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Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies

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Introduction: Air pollution is a significant global public health concern. However, there is a lack of updated and comprehensive evidence regarding the association between exposure to ambient air pollution and adverse birth outcomes (preterm birth, low birth weight, and stillbirth). Furthermore, the existing evidence is highly inconsistent. Therefore, this study aims to estimate the overall association between ambient air pollution and adverse birth outcomes.

Methods: In this study, initially a total of 79,356 articles were identified. Finally, a total of 49 articles were included. We conducted compressive literature searches using various databases, including PubMed, Scientific Direct, *HINARI*, and Google Scholar. Data extraction was performed using Microsoft Excel, and the data were exported to STATA 17 software for analysis. We used the Joanna Briggs Institute's quality appraisal tool to ensure the quality of the included studies. A random effects model was employed to estimate the pooled prevalence. Publication bias was assessed using funnel plots and Egger's regression test.

Results: In this study, the pooled prevalence of at least one adverse birth outcome was 7.69% (95% CI: 6.70–8.69), with high heterogeneity ($I^2 = 100\%$, *p-value* < 0.001). In this meta-analysis, high pooled prevalence was found in preterm birth (6.36%), followed by low birth weights (5.07%) and stillbirth (0.61%). Exposure to $PM_{2.5}$ (≤10 μg/m^3) throughout the entire pregnancy, $PM_{2.5}$ (≤10 μg/m^3) in the first trimester, PM_{10} (>10 μg/m^3) during the entire pregnancy, and O_3 (≤10 μg/m^3) during the entire pregnancy increased the risk of preterm birth by 4% (OR = 1.04, 95% CI: 1.03–1.05), 5% (OR = 1.05, 95% CI: 1.01–1.09), 49% (OR = 1.49, 95% CI: 1.41–1.56), and 5% (OR = 1.05, 95% CI: 1.04–1.07), respectively. For low birth weight, exposure to $PM_{2.5}$ (≤10 μg/m^3) and $PM_{2.5}$ (>10 μg/m^3) throughout the entire pregnancy was associated with an increased risk of 13% (OR = 1.13, 95% CI: 1.05–1.21) and 28% (OR = 1.28, 95% CI: 1.23–1.33), respectively.

Conclusion: This study highlighted a significant association between ambient air pollution and adverse birth outcomes. Therefore, it is crucial to implement a compressive public health intervention.

Systematic review registration: The review protocol was registered with the record ID of CRD42024578630.

KEYWORDS

ambient air pollution, outdoor air pollution, adverse birth outcomes, preterm birth, low birth weights, stillbirth

1 Introduction

Air pollution is a major global public health concern, with growing evidence linking exposure during pregnancy to a range of adverse birth outcomes (1, 2). Exposure to ambient air pollutants such as particulate matter (PM), ozone (O_3), nitrogen dioxides (NO_2), and sulfur dioxide (SO_2) has been linked to a range of adverse birth outcomes, including preterm birth, stillbirth, low birth weight, and congenital anomalies (1, 3, 4). There is no evidence for the biological mechanisms underlying these associations, but they are thought to involve disruption of placental function, inflammation, and oxidative stress (5, 6). The World Health Organization (WHO) estimates that ambient air pollution caused 4.2 million premature deaths globally in 2019, highlighting significant implications for maternal and child health (7).

The effects of ambient air pollution on pregnancy can be attributed to both direct biological mechanisms and indirect socio-environmental factors. For instance, exposure to high levels of PM during critical periods of fetal development can disrupt placental function and fetal growth (8). Socioeconomic disparities often exacerbate the risks associated with air pollution, as marginalized communities frequently reside in areas with higher pollution levels and limited access to healthcare resources (9). Furthermore, the adverse effects of ambient air pollution on fetal development may have long-term consequences, as preterm birth and low birth weight are risk factors for various health problems later in life, including neurological disorders, cardiovascular disease, and diabetes (10).

A review with meta-analysis has revealed that prenatal exposure to ambient $PM_{2.5}$ is associated with an increased risk of stillbirth (11, 12) and decreased birth weights (13). According to Lamichhane et al. (3) and Sun et al. (13), a 10 $\mu g/m^3$ increase in $PM_{2.5}$ exposure during pregnancy was associated with a 15 and 13% higher risk of preterm birth, respectively. Zhu et al. (4) reported that a 10 $\mu g/m^3$ increase in $PM_{2.5}$ exposure during pregnancy was associated with a 5% increased risk of low birth weight and a 10% increased risk of preterm birth. Similarly, Stieb et al. (1) concluded that there is consistent evidence linking air pollution exposure to preterm birth and low birth weight. Maternal exposure to $PM_{2.5}$ (per 10 $\mu g/m^3$ increased) was associated with a 15% increased risk of stillbirth in the entire pregnancy and a 9% increased risk of stillbirth in the third trimester (12). Exposure to major air pollutants throughout pregnancy may increase the risk of low birth weight (14). Several other studies have also indicated possible associations between ambient air pollution and adverse birth outcomes (15–20).

Although several reviews and meta-analyses have explored the association between specific ambient air pollutants and adverse outcomes, their findings have been inconsistent and lack comprehensiveness. Additionally, the conflicting results from previous primary studies underscore the need for a more thorough and integrated analysis of the available evidence. The purpose of this research is to thoroughly estimate the pooled association between ambient air pollutants and adverse birth outcomes, including preterm birth, low birth weight, and stillbirth, while also identifying predictive factors. Up-to-date and comprehensive evidence is crucial for informed decision-making, the development of effective strategies, and support for policymakers and other stakeholders.

2 Methods

This study followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (21) (Figure 1). The review protocol for this study was registered in the International Prospective Register of Systematic Reviews (PROSPERO) with the record ID of CRD42024578630.

2.1 Eligibility criteria

2.1.1 Inclusion criteria

The eligible for this review must meet the following PECOS (Participants/Populations, Exposures, Comparators, Outcomes and Study designs) criteria.

- Participants or populations: the participants are pregnant women at any stage of pregnancy up to birth.
- Exposures: prenatal exposure to ambient air pollution.
- Comparators: pregnant women with lower exposure levels, with or without adverse birth outcomes, as compared to those exposed to higher exposure with adverse birth outcomes.
- Outcomes: the adverse birth outcomes of interest include preterm birth, low birth weight, and stillbirth (reported prevalence [%] and measure of association in adjusted odds ratio [AOR]).
- **Study design**: all observational studies (cross-sectional, cohort, and case control).

Moreover, articles written in English, both published and unpublished, and studies reported from January 1, 2015 to August 30, 2024 were also the inclusion criteria.

2.1.2 Exclusion criteria

Studies that investigated other pregnancy related outcomes besides the specified adverse birth outcomes (preterm birth, low birth weight, and stillbirth). Descriptive epidemiological studies (e.g., descriptive cross-sectional, case reports, and case series), studies without a full report after three personal email contacts with the primary and corresponding authors, conference abstracts, letters to the editors, qualitative studies, systematic reviews, short communications, and commentaries were not considered.

2.1.3 Operational definitions

Low birth weight: "a birth weight of <2,500 g" (22).

Stillbirth: "A baby who dies after 28 weeks of pregnancy, but before or during birth" (23).

Preterm birth: "babies born alive before 37 weeks of pregnancy" (24).

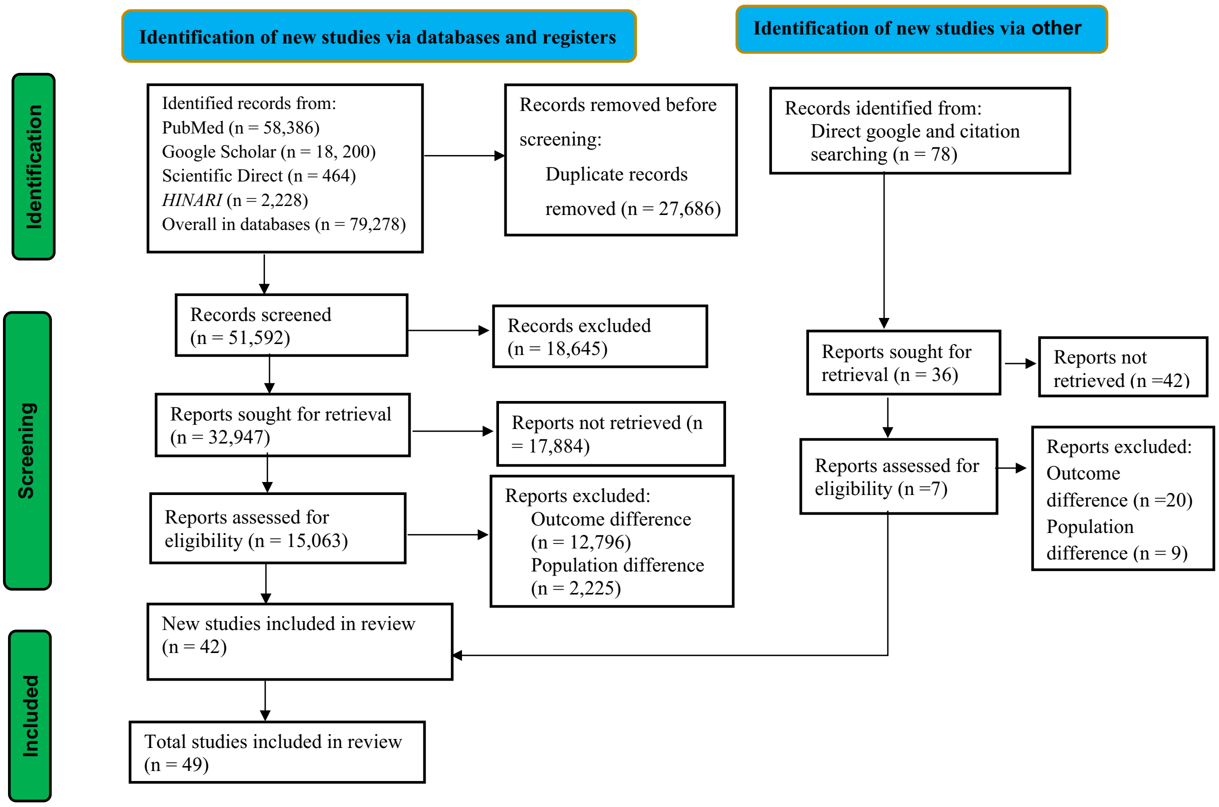

FIGURE 1
PRISMA flow diagram of association between ambient air pollution and adverse birth outcomes, 2024.

In this study, we categorized the reported concentrations of pollutants into two main groups: ≤10 μg/m^3 and >10 μg/m^3. This categorization was necessary due to the variability in concentration levels reported across different studies.

