

Association between atmospheric particulate matter (PM 2.5) pollution during pregnancy and premature birth: a systematic review and meta-analysis

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ABSTRACT

Background: Preterm birth (PTB) remains a major public health challenge and one of the leading contributors to neonatal morbidity, mortality, and the global burden of disease. Increasing evidence suggests that exposure to ambient air pollution, particularly fine particulate matter (PM 2.5), may contribute to adverse pregnancy outcomes. This study aimed to estimate the global prevalence of PTB and evaluate the association between PM 2.5 exposure during different stages of pregnancy and PTB risk.

Methods: A systematic review and meta-analysis were conducted using studies retrieved from PubMed/ Medline, Scopus, and Web of Science databases published between January 1, 2020, and March 1, 2025. Thirty studies (27 cohort, 2 time-series, and 1 cross-sectional) involving 40,142,804 participants were included. Pooled prevalence estimates and effect sizes were calculated to assess the relationship between PM 2.5 exposure and PTB.

Results: The pooled global prevalence of PTB was 6.2% (95% CI: 4.2–8.2%), with the highest prevalence observed in North America (8.5%). Exposure to PM 2.5 during the second trimester was significantly associated with an increased risk of PTB. Specifically, each 10 $\mu\text{g}/\text{m}^3$ increase in PM 2.5 concentration was associated with a 2% increase in PTB risk (HR = 1.02; 95% CI: 1.00– 1.03; $p = 0.01$). No statistically significant associations were identified for PM 2.5 exposure during the first or third trimesters.

Conclusion: The findings indicate that PM 2.5 exposure during the second trimester of pregnancy is associated with an elevated risk of PTB. These results highlight the importance of improving air quality and implementing targeted public health interventions to reduce environmental risks for pregnant women and improve maternal and neonatal health outcomes.

INTRODUCTION

Air pollution has become one of the most widely discussed environmental issues of the modern era, particularly in relation to its impact on human health. One of the primary pollutants of concern is fine particulate matter with a diameter smaller than 2.5 micrometers (PM 2.5), which can penetrate the systemic bloodstream, trigger inflammatory and oxidative processes in the body [1-4].

In this context, ambient air pollution in the city of Almaty (Kazakhstan) poses a serious threat. According to studies, during the winter season, the average concentration of PM 2.5 particles in the city reached 94 $\mu\text{g}/\text{m}^3$, which is nearly 19 times higher than the World Health Organization's recommended annual limit of 5 $\mu\text{g}/\text{m}^3$, and more than double the maximum permissible level established in Kazakhstan (35 $\mu\text{g}/\text{m}^3$) [5-6]. Particularly alarming is the city's position in global pollution rankings: according to IQAir, in December 2024, Almaty was ranked among the most polluted cities in the world for the first time, taking fifth place with an Air Quality Index (AQI) of 169, which is classified as an "unhealthy" level of pollution [7].

Preterm birth, defined as birth occurring before the 37th week of gestation, is one of the leading causes of neonatal morbidity and mortality worldwide. In 2020, approximately 13.4 million newborns were born prematurely, representing about 9.9% of all live births [8-9]. The prevalence of preterm birth remains high across different countries [10,11], and researchers are actively investigating the contributing factors. A particularly important topic is the potential link between air pollution and the risk of preterm birth. PM 2.5 particles are of special concern due to their ability to deeply penetrate the lungs, and enter the bloodstream, potentially affecting maternal and fetal health. Despite a growing number of studies addressing this association, findings remain inconsistent. Some studies have reported a significant relationship between PM 2.5 exposure, and increased risk of preterm birth [12], while others have not found statistically significant associations [13,14]. Additionally, there is variation in identifying the most vulnerable periods of pregnancy. Some studies indicate that the second [15-16], and third trimesters are the most sensitive to PM 2.5 exposure, while others identify the first trimester [17,18] as the critical risk period.

