TOPICAL REVIEW

Short-term exposure to fine particulate matter and pneumonia-related hospitalizations: a systematic review and meta-analysis

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Abstract

Previous epidemiological reports have emphasized the impact of ambient particulate matter (PM) on pneumonia-related hospitalizations. However, these reports vary across different study populations. We aimed to evaluate the impact of short-term exposure to PM on hospital admissions due to pneumonia. A systematic literature review was performed to identify studies quantifying the impact of PM$_{2.5}$ and PM$_{10}$ on pneumonia-related hospitalizations. A meta-analysis was performed by using pooled analyses of each pollutant with a random effects model. Subgroup analyses were performed according to various lag times and age groups, along with meta-regression analyses. A total of ten studies were eligible for analysis. In the overall population, a 10 μg m$^{-3}$ increase in the daily PM$_{2.5}$ was associated with an increased risk ratio (RR) of hospitalization for pneumonia (pooled RR 1.007, 95% confidence interval [CI]: 1.000–1.014 per 10 μg m$^{-3}$ increase), but the PM$_{10}$ was not (pooled RR 1.008, 95% CI: 0.998–1.018 per 10 μg m$^{-3}$ increase). A lag effect was not observed in the subgroup analysis of different lag times. In the subgroup analysis of elderly individuals (≥65 years), both the PM$_{2.5}$ and PM$_{10}$ resulted in increased RRs for pneumonia-related hospitalizations, with pooled RRs of 1.026 (95% CI: 1.006–1.047 per 10 μg m$^{-3}$ increase) and 1.016 (95% CI: 1.013–1.019 per 10 μg m$^{-3}$ increase), respectively. By contrast, studies that included young patients revealed a nonsignificant relationship between exposure to high levels of PM$_{2.5}$ and pneumonia-related hospitalizations (RR 1.003, 95% CI: 0.998–1.008 per 10 μg m$^{-3}$ increase). In the meta-regression analysis, results from recent study periods indicated that the effect of PM$_{2.5}$ on pneumonia-related hospitalizations was less than that of earlier studies ($P = 0.009$). Our results suggest that PM$_{2.5}$ and PM$_{10}$ may affect elderly individuals in terms of pneumonia-related hospitalizations, which may vary over time.

1. Introduction

Pneumonia is an inflammatory condition of the lungs caused by microbiological infection. It is one of the leading causes of death worldwide, with an estimated age-standardized death rate of 41.7 per 100 000 [1]. In the US, more than 1.5 million adults are hospitalized annually due to pneumonia, and approximately one-third of hospitalized patients die within a year [2]. Hospitalizations for pneumonia also result in economic costs. Among US Medicare beneficiaries, the medical cost of pneumonia-related hospitalization...
was $15,682 during 1 year after hospitalization, which was higher than that of the matched control patients without pneumonia [3].

Individual factors such as patient age, smoking history, and underlying chronic diseases have been regarded as risk factors for hospitalization due to pneumonia [4]. However, environmental factors, including outdoor pollution from compounds such as nitrogen dioxide and carbon monoxide, also result in major impacts [5–7]. Among ambient air pollutants, particulate matter (PM) is a complex mixture of extremely small particles and liquid droplets comprising acids, organic chemicals, metals, and soil or dust particles [8]. PM can be harmful to the respiratory system because it cannot be efficiently filtered in the upper airway, and thus it induces oxidative stress with inflammation that leads to the anatomic and physiologic remodeling of the lungs [8]. These effects compromise the host’s ability to cope with ongoing respiratory infections [9]. A recent meta-analysis of 17 studies involving children showed 1.8% and 1.5% increases in pneumonia-related hospitalizations per 10 μg m⁻³ increase in PM₂.₅ and PM₁₀, respectively [10]. However, this knowledge cannot be directly applied to adults. Children may be more susceptible to air pollution, because they inhale more air per unit of body weight than adults [11]. Although the association between PM and the risk of pneumonia-related hospitalization has been emphasized in the overall population [12], it is controversial whether PM affects pneumonia-related hospitalizations among adults [13, 14].

Therefore, the aim of this study was to systematically review associations between increases in PM₂.₅ and PM₁₀ and pneumonia-related hospitalizations in the adult population.

2. Methods

2.1. Study protocol

Our systematic review (SR) was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [15].

