was associated with $PM_{2.5}$ at lag 0–5 (P<0.05). Although O_3 had positive correlation coefficients with PM_{10}, $PM_{2.5}$, and NO_2 in both periods, it did not affect pneumonia while other pollutants did.

Multi-pollutant analysis

In multi-pollutant analyses (*Figure 4*), $PM_{2.5}$ significantly increased pneumonia risk in both periods, before the COVID-19 outbreak and during the COVID-19 outbreak. RRs before the outbreak were higher than those during the outbreak although they were not statistically higher regarding lockdown interaction testing. For single-day exposure lag, the pneumonia risk was statistically significant at lag 0 (RR =1.078, 95% CI: 1.004 to 1.157), lag 4 (RR =1.054, 95% CI: 1.011 to 1.098) and lag 5 (RR =1.090, 95% CI: 1.021 to 1.165) before the outbreak *vs.* lag 1 (RR =1.064, 95% CI: 1.002 to 1.130) during the outbreak. Similarly, greater $PM_{2.5}$-induced pneumonia RRs were observed before the outbreak *vs.* during the outbreak through continuous cumulative exposure as following, lag 0–1 (RR =1.132, 95% CI: 1.056 to 1.214 *vs.* RR =1.098, 95% CI: 1.011 to 1.192), lag 0–2 (RR =1.138, 95% CI: 1.059 to 1.222 *vs.* RR =1.119, 95% CI: 1.021 to 1.225), lag 0–3 (RR =1.144, 95% CI: 1.062 to 1.232 *vs.* RR =1.113, 95% CI: 1.010 to 1.226), lag 0–4 (RR =1.205, 95% CI: 1.114 to 1.304 *vs.* RR =1.134, 95% CI: 1.023 to 1.257), lag 0–5 (RR =1.314, 95% CI: 1.200 to 1.439 *vs.* RR =1.201, 95% CI: 1.073 to 1.344), lag 0–6 (RR =1.298, 95% CI: 1.191 to 1.414 *vs.* RR =1.217, 95% CI: 1.087 to 1.363). Furthermore, we observed that NO_2 daily exposure did not post pneumonia risk with single-day exposure lags, but it significantly posted an increased risk for those inhaling NO_2 cumulative day exposure before the COVID-19 outbreak at lag 0–3 (RR =1.050, 95% CI: 1.001 to 1.100). It was significantly greater than that risk during the outbreak per lockdown interaction P=0.016. Additionally, NO_2 in cumulative-day lags (lag 0–4, lag 0–5, and lag 0–6) was a statistical difference in risk estimates between the two periods.

Discussion

Key findings

This time-series study evaluated the association between short-term exposure to air pollutants (PM_{10}, $PM_{2.5}$, NO_2, and O_3) and pneumonia before *vs.* during the COVID-19 outbreak using GAM. The finding indicated that the effect of PM_{10}, $PM_{2.5}$, and NO_2 were associated with hospital pneumonia visits. As highlighted in the multi-pollutant model, this study showed that the RRs of pneumonia associated with $PM_{2.5}$ increased during the COVID-19 outbreak and the pneumonia risk from NO_2 was significantly greater during before-COVID-19 outbreak than during the outbreak.

Explanations of findings

Air pollutant concentrations

The coronavirus has spread in the world and has an enormous impact on not only people but also the environment. In this regard, we observed that the concentrations of $PM_{2.5}$, PM_{10}, and NO_2 during the COVID-19 period were lower than those before the COVID-19 period. Especially $PM_{2.5}$ was statistically significantly lower, similar to previous studies (17,18). During the full lockdown, residents were restricted to go outside and reduced outdoor activities, leading to a substantial decrease in vehicle and public transportation usage. PM came from car exhaust fumes, coal combustion, industrial chimneys, dust from construction sites, and the interaction of SO_X and NO_X in the air. When transportation and industrial production were reduced due to epidemic control actions, followed are reductions in air pollutants (19). While, a high concentration of O_3 also increased in Khon Kaen, similar to other recent studies (20,21). The mechanisms of the increase in O_3 were correlated between weather conditions, restrictive measures and reduction of air

