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Association between air pollution and risk of non-alcoholic fatty liver disease: an updated meta-analysis

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Objective: Air pollution is a major environmental risk to human health, with increasing evidence linking it to non-alcoholic fatty liver disease (NAFLD). However, findings remain inconsistent. This meta-analysis aimed to assess the relationship between air pollutants and the risk of NAFLD.

Methods: PubMed, Embase, and Web of Science were systematically searched for studies published up to March 20, 2025. A random effects model was used to estimate combined odds ratios (ORs) and 95% confidence intervals (95% CIs). Subgroup analysis, sensitivity analysis, funnel plots, and Egger's test were conducted.

Results: A total of 12 studies, including 49,549,903 participants (published between 2022 and 2024), were analyzed. For each 10 $\mu\text{g}/\text{m}^3$ increase in pollutants, the ORs were 1.22 (1.16–1.29) for particulate matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$ ($\text{PM}_{2.5}$), 1.15 (0.95–1.40) for particulate matter between 2.5 and $10 \mu\text{m}$ in aerodynamic diameter ($\text{PM}_{2.5-10}$), and 1.07 (1.01–1.13) for particulate matter with aerodynamic diameter $\leq 10 \mu\text{m}$ (PM_{10}). For gaseous pollutants, the ORs were 1.45 (0.92–2.28) for sulfur dioxide (SO_2) and 1.10 (1.06–1.14) for nitrogen dioxide (NO_2). No notable connection emerged between ozone (O_3) or carbon monoxide (CO) and NAFLD. Subgroup analysis revealed stronger associations for $\text{PM}_{2.5}$, PM_{10} , and NO_2 with NAFLD in developed countries, Europe, and cohort studies, compared to developing countries, Asia, and cross-sectional studies.

Conclusion: This analysis supports a positive relationship between air pollution and NAFLD risk. Geographic region and economic development appear to moderate this association.

Systematic review registration: <https://www.crd.york.ac.uk/PROSPERO/view/CRD42024594146>, Identifier: CRD42024594146.

KEYWORDS

air pollution, particulate matter, non-alcoholic fatty liver disease, systematic review, meta-analysis

1 Introduction

Non-alcoholic fatty liver disease (NAFLD) ranks among the foremost causes of chronic liver conditions globally, encompassing a progression from simple steatosis and steatohepatitis to severe outcomes like fibrosis and cirrhosis (1). Currently affecting 32.4% of people globally, this condition is expected to see a notable surge in prevalence

over the next 10 years (2–4). Beyond its toll on liver function and survival, NAFLD is connected to various extrahepatic disorders, such as cardiovascular disease, type 2 diabetes mellitus, chronic kidney disease, and select cancers (5–7), posing a growing public health challenge (4). Understanding the risk factors for NAFLD is crucial for early prevention and management.

Air pollution, a major environmental health threat, contributes to an estimated 7 million premature deaths annually (8) and is linked to chronic diseases including cardiovascular disease, respiratory disorders, and cancer (9–12). Key pollutants include particulate matter (PM), ozone (O₃), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and carbon monoxide (CO) (13). Recent evidence suggests that air pollutants may also increase NAFLD risk, though findings remain inconsistent (14–16). For instance, some studies have reported a significant association between particulate matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}) and the risk of NAFLD (17, 18), whereas others have found little to no relationship (19, 20). Experimental studies indicate that the underlying mechanisms may involve oxidative stress, inflammation, and insulin resistance induced by air pollutant exposure (21–23).

A prior meta-analysis (24) focused on NAFLD risk included a limited subset of studies and failed to standardize effect sizes across studies, leading to potential bias. Furthermore, several large, high-quality cohort and cross-sectional studies in recent years have added new insights into the relationship between air pollution and NAFLD risk (17, 20, 25, 26). To address these gaps, we conducted an updated meta-analysis to comprehensively evaluate the relationship between multiple air pollutants (e.g., PM, NO₂, SO₂, CO, O₃) and NAFLD risk, incorporating recent high-quality studies and standardizing effect estimates for improved comparability.

2 Methods

This meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (27) and was registered with PROSPERO (CRD42024594146) before initiation.

2.1 Data sources and searches

PubMed, Embase, and Web of Science were explored for pertinent studies released by March 20, 2025. The search was limited to English-language publications and utilized a blend of medical subject headings (MeSH) and terms associated with liver conditions (e.g., “fatty liver,” “steatohepatitis*,” “Visceral Steatos*,” “liver steatosis*”) and atmospheric pollutants (e.g., “air pollution,” “particulate matter,” “nitrogen oxides,” “ozone,” “sulfur dioxide,” “carbon monoxide”). The detailed search strategy is provided in [Supplementary Tables S1–S3](#).

2.2 Selection criteria

The meta-analysis included studies that met the following Population, Exposure, Comparison, Outcome, Study Design (PECOS) criteria:

Population: general population, including adults and children.

Exposure: air pollutants, including PM_{2.5}, particulate matter between 2.5 and 10 μm in aerodynamic diameter (PM_{2.5–10}), particulate matter with aerodynamic diameter $\leq 10 \mu\text{m}$ (PM₁₀), NO₂, SO₂, CO, and O₃.

Comparator: non-exposed or less-exposed populations.

