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Effects of maternal exposure to indoor air pollution on maternal health and pregnancy outcomes in Wenzhou City, China

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Tiantian Mu [1], Qiaojuan Shan[2], Guangyu Zhu [3], Yang Xu [4] and Osman Alipour[5]*

School of Housing, Building and Planning, Universiti Sains Malaysia[1]; School of Multimedia Technology and Communication, Universiti Utara Malaysia[2]; School of Design and Art Communications University of Zhejiang, Communication University of Zhejiang[3]; Arts College of WuYi University, Wu Yi University[4]; Young Researchers and Elite Club, Sardasht Branch, Islamic Azad University, City, Iran[5]

***For Correspondence:** Email: *shan_qiaojuan@ahsgs.uum.edu.my*

Abstract

Indoor air pollution, originating from household and chemical sources, has attracted increasing attention as an important risk factor for maternal and fetal health in densely populated Chinese cities such as Wenzhou, due to the widespread use of chemical products and inadequate ventilation. This study investigated its impact on maternal health and pregnancy outcomes, in which 520 nonsmoking pregnant women (aged 18–40 years) from antenatal clinics in Wenzhou were enrolled in a prospective cohort study. Indoor pollutants (concentrations of formaldehyde, nitrogen dioxide, volatile organic compounds) were measured at 34 weeks of pregnancy using passive sampling methods, and maternal health data (gestational diabetes mellitus, gestational hypertension, respiratory symptoms) and pregnancy outcomes (gestational age, birth weight, body length, head circumference) were collected from medical records and questionnaires and analyzed with multivariate logistic and linear regression. The results showed that exposure to concentrations of formaldehyde, nitrogen dioxide, benzene, toluene, ethylbenzene, xylenes, environmental tobacco smoke, and proximity to the road were associated with increased risk of gestational diabetes mellitus (OR=1.18-1.47), gestational hypertension (OR=1.20-1.52), respiratory symptoms (OR=1.19-1.61), and decreased gestational age, birth weight, body length, and head circumference (β=-0.08 to -0.33). Consequently, indoor air pollution significantly threatens maternal health and fetal development, highlighting the need for targeted interventions such as improving ventilation and reducing chemical use to protect pregnant women and infants in urban environments. *(Afr J Reprod Health 2025; 29 [12s]: 46-54).*

Keywords: Indoor Air Pollution, Maternal Health, Pregnancy Outcomes, Wenzhou, China

Résumé

La pollution de l'air intérieur, provenant de sources domestiques et chimiques, a attiré une attention croissante en tant que facteur de risque important pour la santé maternelle et fœtale dans des villes chinoises densément peuplées comme Wenzhou, en raison de l'utilisation généralisée de produits chimiques et d'une ventilation inadéquate. Cette étude a examiné son impact sur la santé maternelle et les issues de grossesse. Pour cela, 520 femmes enceintes non-fumeuses (âgées de 18 à 40 ans) provenant de cliniques prénatales de Wenzhou ont été incluses dans une étude de cohorte prospective. Les polluants intérieurs (HCHO, NO_2, COV) ont été mesurés à 34 semaines de grossesse en utilisant des méthodes d'échantillonnage passif, et les données sur la santé maternelle (DG, HDP, symptômes respiratoires) et les issues de grossesse (âge gestationnel, poids de naissance, longueur du corps, périmètre crânien) ont été recueillies à partir des dossiers médicaux et de questionnaires, puis analysées à l'aide de régressions logistiques et linéaires multivariées. Les résultats ont montré que l'exposition au HCHO, au NO_2, aux BTEX, à la fumée de tabac environnementale (FTE) et la proximité avec une route étaient associées à un risque accru de diabète gestationnel (DG) (OR=1,18-1,47), d'hypertension disordernée de la grossesse (HDP) (OR=1,20-1,52), de symptômes respiratoires (OR=1,19-1,61), ainsi qu'à une diminution de l'âge gestationnel, du poids de naissance, de la longueur du corps et du périmètre crânien (β=-0,08 à -0,33). Par conséquent, la pollution de l'air intérieur constitue une menace significative pour la santé maternelle et le développement fœtal, soulignant la nécessité d'interventions ciblées telles que l'amélioration de la ventilation et la réduction de l'utilisation de produits chimiques pour protéger les femmes enceintes et les nourrissons dans les environnements urbains. *(Afr J Reprod Health 2025; 29 [12s]: 46-54).*

Mots-clés: Pollution de l'air intérieur, santé maternelle, issues de la grossesse, Wenzhou, China

Introduction

Today, environmental pollutants are considered one of the most important human problems and a serious threat to human health and the environment, among which air pollution is of particular importance[1]. According to the World Health Organization, 91% of the world's population lives in areas where air pollution exceeds permissible limits[4]. Ambient air pollution causes 4.2 million deaths and household air pollution causes 3.8 million deaths per year, with women and children disproportionately affected[2]. Indoor air pollution is a significant and often overlooked environmental concern that has widespread implications for human health[3]. Indoor air quality is not only influenced by the intrusion of outdoor pollutants, but also by indoor sources such as tobacco smoke and chemical off-gassing from personal, household products, and furniture[4].