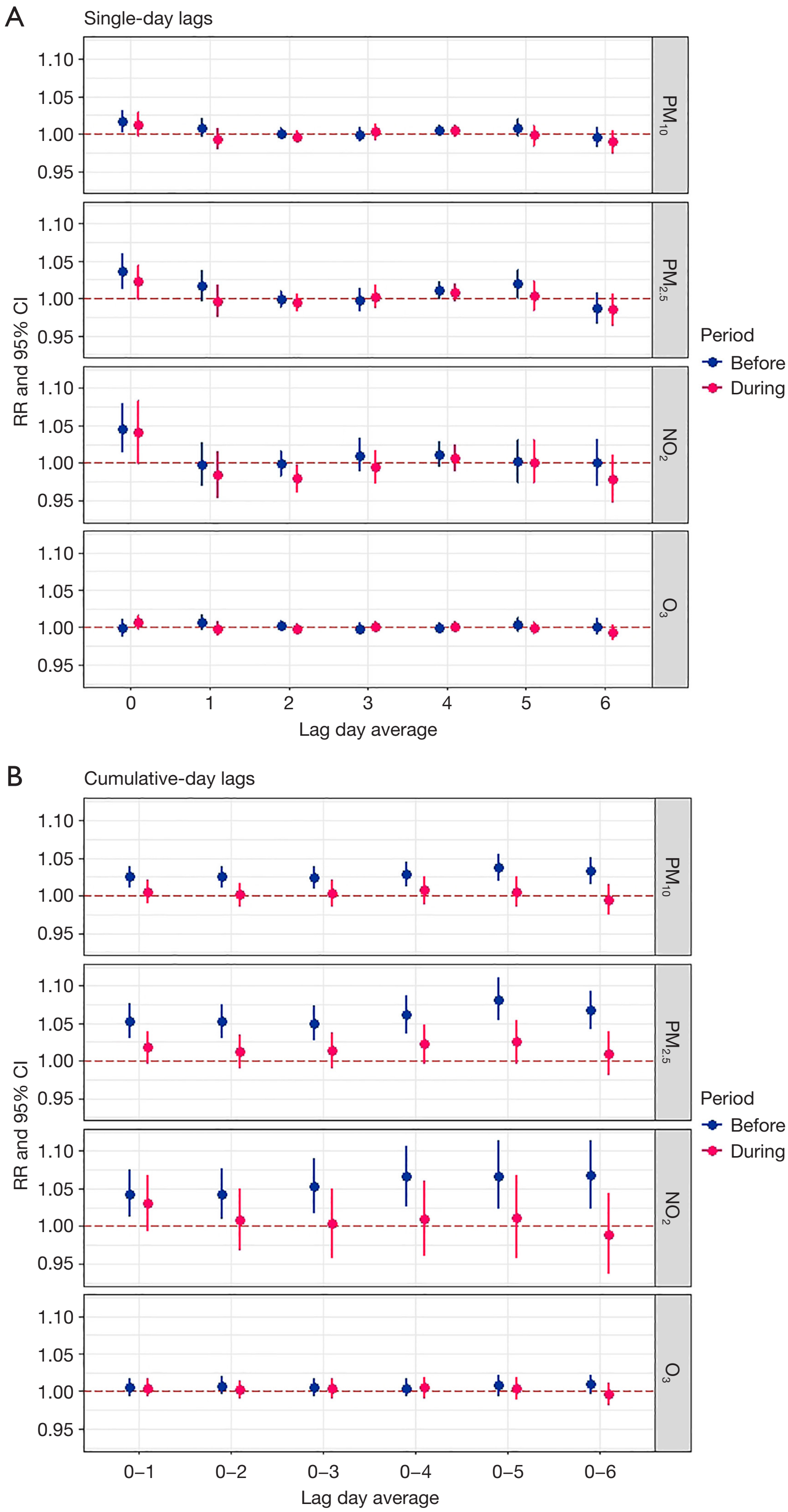