Given the substantial body of literature in this field, we have decided to focus on the most recent studies from the past five years to conduct a systematic review, and meta-analysis to evaluate the most up-to-date scientific evidence. Therefore, our current study aims to investigate the association between exposure to PM 2.5 air pollution, and the risk of preterm birth before 37 weeks of gestation, identify the most vulnerable trimester of pregnancy, and explore regional differences. We hope that the findings will contribute to the development of effective preventive strategies, and protective measures for pregnant women. Furthermore, our conclusions may help raise public awareness about the impact of air pollution on reproductive health and emphasize the need for improved environmental policies to protect the health of future generations.

METHODS

Protocol registration

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 CRD420250650404.

Search strategy

The focus of our systematic review and meta-analysis was on the relationship between ambient air pollution, and the risk of PTB. To identify relevant literature, we systematically searched three English databases: PubMed, Scopus, and Web of Science from 1 January 2020 to 1 March 2025. Comprehensive search terms were used to identify relevant studies. These include MeSH terms, and keywords such as ambient air pollution, outdoor air pollution, adverse studies on birth outcomes other than miscarriages, preterm birth, premature rupture, and particulate matter 2.5. 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.

((PM 2.5 OR Air pollution OR Atmospheric pollutant OR Particulate matter OR Environment OR ("Particulate Matter/ adverse effects"[Mesh] OR "Particulate Matter/ analysis"[Mesh] OR "Particulate Matter/ blood"[Mesh] OR "Particulate Matter/ immunology"[Mesh] OR "Particulate Matter/ metabolism"[Mesh] OR "Particulate Matter/ radiation effects"[Mesh] OR "Particulate Matter/ toxicity"[Mesh]) AND ((y_5[Filter] AND (ffrft[Filter] AND (fha[Filter] AND (fft[Filter]))) AND (Premature rupture of membranes OR Adverse pregnancy outcomes OR Preterm birth OR Preterm delivery OR Premature birth OR ("Fetal Membranes, Premature Rupture/ blood"[Mesh] OR "Fetal Membranes, Premature Rupture/ chemically induced"[Mesh] OR "Fetal Membranes, Premature Rupture/ epidemiology"[Mesh] OR "Fetal Membranes, Premature Rupture/ etiology"[Mesh] OR "Fetal Membranes, Premature Rupture/ metabolism"[Mesh] OR "Fetal Membranes, Premature Rupture/ pathology"[Mesh]) AND ((y_5[Filter] AND (ffrft[Filter] AND (fha[Filter] AND (fft[Filter]))) AND (Pregnant women OR Female reproductive effects OR Maternal health OR Reproductive health OR Pregnancy OR "Pregnant People/psychology"[Mesh] AND ((y_5[Filter] AND (ffrft[Filter] AND (fha[Filter] AND (fft[Filter]))) Filters: Abstract, Free full text, Full text, in the last 5 years Sort by: Most Recent

Eligibility criteria

We followed the population-intervention-comparison-outcomes-study design (PICOS) model for defining our eligibility criteria [19,20].

- Population: pregnant women from 20 and 37 weeks of gestation.
- Intervention: air pollution, PM 2.5.
- Comparators: pregnant women with lower exposure levels, with or without adverse birth outcomes other than miscarriages, as compared to those exposed to higher exposure with adverse birth outcomes other than miscarriages.
- Outcomes: the adverse studies on birth outcomes other than miscarriages of interest include preterm birth (reported prevalence [%] and measure of association in adjusted odds ratio [AOR]).
- Study: all observational studies (cross-sectional, cohort, and time-series studies).

Literature Search Inclusion criteria: 1) published from 1 January 2020 to 1 March 2025, the contents of the literature were all independent epidemiological findings; 2) the study was about the effect of atmospheric pollutant (PM 2.5) preterm birth; 3) in all studies, preterm birth between 20 and 37 weeks of gestation was defined as preterm birth according to WHO criteria; 4) the risk factors studied included air pollutant (PM 2.5) the results of each literature is the quantitative dose- response relationships between air pollution and preterm birth, including parameter estimation and 95% CI of the risk of preterm birth with the increase in air pollutant concentration of per interquartile increase and 10 $\mu\text{g}/\text{m}^3$; 6) the study methods were cohort studies or case-crossover, and time-series studies.