2.2 Information sources

Both published and grey literature were sources of information for this study. A systematic literature search was undertaken using the following databases: PubMed, Scientific Direct, Google Scholar, and HINAR. The search was conducted for studies published from January 1, 2015, to August 30, 2024. In addition to the electronic database search, further articles were obtained by searching for grey literature through direct Google searches and by reviewing the references of the eligible studies.

2.3 Search strategies

Comprehensive search terms were used to identify relevant studies. These include MeSH terms and key words such as ambient air pollution, outdoor air pollution, adverse birth outcomes, preterm birth, low birth weights, and stillbirth. These search terms were used within PubMed as a template database to finalize an advanced search strategy utilizing the Boolean operators "AND" and "OR." The search strategy was modified as appropriate for other databases and other sources.

2.4 Study screening and selection

All stages of reviewing articles were conducted independently by the two researchers (BD and AKG), with conflict managed by evidence-based discussion with the involvement of the third researcher (GB). From the search, the titles of all identified citations with abstracts were uploaded into Zotero reference manager, and duplicates were removed. Then it was followed by screening the titles and abstracts according to the eligibility criteria. The potential full text of eligible studies was retrieved. All studies that do not meet the inclusion criteria were excluded with reasons and presented in the PRISMA flow chart (21).

2.5 Quality (risk of bias) assessment of the selected studies

The quality of selected eligible studies was evaluated using the Joana Briggs Institute (JBI) critical appraisal checklist for cohort and case–control studies (25). The quality assessment was conducted independently by two reviewers (BD and ABK). In case of any discrepancies encountered during the quality assessment, they were managed through evidence-based discussions with the involvement of a third researcher (GB). Only studies that scored more than 50% on the quality assessment were considered for inclusion in this review (25, 26), as depicted in Table 1.

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TABLE 1 Summary of the included studies on the association between ambient air pollution and adverse birth outcomes, 2024.

References	Country/ region	Type of study	Exposure assessment	Pollutants	Outcome	Statistical Methods	Study period	Sample size	Cases	Prevalence (%)	Quality score (%)
Yang et al. (42)	China	Cohort	Daily mean concentrations of air pollutants	$PM_{2.5}$, PM_{10}, SO_2, NO_2, O3, CO	SB	Logistic regressions	2011–2013	95,354	859	0.9	87.5
Quraishi et al. (43)	United States	Cohort	Regulatory and research monitors	$PM_{2.5}$	PTB, LBW	Linear and Poisson regression	2006–2012	2,099	323	15.4	87.5
Chen et al. (44)	China	Cohort	Tracking Air Pollution	O_3	PTB, LBW	Cox proportional-hazards regression model	2014–2016	56,905	4,835	8.5	87.5
Chen et al. (45)	Australia	Birth records	Daily air quality and meteorological data	$PM_{2.5}$, SO_2, NO_2, O_3	PTB, LBW	Cox-proportional hazards	2003–2013	173,720	24,702	14.2	87.5
Qian et al. (46)	China	Cohort	Daily measurement	$PM_{2.5}$, CO, PM_{10}, SO_2, O_3	PTB	Logistic regressions	2011–2013	95,911	4,308	4.5	75
Zhou et al. (47)	China	Cohort	National urban air quality monitoring	$PM_{2.5}$, PM_{10}, O_3, CO, NO_2, SO_2	LBW	Generalized additive model	2015–2020	572,106	24,497	4.28	75
Chen et al. (48)	China	Birth records	Daily measurement	PM_{10}, $PM_{2.5}$, NO_2, SO_2	PTB	Cox proportional hazards regression models	2015–2017	13,111	614	4.7	87.5
Zhou et al. (49)	China	Cohort	Monitoring stations	$PM_{2.5}$, PM_{10}, SO_2, CO, NO_2, O_3	PTB	Generalized additive model	2015–2020	572,116	33,669	5.88	87.5
Melody et al. (50)	Australia	Cohort	Annual estimation	$PM_{2.5}$, NO_2	PTB, LBW	Linear and log-binomial regression models	2012–2015	285,594	23, 187	8.1	75
Li et al. (51)	China	Birth records	Daily measurement	$PM_{2.5}$	PTB	Multilevel logistic models	2014	429,865	12,810	2.98	62.5
Zhao et al. (52)	China	Case–control	Monitoring stations	PM_{10}	PTB	Logistic regression modeling	2010–2012	8,969	677	7.5	75
Padula et al. (53)	United States	Birth records	Daily measurement	CO, NO_2, PM_{10}, $PM_{2.5}$	PTB	Logistic regression models	2000–2006	252,205	28,788	11.4	62.5
Tapia et al. (17)	Peru	Birth records	Ground measurements, satellite data, and a chemical transport model.	$PM_{2.5}$	PTB, LBW	Linear and logistic regression model	2012–2016	123,034	10, 971	8.9	62.5
Liu et al. (54)	China	time-series	Ensemble-based models	$PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, CO	PTB	General Additive model extend Poisson regression	2014–2016	37,389	5,428	14.5	87.5
Lavigne et al. (55)	Canada	Cohort	6 Digit-postal code captured	$PM_{2.5}$, NO_2, O_3	PTB, LBW	Multivariable mixed-effect logistic regression	2005–2012	818,400	90,884	11.1	87.5
Huang et al. (56)	China	Birth records	Air monitoring data	PM_{10}, NO_2	PTB	Multi-pollutant models	2006–2010	50,874	3,203	6.3	87.5
Liu et al. (57)	China	Case–control	National environmental monitoring	$PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, O_3	PTB, LBW	Logistic regression models	2014–2015	86,139	1,784	2.1	87.5

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TABLE 1 (Continued)

References	Country/region	Type of study	Exposure assessment	Pollutants	Outcome	Statistical Methods	Study period	Sample size	Cases	Prevalence (%)	Quality score (%)
Yorifuji et al. (58)	Japan	Cohort	Monitoring stations	SO_2, NO_2	LBW	multilevel logistic regression	200–2001	44,109	2,219	5	87.5
Stieb et al. (59)	Canada	Birth records	Ground-based monitoring data, estimates from remote-sensing, land use variables and, deterministic gradients relative to road traffic	PM2.5, NO2	PTB, LBW	Generalized estimating equations	1999–2008	3,104,090	242,150	7.8	75
Green et al. (60)	United States	Cohort	Air resources board	$PM_{2.5}$, SO_2, NO_2, CO, O_3	SB	Logistic regression models	1999–2009	5,788,117	26,355	0.5	75
Mendola et al. (29)	United States	Cohort	Community multiscale air quality	O_3	SB	Poisson regression models	2002–2008	223,375	992	0.44	87.5
Ji et al. (61)	China	Case–control	Land use regression	NO_2	PTB	Logistic regression	2014–2015	25,493	738	2.9	87.5
Guo et al. (62)	China	Cohort	National environmental monitoring	$PM_{2.5}$	PTB	Cox proportional hazards regression	2014	426,246	35,261	8.3	75
Kingsley et al. (63)	United States	Birth records	Hybrid of land-use regression and satellite remote sensing	$PM_{2.5}$	PTB	Linear and logistic regression models	2001–2012	61, 640	5,007	8.1	87.5
Ho et al. (64)	Vietnam	Time-series	Fixed monitoring stations	$PM_{2.5}$	PTB, LBW	Linear and logistic regression model	2016–2019	163,868	18, 219	11.1	87.5
Wang et al. (65)	China	Cohort	Real-time measurement	PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, O_3	PTB	Generalized additive model	2018–2019	424	17	4	87.5
Xiao et al. (66)	China	Birth records	Satellite-derived estimates or central-site measurements	$PM_{2.5}$	PTB, LBW	Linear and logistic Regressions	2011–2014	132,783	7,117	5.36	87.5
Zang et al. (67)	China	Cohort	Daily measurement	$PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, O_3	SB	Logistic regression	2015–2017	59,868	587	0.98	75
Arroyo et al. (68)	Spain	Time-series	Daily measurement	$PM_{2.5}$, NO_2, O_3	PTB, LBW	Poisson regression models	2001–2009	298,705	64,169	21.5	62.5
DeFranco et al. (69)	United States	Cohort	Monitoring stations	$PM_{2.5}$	SB	Generalized estimating equation	2005–2010	349,188	1,848	0.53	87.5
Coker et al. (70)	United States	Cohort	Land use regression	$PM_{2.5}$, NO_2, NO	LBW	Bayesian profile regression	2000–2006	804,726	16,694	2.07	62.5
Yuan et al. (71)	China	Cohort	Satellite-based estimates and ground-level measurements	$PM_{2.5}$	PTB, LBW	multiple linear models	2013–2016	3,692	274	7.4	87.5

(Continued)

TABLE 1 (Continued)

References	Country/ region	Type of study	Exposure assessment	Pollutants	Outcome	Statistical Methods	Study period	Sample size	Cases	Prevalence (%)	Quality score (%)
Li et al. (72)	China	Time-series	Weekly air quality data	$PM_{2.5}$, PM_{10}, O_3, SO_2, $NO_{2,}$ CO	PTB	Distributed lag non-linear model	2016–2019	120,446	5,408	4.5	87.5
Rammah et al. (73)	United States	Cohort	Daily measurement	O_3	SB	Multipollutant models and measure modification	2008–2013	358,366	1,599	0.45	87.5
Nahian et al. (28)	Bangladesh	Birth records	Air quality index	$PM_{2.5}$, PM_{10}, O_3, SO_2, NO_2	PTB, LBW	Logistic regression model	2014–2017	3,206	1,287	40.1	87.5
Mitku et al. (74)	South Africa	Cohort	Land use regression	$PM_{2.5}$, SO_2	PTB, LBW	Generalized Structure Equation	2013–2017	996	206	20.7	62.5
Li et al. (75)	China	Cohort	Satellite remote sensing, meteorological and land use information	$PM_{2.5}$, PM_{10}	PTB	Cox proportional hazard regression	2013–2014	1,240,978	100,433	8.1	87.5
Bachwenkizi et al. (76)	Africa	Cross-sectional	Global exposure assessment	$PM_{2.5}$, O_3	PTB, LBW	Multivariable logistic regression	2005–2015	131,594	17,591	13.4	87.5
Chu et al. (77)	China	Cohort	Satellite remote sensing	$PM_{2.5}$	PTB	Cox proportional hazard models	2009–2011	5,976	443	7.4	87.5
Han et al. (78)	China	Cohort	Inverse distance weighting	PM_{10}, O_3	PTB	Logistic and linear regression models	2014–2016	6,693	638	9.53	87.5
Zhang et al. (79)	China	Birth records	Daily measurement	O3	PTB, LBW	Cox proportional hazard models	2016–2019	34,122	2,829	8.3	75
Kim et al. (80)	Korea	Birth records	Daily measurement	PM_{10}	PTB, LBW	Linear and logistic regression	2010–2013	1,742,183	148,086	8.5	62.5
Liang et al. (81)	China	Cohort	Air monitoring stations	$PM_{2.5}$	PTB, LBW	Cox proportional hazards regressions	2014–2017	1,455,026	121, 646	8.4	62.5
Chen et al. (82)	China	Cohort	Daily measurement	$PM_{2.5}$, PM_{10}, SO_2, CO, O_3, NO_2	PTB, LBW	Cox proportional hazards regression	2014–2016	10,960	291	2.7	87.5
Johnson et al. (83)	United States	Birth records	Air survey and regulatory monitors	$PM_{2.5}$, NO_2	PTB	Logistic mixed models	2008–2010	132,654	10, 271	7.7	87.5
Siddika et al. (84)	Finland	Cohort	Regional-to-city-scale dispersion modelling and land-use regression	$PM_{2.5}$, PM_{10}, NO_2	PTB	Dispersion modelling and land-use regression	1984–1990	2,568	195	7.6	75
Sun et al. (85)	China	Cohort	Real-time measurement	$PM_{2.5}$, PM_{10}, O_3, SO_2, NO_2	PTB	logistic regressions model	2013–2017	6,275	372	5.9	75
Hao et al. (86)	United States	Cohort	Ensemble-based models	NO_2, $PM_{2.5}$, O_3	PTB	Logistic regression model	2000–2015	596,926	41,936	7.03	62.5
Fang et al. (87)	China	Longitudinal population study	Daily measurement	$PM_{2.5}$	PTB, LBW	Generalized additive distributed lag models	2014–2016	10,738	303	2.8	75

