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The Dual Burden of Air Pollution During Pregnancy: A Systematic Review of Physical and Psychological Consequences

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A R T I C L E I N F O

REVIEW ARTICLE

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ABSTRACT

Introduction: Air pollution affects pregnant women and fetuses, leading to health complications. It increases risks like low birth weight, preterm labor and hypertension. Moreover, mental health issues such as depression and autism spectrum disorders may arise.
Materials and Methods: This systematic review was conducted by examining data from four databases, including Google Scholar, PubMed, Web of Science, and Scopus covering the period from 2020 to 2024. The keywords used included "air pollution," "pregnant women," "fetal health," "pregnancy complications," "particulate matter," and "mental health". Using specific criteria, 109 studies were found. After excluding unrelated articles, 63 studies were analyzedand key information was extracted.
Results: Air pollution significantly affects the physical and mental health of pregnant women. It increases the risk of depression, anxiety and autism spectrum disorders, with $PM_{2.5}$ and NO_2 being major contributors. Physical complications like preterm labor, gestational diabetes, miscarriage and preeclampsia are strongly linked to pollution. Lower-income women face higher exposure and mental health risks due to socioeconomic factors. Furthermore, living in urban areas and near pollution sources elevates health risks for mothers and fetuses. The second and third trimesters are the most vulnerable periods, highlighting the need for effective interventions.
Conclusion: Air pollution severely affects the physical and mental health of pregnant women and fetuses, especially during the second and third trimesters. Preventive measures like air quality improvement and policy-making are crucial to protect maternal and fetal health.

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Introduction

Air pollution is a major environmental and public health challenge worldwide with detrimental effects on both physical and mental health. This issue is particularly significant during pregnancy, which is a crucial period for maternal and fetal health. Pregnant women are more vulnerable to environmental pollutants due to physiological changes such as increased ventilation rates and altered oxygen transport capacity[1]. Studies have shown that pollutants such as particulate matter ($PM_{2.5}$, PM_{10}), nitrogen dioxide (NO_2), and ozone (O_3) can lead to adverse outcomes, including low birth weight, preterm

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birth, gestational diabetes, hypertensive disorders, respiratory problems, preeclampsia, and fetal growth restriction[2-4]. In addition to its physical effects, air pollution can also affect the mental health of pregnant women. Evidence suggests that exposure to pollutants may be associated with increased stress, anxiety, postpartum depression, and a higher risk of autism spectrum disorders in offspring [5-7]. Furthermore, air pollution can increase oxidative stress and inflammation in the mother's body, which negatively affects fetal health[7]. These effects impact both maternal health and the child's psychosocial and developmental outcomes[8, 9]. The underlying mechanisms of these effects include inflammation, hormonal dysregulation, and damage to the blood-brain barrier, which may result in neurological changes in the fetus[10, 11].

Socioeconomic status also plays a crucial role in air pollution severity. Women living in lower-income areas or with limited access to healthcare services are generally at a greater risk. These groups often face challenges such as reliance on biomass fuels for cooking or heating, which can increase pollutant exposure[2, 12]. Moreover, some studies indicate that mothers residing in areas with lower income levels and higher inequality are at a greater risk of preterm delivery; average household income is lower in these regions than in areas with normal deliveries[13, 14]. Geographic factors also contribute significantly to this issue. Pregnant women in urban and industrial regions, particularly developing countries, are more exposed to severe pollution [15]. Additionally, geographic location and environmental conditions, such as proximity to pollution sources or population density, can exacerbate the impact of air pollution[16, 17]. In densely populated urban areas such as Beijing and Los Angeles, high levels of $PM_{2.5}$ have been associated with negative maternal and fetal health outcomes. Similarly, in rural areas, such as Nagpur, India, the use of polluting fuels has led to an increase in diseases[16, 18].

Given growing concerns about the effects of air pollution on maternal and fetal health, a comprehensive examination of its physical and psychological impacts on pregnant women is essential. This review article aims to analyze the existing findings on this topic while identifying factors that influence the severity of these effects. To facilitate the understanding of these impacts, tables and charts that assisted in data analysis were utilized. This review aims to present a comprehensive picture of the effects of air pollution on the health of pregnant mothers and to identify the factors influencing the severity of these impacts.

Materials and Methods

A systematic review was conducted to evaluate the physical and psychological effects of air pollution in pregnant women. Data collection followed the PRISMA guidelines by searching five major databases: Google Scholar, PubMed, Web of Science, Scopus, and ScienceDirect within the period from 2020 to 2024. The search used topic-related keywords, including air pollution, pregnancy, mental health, physical health, AND, OR PM, combined with logical operators (AND, OR). The Prisma diagram (Figure 1) clearly illustrates the article selection process and includes the number of initial articles, articles removed, and final articles included in the ultimate analysis.