Outcome: NAFLD, metabolic-associated fatty liver disease (MAFLD), or metabolic dysfunction-associated steatotic liver disease (MASLD). NAFLD diagnoses were based on ICD-10 codes K75.8 and K76.0, or ultrasonography of hepatic steatosis with complications such as obesity, type 2 diabetes mellitus, or metabolic disorders (MAFLD) (28), or MASLD as defined by hepatic steatosis plus one of five cardiometabolic criteria (29).

Study design: observational studies, including cohort, cross-sectional, and case-control designs.

Studies that reported odds ratios (ORs), risk ratios (RRs), or hazard ratios (HRs) with 95% confidence intervals (CIs), or provided sufficient data for these estimates, were included. Recent or comprehensive studies were prioritized when datasets overlapped (30).

Exclusion criteria included conference abstracts, protocols, reviews, and duplicate publications.

2.3 Study selection

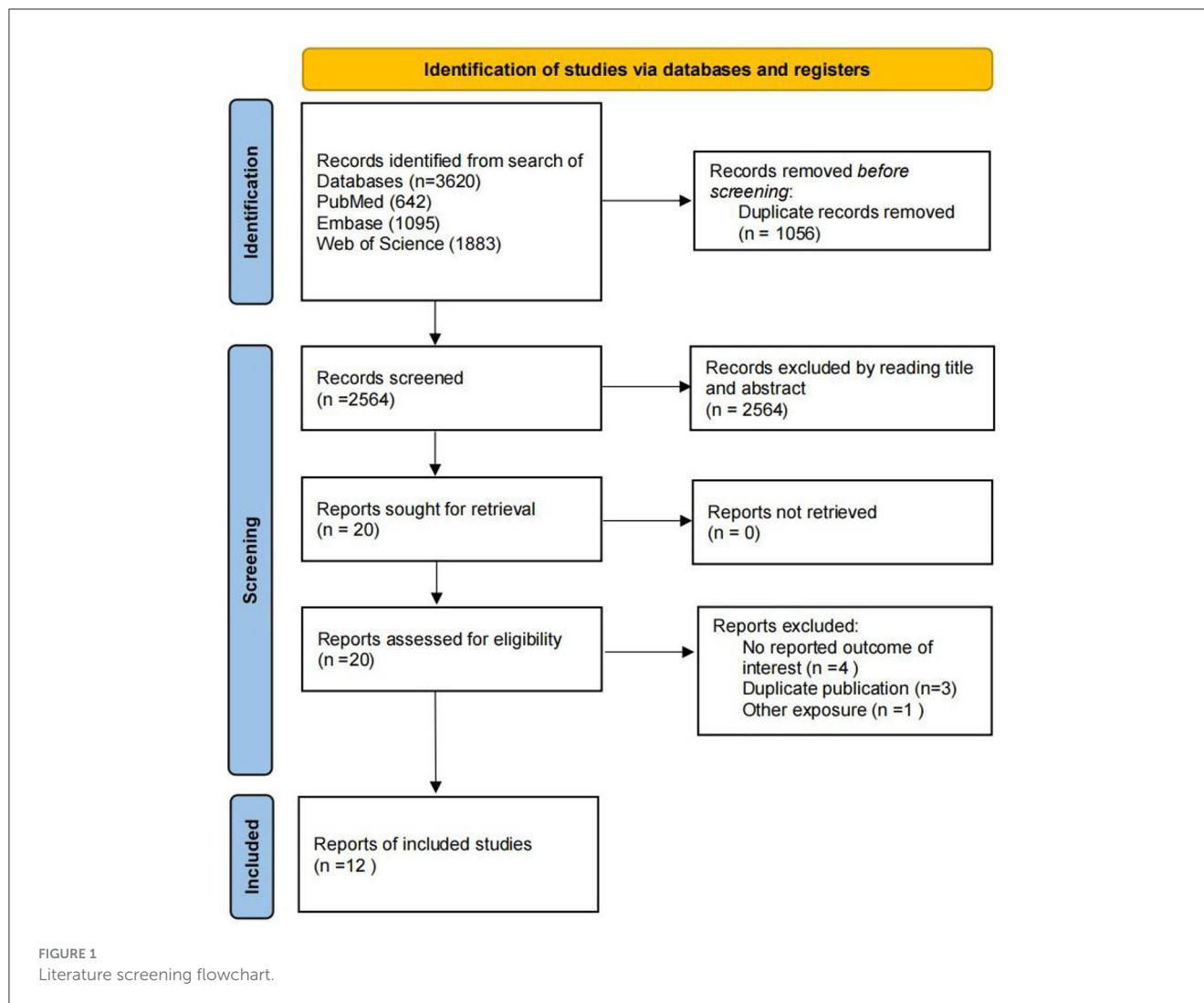
Titles and abstracts were independently reviewed by two authors (XZ and LSH) based on pre-set inclusion and exclusion guidelines. Full texts of potentially qualifying studies were then evaluated to confirm their suitability. Any differences of opinion were settled by involving a third author (XZY) as a mediator.

2.4 Data extraction

Data were independently gathered by two authors (XZ and LSH), with a third author (XZY) addressing any inconsistencies. Collected details included the first author, year of publication, study design, region, survey period, sample size, mean age, female proportion, air pollutants measured, outcome, statistical model, and effect estimates with corresponding 95% CIs.

2.5 Quality assessment

Quality assessments were independently performed by two authors (XZ and LSH). Discrepancies were resolved through discussion. The quality of cohort studies was assessed using the Newcastle-Ottawa Scale (NOS) (31), with scores categorized as: low (0–3), moderate (4–6), or high (7–9) quality. Cross-sectional study quality was assessed using the American Agency for Healthcare Research and Quality criteria (32), with scores classified as: low (0–3), moderate (4–7), or high (8–11).