NB: PTB, Preterm birth; LBW, Low birth weight; SB, Stillbirth; –, not reported.

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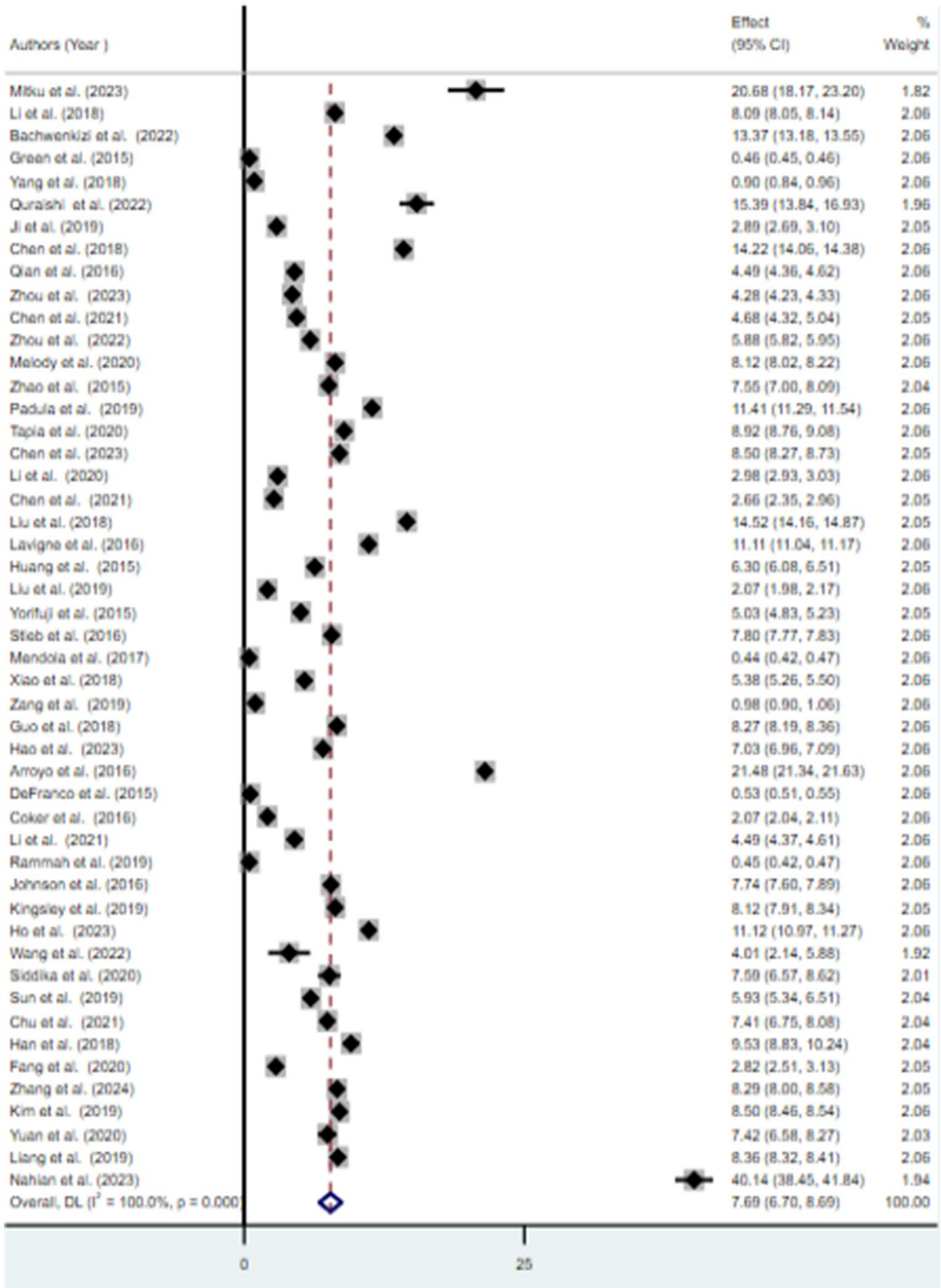

FIGURE 2
Forest plot of the overall prevalence for at least one adverse birth outcome, 2024.

2.6 Data extraction and management

Data extraction was conducted by two authors (BD and AKG) using a data extraction tool. Any disagreements between the two data extractors were resolved through consensus or with the involvement of a third author (GB). The following information was extracted from the selected studies: author information, study setting, study country, type of study, pollutants, outcomes, statistical methods, study periods, sample size, cases, prevalence, and quality scores. The extracted data was organized in a table format (Table 1).

2.7 Statistical methods and data analysis

The extracted data from Microsoft Excel was transported to STATA version 17 for analysis. The Index of heterogeneity (I^2 statistics) was used to assess variations among the included studies, where values of 25–50%, 50–75%, and >75% indicated low, moderate, and high heterogeneity, respectively (27). The metaprop command in STATA was used to estimate the pooled prevalence. Subgroup analysis were conducted to explore potential variations in the pooled prevalence based on study countries and the nature of the outcomes. Sensitivity

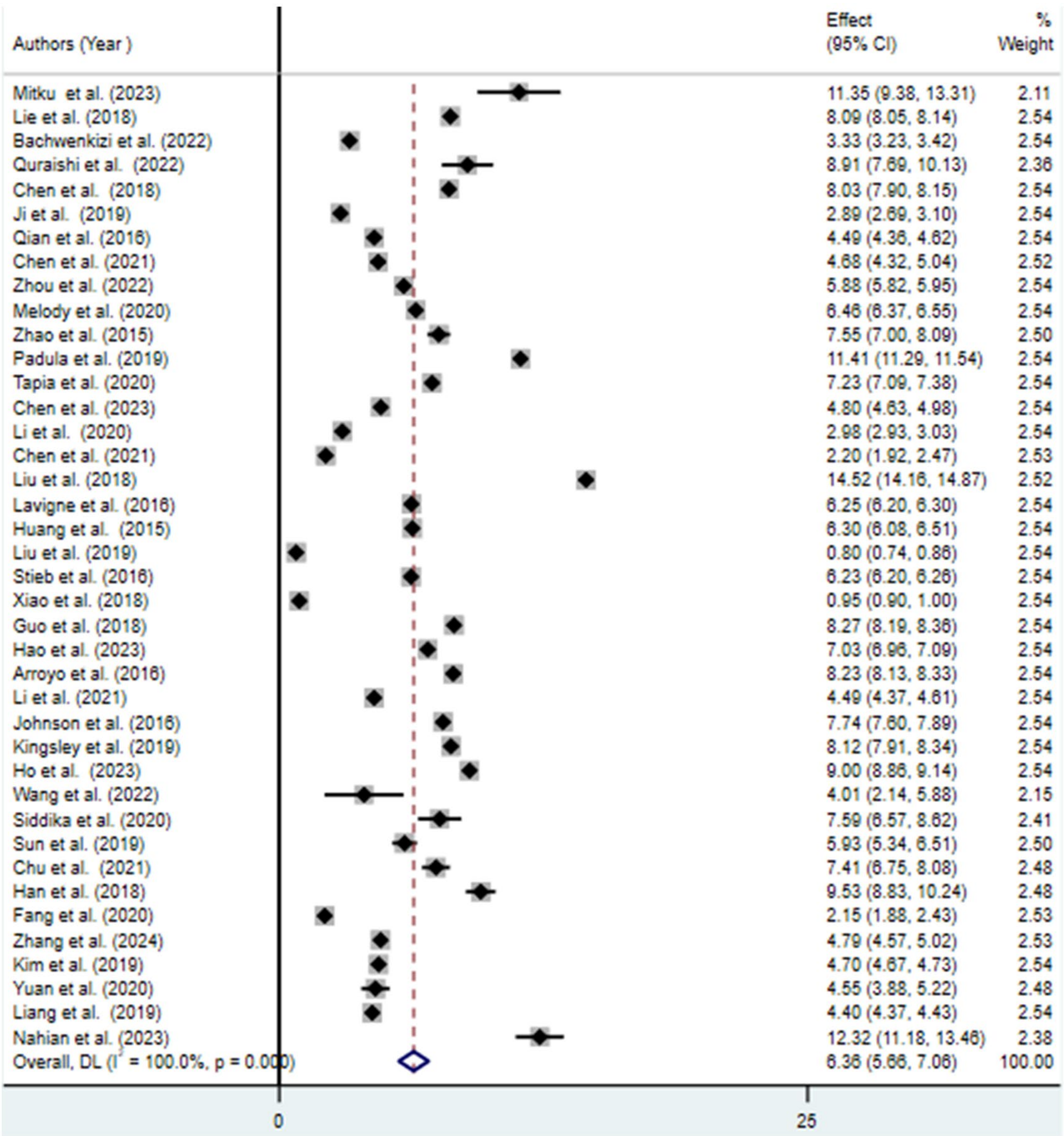

FIGURE 3
Forest plot for the association between ambient air pollution and preterm birth, 2024.

analysis was performed to assess the effect of each individual study on the estimated pooled results. To evaluate publication bias, a funnel plot test and Egger's regression test were used. A meta-regression was employed to identify potential sources of heterogeneity. Finally, the findings of this study are presented using tables, figures, forest plots, and descriptive texts.