The inclusion criteria were articles published in the last five years, studies examining the physical and psychological effects of air pollution on pregnant women, and studies that had full text and sufficient data. The exclusion criteria were duplicate articles, irrelevant studies, and those lacking sufficient scientific quality. In the initial phase, 109 relevant articles were identified through the database searches. The titles and abstracts were screened to exclude studies that did not meet the relevant criteria. In the second phase, the full texts of the remaining articles were reviewed and 63 articles were selected for the final analysis. Key information from the selected articles was extracted and organized into tables. The collected data were categorized according to their physical and psychological effects and systematically analyzed to identify patterns or contradictions. Finally, the findings are presented in tables and the qualitative data analysis.

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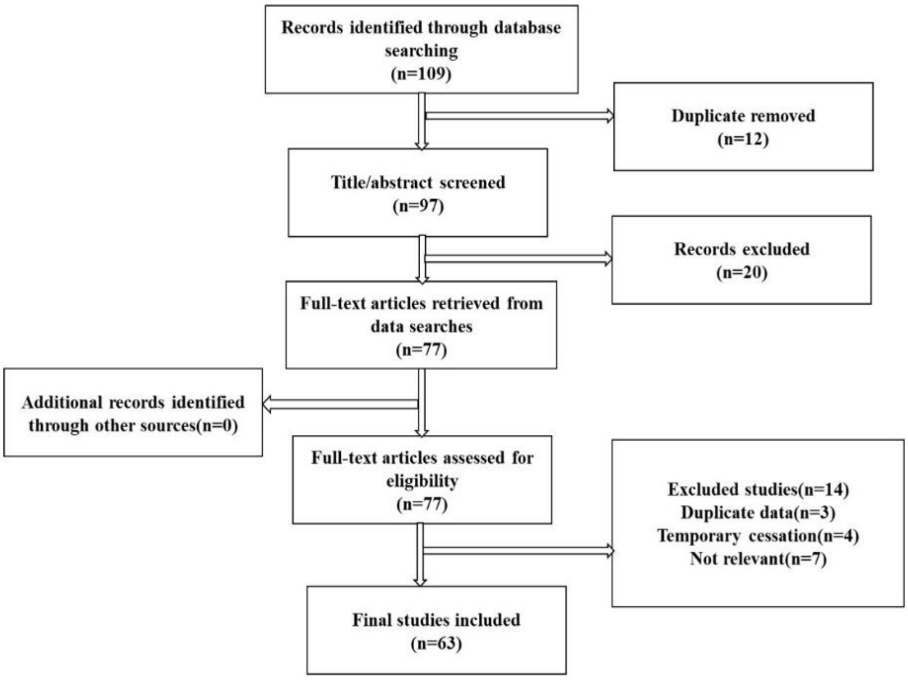

Figure 1: PRISMA flow diagram in this study

Results

Given the significant impact of air pollution on the physical and mental health of pregnant women, examining the various dimensions of its effects are of particular importance. Table 1 summarizes the number of studies conducted on mental disorders caused by pregnant mothers' exposure to air pollution, and clearly depicts the relationship between pollution and various disorders.

Table 1: Number of studies conducted on psychological abnormalities resulting from pregnant mothers' exposure to air pollution

Reference	Disease	Number of studies	Number of cases
6, 19, 20	Depression and anxiety	3	1157
7, 21	Autism spectrum disorders	2	475
22	Psychosocial problems	1	360
5, 20	Depression and psychological stress and their impact on immune responses in infants	2	-
23	Postpartum depression	1	90

Table 2 provides further details on the types of disorders and specific conditions related to pollution. This table summarizes studies linking pregnant mothers' exposure to air pollution with psychological disorders in their offspring. Pollutants such as $PM_{2.5}$, PM_{10}, NO_2, O_3, benzene, toluene, and black carbon are associated with increased risks of prenatal psychosocial stress, depression, anxiety, autism spectrum disorders, and postpartum depression. Study designs included prospective cohort, case-control, and longitudinal cohort studies with sample sizes ranging from 29 to 2153 participants. Affected ages ranged from 23 to 33 years, with some studies noting impacts on participants under 23 years of age. Exposure settings varied between indoor, outdoor, and both, with one study conducted during spring and another during rainy seasons

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Table 2: Psychological disorders and abnormalities resulting from pregnant mothers' exposure to air pollution