2.2. Eligibility criteria

The inclusion criteria were as follows:

(a) Published, peer-reviewed original articles
(b) Studies including a general adult (age ≥ 18 years) population
(c) Studies reporting the impact of air pollution, including the PM₂.₅ and/or PM₁₀, on human health in a quantitative exposure-response relationship (i.e. relative risk, odds ratio, excess risk, or percentage change)
(d) Studies with outcome data including hospitalization for pneumonia or lower respiratory tract infection after short-term (up to 7 d) exposure to PM₂.₅ and/or PM₁₀
(e) Studies performed with case-crossover or time-series study designs

2.3. Study outcomes

Our primary outcome was to identify relationships between the risk of hospital admission due to pneumonia and PM₂.₅ or PM₁₀ levels in the adult population.

2.4. Information sources and search strategy

We searched MEDLINE, EMBASE, and the Cochrane Library through 8 October, 2020, using controlled vocabulary and free text that included ‘air pollutants,’ ‘particulate matter,’ ‘PM₂.₅,’ ‘PM₁₀,’ ‘pneumonia,’ ‘lower respiratory tract infection,’ and ‘hospitalization.’ To design a structural search strategy for our SR, we followed the Peer Review of Electronic Search Strategies [16]. The detailed search strategy is available in the supplementary appendix (available online at https://stacks.iop.org/15/123012/mmedia). We also conducted a manual search using study identifiers or the references from previous studies.

2.5. Study selection

We screened and reviewed potential studies by following the PRISMA flow diagram [15]. After duplicate literature was removed, the titles and abstracts of all the identified studies were screened to identify potentially eligible studies. The studies corresponding to the inclusion criteria were retained for full-text review. Studies including children or those that did not specify the age of the population were excluded. When different outcome data were found in the same study population for overlapping study periods, perennial or long-term data were preferred. Any discrepancy regarding the inclusion of a study was resolved by group discussion.

2.6. Data extraction and data items

We collected baseline information, including the authors, year of publication, study design, country, study period, target age of the study population, exposure type (PM₂.₅ or PM₁₀), outcome definition, the total number of pneumonia-related hospitalization events, and reported lag days from each study. Data regarding the mean or median age, sex distribution, and daily PM were collected for meta-regression analysis.

If the incidence of the outcome is low (<10%), the odds ratio is very similar to the relative risk [17]. Therefore, the reported odds ratios and relative risks were all considered as ‘risk ratios (RRs).’ For studies reporting excess risk, the RR was calculated as ‘1 + excess risk,’ and for studies reporting percentage changes, the RR was calculated as ‘1 + (percentage changes/100).’ To calculate the pooled effects, all of the RRs were standardized with the same increment.
level, 10 µg m\(^{-3}\), which was calculated according to the following formula:

\[
\text{Standardized RR} = \frac{\text{RR}_{\text{measured}}}{\text{RR}_{\text{provided in study}}}\]

Several studies reported different lag times. Because there is no standard approach to analyzing studies with various lag times, the shortest lag time was used in the primary analysis according to previous studies. Cumulative lag was considered an alternative if a single lag estimate was not available. Cumulative lags are reported with numbers and dashes throughout the article (i.e. lag days 0–2 refer to the average exposure to PM 2 d after the measurement of PM\(_{2.5}\) and/or PM\(_{10}\)). If provided, the RR estimates according to different lag times and population age groups were collected to conduct subgroup analyses.

### 2.7. Statistical methods

The meta-analysis was conducted with the ‘Metafor’ package in R statistical software (version 3.6.2; R Foundation for Statistical Computing, Vienna, Austria) [20]. Forest plots with random effects model were used to explore the summary of individual studies visually, and \(\hat{I}^2\) statistics were used to assess the heterogeneity between studies [21]. When heterogeneity was observed, the subgroup analysis including elderly (≥65 years old) participants and the meta-regression analysis including the study period, percentage of females, and baseline air pollution were performed. Funnel plots and Egger's regression tests were used to assess the publication bias [22].

### 3. Results

#### 3.1. Search findings and study characteristics

The initial search revealed 943 studies, which were narrowed to 810 after the removal of duplicates. Based on the titles and abstracts, 720 irrelevant studies were excluded. After 90 full-text articles were reviewed, ten studies were considered eligible for review (figure 1).