3 Results

3.1 Overview of search process

We identified a total of 79,356 studies using a database and through direct Google and citation searching. After duplicate records were removed, 51,592 records were screened for this review. According to the records, only 32,947 studies were sought for retrieval. After being identified for retrieval, 15,063 studies were evaluated for eligibility. Following eligibility, a total of 15,021 studies were excluded due to differences in outcome interest and population differences. Ultimately, a total of 42 studies were included in this review from database sources. In addition to the database sources, seven studies were included in this review from direct Google and citation searching. Finally, a total of 49 articles were included in this study, as presented in the PRISMA flowchart (Figure 1).

3.2 Characteristics of the eligible studies

The majority of the included studies were conducted using birth cohort studies. This meta-analysis included a total of 21,019,317 study participants. The majority of the studies were conducted in China ($n = 26$) and the United States ($n = 10$). This meta-analysis examined

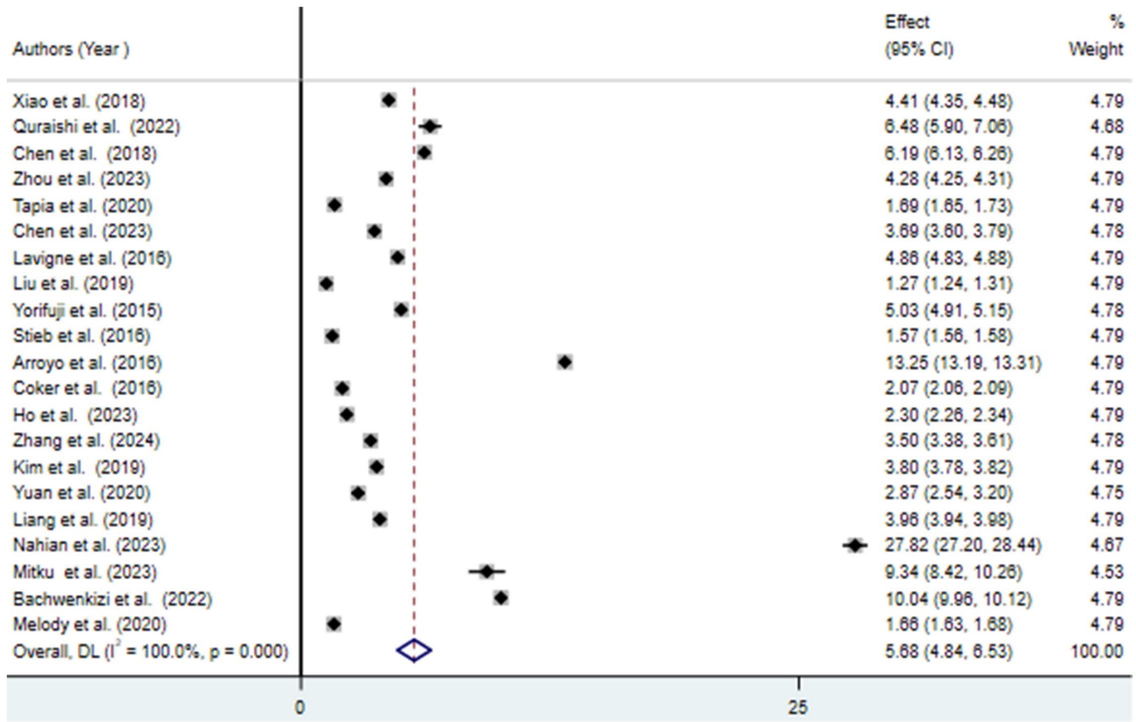

FIGURE 4
Forest plot for the association between ambient air pollution and low birth weight, 2024.

FIGURE 5
Forest plot for the association between ambient air pollution and stillbirth, 2024.

the association between ambient air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, CO) and adverse birth outcomes (preterm birth, low birth weight, and stillbirths). In this study, the main exposure assessment methods were the daily mean concentration of air pollutants, monitoring stations, land use regression model, and real-time measurement. Among the included studies, Bangladesh had the highest at least one birth outcome (40%) (28), while the United States had the lowest rate (0.44%) (29). The quality score of the included studies was between the ranges of 62.5 and 87.5% (Table 1).

3.3 Meta-analysis

The findings from the random effects model indicated that the pooled prevalence of at least one adverse birth outcome was 7.69% (95% CI: 6.70–8.69), with high heterogeneity ($I^2 = 100\%$, *p-value* < 0.001) (Figure 2). In this meta-analysis, high pooled prevalence was found in preterm birth (6.36%) (Figure 3), followed by low birth weights (5.07%) (Figure 4) and stillbirth (0.61%) (Figure 5). Subgroup analysis based on study country: the highest pooled prevalence of at least one adverse birth outcome was observed in Bangladesh at 40.14% (95% CI: 38.45–41.84) and in Spain at 21.5% (95% CI: 21.34–21.63). In contrast, the lowest pooled prevalence of at least one adverse birth outcome was observed in Japan at 5.03% (95% CI: 4.83–5.24) and the United States at 5.12% (95% CI: 4.22–6.02). In addition, subgroup analysis based on the nature of outcomes found that preterm birth and low birth weight were at 11.1% (95% CI: 9.85–12.35), preterm birth at 6.96% (95% CI: 5.86–8.66), low birth weight at 3.79% (95% CI: 2.0–5.59), and stillbirth at 0.615% (95% CI: 0.53–0.699) (Table 2).

In this study, a meta-regression analysis was conducted using the study country and nature of outcomes as factors to identify the source of heterogeneity. The finding revealed that the study country was not a statistically significant source of heterogeneity ($p = 0.196$), but the outcome nature was found to be a statistically significant source of heterogeneity ($p < 0.001$).

A sensitivity analysis was also performed to evaluate a single study effect on the overall results. The analysis showed for the overall prevalence of at least one adverse birth outcome a slightly broader confidence interval of 7.69% (95% CI: 6.05–8.98) compared to the original pooled prevalence of 7.69% (95% CI: 6.70–8.69), but it does not suggest strong evidence for single study effects. Similarly, sensitivity analysis was also conducted for preterm birth, low birth weight, and stillbirth to examine the effect of a single study on the overall prevalence. The findings suggested that there is no evidence for a single study effect on the overall pooled prevalence (Supplementary material 1).

The funnel plot for the overall analysis showed an asymmetrical distribution as visualized of the included articles, revealing the potential of publication biases (Figure 6). However, the Egger-regression test confirmed that there was no statistically significant presence of publication bias (p-value = 0.1001).

Similarly, funnel plots and Egger-regression tests were conducted to assess publication biases for the specific birth outcomes of preterm birth and low birth weights. For preterm birth, the funnel plots showed an asymmetrical distribution as visualized of the included articles (Figure 7), but the Egger-regression test confirmed that there was no statistically significant (p-value = 0.2087) for the presence of publication bias.

In contrast, for low birth weights, the funnel plot also showed an asymmetrical distribution as visualized of the included articles (Figure 8), and the Egger-regression test confirmed the presence of publication bias with statistical significance (p-value = 0.0017). To address the publication bias identified for the low birth weight outcome, Duval and Tweedie's "trim and fill" method was conducted (Supplementary material 2).

TABLE 2 Subgroup analysis of the association between ambient air pollution and at least one adverse birth outcome, 2024.

Variable	Number of studies	OR (95%CI)	Heterogeneity	
			I^2	*p-value*
Region/country				
Africa	2	16.9 (9.5–24.1)	96.9	<0.001
China	26	5.72 (4.6–6.9)	100	<0.001
United States	10	5.12 (4.22–6.02)	100	<0.001
Australia	2	11.2 (5.2–17.15)	100	<0.001
Peru	1	8.92 (8.8–9.08)	–	–
Canada	2	9.45 (6.22–12.69)	100	<0.001
Japan	1	5.03 (4.83–5.24)	–	–
Spain	1	21.5 (21.24–21.63)	–	–
Vietnam	1	11.12 (10.97–11.27)	–	–
Finland	1	7.59 (6.57–8.62)	–	–
Korea	1	8.5 (8.46–8.54)	–	–
Bangladesh	1	40.14 (38.45–41.84)	–	–
Outcome				
PTB and LBW	20	11.1 (9.85–12.35)	100	<0.001
PTB	20	6.96 (5.86–8.66)	99.9	<0.001
LBW	3	3.79 (2.0–5.59)	100	<0.001
SB	6	0.615 (0.53–0.699)	98.8	<0.001

NB: PTB, Preterm birth; LBW, Low birth weight; SB, Stillbirth.

3.4 Factors associated with adverse birth outcomes

In this meta-analysis, exposure to ambient air pollution, such as $PM_{2.5}$, PM_{10}, and O_3, was statistically significant for adverse birth outcomes (preterm birth and low birth weight). For preterm birth,

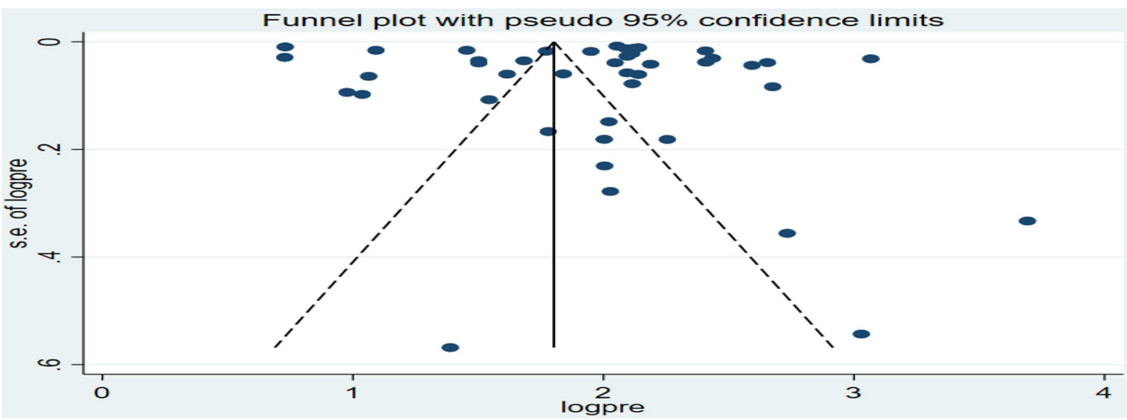

FIGURE 6
Funnel plot for the association between ambient air pollution and at least one adverse birth outcome, 2024.

exposure to $PM_{2.5}$ ($\leq 10\,\mu g/m^3$) during entire pregnancy, $PM_{2.5}$ ($\leq 10\,\mu g/m^3$) in first trimester, PM_{10} ($>10\,\mu g/m^3$) during entire pregnancy, and O_3 ($\leq 10\,\mu g/m^3$) during entire pregnancy increased the risk by 4% (OR = 1.04, 95% CI: 1.03–1.05), 5% (OR = 1.05, 95% CI: 1.01–1.09), 49% (OR = 1.49, 95% CI: 1.41–1.56), and 5% (OR = 1.05, 95% CI: 1.04–1.07), respectively (Figure 9).