Reference	Disease	Study Type	Country	Sample Size	Responsible pollutant	Indoor /Outdoor	Age Group Affected	Season
5	Prenatal Psychosocial Stress	Prospective cohort Study	South Korea	2153	$PM_{2.5}$ PM_{10} O_3	Outdoor	33	Spring
6	Depression and Anxiety	Prospective cohort Study	South Korea (Seoul)	1048(221depression,827 anxiety)	NO_2 O_3 $< PM_{2.5}$ $< PM_{10}$	Indoor	32-33	-
19	Depression	Prospective cohort Study	California	29(180controls)	NO_2 $PM_{2.5}$	Outdoor	29-30	-
7	Autism Spectrum Disorders	Case-control study	California	Total 957 199 (Autism Spectrum Disorder) ASD without intellectual disability, 180 ASD with intellectual disability	$PM_{2.5}$	Outdoor	29	-
22	Psychosocial problems	Prospective cohort Study	South Africa	360	PM_{10} Benzene Toluene	Indoor	26.87	-
20	Depression and psychosocial stress	Longitudinal Prospective cohort	USA	Total 463 80 with depression	$PM_{2.5}$ BC [1]	Outdoor	%94 of participants under age 23	-
23	Postpartum depression	Prospective cohort study	Mexico	90(419 controls)	$PM_{2.5}$	Both	27.4	Rainy
21	Autism spectrum disorders	Observational study	USA	96	$PM_{2.5}$	Outdoor	-	-

[1] Black carbon

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Tables 3 and 4 examine the physical abnormalities caused by air pollution and provide comprehensive information about the various effects on the physical health of pregnant mothers.

Table 3: Number of studies conducted on physical abnormalities resulting from pregnant mothers' exposure to air pollution

Reference	Disease	No. of studies	No. of Cases
2, 24	Anemia	2	1149
3, 25	Preeclampsia	2	2988
16, 17, 26-30 31, 32 14, 33, 13	Preterm labor	12	-
12, 16, 34, 18, 35-38	Respiratory problems and asthma	7	-
26, 31, 32, 39-42	Gestational diabetes	6	19685
17, 29, 35, 43	Miscarriage	4	7704
44-47	Autoimmune thyroid disease	4	3768
48	Effect of exposure to PM on hematological indices in women ready for pregnancy	1	-
49	Infertility	1	-
15, 50-52	Hypertension disorders	4	3575
53	Anencephaly	1	663
37, 54	Congenital anomalies (cardiovascular, gastrointestinal)	2	-
55	Antiphospholipid syndrome	1	182
56	Kidney function disorder	1	10052
57	Oxidative stress	1	100
58	Lead-induced injuries	1	-
59	Glucose intolerance	1	-
60	Polycystic ovary syndrome	1	1652
61	Pregnancy Complications (APPO)	1	-
62	Reduced fertility in IVF patients	1	-
63	Biological stress	1	-
64	Heavy metal poisoning	1	-
65	Selenium deficiency in pregnant woman	1	13
66	Macrosomia	1	15348
36	Respiratory infection, heart disease, lung cancer	1	-
67, 68	No specific disease mentioned (impact of air pollution on pregnant women's health)	2	1368

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Table 4: Physical diseases and abnormalities resulting from pregnant mothers' exposure to air pollution

Reference	Disease	Study type	Country	Sample size	Responsible pollutant	Indoor /Outdoor	Age group affected	Season
2	Anemia	Randomized controlled multicountry trial	Guatemala, India, Peru, Rwanda	853 (2310 controls)	$PM_{2.5}$, CO (less association)	Indoor	18-35, mostly under 25	Cold and warm months
3	Preeclampsia	longitudinal study	USA	1066	$PM_{2.5}$, O_3, NO_2	Outdoor	31.9	All seasons
16	Preterm birth, gestational diabetes, respiratory issues, postpartum depression	Prospective cohort	USA (Los Angeles, California)	63(2)	$PM_{2.5}$	Both	28.7	-
17	Miscarriage, preterm birth, low birth weight	Retrospective cohort	Nepal	1716 total, 74 preterm births, 25 miscarriages, 221 low birth weight (1449 with at least one adverse outcome)	$PM_{2.5}$	Outdoor	24	Wet and dry
44	Thyroid autoimmunity	Prospective cohort	China	1759 (15664 controls)	$PM_{2.5}$	Outdoor	31-32	Various seasons
26	Gestational diabetes, preterm birth	Case-control study	South Korea	60 (cases studied), 10 with gestational diabetes, 4 preterm births	$< PM_{2.5}$	Indoor	-	-
48	Effects of PM on hematological Indices in women preparing for pregnancy	Prospective cohort	China	1,203,565	PM_1, $PM_{2.5}$ (more)	Outdoor	18-25	-
54	Congenital anomalies (cardiovascular, gastrointestinal)	Retrospective cohort	South Korea	1624 total, 216 with anomalies	$PM_{2.5}$	Outdoor	33.8	-
15	Hypertension disorders in pregnancy	Retrospective cohort	China	440 (8336 controls)	$PM_{2.5}$	Outdoor	30.5	-
53	Anencephaly	Case-control	China	663 (7950 controls)	PM_{10}	Outdoor	20-34	Spring
34	Respiratory infections	Retrospective cohort	Israel	57,331 total, 1871 cases	$PM_{2.5}$	Outdoor	28.2	-
39	Gestational diabetes	Prospective cohort	China	394 (4783 controls)	$PM_{2.5}$	Outdoor	30	-