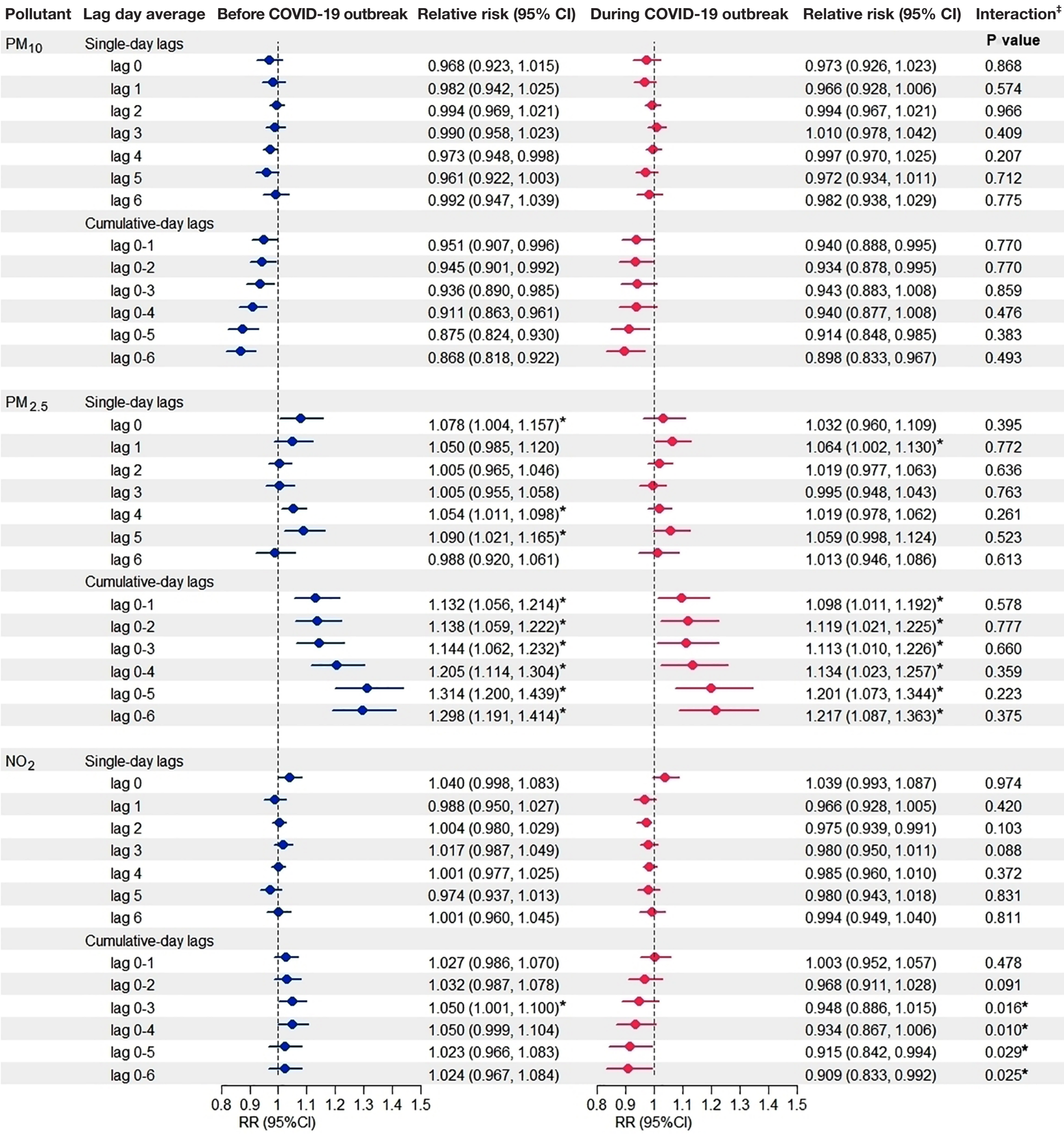