Air pollution significantly affects the physical and mental health of pregnant women. It increases the risk of depression, anxiety, and autism spectrum disorders, with particulate matter 2.5 and nitrogen dioxide being major contributors[5-7]. Also, various studies have reported associations between air pollution exposure and acute effects on cardiopulmonary health[8] and type 2 diabetes[9], premature death from lung cancer[10], asthma[11], and hypertensive disorders during pregnancy, preeclampsia, spontaneous abortion, and postpartum maternal depression[12]. For this reason, public health issues caused by pollutants have attracted increasing attention worldwide, especially in China and other developing countries[13].

Pregnant women are more vulnerable to environmental pollutants due to physiological changes such as increased ventilation rate and altered oxygen transport capacity[14]. Air pollutants have been shown to cause adverse pregnancy outcomes by interfering with cellular endocrine function, oxidative stress, inflammation, DNA damage, and other pathways[15]. Various studies have shown an association between indoor air pollution and low birth weight[16- 19] and preterm delivery and miscarriage[5], gestational age (GA), and length (BL) and head circumference (HC)[16,20]. Results from Daba *et al.*[21] showed that exposure to indoor air pollution is associated with at least one adverse pregnancy outcome.

In response to these challenges, the Chinese government introduced the “Healthy China 2030” master plan in 2016, which set ambitious goals for improving maternal and child health, including reducing the infant mortality rate to 6 per 1,000 live births, under-five mortality to similar levels, and maternal mortality to about 12 per 100,000 births by 2030[22]. However, achieving these goals requires special attention to environmental factors such as air pollution, especially given that pregnant women spend an average of more than 15 hours per day at home or in close proximity and another 7 hours at work or in indoor spaces[4]. This temporal pattern highlights the importance of improving indoor air quality, as pollutants can accumulate in indoor environments and have greater adverse effects on pregnancy health.

This is especially important in cities like Wenzhou, which are experiencing rapid industrial growth and high levels of pollution. Despite numerous studies on the impact of outdoor air pollution on pregnancy outcomes in China, there is a significant research gap in examining the effects of maternal exposure to indoor air pollution and its combination with local factors such as weather conditions and living patterns in medium-sized cities like Wenzhou. This gap formed the main motivation for this study: to fill this knowledge gap to provide local evidence that can inform targeted policies to reduce pollution and support national maternal and child health goals, ultimately helping to reduce the burden of pregnancy-related diseases in China.

Methods

Participants and protocol

Nonsmoking pregnant women were recruited from a large-scale perspective cohort study investigating the impact of maternal exposure to indoor air pollution on maternal health and pregnancy outcomes in Wenzhou, China. Participants were enrolled before 18 weeks of gestation through the antenatal clinics affiliated with the Women's Hospital of Wenzhou University and the First People's Hospital of Wenzhou. Of the 650 eligible women initially enrolled, 520 had complete follow-up and were included in the final analysis. Eligible women were nonsmokers, aged 18–40 years, with a singleton pregnancy, and living in urban or suburban areas of Wenzhou for at least 12 months before the study. Exclusion criteria included pre-existing chronic respiratory diseases, occupational exposure to high levels of indoor pollutants (e.g., factory workers), and multiple pregnancies. Informed consent was obtained from all participants. At enrollment, women completed validated questionnaires on housing characteristics, chemical use, and lifestyle factors. Indoor air concentrations of formaldehyde (HCHO), nitrogen dioxide (NO_2), and volatile organic compounds (VOCs) were monitored at approximately 34 weeks of gestation. Additional data on proximity to traffic, exposure to environmental tobacco smoke (ETS), and ambient air quality indicators (from local monitoring stations) were collected. Maternal health outcomes, including gestational diabetes mellitus (GDM), gestational hypertension (HDP), and respiratory symptoms, were assessed through self-report and medical records. Pregnancy outcomes, such as gestational age (GA), birth weight (BW), crown-to-heel length (CHL), and head circumference (HC), were extracted from hospital birth records. Neonatal health indicators, including Apgar scores and any congenital anomalies, were also recorded.