A total of ten studies reported 3,030,133 pneumonia events. Among them, eight studies reported data on PM\(_{2.5}\), while four studies reported data on PM\(_{10}\). While five were case-crossover studies, the other five were time-series studies. Studies were performed in three countries: six from the US, three from China, and the other one from Italy. These studies included single and multiple cities from eight and two cities, respectively. Various age groups were reported in each study: three studies included patients ≥18 years old, one study had patients ≥35 years old, one study had patients ≥60 years old, and four studies involved patients ≥65 years old. Because the study by Tao et al. [23] did not specify the age of the entire study population, partial data with the specified age group (≥65 years) were included in the analysis. Age stratified analyses were performed in studies by Wu et al. [24], Pirozzi et al. [25], Bell et al. [26], and Belleudi et al. [27]. The rates of hospital admission due to pneumonia were commonly adjusted for temperature, humidity, and day of the week. The studies reported various lag periods, from 0 to 7 lag days. Single lags and cumulative lags were reported in ten and five studies, respectively. The daily median or mean PM\(_{2.5}\) ranged from 9.0 µg m\(^{-3}\) to 123.0 µg m\(^{-3}\), and the PM\(_{10}\) ranged from 28.0 µg m\(^{-3}\) to 275.9 µg m\(^{-3}\) according to each study. When the daily temperatures were calculated in Celsius, they ranged from 9.4 °C to 16.4 °C (table 1).

#### 3.2. Pneumonia hospitalizations and PM\(_{2.5}\)

According to the shortest lag time in each study, the relationships between short-term exposure to PM\(_{2.5}\) and pneumonia-related hospitalizations are summarized in figure 2(A). The pooled RR was calculated as 1.007 (95% CI: 1.000–1.014) per 10 µg m\(^{-3}\) increase in PM\(_{2.5}\) (\(I^2 = 91.51\%, P < 0.001\)). Because the studies reported various lag times, subgroup analyses were performed according to the different lag times. A significant effect size was observed on the day of exposure (pooled RR 1.006, 95% CI: 1.000–1.011 per 10 µg m\(^{-3}\) increase in PM\(_{2.5}\), \(I^2 = 85.23\%, P = 0.003\)), the day after PM\(_{2.5}\) exposure (pooled RR 1.010, 95% CI: 1.002–1.017 per 10 µg m\(^{-3}\) increase in PM\(_{2.5}\), \(I^2 = 96.80\%, P < 0.001\)), and 2 d after PM\(_{2.5}\) exposure (pooled RR 1.005, 95% CI: 1.001–1.009 per 10–10 µg m\(^{-3}\) increase in PM\(_{2.5}\), \(I^2 = 84.29\%, P = 0.002\)). No significant effect was observed for the other lag time periods (lag days 3, 4, and 5) (figure 3).

In the subgroup analysis of the elderly population (age ≥65 years), the estimated RR for hospitalization due to pneumonia increased significantly as the PM\(_{2.5}\) level increased; the RR was 1.026 (95% CI: 1.006–1.047) per 10 µg m\(^{-3}\) increase in PM\(_{2.5}\) (\(I^2 = 95.83\%, P < 0.001\)) (figure 4(A)). Most of the included studies [7, 24, 25, 27, 30] showed the effect sizes and their 95% CIs were larger than 1 except for in one study by Bell et al. [26]. When the studies that included broad age groups were analyzed, the relationship between the PM\(_{2.5}\) and pneumonia-related hospitalization was not significant (RR 1.003, 95% CI: 0.999–1.008 per 10 µg m\(^{-3}\) increase in PM\(_{2.5}\)) (supplementary figure 1).

#### 3.3. Pneumonia-related hospitalizations and PM\(_{10}\)

The relationship between short-term exposure to PM\(_{10}\) and pneumonia hospitalization was analyzed as well. According to the random effects model, the pooled RR was 1.008 (95% CI: 0.998–1.018) per 10 µg m\(^{-3}\) increase in PM\(_{10}\) (\(I^2 = 91.26\%, P < 0.001\)) (figure 2(B)). Further analyses according to various lag times were performed; however, none revealed significant results due to the limited numbers of studies (supplementary figure 2).
Table 1. Characteristics of ten studies included in the meta-analysis evaluating short-term effects of PM$_{2.5}$ and PM$_{10}$ on pneumonia hospitalizations.