Figure 3 Adjusted RR† and 95% CI of hospital visits with pneumonia for a 10 μg/m³ increase of PM_{10}, $PM_{2.5}$, NO_2, and O_3 before the COVID-19 and during the COVID-19 outbreak, in the single-pollutant models: single-day lags (A) and cumulative-day lags (B). †, RR adjusted for temperature, relative humidity, calendar time, day of the week, and public holiday. RR, relative risk; CI, confidence interval; COVID-19, coronavirus disease 2019.



Pollutant	Lag day average	Before COVID-19 outbreak Relative risk (95% CI)	During COVID-19 outbreak Relative risk (95% CI)	Interaction‡ P value
PM_{10}	Single-day lags			
	lag 0	0.968 (0.923, 1.015)	0.973 (0.926, 1.023)	0.868
	lag 1	0.982 (0.942, 1.025)	0.966 (0.928, 1.006)	0.574
	lag 2	0.994 (0.969, 1.021)	0.994 (0.967, 1.021)	0.966
	lag 3	0.990 (0.958, 1.023)	1.010 (0.978, 1.042)	0.409
	lag 4	0.973 (0.948, 0.998)	0.997 (0.970, 1.025)	0.207
	lag 5	0.961 (0.922, 1.003)	0.972 (0.934, 1.011)	0.712
	lag 6	0.992 (0.947, 1.039)	0.982 (0.938, 1.029)	0.775
	Cumulative-day lags			
	lag 0-1	0.951 (0.907, 0.996)	0.940 (0.888, 0.995)	0.770
	lag 0-2	0.945 (0.901, 0.992)	0.934 (0.878, 0.995)	0.770
	lag 0-3	0.936 (0.890, 0.985)	0.943 (0.883, 1.008)	0.859
	lag 0-4	0.911 (0.863, 0.961)	0.940 (0.877, 1.008)	0.476
	lag 0-5	0.875 (0.824, 0.930)	0.914 (0.848, 0.985)	0.383
	lag 0-6	0.868 (0.818, 0.922)	0.898 (0.833, 0.967)	0.493
$PM_{2.5}$	Single-day lags			
	lag 0	1.078 (1.004, 1.157)*	1.032 (0.960, 1.109)	0.395
	lag 1	1.050 (0.985, 1.120)	1.064 (1.002, 1.130)*	0.772
	lag 2	1.005 (0.965, 1.046)	1.019 (0.977, 1.063)	0.636
	lag 3	1.005 (0.955, 1.058)	0.995 (0.948, 1.043)	0.763
	lag 4	1.054 (1.011, 1.098)*	1.019 (0.978, 1.062)	0.261
	lag 5	1.090 (1.021, 1.165)*	1.059 (0.998, 1.124)	0.523
	lag 6	0.988 (0.920, 1.061)	1.013 (0.946, 1.086)	0.613
	Cumulative-day lags			
	lag 0-1	1.132 (1.056, 1.214)*	1.098 (1.011, 1.192)*	0.578
	lag 0-2	1.138 (1.059, 1.222)*	1.119 (1.021, 1.225)*	0.777
	lag 0-3	1.144 (1.062, 1.232)*	1.113 (1.010, 1.226)*	0.660
	lag 0-4	1.205 (1.114, 1.304)*	1.134 (1.023, 1.257)*	0.359
	lag 0-5	1.314 (1.200, 1.439)*	1.201 (1.073, 1.344)*	0.223
	lag 0-6	1.298 (1.191, 1.414)*	1.217 (1.087, 1.363)*	0.375
NO_2	Single-day lags			
	lag 0	1.040 (0.998, 1.083)	1.039 (0.993, 1.087)	0.974
	lag 1	0.988 (0.950, 1.027)	0.966 (0.928, 1.005)	0.420
	lag 2	1.004 (0.980, 1.029)	0.975 (0.939, 0.991)	0.103
	lag 3	1.017 (0.987, 1.049)	0.980 (0.950, 1.011)	0.088
	lag 4	1.001 (0.977, 1.025)	0.985 (0.960, 1.010)	0.372
	lag 5	0.974 (0.937, 1.013)	0.980 (0.943, 1.018)	0.831
	lag 6	1.001 (0.960, 1.045)	0.994 (0.949, 1.040)	0.811
	Cumulative-day lags			
	lag 0-1	1.027 (0.986, 1.070)	1.003 (0.952, 1.057)	0.478
	lag 0-2	1.032 (0.987, 1.078)	0.968 (0.911, 1.028)	0.091
	lag 0-3	1.050 (1.001, 1.100)*	0.948 (0.886, 1.015)	0.016*
	lag 0-4	1.050 (0.999, 1.104)	0.934 (0.867, 1.006)	0.010*
	lag 0-5	1.023 (0.966, 1.083)	0.915 (0.842, 0.994)	0.029*
	lag 0-6	1.024 (0.967, 1.084)	0.909 (0.833, 0.992)	0.025*

Figure 4 Adjusted RR† and 95% CI of hospital visits with pneumonia for a 10 μg/m^3 increase of PM_{10}, $PM_{2.5}$, and NO_2 before the COVID-19 and during the COVID-19 outbreak, based on the multi-pollutant models. †, RR adjusted for air pollutants, temperature, relative humidity, calendar time, day of the week, and public holiday; ‡, *Z*-test for interaction P value; *, P<0.05. COVID-19, coronavirus disease 2019; CI, confidence interval; RR, relative risk.

pollution (NO_x and VOC) (22,23).