Exclusion criteria

1) animal studies, in vitro toxicology studies, reviews, and review articles; 2) studies with risk factors limited to indoor pollution, specific heavy metals or organic pollution; 3) studies examining the effects of air pollution due to occupational exposure on adverse pregnancy outcomes; 4) studies on birth outcomes other than miscarriages; 5) studies for which OR, RR, HR values and 95% CI were not available; 6) the original article contains no original data [21-23].

Data extraction

The literature search was conducted independently by two researchers, and the literature initially examined was screened one by one according to the inclusion, and exclusion criteria, and relevant information was extracted, and checked for differences. When disagreements arose during the data extraction process, they were resolved through discussion and consensus among all reviewers. After selecting the articles, the necessary information was extracted into a standardized form. The following information was collected for each study: the names of the authors, the country where the study was conducted, the publication year, the study year, the

study design, the sample size, the number of preterm births, the period of air pollution exposure, the unit of increase in pollutant concentration, the method of exposure assessment, and the adjusted covariates. Effect estimates including odds ratio (OR), risk ratio (RR), or hazard ratio (HR) with associated 95% confidence intervals, and adjusted covariates were extracted and analyzed [24].

Quality and risk of bias assessment

To assess the quality of cohort and longitudinal studies, the Newcastle–Ottawa Scale (NOS) was used. The assessment included eight items and a score of 7 or higher was considered indicative of high quality. For cross-sectional studies, quality was evaluated using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Analytical Cross-Sectional Studies. This tool includes ten items, and a JBI score of ≥ 16 indicated high quality. Currently, there is no standardized scale for evaluating the quality of time-series studies. Therefore, the quality of such studies was assessed using the scale developed by [24,25]. This scale is based on the NOS and the Cochrane Risk of Bias Assessment Tool [26] and evaluates study quality across three domains: validation of patient-reported outcomes; quality of air pollution measurements; and extent of confounding adjustment. A total score of five across all three domains was classified as “high quality.” Studies that scored zero in any of the three domains were classified as low quality, while studies with scores ranging from one to four were categorized as moderate quality.

Statistical analysis

We calculated a pooled OR ratio and corresponding 95%CI using adjusted OR and its 95%CI from each study to evaluate the association between air pollutants (PM 2.5) and preterm birth. Statistical analysis was performed using OpenMeta [Analyst] (Brown University, Providence, Rhode Island, United States of America) and Review Manager 5.4 (Cochrane software for writing Cochrane reviews). A random effects model and a limited maximum likelihood method were used to calculate the prevalence of preterm birth in women living in polluted air with 95% confidence intervals (CI). The heterogeneity index (I^2) value was calculated to assess heterogeneity between studies, and the p-value was determined using a chi-square test to assess the statistical significance of heterogeneity. The subgroup analysis was performed when the prevalence was stratified by region. The (HR) ratio of the overall risks of premature birth in pregnant women, depending on the air pollutant (PM 2.5), and in each trimester of pregnancy, was calculated taking into account the unit increase in the concentration of the pollutant [27,28].

RESULTS

Literature retrieval and study characteristics

In total, 3312 records were initially identified from the three databases searched. After duplicate records were removed, 562 records were screened for this review. According to the records, only 92 studies were sought for retrieval. After being identified for retrieval, 62 studies were evaluated for eligibility. Following eligibility, a total of 32 studies were excluded for the following reasons: unavailability of full text ($n=12$); reviews ($n=6$); it was not possible to standardize the results ($n=5$); language not being English ($n=1$); classified as low- or moderate- quality studies ($n=6$) and air pollutant not included ($n=2$). Finally, a total of 30 articles were included in this study, as presented in the PRISMA flowchart (Figure 1). The types of studies included 27 cohort studies, 2 time-series studies, and 1 cross-sectional study. The total sample size of the studies included in this study was 40,142,804. The majority of the studies were conducted in China ($n = 15$), and the United States ($n = 5$). In terms of literature quality, the average NOS score was 8.25 ± 0.7 , with 16 articles scoring >8 points, and 4 articles ≤ 7 points (Table 1).

Global prevalence of preterm birth

Analyzing the prevalence of preterm birth among women living in areas with elevated levels of air pollution (PM 2.5) worldwide, using a random-effects model, we found that the pooled prevalence based on 30 studies was 6.2% (95% CI: 4.2–8.2%; $I^2 = 100\%$, $p < 0.001$).