For low birth weight, exposure to $PM_{2.5}$ ($\leq 10\,\mu g/m^3$) and $PM_{2.5}$ ($>10\,\mu g/m^3$) during entire pregnancy was found to increase the risk by 13% (OR = 1.13, 95% CI 1.05–1.21) and 28% (OR = 1.28, 95% CI 1.23–1.33), respectively (Figure 10).

4 Discussion

This systematic review and meta-analysis aimed to estimate the pooled association between exposure to ambient air pollution and adverse birth outcomes (preterm birth, low birth weight, and stillbirth), as well as to identify predictive factors. The pooled prevalence of at least one adverse birth outcome was found to be 7.69% (95% CI: 6.70–8.69), with notable extreme heterogeneity among the included studies ($I^2 = 100$, $p < 0.001$). Specifically, exposure to ambient air pollution was associated with a 6.36% (95% CI: 5.66–7.06) increased risk of preterm birth, a 5.07% (95% CI: 4.32–5.81) increase in low birth weight, and a 0.65% (95% CI: 0.53–0.7) increase in the risk of stillbirth. These findings suggest that exposure to ambient air pollution during pregnancy negatively affects various birth outcomes (30, 31).

Daba et al. (32) support the present findings, reporting a 15.5% (95% CI: 12.6–18.5) prevalence of adverse pregnancy outcomes linked to indoor air pollution exposure. The WHO reported low birth weight at 15.5% globally, 16.5% in developing countries, and 7% in developed countries in 2015.

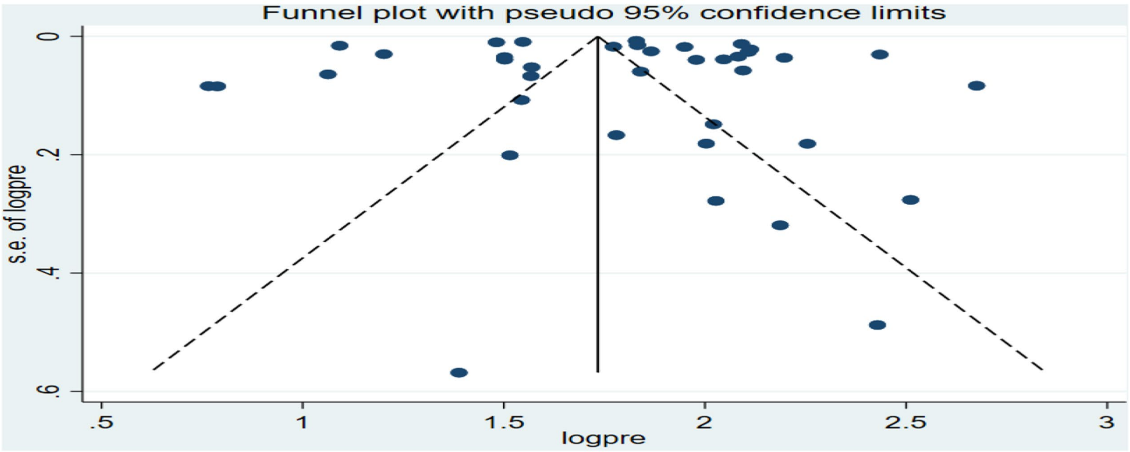

FIGURE 7
Funnel plot of the association between ambient air pollution and preterm birth, 2024.

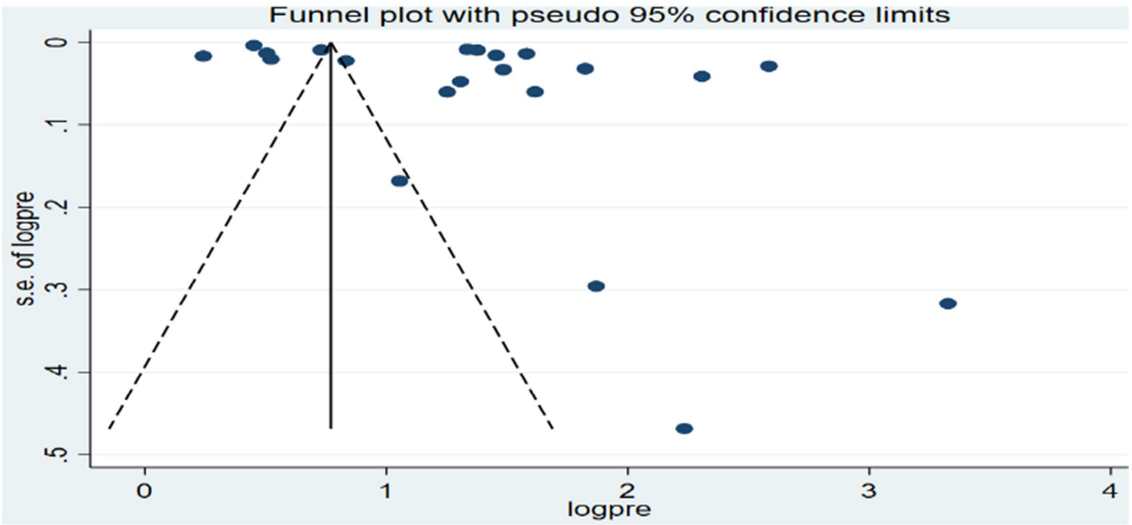

FIGURE 8
Funnel plot of the association between ambient air pollution and low birth weight, 2024.

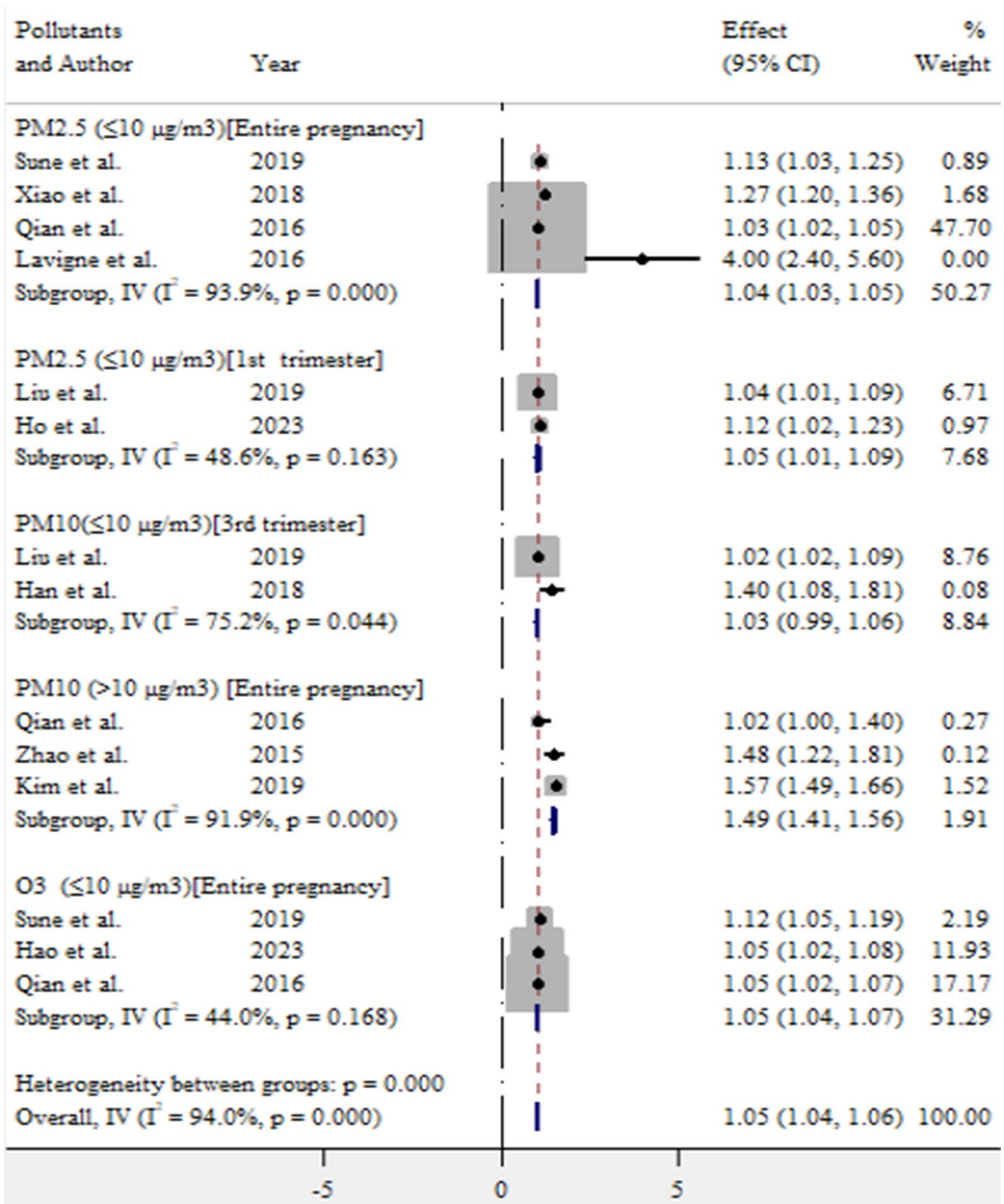

FIGURE 9
Pooled effect size of ambient air pollution associated with preterm birth, 2024.

The current findings are also supported by numerous studies indicating that exposure to ambient air pollution increases the risk of preterm birth, low birth weight, and stillbirth (30, 31, 33). Variations in findings may be attributed to different factors such as maternal educational level, age differences, socioeconomic conditions, type of pollutants, and the duration and level of exposure during the perinatal period (34, 35). Dzekem et al. (36) highlighted the need to address disparities, such as socioeconomic issues, when examining the relationship between air pollution exposure and pregnancy outcomes. Therefore, it is crucial to ensure that the interaction between pregnant women and their environment is safe and well-maintained to prevent adverse effects.