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Reference	Disease	Study type	Country	Sample size	Responsible pollutant	Indoor /Outdoor	Age group affected	Season
42	Adverse pregnancy outcomes	Retrospective cohort	Peru	123,034 total, 16% mothers with gestational diabetes (19685)	$PM_{2.5}$	Outdoor	22-39	-
45	Thyroid disorders	Prospective cohort	China	921 (1521 controls)	$PM_{2.5}$	Outdoor	28	-
46	Hypothyroidism	Retrospective case-control	China	795 (2385 controls)	PM	Outdoor	31	Winter
12	Pregnancy complications (preterm birth, respiratory issues)	Population-based Cohort	USA (Texas)	7,043,598 totals	NO_2	Outdoor	26.8	-
68	Health problems	Cross-sectional questionnaire-based	Poland	1095 (3451)	$< PM_{2.5}$ $PM_{2.5}$	Outdoor	31-35	-
38	Asthma	Multicenter Prospective cohort	USA	311	$PM_{2.5}$	Both	30	-
67	No specific disease mentioned (impact of air pollution on pregnant women's health)	Prospective Cohort	New York	273 (224 controls)	NO_2 PM	Both	33	-
55	Antiphospholipid syndrome	Pilot study	China	182 (189 controls)	$PM_{2.5}$ PM_{10}	Outdoor	31-32	All seasons
56	Renal dysfunction	Prospective cohort	China	1052 (2350 controls)	$PM_{2.5}$	Outdoor	35	Winter
27	Preterm birth	Retrospective cohort	China	7974	$PM_{2.5}$	Outdoor	Over 35	-
57	Oxidative stress	Case-control	China	200 total, 100 cases	$PM_{2.5}$	Outdoor	32	-
58	Lead exposure injuries	Cross-sectional	Japan	87	Lead	Indoor	32.2	Winter and autumn
40	Gestational diabetes	Observational cohort	Finland	6189 total, 1003 (5186 controls)	PM_{10}	Outdoor	30	-
28	Preterm birth	Prospective cohort	France (Guadeloupe)	906	Desert dust, PM_{10}	Outdoor	-	Spring and summer
50	Hypertension disorders	Prospective cohort	China	7658 studied, 410 cases (7248 controls)	$PM_{2.5}$	Outdoor	28.3	Cold
59	Glucose intolerance	Cross-sectional	Iran (Sabzevar)	250	PM_1 $PM_{2.5}$ PM_{10}	Outdoor	28	Summer

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Reference	Disease	Study type	Country	Sample size	Responsible pollutant	Indoor /Outdoor	Age group affected	Season
24	Anemia	Cross-sectional	Ethiopia	732 total, 296 (436 controls)	Indoor pollution from fuels	Indoor	25-34	-
43	Miscarriage	Epidemiological observational study	Australia	967694 controls, 4287 cases	< $PM_{2.5}$ < PM_{10} O_3	Outdoor	< 35	-
60	Polycystic ovary syndrome (PCOS)	Retrospective Cohort	Chi/na (Shanghai)	14295 totals, 1652 with PCOS (Polycystic Over Syndrome), 12543 without PCOS	< $PM_{2.5}$ < PM_{10} O_3 NO_2 SO_2 CO	Outdoor	< 30	Summer
41	Gestational diabetes syndrome	Retrospective cohort	China	372 (9820 controls)	PM_{10} $PM_{2.5}$ NO_2	Outdoor	Over 35	-
61	Pregnancy complications	Prospective cohort	South Korea	1200 total participants, 333 cases studied	< $PM_{2.5}$ < PM10	Both	33.6	All seasons
62	Reduced fertility in IVF (In Vitro Fertilization) patients	Prospective cohort	Spain (Barcelona)	194	PM, especially $PM_{2.5}$, PM_{10}	Indoor	Over 35	-
25	Preeclampsia	Retrospective Cohort	China	116042 total, 2988 cases (113054 controls)	NO_2, O_3, $PM_{2.5}$, PM_{10}	Outdoor	Over 35 and under 20	Cold and warm seasons
29	Preterm birth, miscarriage	Retrospective cohort	London	581774 total, 33712 preterm births, 3392 miscarriages	O_3 $PM_{2.5}$	Outdoor	Over 35	Spring
52	Hypertension disorders in pregnancy HDP (Hypertensive Disorders of Pregnancy)	Prospective cohort	Italy (Lombardy)	528	$PM_{2.5}$ PM_{10}	Outdoor	33	Winter
30	Preterm birth	Cross-sectional	China (Hubei Province)	429865 totals studied, 2.98% affected	<$PM_{2.5}$	Outdoor	26-27	-
31	Preterm birth, gestational diabetes	Multicenter prospective cohort	Korea	662 studied, 138 with pregnancy complications,	$PM_{2.5}$ PM_{10}	Indoor	Over 35	Winter and spring