Prevalence of preterm birth by region of the world

When the prevalence was stratified by global region, we found that the prevalence among women living in areas with elevated levels of air pollution was 8.5% (95% CI: 7.5–9.4%) in North America, 5.9% (95% CI: 1.8–13.6%) in South America, and 4.8% (95% CI: 4.0–5.6%) in East Asia. High statistical heterogeneity was observed in North America ($I^2 = 99.87\%$, $p < 0.001$), South America ($I^2 = 100\%$, $p < 0.001$), and Asia ($I^2 = 99.87\%$, $p < 0.001$) (Table 1).

Cumulative exposure to PM 2.5 depending on the measure of increase

A $10 \mu\text{g}/\text{m}^3$ increase in ambient PM 2.5 concentration throughout pregnancy is associated with a statistically significant 22% increased risk of preterm birth among pregnant women, compared to those living in areas with cleaner air (HR = 1.22; 95% CI: 1.14–1.32; $p < 0.00001$). The heterogeneity of the included studies was moderate, but statistically significant ($I^2 = 68\%$, $p = 0.009$) (Table 2).

An interquartile range increase in PM 2.5 concentration during the entire pregnancy was associated with a statistically significant 14% higher risk of preterm birth among pregnant women compared to those living in areas with cleaner air (HR = 1.14; 95% CI: 1.08–1.22; $p < 0.0001$). The heterogeneity of the included studies was high and statistically significant ($I^2 = 97\%$, $p < 0.00001$).

Meta-analysis results of HR for preterm birth among pregnant women associated with PM 2.5 air pollution, based on an interquartile range increase in concentration throughout pregnancy.

The pooled effects of PM 2.5 exposure in different trimesters of pregnancy on preterm birth

1st trimester

A $10 \mu\text{g}/\text{m}^3$ increase in PM 2.5 concentration during the first trimester of pregnancy was associated with a non-significant 3% increase in the risk of preterm birth among pregnant women, compared to those living in areas with cleaner air (HR = 1.03; 95% CI: 0.99–1.08; $p = 0.17$). The heterogeneity of the studies included was high, and statistically significant ($I^2 = 89\%$, $p < 0.00001$).

Meta-analysis results of HR for preterm birth among pregnant women during the first trimester of pregnancy associated with PM 2.5 exposure, based on a $10 \mu\text{g}/\text{m}^3$ increase in ambient concentration.

2nd trimester

A $10 \mu\text{g}/\text{m}^3$ increase in PM 2.5 concentration during the second trimester of pregnancy was associated with a statistically significant 2% increase in the risk of preterm birth among pregnant women, compared to those living in areas with cleaner air (HR = 1.02; 95% CI: 1.00–1.03; $p = 0.01$). The heterogeneity of the included studies was moderate, and statistically significant ($I^2 = 77\%$, $p < 0.0001$).

Meta-analysis results of Hazard Ratio for preterm birth among pregnant women during the second trimester of pregnancy associated with PM 2.5 exposure, based on a $10 \mu\text{g}/\text{m}^3$ increase in ambient concentration.

3rd trimester

A $10 \mu\text{g}/\text{m}^3$ increase in PM 2.5 concentration during the third trimester of pregnancy was associated with a non-significant 4% increase in the risk of preterm birth among pregnant women compared to those living in areas with cleaner air (HR = 1.04; 95% CI: 0.99–1.09; $p = 0.15$). The heterogeneity of the included studies was high and statistically significant ($I^2 = 97\%$, $p < 0.00001$).