In this study, the heterogeneity among the included studies was significantly high, a finding that is supported by previous research (14, 31–33, 37, 38). This variability may be attributed to various factors, including differences in study settings, designs, and exposure assessment methods. To identify the potential sources of this heterogeneity, we conducted a subgroup analysis based on the study country and the type of adverse birth outcomes. Subsequently, the meta-regression analysis confirmed that the primary source of heterogeneity was related to the nature of the adverse birth outcomes. This may be linked to the levels and types of pollutants, as well as the conditions of pregnant women.

In this meta-analysis, exposure to $PM_{2.5}$ ($\leq 10\ \mu g/m^3$) throughout the entire pregnancy and during the first trimester was associated

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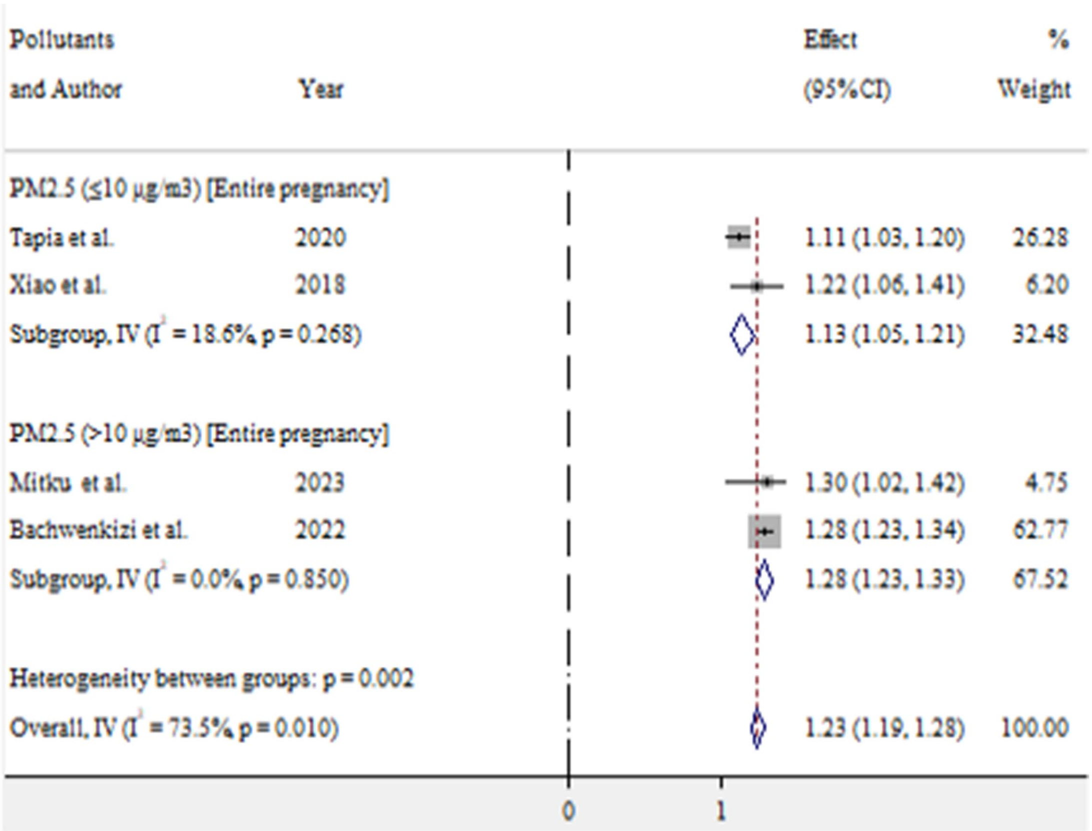

FIGURE 10
Pooled effect size of ambient air pollution associated with low birth weight, 2024.

with an increased risk of preterm birth, with an OR of 1.04 (95% CI: 1.03–1.05) and 1.05 (95% CI: 1.01–1.04), respectively. Sapkota et al. (37) reported that exposure to $PM_{2.5}$ at levels of 10 μg/m^3 during pregnancy increased the risk of preterm birth with an OR of 1.15 (95% CI: 1.14–1.16). Liu et al. (39) found a similar positive association, reporting an OR of 1.15 (95% CI: 1.07–1.23) for $PM_{2.5}$ exposure during pregnancy. Additionally, Lamichhane et al. (3) estimated an OR of 1.14 (95% CI = 1.06–1.22) for preterm birth per 10 μg/m^3 increase in $PM_{2.5}$ exposure during the entire pregnancy. Therefore, these findings highlighted the importance of protecting pregnant mothers from $PM_{2.5}$ exposure to reduce the risk of adverse outcomes of preterm birth (39–41).

In this study, we found a 49% increase in the risk of preterm birth for each >10 μg/m^3 increase in PM_{10} exposure during the entire pregnancy. Stieb et al. (1) reported a high risk of preterm birth associated with a 20 μg/m^3 increase in PM_{10} over the same period. Similarly, Lamichhane et al. (3) noted that exposure to PM_{10} increased the risk of preterm birth by 23% for each 10 μg/m^3 increment. The slight difference in findings may be attributed to variation in exposure levels and duration. Therefore, addressing ambient air pollution is essential for reducing the occurrence of preterm birth.

In the present study, exposure of O_3 at levels of ≤10 μg/m^3 during pregnancy was positively associated with a 5% increased risk of preterm birth, with (OR = 1.05, 95% CI: 1.04–1.07). This finding is consistent with previous research (31, 33), which suggests that exposure to ozone throughout pregnancy may significantly elevate the risk of preterm birth. These findings underscoring the need for protective measures to minimize pregnant women's exposure to ozone.

In this meta-analysis, maternal exposure to $PM_{2.5}$ during the entire pregnancy at levels of >10 μg/m^3 was associated with a 28% increase in the risk of low birth weight (OR = 1.28, 95% CI: 1.23–1.33). Additionally, exposure to $PM_{2.5}$ (≤10 μg/m^3) also showed a 13% increase in risk (OR = 1.13, 95% CI: 1.05–1.21). These findings suggest that as $PM_{2.5}$ exposure increases, the risk of low birth weight also increases. Supporting this, Zhu et al. (4) reported a 5% increase in low birth weight per 10 μg/m^3 increment in $PM_{2.5}$ exposure during the entire pregnancy (OR = 1.05, 95% CI: 1.02–1.07). The difference in findings may be attributed to variations in exposure assessment methods. Thus, exposure to $PM_{2.5}$ throughout pregnancy could significantly impact the final birth weight.

4.1 Limitation of the study

This study focusses exclusively on studies conducted in the English language. Additionally, it does not explore the underlying mechanisms that link ambient air pollution to adverse birth outcomes. Furthermore, this study also focused on selected adverse birth outcomes, but other birth outcomes like congenital anomalies or birth defects and others might be important.

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5 Conclusion

This meta-analysis highlighted a significant association between ambient air pollution and adverse birth outcomes. In this study, $PM_{2.5}$, PM_{10}, and O_3 were found to be positively associated with these adverse birth outcomes (preterm birth and low birth weight). Given these findings, it is essential for healthcare professionals, the Ministries of Health, non-governmental organizations, and other relevant stakeholders to implement compressive public health interventions aimed at reducing the incidence of adverse birth outcomes related to ambient air pollution. Such interventions could include policies to improve air quality, strict regulations, public awareness campaigns, and targeted support for vulnerable populations of pregnant women. Furthermore, to gain a deeper understanding of the mechanisms underlying the association between ambient air pollution and adverse birth outcomes, future research is highly recommended. Investigating these mechanisms will provide valuable insights that can help inform more effective strategies for mitigating the risks associated with air pollution during pregnancy. In addition, future researchers are encouraged to investigate the impact of ambient air pollution on congenital anomalies and other significant adverse birth outcomes.

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 author.

Author contributions

BD: Methodology, Software, Validation, Writing – original draft, Writing – review & editing. GB: Conceptualization, Data curation, Visualization, Writing – review & editing. AG: Data curation, Methodology, Software, Writing – review & editing. LB: Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. CD: Data curation, Methodology, Software, 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.

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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.2024.1488028/full#supplementary-material

References

1. Stieb DM, Chen L, Eshoul M, Judek S. Ambient air pollution, birth weight and preterm birth: a systematic review and meta-analysis. *Environ Res*. (2012) 117:100–11. doi: 10.1016/j.envres.2012.05.007

2. Glinianaia SV, Rankin J, Bell R, Pless-Mulloli T, Howel D. Particulate air pollution and fetal health: a systematic review of the epidemiologic evidence. *Epidemiology*. (2004) 15:36–45. doi: 10.1097/01.ede.0000101023.41844.ac

3. Lamichhane DK, Leem J-H, Lee J-Y, Kim H-C. A meta-analysis of exposure to particulate matter and adverse birth outcomes. *Environ Health Toxicol*. (2015) 30:e2015011. doi: 10.5620/eht.e2015011

4. Zhu X, Liu Y, Chen Y, Yao C, Che Z, Cao J. Maternal exposure to fine particulate matter (PM2.5) and pregnancy outcomes: a meta-analysis. *Environ Sci Pollut Res Int*. (2015) 22:3383–96. doi: 10.1007/s11356-014-3458-7

5. Proietti E, Röösli M, Frey U, Latzin P. Air pollution during pregnancy and neonatal outcome: a review. *J Aerosol Med Pulm Drug Deliv*. (2013) 26:9–23. doi: 10.1089/jamp.2011.0932

6. Kannan S, Misra DP, Dvonch JT, Krishnakumar A. Exposures to airborne particulate matter and adverse perinatal outcomes: a biologically plausible mechanistic framework for exploring potential effect modification by nutrition. *Environ Health Perspect*. (2006) 114:1636–42. doi: 10.1289/ehp.9081

7. World Health Organization. (2022). Ambient (outdoor) air pollution. Available at: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (Accessed August 12, 2024).