2.6 Statistical analysis

Adjusted ORs and their 95% CIs were relied upon to evaluate the link between air pollutants and NAFLD risk. Studies reporting RRs or HRs were considered equivalent to ORs (33). Pollutant levels reported in parts per billion (ppb) were transformed to $\mu\text{g}/\text{m}^3$ using conversion rates: 1.88 for NO_2 , 2.62 for SO_2 , 1.96 for O_3 , and 1.15 for CO. Due to varying increments of air pollutant exposure, ORs and 95% CIs were standardized to a 10 $\mu\text{g}/\text{m}^3$ increase using the formula (34):

$$\text{OR}_{(\text{standardized})} = \text{OR}_{(\text{original})}^{10/\text{Increment}(\text{original})}$$

A random-effects model was employed to derive pooled ORs linking NAFLD with pollutant exposure. Heterogeneity was examined using Cochran's Q test and the I^2 metric, where I^2 exceeding 50% denoted substantial variability. Subgroup analyses explored heterogeneity sources, considering factors like study type, sample size, female ratio, economic context, smoking prevalence, region, education, and outcome classification. Sensitivity tests verified the stability of results. Funnel plots and Egger's regression test were used to detect publication

bias (35), with a minimum of 10 studies required for this analysis (36). Statistical analyses were performed using Stata version 14.0.

3 Results

3.1 Literature selection

The search strategy identified 3,620 relevant articles. After removing duplicates, 2,564 records underwent title and abstract evaluation. Full-text assessment was performed on 20 articles, of which eight were excluded: four for lack of relevant results, three for duplication, and one for addressing a different exposure. Ultimately, 12 studies were retained for the meta-analysis (Figure 1).

3.2 Study characteristics

The 12 included studies (14–18, 20, 25, 26, 37–40), published between 2022 and 2024, involved a total of 49,549,903 participants.

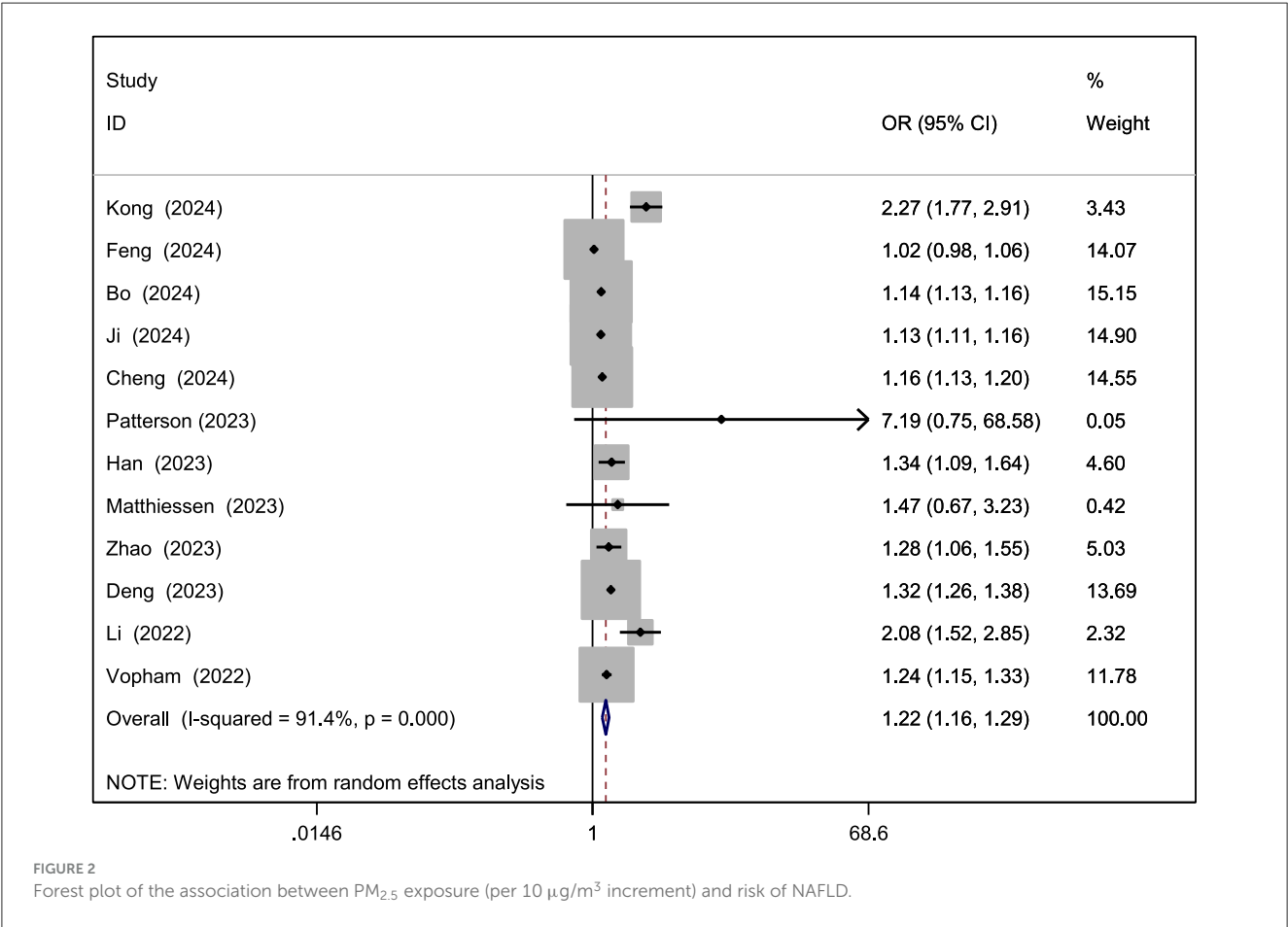
TABLE 1 Characteristics of studies included in the meta-analysis.