Sensitivity analysis

We observed significant heterogeneity in most of the meta-analyses. The results showed that, after applying the fixed-effects model, the estimates for the prevalence of preterm birth (PTB) in the global and South American subgroups, as well as the interquartile increase in PM 2.5 concentration, changed compared to the random-effects model (OR = 0.015, 95% CI: 0.015–0.015, $p < 0.001$; OR = 0.013, 95% CI: 0.013–0.013, $p < 0.0001$; OR = 1.14, 95% CI: 1.08–1.22, $p < 0.00001$). Despite these changes, the associations remained statistically significant (OR=0.062, 95% CI 0.042 to 0.082, $p < 0.001$; OR=0.059, 95% CI -0.018 to 0.136, $p < 0.0001$; OR=1.04, 95% CI 1.03 to 1.04, $p < 0.00001$; table 2). A sensitivity analysis was also performed to evaluate a single study's effect on the overall results. The sensitivity analysis of each combined result, after excluding any one of the studies, showed no significant changes in the overall results, suggesting good stability (table 3).

Figures

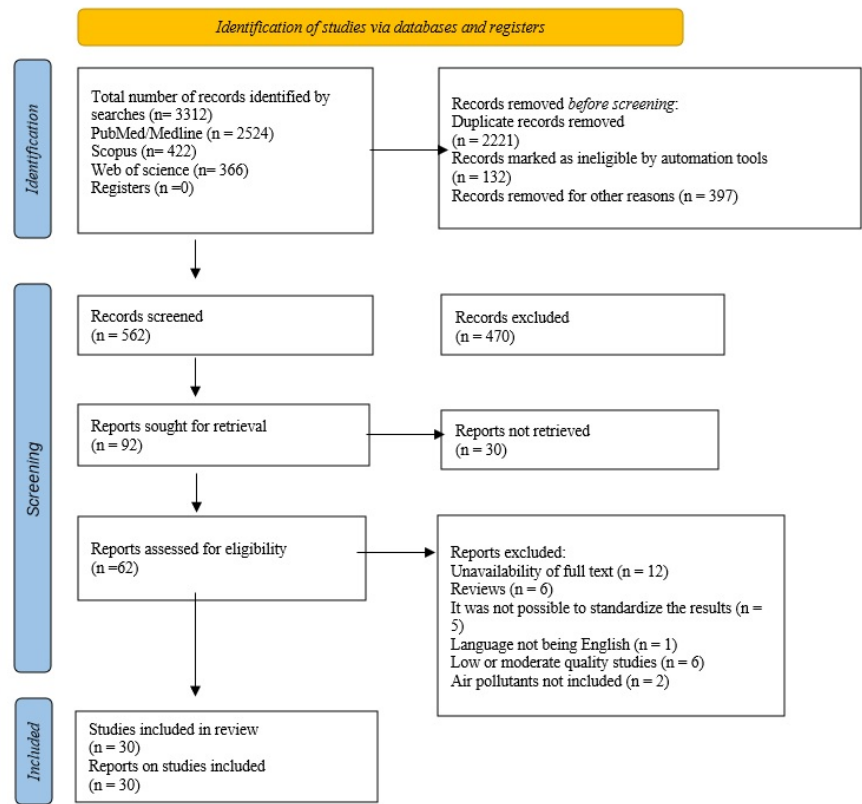


Figure 1: The flowchart of literature search and selection. Figure 1 shows the process of searching and selecting identified literature. We searched three databases (PubMed, Scopus, and Web of Science) up to March 2025. The references of all identified literature were also screened [29].

Tables

Study	Country	Design	Sample Size	Exposure Window	PM2.5 Metric	Effect Estimate (95% CI)	Main Finding
Cassidy-Bushrow et al., 2020	USA	Cohort	7,961	Whole pregnancy	5 µg/m³	OR 0.86 (0.62–1.20)	No significant association
Mitku et al., 2023	South Africa	Cohort	656	Whole pregnancy	IQR	OR 1.20 (1.09–1.29)	Increased PTB risk
Bachwenkizi et al., 2022	Africa (15 countries)	Cohort	131,594	Whole pregnancy	IQR	OR 1.08 (1.01–1.16)	Increased PTB risk
Chen et al., 2021	China	Cohort	10,960	Whole pregnancy	5 µg/m³	HR 1.58 (1.43–1.75)	Increased PTB risk
Fang et al., 2020	China	Cohort	10,738	2nd–3rd trimester	IQR	RR 1.07–1.09	Increased risk in late pregnancy
Yuan et al., 2020	China	Cohort	3,692	Whole pregnancy & trimesters	10 µg/m³	OR 0.89–1.11	No significant association
Wang et al., 2022	China	Cohort	424	Whole pregnancy	IQR	OR 1.37 (1.19–1.61)	Increased PTB risk
Li et al., 2020	China	Cohort	429,865	Whole pregnancy	IQR	OR 1.06 (1.04–1.09)	Increased PTB risk
Ottone et al., 2020	Italy	Cohort	23,708	Whole pregnancy	IQR	OR 1.35 (1.11–1.64)	Increased PTB risk
Siddika et al., 2020	Finland	Cohort	2,568	Whole pregnancy/3rd trimester	IQR	OR 1.67 (1.14–2.46)	Increased PTB risk