| Author       | Year | Design | Country and region | Study period | Age | Exposure | Outcome definition | Events | Adjustment | Reported lag days | Average daily PM$_{2.5}$a | Average daily PM$_{10}$a | Average daily temperaturea |
|--------------|------|--------|--------------------|--------------|-----|----------|-------------------|--------|------------|-------------------|----------------------------|----------------------------|----------------------------|
| Wu et al [24]| 2020 | TS     | China (Beijing)    | 2010–2012    | ≥18 | PM$_{2.5}$ | Admission for pneumonia | 37 552 | T, H, D, PH | 0, 1, 2, 3, 4, 5, 0–1, 0–2, 0–3 | 99.5 µg m$^{-3}$ (mean) | NA                         | 12.6 °C (mean) |
| Croft et al [28] | 2019 | CC     | US (New York)     | 2005–2016    | ≥18 | PM$_{2.5}$ | Admission for bacterial pneumonia | 37 609 | T, H | 0, 0–1, 0–2, 0–3, 0–4, 0–5, 0–6 | 9.0 µg m$^{-3}$ (mean of medians) | NA | NA |
| Pirozzi et al [25] | 2018 | CC     | US (Utah)         | 2009–2012    | ≥18 | PM$_{2.5}$ | Admission for pneumonia | 2590  | T, H, D | 1, 2, 3, 4, 5, 6, 7 | 7.3 µg m$^{-3}$ (mean of medians) | NA | NA |
| Bai et al [29] | 2016 | CC     | China (Shijiazhuang) | 2013         | ≥60 | PM$_{2.5}$, PM$_{10}$ | Admission for lower respiratory tract infection | 3126 | T | 0, 1, 2, 3, 4, 5 | 123.0 µg m$^{-3}$ | 275.9 µg m$^{-3}$ | 14.5 °C |
| Bell et al [26] | 2015 | TS     | US (Medicare beneficiares) | 1996–2010    | ≥65 | PM$_{2.5}$ | Admission for respiratory tract infection | 2720 705 | T, DP, D | 0, 1, 2 | 12.3 µg m$^{-3}$ (mean) | NA | 14.1 °C (mean) |
| Tao et al [23] | 2014 | TS     | China (Lanzhou)   | 2001–2005    | ≥65 | PM$_{10}$ | Admission for pneumonia | 777   | T, H, BP, D, V, W | 3 | NA | 196.6 µg m$^{-3}$ (mean) | 11.2 °C (mean) |
| Author          | Year | Design | Country and region | Study period | Age | Exposure | Outcome definition | Events | Adjustment | Reported lag days | Average daily PM$_{2.5}^a$ | Average daily PM$_{10}^a$ | Average daily temperature$^a$ |
|-----------------|------|--------|-------------------|--------------|-----|----------|-------------------|--------|-------------|-------------------|--------------------------|--------------------------|-----------------------------|
| Belleudi et al [27] | 2010 | CC     | Italy (Rome)      | 2001–2005    | ≥35 | PM$_{2.5}$, PM$_{10}$ | Admission for lower respiratory tract infection | 11 331 | T, BP, P, I | 0, 1, 2, 3, 4, 5, 6, 0–1, 0–2, 0–5, 0–6 | 20.5 µg m$^{-3}$ | 35.9 µg m$^{-3}$ | 16.4 °C |
| Zanobetti et al [7] | 2006 | CC     | US (Boston)       | 1995–1999    | ≥65 | PM$_{2.5}$ | Admission for pneumonia | 24 587 | T           | 0, 0–1          | 11.1 µg m$^{-3}$ | NA | 9.4 °C |
| Lippmann et al [30] | 2000 | TS     | US (Michigan)     | 1992–1994    | ≥65 | PM$_{2.5}$ | Admission for pneumonia | 12 045 | T, H, D | 1               | 15.0 µg m$^{-3}$ | 28.0 µg m$^{-3}$ | 10.6 °C |
| Zanobetti et al [31] | 2000 | TS     | US (ten cities)$^b$ | 1986–1994    | ≥65 | PM$_{10}$ | Admission for pneumonia | 179 811 | T, H, D | 0, 0–1 | NA | 28.8 µg m$^{-3}$ (mean of medians) | 10.8 °C |

$^a$Median values are presented unless specified otherwise.

$^b$Includes Akron, Birmingham, Chicago, Colordo Springs, Detroit, Minneapolis, New Haven, Pittsburgh, Seattle, Spokane.

Abbreviations: PM$_{2.5}$, particulate matter with aerodynamic diameter ≤2.5 µg m$^{-3}$; PM$_{10}$, particulate matter with aerodynamic diameter ≤10 µg m$^{-3}$; CC, case-crossover; TS, time-series; T, Temperature; H, humidity; D, Day of the week; PH, public holiday; DP, dew point; BP, barometric pressure; V, visibility; W, wind speed; P, population change; I, influenza epidemics; and NA, not available.
Figure 1. Flow diagram of the systematic literature review.