Hospital visits with pneumonia

Thailand was the first nation to report a verified COVID-19 case outside of China. Thailand's government enacted the Public Administration in Emergency Situation. A national lockdown policy, almost all hospitals had limited health care service, for example, by solely opening some wards, sending medication to the patient's house rather than having them picked it up at the hospital, and use the phone to contact a doctor, which resulted in a drop in the daily number of patients during an early lock down phase but alleviating for following phases. The result of this study found that the number of pneumonia cases in Khon Kaen from 2020 to 2021 during the outbreak was lower than in the earlier 2 years [2018–2019]. Similarly, in countries imposing lockdowns, a reduction in hospitalization for many diseases has presented. In Korea, the investigation of Huh *et al.* [2021] highlighted the decrease in hospital admissions for respiratory diseases during the COVID-19 pandemic. Hospital admissions reduced by 0.47 times for pneumonia, pneumonia (patients with COPD) reduced by 0.54 times, and pneumonia (patients with asthma) reduced by 0.38 times when comparison with 2016–2019 (24). Additionally, the study of Bodilsen *et al.* [2021] and Dias *et al.* [2022] showed a decrease in hospitalizations and mortality due to pneumonia during the lockdown intervention period (25,26). These studies also suggested that a decrease in pneumonia may be related to the prevention and control measures during the COVID-19 pandemic. Because of the difficulty accessing hospital services due to strict quarantine measures, together with hospital avoidance behavior during COVID-19, many patients preferred staying more at home and may have delayed treatment resulted from concerns about being infected by the COVID-19 virus in the community and hospitals.

The association between air pollution and pneumonia in single-pollutant analysis

Single-pollutant models showed that the short-term effect of PM_{10}, $PM_{2.5}$, and NO_2 in single-day lags was associated with hospital visits with pneumonia at lag day 0 before the COVID-19 period. Similarly, the study in Turkey, Tasci *et al.* [2018] showed that atmospheric PM_{10}, and NO_X concentrations were associated with the number of elderly patients admitted to the hospital due to pneumonia on day 0 and the previous 1–4 days (27). Another report had also highlighted the changes in $PM_{2.5}$ and PM_{10} that were associated with the increase in the hospitalization of childhood pneumonia at lag day 0 and lag 0–2 (28). For all analyses of PM_{10}, $PM_{2.5}$, and NO_2 in single-day lags, the strongest effects were observed on the same day as the day going for a hospital visit. Although pneumonia is a type of lower respiratory tract infection, these studies support that the effect of air pollution on pneumonia tends to be short-term risk. It shows harmful to human health and this further implies the need of protecting short-term risk of respiratory health.

The association between air pollution and pneumonia in multi-pollutant analysis

RRs derived by multi-pollutant analyses of the combinations of PM_{10}, $PM_{2.5}$, NO_2, and O_3 based on the positive single-pollutant model provided different results for these pollutants. PM_{10}, $PM_{2.5}$, and NO_2 in single-pollutant model was significantly associated with pneumonia. Nevertheless, only $PM_{2.5}$ and NO_2 had a significant effect on pneumonia in multi-pollutant model. In general, fine particulate matter is not a single pollutant, but rather is a mixture of many chemical species. $PM_{2.5}$, after adjusting for PM_{10}, NO_2, and O_3, was strongly significantly associated with pneumonia. Similarly, Wang *et al.* [2021] found that $PM_{2.5}$ had an adverse effect on pneumonia after adjusting for meteorological factors and other pollutants (28). Epidemiological confirmation, the impact of $PM_{2.5}$ cause damage to the respiratory epithelial cells. The evidence presented that $PM_{2.5}$ exposure has adverse consequences for precipitate inflammatory and tissue remodeling changes in human lungs (29). Additionally, Schulze *et al.* [2017] tried to identify the mechanism of $PM_{2.5}$ that interferes with alveolar macrophages and pulmonary epithelial cells and stimulates the release of cytokines that the respiratory tract could also activate inflammatory (30).