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Reference	Disease	Study type	Country	Sample size	Responsible pollutant	Indoor /Outdoor	Age group affected	Season
				61 preterm births				
32	Pregnancy complications (preterm birth, gestational diabetes)	Retrospective cohort	Kansas	41936 preterm births, 20455 gestational Diabetes, 24258 hypertension disorders	O_3, NO_2	Outdoor	27	-
51	Hypertension disorders	Retrospective cohort	China (Handan)	2197 (9820 controls)	$PM_{2.5}$, PM_{10}, O_3, NO_2	Indoor	25-35	-
33	Preterm birth	Retrospective Cohort	Brazil	313286 studied, 21928 preterm births	PM	Outdoor	25	-
49	Infertility	Cross-sectional	Poland	511	$PM_{2.5}$, O_3, CO, NO_x, SO_2	Outdoor	31-39	-
63	Biological stress	Prospective Cohort	Belgium	133	$PM_{2.5}$, NO_2, BC	Outdoor	26-30	All seasons
14	Preterm birth	Retrospective	California	966652 population studied, 88895 preterm births	$PM_{2.5}$, O_3	Outdoor	Under 20 and over 35	Spring and summer
18	Respiratory diseases	Cross-sectional	India	60	Indoor air pollution, PM environmental toxins	Indoor	23	-
47	Hypothyroidism	Retrospective	Greece	293	$< PM_{2.5}$	Indoor	30.9	Winter
64	Heavy metal poisoning	Cross-sectional	Israel	143	Nitrogen oxides, PM, sulfur dioxide	Both	28	-
65	Selenium deficiency in pregnant women	Cross-sectional	China	273 studied, 13 with selenium deficiency, 65 high levels, 195 normal	Indoor air pollution from coal burning	Indoor	26.45	-
35	Respiratory issues (asthma, cough, sneezing), eye irritation, suffocation, miscarriage	Qualitative phenomenological study	Ethiopia	15	PM from biomass fuels (wood, agricultural waste)	Indoor	27	-
66	Macrosomia	Retrospective Cohort	China	197,877 totals (15,348 cases, 182,529 controls)	$PM_{2.5}$, SHS	Both	25	Spring and winter
36	Respiratory infections, cardiovascular disease, lung cancer	Feasibility study	Bangladesh	Total population 30, data from 22 individuals	$< PM_{2.5}$ CO	Indoor	-	-

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Reference	Disease	Study type	Country	Sample size	Responsible pollutant	Indoor /Outdoor	Age group affected	Season
69	Respiratory and health issues (fatigue, headache, eye problems)	Cross-sectional study	Western Kenya	251	Smoke from wood burning (PM, CO, VOCs), NO_x	Indoor	36.49	-
37	Negative effects on reproductive health (respiratory, cardiovascular issues, infertility)	Cross-sectional study	Pakistan, India, Bangladesh	Approximately 1.7 billion (14.325 million Pakistan, 600,105 India, 17.205 million Bangladesh)	Pollutants from cooking fuels	Indoor	-	-
13	Preterm birth	Cross-sectional study	California	341123 (3,753,799)	< $PM_{2.5}$, NO_2, O_3	Outdoor	-	-

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Discussion

Effects of Air Pollution on Mental Health

The results presented in Table 2 indicate that air pollution affects not only the physical health but also the mental health of pregnant women. Pollutants, such as NO_2, $PM_{2.5}$, and O_3, are specifically associated with an increased risk of mental health disorders, including depression, anxiety, and autism spectrum disorders (ASD)[6, 7]. These findings highlight the critical need to improve air quality in the living environments of pregnant women and call for effective measures to reduce air pollution and support this vulnerable group in society[6, 7].

Effects on the Fetus

Studies have shown that air pollution can have varying effects on the fetus during different trimesters of pregnancy. In particular, the second trimester has been identified as a sensitive period for fetal brain development. Exposure to air pollution during this phase has been linked to future cognitive and behavioralproblems[6, 7]. Additionally, psychological stress caused by air pollution can negatively affect fetal growth. Research indicates that women exposed to high levels of air pollution are more likely to have fetuses with growth impairments and behavioral disorders [5].