| Study ID | Study type | Region | Survey time | Sample size (Case/Control) | Age (Mean ± SD, years) | Female ratio | Pollutant | Outcome | Statistical model | Quality score |
|---------------------|------------------------------------|---------|--|------------------------------------|---------------------------|-------------------|---|---------|---|------------------|
| Kong 2024 | Prospective cohort | UK | 2006–2010 | 417,250 (4,752/412,273) | 56.3 ± 8.1 | 223,892 (53.7) | PM _{2.5} , PM _{2.5–10} , PM ₁₀ , NO ₂ | NAFLD | Cox proportional hazard model | 7 |
| Feng 2024 | Retrospective cohort | China | 3 years preceding outcome assessment | 27,699 (7,374/20,325) | NA | 4,052 (14.6) | PM _{2.5} , SO ₂ , NO ₂ , O ₃ , CO | MAFLD | Logistic regression model | 6 |
| Bo 2024 | Cross-sectional | China | 2001–2018 | 329,048 (96,852/232,196) | 41.0 ± 13.0 | 185,164 (56.3) | PM _{2.5} , NO ₂ , O ₃ | NAFLD | Logistic regression model | 8 |
| Ji 2024 | Cross-sectional | China | 2017–2020 | 2,711,207 (191,592/2,519,615) | 49.7 ± 15.4 | 1,432,694 (52.8) | PM _{2.5} , PM ₁₀ , SO ₂ , O ₃ , CO | MAFLD | Spatial generalized linear mixed models | 7 |
| Cheng 2024 | Cross-sectional | China | 2010–2017 | 131,592 (53,431/78,161) | NA | 68,396 (52.0) | PM _{2.5} , PM ₁₀ , SO ₂ , NO ₂ , O ₃ , CO | MASLD | Logistic regression model | 7 |
| Patterson 2023 | Prospective cohort | US | 2014–2018 | 170 (30/110) | 19.7 ± 1.2 | 56 (45.2) | PM _{2.5} , PM ₁₀ , NO ₂ , O ₃ | NAFLD | Logistic regression model | 7 |
| Han 2023 | Longitudinal cohort | China | 2018–2019 | 6,350 (744/5,786) | NA | 4,145 (63.5) | PM _{2.5} , PM ₁₀ , NO ₂ | MAFLD | Multiple logistic regression models | 7 |
| Matthiessen 2023 | Cross-sectional | Germany | 2000–2003 | 4,065 (1,288/2,777) | 59.6 ± 7.8 | 2,157 (53.1) | PM _{2.5} , PM _{2.5–10} , PM ₁₀ , NO ₂ | NAFLD | Logistic regression model | 8 |
| Zhao 2023 | Prospective cohort | China | June 2011–December 2013 | 15,337 (1,516/13,821) | 47.6 ± 7.9 | 6,914 (45.1) | PM _{2.5} | MAFLD | Cox proportional hazard model | 7 |
| Deng 2023 | Population-based dynamic cohort | China | 2005–2013 | 17,106 (4,640/12,466) | NA | 12,231 (71.5) | PM _{2.5} | NAFLD | Cox proportional hazard model | 8 |
| Li 2022 | Prospective cohort | UK | 2006–2010 | 456,687 (4,978/451,709) | NA | NA | PM _{2.5} , PM _{2.5–10} , PM ₁₀ , NO ₂ | NAFLD | Cox proportional hazard model | 8 |
| VoPham 2022 | Cross-sectional | US | 2001–2011 | 45,433,392 (269,705/45,163,687) | 48.6 ± 28.0 | 26,550,788 (58.4) | PM _{2.5} | NAFLD | Multivariable logistic regression model | 6 |

PM_{2.5}, particulate matter with aerodynamic diameter ≤2.5 μm; PM_{2.5–10}, particulate matter between 2.5 and 10 μm in aerodynamic diameter; PM₁₀, particulate matter with aerodynamic diameter ≤10 μm; NO₂, nitrogen dioxide; O₃, ozone; SO₂, sulfur dioxide; UK, United Kingdom; US, United States; SD: standard deviation; NA, not available.