8. Fussell JC, Jauniaux E, Smith RB, Burton GJ. Ambient air pollution and adverse birth outcomes: a review of underlying mechanisms. *BJOG*. (2024) 131:538–50. doi: 10.1111/1471-0528.17727

9. Hajat A, Hsia C, O'Neill MS. Socioeconomic disparities and air pollution exposure: a global review. *Curr Environ Health Rep*. (2015) 2:440–50. doi: 10.1007/s40572-015-0069-5

10. Barker DJP. The origins of the developmental origins theory. *J Intern Med*. (2007) 261:412–7. doi: 10.1111/j.1365-2796.2007.01809.x

11. Zhang H, Zhang X, Wang Q, Xu Y, Feng Y, Yu Z, et al. Ambient air pollution and stillbirth: an updated systematic review and meta-analysis of epidemiological studies. *Environ Pollut*. (2021) 278:116752. doi: 10.1016/j.envpol.2021.116752

12. Xie G, Sun L, Yang W, Wang R, Shang L, Yang L, et al. Maternal exposure to PM2.5 was linked to elevated risk of stillbirth. *Chemosphere*. (2021) 283:131169. doi: 10.1016/j.chemosphere.2021.131169

13. Sun X, Luo X, Zhao C, Zhang B, Tao J, Yang Z, et al. The associations between birth weight and exposure to fine particulate matter (PM2.5) and its chemical constituents during pregnancy: a meta-analysis. *Environ Pollut*. (2016) 211:38–47. doi: 10.1016/j.envpol.2015.12.022

14. Li C, Yang M, Zhu Z, Sun S, Zhang Q, Cao J, et al. Maternal exposure to air pollution and the risk of low birth weight: a meta-analysis of cohort studies. *Environ Res*. (2020) 190:109970. doi: 10.1016/j.envres.2020.109970

15. Bekkar B, Pacheco S, Basu R, DeNicola N. Association of air pollution and heat exposure with preterm birth, low birth weight, and stillbirth in the US: a systematic review. *JAMA Netw Open*. (2020) 3:e208243. doi: 10.1001/jamanetworkopen.2020.8243

16. Ji Y, Song F, Xu B, Zhu Y, Lu C, Xia Y. Association between exposure to particulate matter during pregnancy and birthweight: a systematic review and a meta-analysis of birth cohort studies. *J Biomed Res*. (2017) 33:56–68. doi: 10.7555/JBR.31.20170038

17. Tapia VL, Vasquez BV, Vu B, Liu Y, Steenland K, Gonzales GF. Association between maternal exposure to particulate matter (PM2.5) and adverse pregnancy outcomes in Lima, Peru. *J Expo Sci Environ Epidemiol*. (2020) 30:689–97. doi: 10.1038/s41370-020-0223-5

18. Sapkota A, Chelikowsky A, Nachman K, Cohen A, Ritz B. Exposure to particulate matter and adverse birth outcomes: a comprehensive review and meta-analysis. *Air Qual Atmos Health*. (2010) 5:1–13.

19. Li X, Huang S, Jiao A, Yang X, Yun J, Wang Y, et al. Association between ambient fine particulate matter and preterm birth or term low birth weight: an updated systematic review and meta-analysis. *Environ Pollut*. (2017) 227:596–605. doi: 10.1016/j.envpol.2017.03.055

20. Li Z, Tang Y, Song X, Lazar L, Li Z, Zhao J. Impact of ambient PM2.5 on adverse birth outcome and potential molecular mechanism. *Ecotoxicol Environ Saf*. (2019) 169:248–54. doi: 10.1016/j.ecoenv.2018.10.109

21. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Syst Rev*. (2021) 10:89. doi: 10.1186/s13643-021-01626-4

22. World Health Organization. Geneva. Low birth weight. Available at: https://www.who.int/data/nutrition/nlis/info/low-birth-weight (Accessed August 27, 2024).

23. World Health Organization. Geneva. Stillbirth. Available at: https://www.who.int/health-topics/stillbirth (Accessed August 27, 2024).

24. World Health Organization. Geneva. Preterm birth. Available at: https://www.who.int/news-room/fact-sheets/detail/preterm-birth (Accessed August 27, 2024).

25. Aromataris E, Lockwood C, Porritt K, Pilla B, Jordan Z, editors. JBI manual for evidence synthesis - confluence. Available at: https://synthesismanual.jbi.global (Accessed October 7, 2024).

26. Munn Z, Moola S, Lisy K, Riitano D, Tufanaru C. Methodological guidance for systematic reviews of observational epidemiological studies reporting prevalence and cumulative incidence data. *Int J Evid Based Healthc*. (2015) 13:147–53. doi: 10.1097/XEB.0000000000000054

27. Higgins JPT, Thompson SG. Quantifying heterogeneity in a meta-analysis. *Stat Med*. (2002) 21:1539–58. doi: 10.1002/sim.1186

28. Nahian M, Ahmad T, Jahan I, Chakraborty N, Nahar Q, Streatfield P. Air pollution and pregnancy outcomes in Dhaka, Bangladesh. *J Climate Change Health*. (2022) 9:100187. doi: 10.1016/j.joclim.2022.100187

29. Mendola P, Ha S, Pollack AZ, Zhu Y, Seeni I, Kim SS, et al. Chronic and acute ozone exposure in the week prior to delivery is associated with the risk of stillbirth. *Int J Environ Res Public Health*. (2017) 14:731. doi: 10.3390/ijerph14070731

30. Tan Y, Yang R, Zhao J, Cao Z, Chen Y, Zhang B. The associations between air pollution and adverse pregnancy outcomes in China. *Adv Exp Med Biol*. (2017) 1017:181–214. doi: 10.1007/978-981-10-5657-4_8

31. Wang X, Wang X, Gao C, Xu X, Li L, Liu Y, et al. Relationship between outdoor air pollutant exposure and premature delivery in China- systematic review and meta-analysis. *Int J Public Health*. (2023) 68:1606226. doi: 10.3389/ijph.2023.1606226

32. Daba C, Asmare L, Demeke Bayou F, Arefaynie M, Mohammed A, Tareke AA, et al. Exposure to indoor air pollution and adverse pregnancy outcomes in low and middle-income countries: a systematic review and meta-analysis. *Front Public Health*. (2024) 12:1356830. doi: 10.3389/fpubh.2024.1356830

33. Ju L, Li C, Yang M, Sun S, Zhang Q, Cao J, et al. Maternal air pollution exposure increases the risk of preterm birth: evidence from the meta-analysis of cohort studies. *Environ Res*. (2021) 202:111654. doi: 10.1016/j.envres.2021.111654

34. Coker E, Ghosh J, Jerrett M, Gomez-Rubio V, Beckerman B, Cockburn M, et al. Modeling spatial effects of PM2.5 on term low birth weight in Los Angeles County. *Environ Res*. (2015) 142:354–64. doi: 10.1016/j.envres.2015.06.044

35. Dibben C, Clemens T. Place of work and residential exposure to ambient air pollution and birth outcomes in Scotland, using geographically fine pollution climate mapping estimates. *Environ Res*. (2015) 140:535–41. doi: 10.1016/j.envres.2015.05.010

36. Dzekem BS, Aschebrook-Kilfoy B, Olopade CO. Air pollution and racial disparities in pregnancy outcomes in the United States: a systematic review. *J Racial Ethn Health Disparities*. (2024) 11:535–44. doi: 10.1007/s40615-023-01539-z

37. Sapkota A, Chelikowsky AP, Nachman KE, Cohen AJ, Ritz B. Exposure to particulate matter and adverse birth outcomes: a comprehensive review and meta-analysis. *Air Qual Atmos Health*. (2012) 5:369–81. doi: 10.1007/s11869-010-0106-3

38. Sun X, Luo X, Zhao C, Chung Ng RW, Lim CED, Zhang B, et al. The association between fine particulate matter exposure during pregnancy and preterm birth: a meta-analysis. *BMC Pregnancy Childbirth*. (2015) 15:300. doi: 10.1186/s12884-015-0738-2

39. Liu C, Sun J, Liu Y, Liang H, Wang M, Wang C, et al. Different exposure levels of fine particulate matter and preterm birth: a meta-analysis based on cohort studies. *Environ Sci Pollut Res Int*. (2017) 24:17976–84. doi: 10.1007/s11356-017-9363-0

40. Bosetti C, Nieuwenhuijsen MJ, Gallus S, Cipriani S, La Vecchia C, Parazzini F. Ambient particulate matter and preterm birth or birth weight: a review of the literature. *Arch Toxicol*. (2010) 84:447–60. doi: 10.1007/s00204-010-0514-z

41. Srám RJ, Binková B, Dejmek J, Bobak M. Ambient air pollution and pregnancy outcomes: a review of the literature. *Environ Health Perspect*. (2005) 113:375–82. doi: 10.1289/ehp.6362

42. Yang S, Tan Y, Mei H, Wang F, Li N, Zhao J, et al. Ambient air pollution the risk of stillbirth: a prospective birth cohort study in Wuhan, China. *Int J Hyg Environ Health*. (2018) 221:502–9. doi: 10.1016/j.ijheh.2018.01.014

43. Quraishi SM, Hazlehurst MF, Loftus CT, Nguyen RHN, Barrett ES, Kaufman JD, et al. Association of prenatal exposure to ambient air pollution with adverse birth outcomes and effect modification by socioeconomic factors. *Environ Res*. (2022) 212:113571. doi: 10.1016/j.envres.2022.113571

44. Chen J, Guo L, Liu H, Jin L, Meng W, Fang J, et al. Modification effects of ambient temperature on associations of ambient ozone exposure before and during pregnancy with adverse birth outcomes: a multicity study in China. *Environ Int*. (2023) 172:107791. doi: 10.1016/j.envint.2023.107791

45. Chen G, Guo Y, Abramson MJ, Williams G, Li S. Exposure to low concentrations of air pollutants and adverse birth outcomes in Brisbane, Australia, 2003–2013. *Sci Total Environ*. (2018) 622-623:721–6. doi: 10.1016/j.scitotenv.2017.12.050

46. Qian Z, Liang S, Yang S, Trevathan E, Huang Z, Yang R, et al. Ambient air pollution and preterm birth: A prospective birth cohort study in Wuhan, China. *Int J Hyg Environ Health*. (2016) 219:195–203. doi: 10.1016/j.ijheh.2015.11.003

47. Zhou W, Ming X, Yang Y, Hu Y, He Z, Chen H, et al. Associations between maternal exposure to ambient air pollution and very low birth weight: a birth cohort study in Chongqing, China. *Front Public Health*. (2023) 11:1123594. doi: 10.3389/fpubh.2023.1123594

48. Chen Q, Ren Z, Liu Y, Qiu Y, Yang H, Zhou Y, et al. The association between preterm birth and ambient air pollution exposure in Shiyan, China, 2015-2017. *Int J Environ Res Public Health*. (2021) 18:4326. doi: 10.3390/ijerph18084326

49. Zhou W, Ming X, Yang Y, Hu Y, He Z, Chen H, et al. Association between maternal exposure to ambient air pollution and the risk of preterm birth: a birth cohort study in Chongqing, China, 2015-2020. *Int J Environ Res Public Health*. (2022) 19:2211. doi: 10.3390/ijerph19042211

50. Melody S, Wills K, Knibbs LD, Ford J, Venn A, Johnston F. Adverse birth outcomes in Victoria, Australia in association with maternal exposure to low levels of ambient air pollution. *Environ Res*. (2020) 188:109784. doi: 10.1016/j.envres.2020.109784