Geographical Context

Geographical location, particularly in low- and middle-income countries (LMICs), can profoundly affect the mental health of pregnant women. In these regions, urban air pollution is mainly driven by industrialization, and heavy traffic places pregnant women at a heightened risk. Additionally, poor environmental conditions and limited access to green spaces exacerbate psychological problems. Pregnant women in these areas often face greater socioeconomic challenges, which can further contribute to mental health problems[6, 22].

Some studies have focused on urban areas, such as Seoul and Los Angeles, where high population density and heavy traffic significantly increase air pollution levels. In Los Angeles, many participants were from low-income communities, highlighting their increased vulnerability to pollution[5, 19]. Furthermore, research conducted in South Africa and Massachusetts identified proximity to highways and use of alternative fuels as risk factors for pregnant women[20, 22].

Effects of Air Pollution on Physical Health

The results presented in Tables 3 and 4 demonstrate that air pollution significantly affected the physical health of pregnant women. Pollutants, such as NO_2, $PM_{2.5}$, PM_{10}, and O_3, are specifically associated with an increased risk of physical conditions, including respiratory problems, preterm birth, infertility, and preeclampsia. Additionally, air pollution can lead to increased oxidative stress and inflammation in the mother's body, which can adversely affect fetal health. These findings underscore the urgent need to focus on improving air quality in the living environment of pregnant women and implementing effective measures to reduce air pollution exposure.

Effects on the Fetus

Research indicates that the impact of air pollution on the fetus varies across different stages of pregnancy, with potentially serious consequences for both maternal and fetal health. During the first trimester, the fetus is highly dependent on maternal thyroid hormones, and any disruption in these hormones can significantly affect fetal growth and development[45]. Exposure to $PM_{2.5}$ during this period is directly linked to an increased risk of gestational diabetes mellitus (GDM) and hypertensive disorders of pregnancy (HDP), with a reported relative risk (RR) of 3.89 (95% CI: 1.45–10.43)[15]. Additionally, a 26% increase in congenital anomalies has been observed for every 7.23 $\mu g/m^3$ rise in $PM_{2.5}$ concentration[54]. Thus, this period is recognized as a critical window for the adverse effects of air pollution.

In the second trimester, the effects of $PM_{2.5}$, and NO_2 become more pronounced, particularly concerning maternal and fetal health. $PM_{2.5}$, during this phase, is strongly associated with an increased risk of HDP and preterm birth[32, 50]. This stage is also linked to a higher likelihood of fetal anomalies and growth impairments due to elevated

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concentrations of NO_2 and $PM_{2.5}$[19].

Although the effects of air pollution remain significant in the third trimester, they are particularly evident in the reduced estimated glomerular filtration rate (eGFR) and increased risk of anemia in pregnant women[24, 56]. Moreover, the highest risk for preterm birth is associated with cumulative $PM_{2.5}$ exposure throughout pregnancy[14]. These effects can lead to severe complications, such as preterm delivery and low birth weight.

Overall, the most substantial effects of air pollution were observed during the first and second trimesters, which are critical periods for fetal growth and development. Exposure during these sensitive windows increases the risk of complications such as GDM, HDP, congenital anomalies, preterm birth, and growth impairments[19, 45, 50].

It is important to note that there is considerable heterogeneity among the studies included in this systematic review. Differences in study design (e.g., cohort vs. case-control), population characteristics (e.g., maternal age, socioeconomic status, and underlying health conditions), and methods of exposure assessment (e.g., direct environmental monitoring, satellite-based estimates, or self-reported data) may significantly influence the reported outcomes. For instance, while some studies estimated $PM_{2.5}$ concentrations using modeling techniques, others relied on stationary air quality monitoring stations or participant surveys. Additionally, the timing and duration of exposure assessment (e.g., a specific trimester vs. the entire pregnancy) varied across studies, which could explain some inconsistencies in the results.[10, 14, 67]

Therefore, these differences should be carefully considered when interpreting the overall findings as they may affect the strength and generalizability of the associations between air pollution and pregnancy outcomes.

Geographical Context

Research has shown that the incidence of anemia in pregnant women is significantly higher in countries with severe air pollution. India has the highest prevalence, with 51.8% of pregnant women affected, followed by Peru (26.5%), Rwanda (15.4%), and Guatemala (6.3%). The primary cause of this condition is air pollution resulting from the use of biomass fuels for cooking and heating, which is strongly associated with exposure to $PM_{2.5}$) and carbon monoxide (CO)[2]. Women residing in urban areas, particularly in Los Angeles, are exposed to higher levels of $PM_{2.5}$, owing to traffic and industrial emissions[16]. In Nepal, urban residency has been linked to adverse effects on birth weight[17].