TABLE 2 Meta-analysis of NAFLD in association with a 10 $\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$, $\text{PM}_{2.5-10}$, PM_{10} , SO_2 , NO_2 , O_3 , and CO.

| Overall analysis | Pooled OR (95% CIs) | <i>P</i> value | No. of studies | Heterogeneity | |
|----------------------|---------------------|----------------|----------------|----------------|-----------------------|
| | | | | <i>P</i> value | <i>I</i> ² |
| $\text{PM}_{2.5}$ | 1.22 (1.16, 1.29) | <0.001 | 12 | <0.001 | 91.4% |
| $\text{PM}_{2.5-10}$ | 1.15 (0.95, 1.40) | 0.150 | 3 | 0.937 | 0.0% |
| PM_{10} | 1.07 (1.01, 1.13) | 0.016 | 7 | <0.001 | 86.9% |
| SO_2 | 1.45 (0.92, 2.28) | 0.113 | 3 | <0.001 | 98.4% |
| NO_2 | 1.10 (1.06, 1.14) | <0.001 | 8 | <0.001 | 92.9% |
| O_3 | 1.01 (0.90, 1.13) | 0.837 | 5 | <0.001 | 98.7% |
| CO | 1.02 (0.99, 1.05) | 0.281 | 3 | <0.001 | 99.4% |



Of these, seven were cohort studies (17, 18, 20, 25, 37, 39, 40) and five were cross-sectional (14–16, 26, 38). Sample sizes ranged from 170 to 45,433,392. Studies focused on various air pollutants: 12 on $\text{PM}_{2.5}$, three on $\text{PM}_{2.5-10}$, seven on PM_{10} , three on SO_2 , eight on NO_2 , five on O_3 , and three on CO. Geographically, seven studies were conducted in Asia, three in Europe, and two in North America. Confounders adjusted for in the studies varied slightly. Quality assessment revealed eight studies rated as high quality and four as medium quality (Supplementary Tables S4, S5). Detailed study characteristics are provided in Table 1.

3.3 Exposure of air pollution and NAFLD

Table 2 presents the ORs linking air pollutants to NAFLD, with forest plots for analyses involving over five studies shown in Figures 2–4. A 10 $\mu\text{g}/\text{m}^3$ rise in $\text{PM}_{2.5}$, PM_{10} , and NO_2 levels was notably tied to elevated NAFLD risk ($\text{PM}_{2.5}$ OR = 1.22, 95% CI: 1.16–1.29; PM_{10} OR = 1.07, 95% CI: 1.01–1.13; NO_2 OR = 1.10, 95% CI: 1.06–1.14; Figures 2–4). However, significant heterogeneity was observed across studies ($\text{PM}_{2.5}$ I^2 = 91.4%, P < 0.001; PM_{10} I^2 = 86.9%, P < 0.001; NO_2 I^2 = 92.9%, P < 0.001). For $\text{PM}_{2.5-10}$ and SO_2 , a 10 $\mu\text{g}/\text{m}^3$ increase suggested

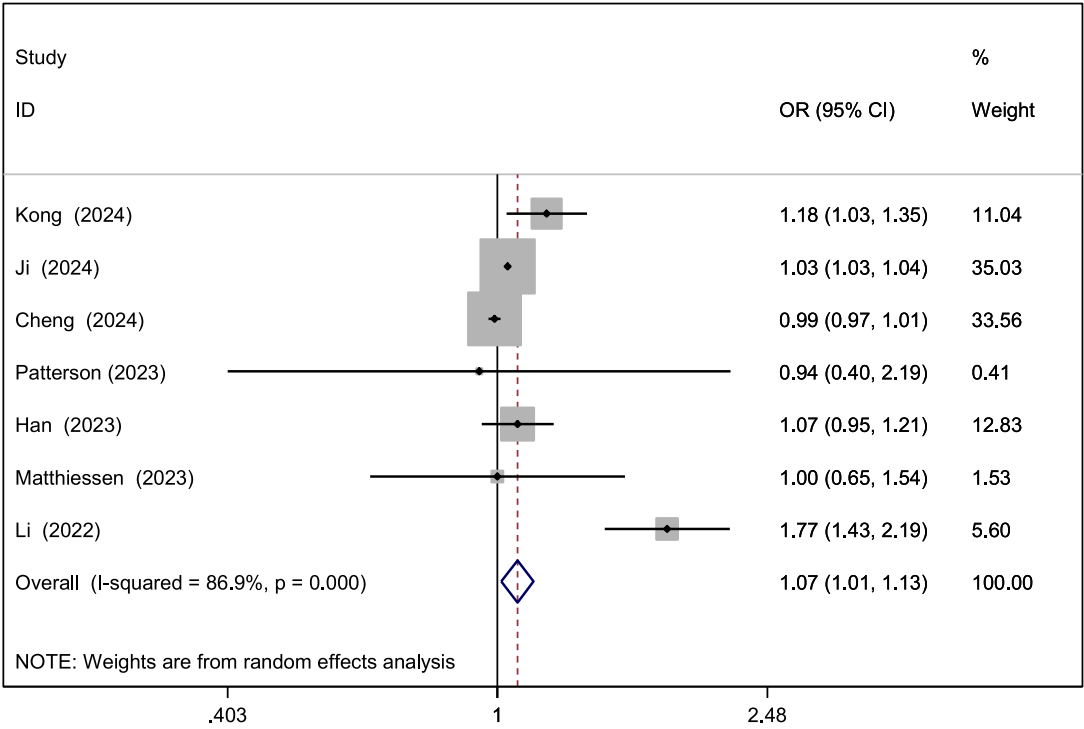


FIGURE 3 Forest plot of the association between PM₁₀ exposure (per 10 µg/m³ increment) and risk of NAFLD.