Table 1: Characteristics and Main Findings of Included Studies (n = 30).

Study	Hazard Ratio (HR)	95% CI	Weight (%)	SE
Lei Yuan 2020	0.92	0.60–1.41	2.7	0.218
Qihao Chen 2021	1.73	1.36–2.20	7.3	0.1227
Wenzheng Zhou 2021	1.19	1.16–1.22	34.0	0.0125
Xiaotong Zhang 2020	1.13	1.06–1.21	27.3	0.0342
Yiwen Zhang 2024	1.40	1.01–1.94	4.4	0.1665
Youngrin Kwag 2021	1.26	1.16–1.37	24.3	0.0425

Table 2: Summary of studies included in the hazard ratio meta-analysis.

Subgroups	Random-effects model	P value	Fixed-effects model	P value
	Prevalence Proportion (95% CI)		Prevalence Proportion (95% CI)	
Prevalence PTB				
Global	0.062(0.042 to 0.082)	<0.001	0.015(0.015 to 0.015)	<0.001
Eastern Asia	0.048(0.040 to 0.056)	<0.00001	0.039(0.039 to 0.040)	<0.0001
North America	0.085(0.075 to 0.094)	<0.00001	0.080(0.080 to 0.080)	<0.0001
South America	0.059(-0.018 to 0.136)	<0.00001	0.013(0.013 to 0.013)	<0.0001
An increase in the concentration of PM 2.5 in the air				
10-µg/m3	1.22(1.14 to 1.32)	<0.00001	1.19(1.16 to 1.22)	<0.00001
Interquartile	1.14(1.08 to 1.22)	<0.00001	1.04(1.03 to 1.04)	<0.00001
Risks of PTB with an increase by 10-µg/m3 in the second trimester				
PM 2.5	1.02(1.00 to 1.03)	0.01	1.01(1.01 to 1.02)	<0.0001

Table 3: Sensitivity analysis of results of preterm birth (PTB) in the global and South American subgroups.

Subgroups	Excluded study	After study exclusion			
		Random-effects model	P value	Fixed-effects model	P value
		Hazard Ratio (95% CI)		Hazard Ratio (95% CI)	
Prevalence PTB					
Global	Weeberb J. Reguia et al.	0.064(0.051 to 0.077)	<0.001	0.078(0.078 to 0.078)	<0.001
Eastern Asia	Wenzheng Zhou et al.	0.047(0.040 to 0.054)	<0.0001	0.035(0.035 to 0.035)	<0.0001
North America	Zesemayat K. Mekonnen et al.	0.082(0.075 to 0.089)	<0.0001	0.074(0.074 to 0.075)	<0.0001
South America	Weeberb J. Reguia et al.	0.087(0.059 to 0.114)	<0.0001	0.100(0.100 to 0.101)	<0.0001
An increase in the concentration of PM 2.5 in the air					
10-µg/m3	Wenzheng Zhou et al.	1.27(1.11 to 1.45)	0.0005	1.20(1.14 to 1.26)	<0.0001
Interquartile	Liuyan Zheng et al.	1.15(1.10 to 1.200)	<0.00001	1.12(1.11 to 1.14)	<0.00001
Risks of PTB with an increase by 10-µg/m3 in the second trimester					
PM 2.5	Sha Li et al.	1.03(1.01 to 1.05)	0.01	1.01(1.01 to 1.02)	<0.0001

Table 4: The sensitivity analysis of each combined result, after excluding any one of the studies.