In China, the highest prevalence of autoimmune thyroid disorders has been observed among women with annual incomes below $27,597 USD, highlighting the relationship between economic status and health outcomes[44]. Similarly, Daegu, South Korea, reported the highest incidence of autoimmune diseases in the region[54]. Studies conducted in major industrial cities, such as Shanghai and Beijing, have revealed that air pollution from industrial activities and traffic is particularly severe in these areas[15]. In Lima, the eastern regions with unique geographical conditions and the highest $PM_{2.5}$ concentrations also reported the highest prevalence of anemia[42].

Poland accounts for 36 of the 50 most polluted cities in the European Union owing to its dense industrial activity and reliance on fossil fuels[49]. In California, poverty and socioeconomic inequalities are major contributors to the increased risk of preterm birth in polluted regions[14]. Additionally, rural areas such as Butajira in Ethiopia face heightened pollution levels due to poor socioeconomic conditions and reliance on polluting fuels, exacerbating health risks for pregnant women[35].

Economy and Income

Economic status and income play critical roles in the severity of the physical and psychological effects of air pollution on pregnant women. Studies indicate that pregnant women living in poor economic conditions are more likely to experience psychological stress, which may stem from limited access to adequate healthcare, lack of supportive

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resources, and financial concerns. Financial crises and economic insecurity often lead to feelings of hopelessness and an inability to meet their own and their fetuses' needs, increasing the risk of anxiety disorders and depression during pregnancy[22].

Even among women with relatively higher incomes, such as those earning more than $2,738.59 per month, approximately 50% reported annual incomes below $30,000, reflecting the existing economic challenges[5, 19]. Additionally, 35.6% of the mothers relied on public insurance, highlighting their middle or low economic status[7]. Pregnant women living in lower-income areas are generally exposed to higher levels of air pollution, underscoring the socioeconomic disparities in air pollution exposure[3]. Furthermore, the average household income in regions with higher rates of preterm births is lower than that in areas with normal deliveries[14].

Low economic status not only increases pregnant women's exposure to air pollution but also limits their access to medical services. This situation leads to greater reliance on polluting fuels, which increases the risk of diseases such as anemia[24]. Conversely, women with higher incomes and better access to healthcare were able to mitigate the negative effects of air pollution. For instance, 67.2% of women with annual incomes exceeding $6,870 or those with university education reported better physical and mental health outcomes[43, 50].

In summary, economic status is a key determinant of the severity of the physical and psychological effects of air pollution in pregnant women. Women living in poor economic conditions face simultaneous challenges from financial stress and the physical impact of exposure to air pollution.

Another important limitation of the included studies is the limited consideration of individual-level confounding factors that may have significantly influenced the observed associations between air pollution and pregnancy outcomes. For instance, maternal smoking, dietary habits, physical activity, and alcohol consumption can independently affect fetal development and may correlate with environmental exposure levels[5, 11]. Pre-existing conditions, such as diabetes, hypertension, or asthma, may increase physiological vulnerability to air pollutants and thus amplify health risks, independent of pollution levels. Access to healthcare services, including prenatal checkups and mental health support, can also moderate the impact of air pollution but was rarely accounted for in the reviewed studies. Furthermore, differences in maternal education and health literacy influence how well mothers can avoid or respond to pollution exposure, particularly in high-risk environments[7, 21, 22]. Failure to consistently adjust for these variables may result in either an overestimation or underestimation of the true effects of air pollution. Therefore, future studies should incorporate these factors through robust multivariate analyses or matched-cohort designs to isolate the direct impact of air pollution with greater accuracy[12, 21].

Mean Age of Pregnant Women

The mean age of pregnant women varies significantly across studies and plays a crucial role in the physical and psychological effects of air pollution. In most studies, the mean age is approximately 26.9 years, which is considered a critical period for the psychological and physical development of pregnant women. Women who become pregnant at this age may face unique challenges such as hormonal changes and social pressures, which can increase the risk of psychological issues[5, 6].

In some studies, the mean maternal age ranged from 26.87 to 33 years, with others reporting an average of 29. These data suggest that pregnancy is more common among younger women, although factors such as economic status, education, and cultural attitudes may influence this trend[7, 19]. Additionally, research has shown that younger women are more affected by air pollution, emphasizing the importance of considering maternal age in studies on the effects of air pollution[22].

Some studies have specifically examined the mean age of mothers within groups that are

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affected by certain conditions. For instance, one study reported a mean maternal age of 25.4, with 48.7% under 25 and 36.6% over 25 [2]. Another study highlighted differences in the mean age of mothers with conditions such as PCOS or gestational diabetes mellitus (GDM); for example, the mean age of women with PCOS was approximately 29.49 compared to 32.46 for those without PCOS[60]. Women aged > 35 years are also at higher risk of conditions such as GDM or preeclampsia[25, 41].