Figure 2. Forest plot of pneumonia-related hospitalizations and exposure to outdoor ambient particulate matter according to the meta-analysis. The risk ratios are expressed per 10 µg m\(^{-3}\) increase in the level of particulate matter. (A) Exposure to outdoor particulate matter with an aerodynamic diameter of ≤2.5 µg m\(^{-3}\). (B) Exposure to outdoor particulate matter with an aerodynamic diameter of ≤10 µg m\(^{-3}\).

When only the elderly population (age ≥ 65 years) was included in the subgroup analysis, the overall pooled RR was higher than that in the original analysis and was statistically significant, at 1.016 (95% CI: 1.013–1.019) per 10 µg m\(^{-3}\) increase in PM\(_{10}\) (\(I^2 = 0.22\%, P = 0.264\)) (figure 4(B)). The degree of heterogeneity was significantly reduced, with two among three studies \([27, 31]\) showing effect sizes and their 95% CIs larger than 1.

3.4. Meta-regression analysis

Because of the high degree of heterogeneity between studies, we conducted a random effects meta-regression analysis with linear trends for the articles reporting the PM\(_{2.5}\). In the analysis, studies performed recently tended to estimate the effect of PM\(_{2.5}\) on pneumonia-related hospitalization as less than that in earlier studies \((P = 0.009)\) (figure 5(A)). This trend was also observed when five studies from the same country (United States) were analyzed according to their study periods. Studies with recent study period tended to reveal less of an association between the levels of PM\(_{2.5}\) and pneumonia-related hospitalizations (supplementary figure 3). The percentage of females in the study population \((P = 0.640, \text{figure 5(B)})\) or the average (mean or median) PM\(_{2.5}\) presented in each study \((P = 0.574, \text{figure 5(C)})\) did not have an impact on the RR of pneumonia-related hospitalization in the context of the PM\(_{2.5}\). The meta-regression of studies that reported the PM\(_{10}\) was not
considered viable because of the small number of studies ($n = 4$).

3.5. Assessment of publication bias
The possible publication bias was evaluated with funnel plots and Egger’s regression test for pneumonia-related hospitalizations and PM exposure. For our primary analyses regarding the shortest lag times for PM$_{2.5}$ and PM$_{10}$, the funnel plot did not reveal significant publication bias (supplementary figure 4). Egger’s regression test also did not detect any publication bias; the bias values were 2.227 ($P = 0.068$) and 0.008 ($P = 0.952$) in each analysis, respectively.

4. Discussion
This was the first SR to investigate the impact of PM$_{2.5}$ and PM$_{10}$ on hospital admissions due to pneumonia in the general adult population. Although the impact was not as noteworthy as that in the overall population, positive associations between both PM$_{2.5}$ and PM$_{10}$ and pneumonia hospitalizations were shown in the elderly population (pooled RRs, 1.026 and 1.016, respectively). However, high heterogeneity was observed across studies, which prevented exact estimations of the impact of PM on pneumonia-related hospitalizations. Intriguingly, some heterogeneity could be explained by the period of study and patient age. Studies performed recently reported a weaker effect from the PM on pneumonia hospitalizations than those from earlier periods.

Our study has its strength in that it is the first SR to report the association between PM and pneumonia-related hospitalizations in the adult population. The impact of PM$_{2.5}$ and PM$_{10}$ on similar respiratory outcomes has been emphasized in other reports. Short-term exposure to a 10 µg m$^{-3}$ increase in PM$_{2.5}$ was associated with a 0.92% increased risk of hospital admission for respiratory infection and other cardiopulmonary diseases in US Medicare enrollees (ages ≥65 years) [32, 33]. A higher PM$_{2.5}$ (200 µg m$^{-3}$) was associated with a higher risk (relative risk of 1.40) of intensive care unit admission due to pneumonia than a lower PM$_{2.5}$ (30 µg m$^{-3}$) [34]. A recent study also revealed independent associations between short-term exposure to PM and all-cause mortality, including respiratory-associated mortality, in 652 cities worldwide [35].