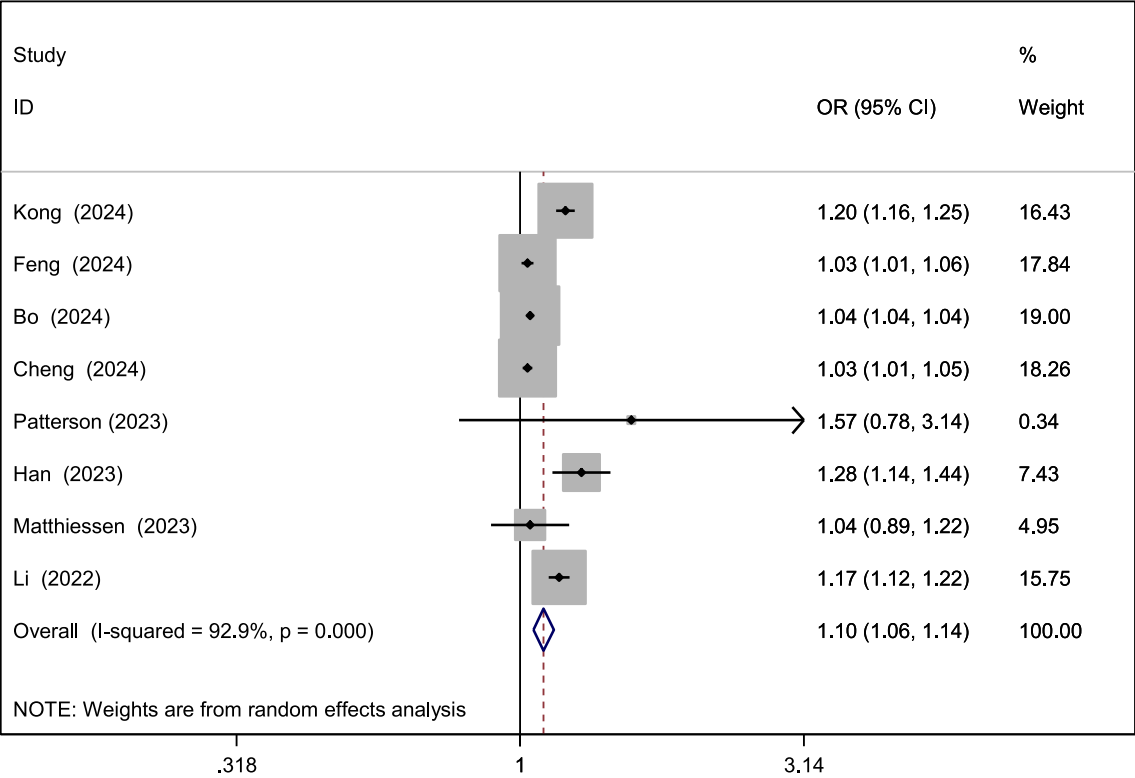


FIGURE 4 Forest plot of the association between NO₂ exposure (per 10 µg/m³ increment) and risk of NAFLD.

TABLE 3 Association between exposure to PM_{2.5} and risk of NAFLD by subgroup analysis.

| Subgroups | Categories | No. of studies | OR, 95%CI | I ² (%) | P values within subgroups |
|-------------------|----------------------|----------------|-------------------|--------------------|---------------------------|
| Study design | Cross-sectional | 5 | 1.15 (1.13, 1.17) | 48.5 | <0.001 |
| | Cohort | 7 | 1.45 (1.21, 1.74) | 95.0 | <0.001 |
| Sample size | <100,000 | 6 | 1.25 (1.04, 1.49) | 93.5 | 0.015 |
| | >100,000 | 6 | 1.20 (1.15, 1.27) | 90.0 | <0.001 |
| Female, % | <50% | 3 | 1.15 (0.89, 1.49) | 75.3 | 0.275 |
| | >50% | 9 | 1.25 (1.18, 1.31) | 90.9 | <0.001 |
| Economic level | Developed countries | 4 | 1.72 (1.05, 2.82) | 87.2 | 0.031 |
| | Developing countries | 8 | 1.18 (1.12, 1.24) | 92.2 | <0.001 |
| Current smoker, % | <25% | 7 | 1.22 (1.15, 1.29) | 86.8 | <0.001 |
| | >25% | 2 | 1.12 (0.90, 1.39) | 81.0 | 0.310 |
| Geographic area | Asia | 7 | 1.16 (1.11, 1.22) | 92.1 | <0.001 |
| | Europe | 3 | 2.15 (1.78, 2.59) | 0.0 | <0.001 |
| College or above | <50% | 3 | 1.20 (1.08, 1.34) | 51.4 | 0.001 |
| | >50% | 5 | 1.16 (1.08, 1.24) | 94.6 | <0.001 |
| Outcome | NAFLD | 7 | 1.42 (1.25, 1.61) | 93.0 | <0.001 |
| | MAFLD | 4 | 1.14 (1.04, 1.24) | 88.8 | 0.006 |

TABLE 4 Association between exposure to PM₁₀ and risk of NAFLD by subgroup analysis.