Overall, studies indicate that the average age of pregnant women generally falls between 25 and 35 [51]. However, variations across studies highlight the influence of factors such as socioeconomic status, education level, and environmental conditions on this metric. Furthermore, the association between advanced maternal age and increased risk of preterm birth or pregnancy-related complications underscores the importance of considering maternal age in research on the physical and psychological effects of air pollution[27]. These findings suggest that maternal age is a critical variable that requires close attention in future studies regarding the impact of air pollution on pregnancy outcomes.

Factors Influencing Exposure

The exposure of pregnant women to $PM_{2.5}$, PM_{10}, and other air pollutants is influenced by a range of factors, including individual characteristics, socioeconomic conditions, geographical and environmental factors, and lifestyle behaviors. Studies have shown that air pollution, particularly from PM and volatile organic compounds (VOCs), can lead to physical and psychological health problems in pregnant women. These include an increased risk of anxiety disorders, depression, and even behavioral and cognitive disorders in children [5, 6].

Individual factors, such as maternal age, education level, socioeconomic status, and pre-pregnancy body mass index (BMI) are significant determinants of air pollution exposure. Younger women and those with lower educational levels are typically more affected by air pollution[6]. Behavioral habits, such as smoking or using polluting fuels for cooking, can also increase exposure to $PM_{2.5}$. The use of solid fuels, such as coal or wood, in poorly ventilated indoor environments has been linked to reduced hemoglobin levels and a higher prevalence of anemia in pregnant women[2, 34].

Geographical factors also play critical roles in PM exposure. Living near pollution sources, such as highways or industrial areas, significantly increases exposure levels[22]. In rural areas where open fires are often used for cooking or where homes lack proper ventilation, indoor $PM_{2.5}$ concentrations can be particularly high [38, 69]. Regression models estimating exposure based on participants' residential addresses have identified location and traffic density as key determinants of pollution levels [7].

Socioeconomic conditions further influenced PM exposure. Pregnant women living in poverty or income inequality are often more exposed to air pollution because of limited access to healthcare services and residence in areas with poorer air quality[14]. Additionally, low socioeconomic status can exacerbate psychological stress from family problems or a lack of social support, compounding the physical and mental effects of air pollution[21].

Overall, the factors influencing PM exposure represent a complex interplay of individual, environmental, and socioeconomic variables that directly or indirectly affect the physical and mental health of pregnant women. These findings highlight the need for policies aimed at reducing pollution sources, improving the living conditions of pregnant women, and providing socioeconomic support to mitigate the adverse effects of air pollution.

Conclusion

These studies demonstrate that air pollution has significant physical and psychological effects on pregnant women and their fetuses. Pollutants such as $PM_{2.5}$, PM_{10}, NO_2, and O_3 are specifically associated with an increased risk of mental health disorders, including depression, anxiety, autism spectrum disorders, and psychological stress, as well as physical complications, such as preterm

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birth, gestational diabetes, preeclampsia, anemia, respiratory issues, miscarriage, and congenital anomalies. Exposure to air pollution during pregnancy not only threatens maternal mental health but also affects fetal development by altering immune responses.

Research highlights that the second and third trimesters are the most sensitive periods to the adverse effects of air pollution. Socioeconomic factors also play a crucial role in the severity of these effects. Women living in low-income areas or with limited access to healthcare are at higher risk. Geographical location is another key factor; residing in densely populated urban areas or near pollution sources, such as highways, increases exposure levels. Seasonal variations also influence the severity of pollution effects, with $PM_{2.5}$, having the most pronounced impact during winter months.

These findings emphasize the urgent need for preventive measures to reduce the exposure of pregnant women to air pollution. Environmental policies aimed at reducing pollutant emissions, improving urban air quality, increasing access to adequate healthcare services, and providing social and economic support to pregnant women should be prioritized. Public education on the risks of air pollution and strategies for minimizing exposure can also play a vital role in mitigating negative outcomes. Ultimately, ensuring clean air in the living environment of pregnant women must be a primary focus of public health policies to prevent physical and psychological complications and safeguard the health of future generations. Given the diversity in study designs, differences in study populations, and variations in exposure assessment methods, generalization of the findings from this systematic review should be approached with caution. The use of advanced analytical methods and meta-analyses in future studies provided that data homogeneity can contribute to more precise and reliable results.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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Ethical Consideration

This study was conducted without ethical approval.

Code of Ethics

This review article is an independent scientific research and has not been registered as a university research project; nevertheless, all relevant research ethics principles have been duly respected**.**

Author's contributions

All the authors contributed equally to this article.

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