Although significant heterogeneity made it difficult to estimate the exact impact of PM on pneumonia-related hospitalizations, our results showed that PM$_{2.5}$ and PM$_{10}$ increased the risk of hospital admission due to pneumonia in the elderly population. By contrast, the impact of PM on
pneumonia-related hospitalization was not significant when younger participants were included. The different relationships between PM and pneumonia-related hospitalization according to age could be explained by the following.

First, PM could augment a greater inflammatory response in the lungs of elderly adults than in the lungs of younger adults. In a bronchoalveolar fluid study that included healthy volunteers [36], higher proportions of neutrophils and lower percentages of macrophages were observed in the older group than in the younger group. In a clinical study, older adults (age ≥ 55) had higher levels of serum high-sensitivity C-reactive protein, interleukin 6, and tumor necrosis factor-alpha than younger adults (age <55) when exposed to similar levels of PM$_{10}$ [37]. In contrast to a study reporting that exposure to PM$_{2.5}$ increased the risk of mortality among the elderly US Medicare population (age ≥ 65) [38], there was no association between PM and respiratory-related hospitalizations in studies that included children and adolescents [38, 39].

Second, these findings may reflect that older age is a risk factor for hospitalization and pneumonia severity. In a previous population-based surveillance study, the rate of pneumonia-related hospitalizations was more than nine times higher in the senior group (age 65 or older) than in the younger group (age 18–49) [40]. Commonly employed scoring systems for assessing the severity and mortality risk of community-acquired pneumonia, including the pneumonia severity index and CURB-65, include age as one of the major variables [41–43].

In our meta-regression analysis, heterogeneity among the impact of PM on pneumonia-related hospitalizations in the elderly and overall populations could be explained by differences in study periods. Studies covering recent time periods reported a lower impact from PM$_{2.5}$ on pneumonia-related hospitalizations than earlier studies in our analysis. These differences can be explained by several reasons. First, the changing incidence of pneumonia over time may influence the frequency of pneumonia-related hospitalizations. In the US, which accounted for five of the eight papers regarding PM$_{2.5}$ in our review, the incidence of pneumonia increased in the elderly population until the 1990s [44, 45] and then decreased after 2003 [46]. Second, behavioral changes could occur over time. As general knowledge about the harmful effects of air pollution deepens, patients with risk factors for pneumonia may have learned to avoid unnecessary exposure to outdoor air pollution. These behavioral changes along with changes in general knowledge have been suggested in a previous SR of physical activity [47]; healthy adults tended to increase their physical activity after interventions in recent studies compared to early studies. Third, as the life expectancy increases over time [48], the proportion of patients with comorbidities increases; thus, the impact of PM$_{2.5}$ on pneumonia-related hospitalizations may play a smaller role than it did in the past.

In the subgroup analyses in our study, the lag effects of PM were unclear. Regarding the PM$_{2.5}$, the impact was significant on the day and until 2 d after exposure but was nonsignificant on lag days 3–5. None of the subgroup analyses of various lag times regarding PM$_{10}$ revealed significant results. This finding is contrary to a previous study suggesting a lagged effect for respiratory outcomes compared to cardiovascular outcomes following exposure to PM$_{2.5}$ [49]. Our results have limitations due to the small number of included studies, but they may be a consequence of the urgent nature of pneumonia compared to other respiratory diseases. For example, admissions for asthma are mostly children, but mortality is low in these young patients [50, 51]. This trend contrasts that of pneumonia, because the elderly population is most susceptible to hospitalization and mortality [40, 42].

We should acknowledge the limitations of this study. First, our SR could only include small number of studies conducted in a restricted number of countries. This approach may limit the generalizability of the results. Second, the heterogeneity of results disturbs the exact interpretation of results, although the
age and study period could partly explain the heterogeneity. PM consists of many chemical constituents that may differ according to regional environments [8]. The socio-economic status also varies between countries. Therefore, the inclusion of studies from different locations could contribute to the heterogeneity. Third, our study did not consider confounding effects, although there could be confounders in the association between PM and pneumonia. Since all the studies included in our SR were population-based studies, information on confounding variables such as comorbidities and socioeconomic status was lacking.

5. Conclusion

In conclusion, this meta-analysis showed that PM$_{2.5}$ and PM$_{10}$ increased the risk of pneumonia-related hospitalization among the aged population (>65 years) but not among a broader age group including young adults. Studies covering recent time periods reported weaker effects from PM on pneumonia outcomes than earlier studies. Our results suggest that PM may affect the elderly population in terms of pneumonia-related hospitalizations, which may vary over time.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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