DISCUSSION

This meta-analysis included 30 studies published over the past five years, comprising a total sample of over 40.1 million births, to investigate the association between increased PM 2.5 concentrations during pregnancy and the risk of preterm birth (PTB). Despite the quantitatively substantial number of studies included most of the data originated from a limited number of cohorts, primarily located in East Asia and high-income countries.

The results showed that for every 10 µg/m³ increase in PM 2.5 concentration, the risk of PTB increased by 7%. The strongest effect of PM 2.5 exposure was observed with long-term exposure throughout the entire pregnancy.

Fine particulate matter (PM 2.5) poses a serious threat to human health due to its unique characteristics, including small particle size, large surface area, long atmospheric residence time, and high adsorption capacity. Studies by scientists [33] found that PM 2.5 exposure during pregnancy increased the risk of PTB among women in China and the United States. Meanwhile, the systematic review by scholars examined the effects of a broad spectrum of air pollutants and reported that PM 2.5 significantly contributed to the risk of premature rupture of membranes [34]. Our study builds on these findings by providing a comprehensive estimation of

the overall global risk of PTB associated with PM 2.5 exposure, thus contributing to a deeper understanding of the mechanisms by which air pollutants affect reproductive health.

Our analysis also revealed that sensitivity to PM 2.5 exposure varied by gestational trimester. A slight but statistically significant increase in PTB risk was observed during the second trimester, whereas effects in the first and third trimesters did not reach statistical significance. However, studies by scientists identified the third trimester as the most vulnerable period [34-36]. Similarly, [37,38] reported significant associations during both the second and third trimesters, while also observed the strongest effects during the third trimester. These discrepancies may be attributed to several factors. First, variability in exposure assessment methodologies may influence the observed associations. Second, demographic and socioeconomic characteristics of the study populations could play a significant role, as susceptibility to air pollution may differ depending on healthcare access and overall health status. Lastly, regional differences in climate and environmental conditions may have also contributed to the variability in findings. These inconsistencies highlight the need for future research to better identify the most sensitive gestational windows for air pollution exposure [39-41].

Our analysis also found that the impact of PM 2.5 on PTB risk varied by geographic region. The strongest associations were observed in North and South America, while minimal effects were reported in Africa and Southern Europe. Notably, a significant number of studies were conducted in the United States, allowing for more accurate assessment of air pollution's impact on adverse pregnancy outcomes [42-45]. However, data from Africa and Europe remain limited, making it difficult to fully understand regional differences. Future studies in these underrepresented areas are necessary.

Despite the important findings, our study has several limitations. Significant heterogeneity among the included studies may influence the overall conclusions. Differences in air pollution assessment methods, PM 2.5 modeling, and measurement time intervals may contribute to result variability. Second, although the meta-analysis includes a large number of births, systematic errors may exist due to variations in how PTB was defined and assessed across studies [46,47]. Another limitation is the exclusive focus on outdoor air pollution, while indoor exposure to pollutants – which may also significantly impact pregnancy outcomes – was not considered.

The observed variation in PM 2.5 sensitivity across trimesters underscores the need for further research, as well as studies in regions with limited available data [48,49]. This review confirms the significant impact of PM 2.5 exposure on the risk of preterm birth, with notable differences identified across pregnancy trimesters and geographic regions. The findings underscore the urgent need to implement effective measures to reduce air pollution, including the tightening of air quality standards, the development of comprehensive monitoring and early warning systems and the promotion of green technologies. Additionally, efforts to protect vulnerable populations – particularly pregnant women – should be strengthened through educational initiatives, guidance on minimizing personal exposure to pollutants, and improved access to quality healthcare services.

CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHOR CONTRIBUTIONS

Zhanar Sabyrdilda conceived the study, designed the methodology, performed the statistical analysis, and led the writing of the manuscript. Akmaral Abikulova contributed to data collection, literature review, and drafting of the manuscript. Ainur B. Qumar carried out data extraction and quality assessment. Kamshat Tolganbayeva contributed to interpreting the results and assisted in manuscript editing. Lyazzat Kosherbayeva supervised the study, provided critical revisions, and approved the final version of the manuscript. All authors read and approved the final manuscript.

Data Availability

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

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