| Subgroups | Categories | No. of studies | OR, 95%CI | I ² (%) | P values within subgroups |
|-----------------|----------------------|----------------|-------------------|--------------------|---------------------------|
| Study design | Cross-sectional | 3 | 1.01 (0.97, 1.06) | 87.7 | 0.542 |
| | Cohort | 4 | 1.26 (1.00, 1.60) | 82.2 | 0.053 |
| Sample size | <100,000 | 3 | 1.06 (0.95, 1.19) | 0.0 | 0.305 |
| | >100,000 | 4 | 1.07 (1.01, 1.14) | 93.4 | 0.021 |
| Economic level | Developed countries | 3 | 1.16 (1.02, 1.31) | 0.0 | 0.025 |
| | Developing countries | 4 | 1.06 (1.00, 1.12) | 92.8 | 0.058 |
| Geographic area | Asia | 3 | 1.02 (0.98, 1.06) | 88.0 | 0.380 |
| | Europe | 3 | 1.31 (0.95, 1.81) | 82.8 | 0.097 |
| Outcome | NAFLD | 4 | 1.27 (0.95, 1.71) | 75.4 | 0.107 |
| | MAFLD | 2 | 1.03 (1.03, 1.04) | 0.0 | <0.001 |

increased NAFLD likelihood, though these findings did not achieve statistical significance (PM_{2.5–10} OR = 1.15, 95% CI: 0.95–1.40, $P = 0.15$; SO₂ OR = 1.45, 95% CI: 0.92–2.28, $P = 0.113$), with SO₂ showing marked heterogeneity ($I^2 = 98.4\%$, $P < 0.001$). No notable connection emerged between O₃ or CO and NAFLD.

3.4 Subgroup analysis

Given the scarcity of studies, subgroup analyses were not feasible for PM_{2.5–10}, SO₂, O₃, or CO. Subgroup analyses for PM_{2.5}, PM₁₀, and NO₂ are presented in [Tables 3–5](#). In most subgroups, exposure to these pollutants remained positively associated with NAFLD, although heterogeneity remained at moderate to high levels. Stronger associations were observed in studies from developed countries, Europe, and cohort studies compared to

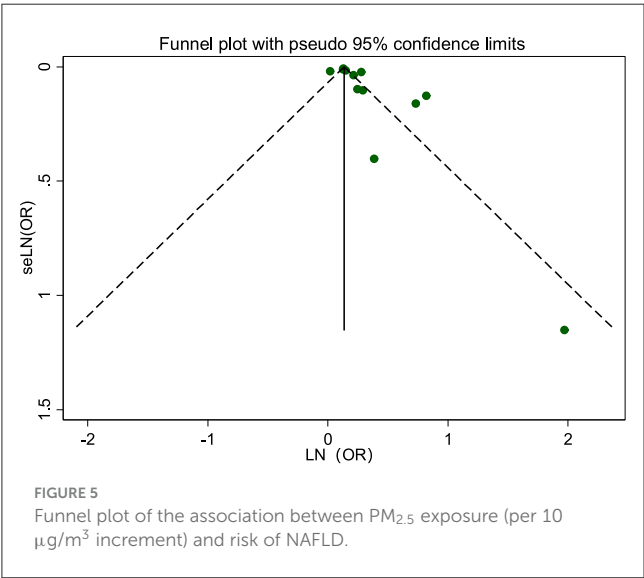
those from developing countries, Asia, and cross-sectional studies. Specifically, a significant and robust association was found for PM_{2.5} in Europe (OR = 2.15, 95% CI: 1.78–2.59, $P < 0.001$, $I^2 = 0\%$). Stratified analysis of PM₁₀ in developed countries, with sample sizes <100,000, showed $I^2 = 0\%$, as did stratified analysis of NO₂ in cross-sectional studies.

3.5 Sensitivity analysis and publication bias

Sensitivity analysis, conducted by excluding one study at a time, indicated that the results for most air pollutants were stable ([Supplementary Figure S1](#)). Publication bias tests were not conducted for exposures with fewer than 10 studies. Visual inspection of the funnel plot for PM_{2.5} indicated no significant

TABLE 5 Association between exposure to NO₂ and risk of NAFLD by subgroup analysis.

| Subgroups | Categories | No. of studies | OR,95%CI | I ² (%) | P values within subgroups |
|-----------------|----------------------|----------------|-------------------|--------------------|---------------------------|
| Study design | Cross-sectional | 3 | 1.04 (1.03, 1.04) | 0.0 | <0.001 |
| | Cohort | 5 | 1.16 (1.06, 1.28) | 93.8 | 0.002 |
| Sample size | <100,000 | 4 | 1.12 (0.97, 1.29) | 78.7 | 0.110 |
| | >100,000 | 4 | 1.01 (1.04, 1.17) | 96.5 | <0.001 |
| Economic level | Developed countries | 3 | 1.16 (1.03, 1.30) | 44.3 | 0.016 |
| | Developing countries | 5 | 1.07 (1.04, 1.11) | 90.6 | <0.001 |
| Geographic area | Asia | 4 | 1.04 (1.02, 1.07) | 78.0 | <0.001 |
| | Europe | 3 | 1.18 (1.13, 1.23) | 40.8 | <0.001 |
| Outcome | NAFLD | 5 | 1.12 (1.02, 1.24) | 95.3 | 0.015 |
| | MAFLD | 2 | 1.14 (0.92, 1.41) | 92.2 | 0.229 |



publication bias (Figure 5). Additionally, Egger’s regression test ($P = 0.069$) supported the absence of publication bias.

4 Discussion

Based on 12 studies involving 49,549,903 participants, the results indicate that exposure to air pollutants, including PM_{2.5}, PM_{2.5–10}, PM₁₀, SO₂, NO₂, O₃, and CO, correlates with an increased risk of NAFLD. However, considerable heterogeneity was observed across studies, with the associations for PM_{2.5–10} and SO₂ not reaching statistical significance. Subgroup and sensitivity analyses supported these overall findings, with consistent associations observed across most subgroups.