NO_2 showed a result similar to $PM_{2.5}$, the significance of NO_2 remained strong after adjusting for PM_{10}, $PM_{2.5}$, and O_3 at lag 0–3 before the COVID-19 outbreak. Another study highlighted that NO_2 was significantly associated with an increased risk of hospital admissions for pneumonia after adjusting for PM_{10} and SO_2 (31). In terms of toxicology, NO_2 might damage macrophages, and natural killer cells in the respiratory tract related to decreased mucociliary clearance and vulnerable respiratory epithelium (32). Laboratory studies have shown that exposure to PM and NO_2 significantly affects the susceptibility of respiratory epithelial and increased susceptibility to both bacterial and viral infection (33,34). These studies were evidence to support our finding that $PM_{2.5}$ and NO_2 were significantly associated with the number of hospital visits with pneumonia in Khon Kaen.

Comparison between two periods

During the COVID-19 outbreak, single- and multi-pollutant model results showed that the RR of air pollution displayed declined. As a result of this study, there was a lower RR of $PM_{2.5}$ as compared to pre-COVID-19 period in Khon Kaen, Thailand. Supportively, a study by Bherwani *et al.* [2021], $PM_{2.5}$ was found to decrease in 2020 for Brazil, India, Iran, Kenya, Malaysia, Mexico, Pakistan, Peru, Sri Lanka, and Thailand and was compared with year 2019 to calculate the reduced health burden during lockdown period. Interestingly, total morbidity (respiratory diseases, cardiovascular diseases, and COPD) cases showed a reduction of 4.7% for Thailand (35). In China, the spread of the COVID-19 pandemic brought about changes in air quality and its health impacts. Chen *et al.* [2021] also observed health burden attributable to a significant decrease air pollutant and the positive values of mortality of all causes, cardiovascular, and respiratory disease indicated the health gains from the $PM_{2.5}$ improvement in 2020 compared with same period in 2018–2019 (36).

NO_2 daily exposure before the COVID-19 outbreak was significantly greater than that risk during the outbreak in cumulative-day lags (lag 0–3, lag 0–4, lag 0–5, and lag 0–6). A previous study in Grenoble, France, Aix *et al.* [2022] tried to determine the lower concentrations of NO_2, O_3, $PM_{2.5}$, and PM_{10} and how they affected human health compared to the 2020 period with a reference period 2015–2019. Aix *et al.* found that $PM_{2.5}$ and NO_2 associated with the highest health risk reductions and reductions in short-term risks were related to reductions in NO_2 (−1.5% in hospitalizations for respiratory causes) (20). Many above studies investigated the effect of air pollutants and concluded that $PM_{2.5}$ and NO_2 associated with the risk reduction of hospitalizations for respiratory causes. Researchers have agreed for the reason that the decreased sensitivity of respiratory illness might be the response to air pollution changes during the COVID-19 lockdown.

Another critical aspect, different effect sizes in the two periods may also be attributed to the different population behavior and intervention measures due to the spread of COVID-19 disease. Limiting social interaction, hand hygiene, and self-protective equipment such as mask-wearing during the pandemic could have helped prevent some of the incidence of respiratory diseases (37,38). Some of these regulations (e.g., stay-at-home measure, lockdowns or curfews, limiting travel, and restrictions on social gatherings) which restricted the behaviors of individuals and reduced human activity had a direct impact on public health. Since people spent less time outdoors, it could reduce or make people avoid exposing to ambient air pollution. As with previous findings, Ko *et al.* [2023] tried to clarify the impact of the COVID-19 on a marked reduction in non-COVID pneumonia in Hong Kong. PM and influenza rates were mediators for changes in hospital admissions of non-COVID pneumonia before and during the COVID-19 pandemic (11% and 52%, respectively). The study provided supplementary evidence that mask-wearing rates were associated with respiratory illness. However, the report of Ko *et al.* did not assess the mask-wearing rates that would contribute to the pneumonia in the study (39). Most literatures in this study did not include the patient's factors in the model analyses. Some studies suggested that an increase in these factors (mask-wearing rate and social distancing measures) might be contributed for reduced risk of diseases. Principally, it may be assumed that interventions to prevent COVID-19, in conjunction with improved air quality and changes in human behavior have reduced the risk of pneumonia.