51. Li L, Ma J, Cheng Y, Feng L, Wang S, Yun X, et al. Urban-rural disparity in the relationship between ambient air pollution and preterm birth. *Int J Health Geogr*. (2020) 19:23. doi: 10.1186/s12942-020-00218-0

52. Zhao N, Qiu J, Zhang Y, He X, Zhou M, Li M, et al. Ambient air pollutant PM10 and risk of preterm birth in Lanzhou, China. *Environ Int*. (2015) 76:71–7. doi: 10.1016/j.envint.2014.12.009

53. Padula AM, Yang W, Lurmann FW, Balmes J, Hammond SK, Shaw GM. Prenatal exposure to air pollution, maternal diabetes and preterm birth. *Environ Res*. (2019) 170:160–7. doi: 10.1016/j.envres.2018.12.031

54. Liu W-Y, Yu Z-B, Qiu H-Y, Wang J-B, Chen X-Y, Chen K. Association between ambient air pollutants and preterm birth in Ningbo, China: a time-series study. *BMC Pediatr*. (2018) 18:305. doi: 10.1186/s12887-018-1282-9

55. Lavigne E, Yasseen AS, Stieb DM, Hystad P, van Donkelaar A, Martin RV, et al. Ambient air pollution and adverse birth outcomes: differences by maternal comorbidities. *Environ Res*. (2016) 148:457–66. doi: 10.1016/j.envres.2016.04.026

56. Huang C, Nichols C, Liu Y, Zhang Y, Liu X, Gao S, et al. Ambient air pollution and adverse birth outcomes: a natural experiment study. *Popul Health Metrics*. (2015) 13:17. doi: 10.1186/s12963-015-0050-4

57. Liu Y, Xu J, Chen D, Sun P, Ma X. The association between air pollution and preterm birth and low birth weight in Guangdong, China. *BMC Int Health Hum Rights*. (2019) 19:3. doi: 10.1186/s12889-018-6307-7

58. Yorifuji T, Kashima S, Doi H. Outdoor air pollution and term low birth weight in Japan. *Environ Int*. (2015) 74:106–11. doi: 10.1016/j.envint.2014.09.003

59. Stieb DM, Chen L, Hystad P, Beckerman BS, Jerrett M, Tjepkema M, et al. A national study of the association between traffic-related air pollution and adverse pregnancy outcomes in Canada, 1999-2008. *Environ Res*. (2016) 148:513–26. doi: 10.1016/j.envres.2016.04.025

60. Green R, Sarovar V, Malig B, Basu R. Association of stillbirth with ambient air pollution in a California cohort study. *Am J Epidemiol*. (2015) 181:874–82. doi: 10.1093/aje/kwu460

61. Ji X, Meng X, Liu C, Chen R, Ge Y, Kan L, et al. Nitrogen dioxide air pollution and preterm birth in Shanghai, China. *Environ Res*. (2019) 169:79–85. doi: 10.1016/j.envres.2018.11.007

62. Guo T, Wang Y, Zhang H, Zhang Y, Zhao J, Wang Q, et al. The association between ambient PM2.5 exposure and the risk of preterm birth in China: a retrospective cohort study. *Sci Total Environ*. (2018) 633:1453–9. doi: 10.1016/j.scitotenv.2018.03.328

63. Kingsley SL, Eliot MN, Glazer K, Awad YA, Schwartz JD, Savitz DA, et al. Maternal ambient air pollution, preterm birth and markers of fetal growth in Rhode Island: results of a hospital-based linkage study. *J Epidemiol Community Health*. (2017) 71:1131–6. doi: 10.1136/jech-2017-208963

64. Ho TH, Van Dang C, Pham TTB, Thi Hien T, Wangwongwatana S. Ambient particulate matter (PM2.5) and adverse birth outcomes in Ho Chi Minh City, Vietnam. *Hygiene Environ Health Adv*. (2023) 5:100049. doi: 10.1016/j.heha.2023.100049

65. Wang L, Fang L, Fang Z, Zhang M, Zhang L. Assessment of the association between prenatal exposure to multiple ambient pollutants and preterm birth: a prospective cohort study in Jinan, East China. *Ecotoxicol Environ Saf.* (2022) 232:113297. doi: 10.1016/j.ecoenv.2022.113297

66. Xiao Q, Chen H, Strickland MJ, Kan H, Chang HH, Klein M, et al. Associations between birth outcomes and maternal PM2.5 exposure in Shanghai: a comparison of three exposure assessment approaches. *Environ Int*. (2018) 117:226–36. doi: 10.1016/j.envint.2018.04.050

67. Zang H, Cheng H, Song W, Yang M, Han P, Chen C, et al. Ambient air pollution and the risk of stillbirth: a population-based prospective birth cohort study in the coastal area of China. *Environ Sci Pollut Res Int*. (2019) 26:6717–24. doi: 10.1007/s11356-019-04157-7

68. Arroyo V, Díaz J, Carmona R, Ortiz C, Linares C. Impact of air pollution and temperature on adverse birth outcomes: Madrid, 2001–2009. *Environ Pollut*. (2016) 218:1154–61. doi: 10.1016/j.envpol.2016.08.069

69. DeFranco E, Hall E, Hossain M, Chen A, Haynes EN, Jones D, et al. Air pollution and stillbirth risk: exposure to airborne particulate matter during pregnancy is associated with fetal death. *PLoS One*. (2015) 10:e0120594. doi: 10.1371/journal.pone.0120594

70. Coker E, Liverani S, Ghosh JK, Jerrett M, Beckerman B, Li A, et al. Multi-pollutant exposure profiles associated with term low birth weight in Los Angeles County. *Environ Int*. (2016) 91:1–13. doi: 10.1016/j.envint.2016.02.011

71. Yuan L, Zhang Y, Wang W, Chen R, Liu Y, Liu C, et al. Critical windows for maternal fine particulate matter exposure and adverse birth outcomes: the Shanghai birth cohort study. *Chemosphere*. (2020) 240:124904. doi: 10.1016/j.chemosphere.2019.124904

72. Li S, Peng L, Wu X, Xu G, Cheng P, Hao J, et al. Long-term impact of ambient air pollution on preterm birth in Xuzhou, China: a time series study. *Environ Sci Pollut Res Int*. (2021) 28:41039–50. doi: 10.1007/s11356-021-13621-2

73. Rammah A, Whitworth KW, Han I, Chan W, Symanski E. Time-varying exposure to ozone and risk of stillbirth in a nonattainment urban region. *Am J Epidemiol*. (2019) 188:1288–95. doi: 10.1093/aje/kwz095

74. Mitku AA, Zewotir T, North D, Jeena P, Asharam K, Muttoo S, et al. Impact of ambient air pollution exposure during pregnancy on adverse birth outcomes: generalized structural equation modeling approach. *BMC Public Health*. (2023) 23:45. doi: 10.1186/s12889-022-14971-3

75. Li Q, Wang Y, Guo Y, Zhou H, Wang X, Wang Q, et al. Effect of airborne particulate matter of 2.5 μm or less on preterm birth: a national birth cohort study in China. *Environ Int*. (2018) 121:1128–36. doi: 10.1016/j.envint.2018.10.025

76. Bachwenkizi J, Liu C, Meng X, Zhang L, Wang W, van Donkelaar A, et al. Maternal exposure to fine particulate matter and preterm birth and low birth weight in Africa. *Environ Int*. (2022) 160:107053. doi: 10.1016/j.envint.2021.107053

77. Chu C, Zhu Y, Liu C, Chen R, Yan Y, Ren Y, et al. Ambient fine particulate matter air pollution and the risk of preterm birth: a multicenter birth cohort study in China. *Environ Pollut*. (2021) 287:117629. doi: 10.1016/j.envpol.2021.117629

78. Han Y, Jiang P, Dong T, Ding X, Chen T, Villanger GD, et al. Maternal air pollution exposure and preterm birth in Wuxi, China: effect modification by maternal age. *Ecotoxicol Environ Saf.* (2018) 157:457–62. doi: 10.1016/j.ecoenv.2018.04.002

79. Zhang C, Yang J, Wei J, Liu Y, Zhu H, Li X, et al. Individual ambient ozone exposure during pregnancy and adverse birth outcomes: exploration of the potentially vulnerable windows. *J Hazard Mater*. (2024) 464:132945. doi: 10.1016/j.jhazmat.2023.132945

80. Kim YJ, Song IG, Kim K-N, Kim MS, Chung S-H, Choi Y-S, et al. Maternal exposure to particulate matter during pregnancy and adverse birth outcomes in the Republic of Korea. *Int J Environ Res Public Health*. (2019) 16:633. doi: 10.3390/ijerph16040633

81. Liang Z, Yang Y, Qian Z, Ruan Z, Chang J, Vaughn MG, et al. Ambient PM2.5 and birth outcomes: estimating the association and attributable risk using a birth cohort study in nine Chinese cities. *Environ Int*. (2019) 126:329–35. doi: 10.1016/j.envint.2019.02.017

82. Chen J, Fang J, Zhang Y, Xu Z, Byun H-M, Li P, et al. Associations of adverse pregnancy outcomes with high ambient air pollution exposure: results from the project ELEFANT. *Sci Total Environ*. (2021) 761:143218. doi: 10.1016/j.scitotenv.2020.143218

83. Johnson S, Bobb JF, Ito K, Savitz DA, Elston B, Shmool JLC, et al. Ambient fine particulate matter, nitrogen dioxide, and preterm birth in New York City. *Environ Health Perspect*. (2016) 124:1283–90. doi: 10.1289/ehp.1510266

84. Siddika N, Rantala AK, Antikainen H, Balogun H, Amegah AK, Ryti NRI, et al. Short-term prenatal exposure to ambient air pollution and risk of preterm birth - a population-based cohort study in Finland. *Environ Res*. (2020) 184:109290. doi: 10.1016/j.envres.2020.109290

85. Sun Z, Yang L, Bai X, Du W, Shen G, Fei J, et al. Maternal ambient air pollution exposure with spatial-temporal variations and preterm birth risk assessment during 2013–2017 in Zhejiang Province, China. *Environ Int*. (2019) 133:105242. doi: 10.1016/j.envint.2019.105252

86. Hao H, Yoo SR, Strickland MJ, Darrow LA, D'Souza RR, Warren JL, et al. Effects of air pollution on adverse birth outcomes and pregnancy complications in the U.S. state of Kansas (2000–2015). *Sci Rep*. (2023) 13:21476. doi: 10.1038/s41598-023-48329-5

87. Fang J, Kang C-M, Osorio-Yáñez C, Barrow TM, Zhang R, Zhang Y, et al. Prenatal PM2.5 exposure and the risk of adverse births outcomes: results from project ELEFANT. *Environ Res*. (2020) 191:110232. doi: 10.1016/j.envres.2020.110232