A prior meta-analysis by He et al. reported that PM_{2.5}, NO_x, PM₁₀, and PM_{2.5–10} elevate NAFLD risk, while suggesting a protective role for O₃ (24). That review, however, was limited to a subset of earlier studies on air pollution and MAFLD risk, introducing potential selection bias. In addition, the meta-analysis did not normalize effect sizes to the same increments across studies.

In contrast, this work involved an exhaustive review of research linking air pollution to NAFLD, MAFLD, or MASLD, included several recent, large-sample, high-quality studies, and standardized effect sizes to 10 μg/m³ increments. Therefore, this research has more advantages in timeliness and comparability. In addition, instead of including the cross-sectional study by Guo et al. (41), the same sample, the latest cohort study by Han et al. (25), was chosen, which contributes to the reliability of causal inference. Notably, unlike the results from He et al., no significant association was found between O₃ and NAFLD. Stronger associations were observed between PM_{2.5}, PM₁₀, NO₂, and NAFLD in developed countries, particularly in Europe, and in cohort studies.

Subgroup analysis indicated a stronger association between PM_{2.5}, PM₁₀, and NO₂ with NAFLD in cohort studies, which offer greater reliability for inferring correlation compared to cross-sectional studies. Additionally, a more pronounced and statistically significant association was found for PM_{2.5} in women over 50%. This may be linked to sex-specific differences in susceptibility to air pollution, as previous studies have suggested women may have a higher susceptibility to respiratory and cardiovascular issues related to PM_{2.5} exposure (42, 43). Furthermore, estrogen has been shown to regulate liver lipid metabolism, potentially offering protective effects in women (44–47). The decline in estrogen levels post-menopause may increase susceptibility to NAFLD in women exposed to air pollution, contributing to the observed gender differences. Gender differences in NAFLD risk may, therefore contribute to heterogeneity in the results. Regional variations were also evident, with stronger associations found in studies from developed countries, particularly Europe, for PM_{2.5} and NO₂, possibly reflecting economic and environmental influences—though limited study numbers constrain broader conclusions.

In stratified analysis comparing NAFLD and MAFLD outcomes, no significant differences were observed regarding their associations with PM_{2.5}, PM₁₀, and NO₂. Notably, a study by the European LITMUS “Liver Investigation: Testing Marker Utility in Steatohepatitis” Consortium found that 98% of NAFLD cases met the MASLD criteria (29), and data from Song et al. indicated that most NAFLD patients met the metabolic criteria for MAFLD and MASLD (48). This suggests that findings for NAFLD are applicable under both the MAFLD and MASLD definitions.

The mechanisms by which air pollution contributes to NAFLD remain incompletely understood, though animal studies offer valuable insights. Chronic exposure to PM_{2.5} has been demonstrated to cause liver inflammation, oxidative stress, and insulin resistance, which are pivotal factors in the pathogenesis of NAFLD (49–52). Experimental studies also suggest that PM_{2.5} disrupts liver glycogen storage, causes glucose intolerance, and contributes to non-alcoholic steatohepatitis (53, 54). Furthermore, PM_{2.5} exposure activates hepatic stellate cells, promoting liver fibrosis (55, 56). NO₂ and O₃ exposure may also impair lipid metabolism and trigger insulin resistance, potentially exacerbating NAFLD risk (57–59). However, this analysis did not show a significant correlation between O₃ and NAFLD, possibly due to differences in species, exposure levels, or study design. The effects of SO₂ and CO on NAFLD remain unclear and warrant further research.

Given the global health burden of air pollution and rising NAFLD prevalence, our findings highlight the urgent need for improved air quality, which may help prevent NAFLD and other related non-communicable diseases, like cardiovascular and respiratory conditions (60, 61).

This study has several limitations. First, methodological and clinical heterogeneity was observed due to variations in confounder adjustment and study designs. Although subgroup analyses were conducted to explore potential sources of heterogeneity, the limited number of studies restricted a comprehensive identification of contributing factors. Second, the analysis focused on individual pollutants, despite the potential for combined effects of air pollutants on health outcomes. The complexity of joint effects and the scarcity of relevant studies precluded their inclusion in this meta-analysis. Third, the included studies did not consistently stratify NAFLD by severity (e.g., simple steatosis vs. non-alcoholic steatohepatitis or fibrosis), limiting the ability to assess the impact of air pollution on non-reversible forms of the disease. Future studies stratifying outcomes by NAFLD severity could reduce heterogeneity and provide clearer insights into the role of air pollution. Finally, given the heterogeneity and limited number of studies for certain pollutants, caution is warranted when interpreting the findings. Larger-scale cohort studies are needed to validate these results and further elucidate the relationship between air pollution and NAFLD risk.

5 Conclusion

This meta-analysis provides evidence that exposure to air pollutants, particularly PM_{2.5}, PM₁₀, and NO₂, is associated with an increased risk of NAFLD. These findings underscore the importance of improving air quality to mitigate the burden of NAFLD and related diseases. However, it remains to be determined whether air pollutants directly target the liver or contribute to NAFLD by aggravating obesity and insulin resistance in air-polluted environments. Future research should focus on large-scale, longitudinal cohort studies that stratify NAFLD by severity, evaluate the combined effects of multiple air pollutants, and explore underlying biological mechanisms.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

XZ: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. XY: Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing. LH: Data curation, Methodology, Software, Writing – original draft. LT: Data curation, Investigation, Writing – original draft. XL: Data curation, Writing – original draft. YC: Formal analysis, Writing – original draft. SR: Conceptualization, Data curation, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fpubh.2025.1606959/full#supplementary-material>

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