Strengths and limitations

To the best of our knowledge, this is the first study that evaluated the association between air pollution and pneumonia comparing before *vs.* during the COVID-19 outbreak in Thailand. Using a time-series design, the effect of air pollutants modeled had significantly related to pneumonia. As the result, we identified decreased RR of pneumonia and reduced $PM_{2.5}$, and NO_2 concentrations during the COVID-19 outbreak. The additional explanations for this study comprehensively explained that the environmental improvements and public health policies were effective in lowering associated pneumonia risk.

The limitations of this study should be acknowledged. First, the modelling parameters were limited because of the integrity of each air pollution data as it is possible that other air pollutants might have influenced pneumonia illness. Second, we directly applied the ambient air pollutant concentrations to represent people's exposure levels. In fact, we cannot truly quantify the decreased numbers of hospital visits with pneumonia associated with the reduced air pollution because of the difference of human health behaviors between the two periods. Nevertheless, the national lockdown was associated with the limitation of human flow. Protective measures started to rise sharply during the COVID-19 outbreak and stayed at a high level during the entire epidemic period, impacted respiratory protection in two periods that were independent. Due to the collinearity in modelling the hospitalization with mask-wearing rate and other factors such as behavior changes in the period of before and during the COVID-19 outbreak, we could not conclude what factors mediate the change in pneumonia hospitalization. Moreover, as a limitation of the time-series model purely based on variable counts or values per day, and thus individual patient characteristics cannot be fitted. Therefore, we could not consider changes in people's behaviors and community hygienic measures in the model. Future study design such as case-cross over modelling should be considered for the patient's factors or existing respiratory diseases, as well as for other regions of Thailand where air pollution sources are different.

Implications and actions needed

As mentioned above, the key finding of this study has shown that the respiratory health impacts were related to air pollutants. PM and NO_2 model showed the association between hospital visits with pneumonia. Additionally, pneumonia risks of air pollution displayed declined during the COVID-19 period. A better quality of air pollutants along with public health policies during the pandemic was evidence to support the changes in risks of pneumonia. The findings of this study support raising awareness about measures and policies to preserve the air quality to decrease respiratory ailments.

Conclusions

The effect of PM and NO_2 modeled significantly related to pneumonia in Khon Kaen, Thailand. Specifically, our findings showed that the influence of air pollutants on pneumonia was higher through cumulative exposure days before the COVID-19 outbreak than during the outbreak. This was consistent with several studies showing greater decreases in air pollutants concentrations because of the control of the COVID-19 measures, which could provide more useful information for environmental policies and measurements to reduce the emission sources of air pollution. The human health benefits can be achieved if control measures are taken to reduce air pollution.

Acknowledgments

The authors would like to acknowledge the Thai PCD, Thai Meteorological Department, and Information and Communication Technology Center, Ministry of Public Health for providing the data for this study.
Funding: This work was supported by the graduate program in Industrial Toxicology and Risk Assessment, Faculty of Science at Chulalongkorn University, Thailand.

Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at https://jtd.amegroups.com/article/view/10.21037/jtd-23-1051/rc

Data Sharing Statement: Available at https://jtd.amegroups.com/article/view/10.21037/jtd-23-1051/dss

Peer Review File: Available at https://jtd.amegroups.com/article/view/10.21037/jtd-23-1051/prf

Conflicts of Interest: Both authors have completed the ICMJE uniform disclosure form (available at https://jtd.amegroups.com/article/view/10.21037/jtd-23-1051/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). This study was reviewed by the graduate program, Faculty of Science, Chulalongkorn University, and was considered exempt from institutional review board approval, since this study used secondary data without any personal identifiers and did not contain confidential patient data. For this type of study, informed consent from the subjects is not required.

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Cite this article as: Roudreo B, Puangthongthub S. A decreased impact of air pollution on hospital pneumonia visits during COVID-19 outbreak in northeastern Thailand. J Thorac Dis 2024;16(1):133-146. doi: 10.21037/jtd-23-1051