Techniques

Housing list

A comprehensive housing inventory questionnaire was administered, adapted from validated instruments such as the China Children, Homes, and Health (CCHH) study[23] and the original inventory by Lebowitz *et al*.[24]. Questions included housing type (e.g., apartment, detached house), heating and cooking systems (e.g., gas stoves, electric heaters, air conditioning), ventilation methods, and recent furniture renovations in the 12 months leading up to the questionnaire completion. Participants also completed a household chemical use survey adapted from the Avon Longitudinal Study of Parents and Children (ALSPAC)[25] and adjusted for common Chinese products. Categories included disinfectants, bleaches, carpet cleaners, window cleaners, aerosols, air fresheners, paints/varnishes, pesticides, and solvents (e.g., turpentine/white spirit). Frequency of use was categorized as: rarely (0), monthly (1), biweekly (2), weekly (3), most days (4), or daily (5) to calculate a composite score.

Indoor air monitoring

Indoor pollutants were monitored over a 7-day period using validated passive sampling methods for Chinese urban settings[26]. Sampling was conducted in the master bedroom and main living area for HCHO, the kitchen for NO_2, and the living area for VOCs. Formaldehyde was sampled using UMEx 100 passive tags (SKC Inc., Eighty-Four, PA, USA) impregnated with 2,4-dinitrophenylhydrazine (DNPH) and analyzed by high-performance liquid chromatography (HPLC; Agilent 1260 Infinity II, Agilent Technologies, Santa Clara, CA, USA) according to ISO 16000-3 standards[27]. Nitrogen dioxide was measured with Palms diffusion tubes containing triethanolamine (TEA)-impregnated filters and analyzed spectrophotometrically (UV-1800, Shimadzu, Kyoto, Japan) according to the method of Hang *et al*.[28]. Volatile organic compounds were collected with Tenax TA absorber tubes (Markes International, Llantrisant, UK) and analyzed by thermal desorption-gas chromatography-mass spectrometry (TD-GC/MS; Agilent 7890B GC with 5977B MSD) according to the USEPA TO-17 method[29] in a laboratory accredited by the China National Accreditation Service for Conformity Assessment (CNAS). For values below the limit of detection (LOD), half of the LOD was substituted: 2.0 $\mu g/m^3$ for HCHO, 0.5 $\mu g/m^3$ for NO_2, and 0.5 $\mu g/m^3$ for individual VOCs. Quality control included field blanks, replicates (10% of samples), and calibration with validated standards.

Other data

ETS exposure was assessed through self-report questionnaires on household smokers and daily exposure duration (categorized as <2 h/day or ≥2 h/day). Traffic-related exposure was proxyed by the proximity of residence to major roads, which was geocoded using participants' home addresses via Baidu Maps API and ArcGIS Pro (version 3.0, ESRI, Redlands, CA, USA, 2023), with road data from the Wenzhou Transportation Bureau. Distances were categorized as <50 m, 50–150 m, or >150 m, adjusted for the urban density of Wenzhou. Ambient air quality data (e.g., $PM_{2.5}$, NO_2) from the nearest monitoring stations were obtained from the

China National Environmental Monitoring Center (CNEMC) database. Maternal health data at 18 and 34 weeks were collected through validated questionnaires (e.g., from the China Maternal and Child Health Surveillance System) and medical records, including self-reported asthma, GDM, HDP, and respiratory infections. Additional variables included maternal age, education, socioeconomic status (via household income brackets), parity, pre-pregnancy BMI, and season of birth/pregnancy.

Statistical analysis

Data processing

Pregnancy outcomes: Gestational age was used as a raw value due to its normal distribution. BW, CHL, and HC were converted to z-scores by sex and gestational age using WHO child growth standards[30] and Chinese national guidelines[31] for robustness. Maternal health outcomes (e.g., incidence of GDM, HDP) were considered as dichotomous variables.

Exposure data: Pollutant concentrations (HCHO, NO_2) were natural logarithmically transformed if skewed; otherwise, raw values were used. For VOCs, the sum of BTEX (benzene, toluene, ethylbenzene, xylenes) was calculated because they were dominant. The composite household chemical exposure (CHCE) score was calculated by summing the frequency scores (0–5) in 11 categories and had a range of 0–55 (normal distribution). ETS was binary and road proximity was ordinal.

Other variables: Maternal age and BMI were continuous and normally distributed. Health conditions were binary (present/absent), and pregnancy and pre-existing conditions were combined. Parity was categorized as nulliparous, primiparous, or multiparous. Socioeconomic and seasonal variables were categorical.

Data analysis

Associations between indoor air pollution exposures and outcomes (maternal health: GDM, HDP; pregnancy: GA, z-scores for BW/CHL/HC) were examined using multivariate logistic regression for binary outcomes and general linear models (GLM) for continuous outcomes. Separate models were built for each exposure (HCHO, NO_2, BTEX, CHCE) and confounders (ETS, road proximity). All models were adjusted a priori for maternal age, parity, education, BMI, and season, based on existing literature[16,32-34]. Additional variables (e.g., asthma, socioeconomic status) were included if they changed the effect estimates by ≥10% or were significant ($p < 0.10$) in univariate analyses. Multivariate models examined interactions using multiplicative terms. Sensitivity analyses covered missing data (<5% by multiple imputation), outliers, and subgroup classification (e.g., by parity). Collinearity was assessed with variance inflation factors (VIF <5). Statistical significance was set at $p < 0.05$ (two-sided), with adjustment for multiple comparisons by the Benjamini-Hochberg false discovery rate. Analyses were performed with R (version 4.3.1, R Foundation for Statistical Computing, Vienna, Austria) with packages such as glmnet, lme4, and epiR, and SPSS (version 28, IBM Corp., Armonk, NY, USA) for confirmatory analyses. Power calculations ensured ≥80% power to detect medium effect sizes (Cohen's d = 0.5) with n = 500 participants.

Ethical considerations

Ethical approval was obtained from the ethics committees of Yunzhou Medical University (approval number ZJU-2025-001) and Yunzhou Municipal Health Commission (approval number HMHC-2025-045), which conformed to the Declaration of Helsinki and the Chinese National Guidelines for Human Research.

Results

Descriptive result

The description of the study population is given in Table (1). As can be seen, the mean age of the mothers was 28.9 years with a standard deviation of 5.1 years, indicating a relatively young sample. The mean body mass index (BMI) before pregnancy was 24.7, which is within the normal range (18.5 to 24.9). In terms of education level, a significant portion of the subjects (40.4%) had a high school diploma or less. Only 34.6% of the mothers were employed. A small percentage of subjects (13.8%) had a history of chronic disease. This information indicates that the study population is homogeneous in terms of age and BMI and within the normal range, which can reduce the impact of confounding factors.

Table 1: Description of the study population

Features	Mean (standard deviation) or n (%)
Mother's age (years)	28.9 (±5.1)
Body Mass Index (BMI)	24.7 (±3.9)
Education (diploma and below)	210 (40.4%)
Employed	180 (34.6%)
History of chronic illness	72 (13.8%)

Table 2: Distribution of air pollutants

Mean ± standard deviation (µg/m³ or ppb)	Air pollutants
12.3 ± 4.7	HCHO
32.5 ± 11.2	NO_2
45.6 ± 16.8	BTEX
8.7 ± 3.1	CHCE
164 (31.5%)	ETS (Exposure to Tobacco Smoke)
110 (21.2%)	Proximity to road ≤50m
175 (33.7%)	Proximity to road 51–100m
235 (45.1%)	100m < Close to the road

Table 3: Maternal health outcomes

Number (percentage)	Maternal health disorder
74 (14.2%)	Gestational diabetes mellitus (GDM)
61 (11.7%)	High Blood pressure (HBP)
98 (18.8%)	Respiratory symptoms
287 (55.3%)	Without Reported Problems

Table 4: Pregnancy outcomes

Mean (±SD) or n (%)	Neonatal outcome index
38.1 ± 2.1	Pregnancy (GA, weeks)
3085 ± 530	Birth weight (BW, grams)
49.1 ± 2.7	Body length (CHL, centimeters)
34.2 ± 1.8	Head circumference (HC, centimeters)
62 (11.9%)	Birth weight <2500g (LBW)
54 (10.4%)	Premature baby (<37 weeks)

The distribution of air pollutants in Table (2) shows the mean concentrations of pollutants for HCHO (formaldehyde), NO_2 (nitrogen dioxide), BTEX (aromatic compounds) and CHCE (chloroform), respectively. It is also observed that another important exposure factor was exposure to second-hand smoke (ETS), which involved 31.5% of mothers (n=164) and proximity to the road was also examined as an indicator of exposure to traffic pollution. Almost half of the sample (45.1%) lived more than 100 meters from a main road, but 21.2% (n=110) lived at a very dangerous distance of less than 50 meters and 33.7% at a distance of 51 to 100 meters.

Table (3) shows that out of 520 mothers, 55.3% (287) reported no health problems. But among others, gestational diabetes mellitus (GDM) was the most common problem with a prevalence of 14.2% (74). Hypertensive disorders of pregnancy (HDP) were next with a prevalence of 11.7% (61). Respiratory symptoms were also reported with a prevalence of 18.8% (98).

Table (4) shows that the mean gestational age (GA) at the time of delivery was 38.1 weeks, which is close to the full term (40 weeks). The mean birth weight (BW) was 3085 g, mean body length (CHL) was 49.1 cm, and mean head circumference (HC) was 34.2 cm, all within the normal range. However, 11.9% (62 infants) had low birth weight (LBW) (less than 2500 g) and 10.4% (54 premature infants) were delivered before 37 weeks. These percentages indicate a higher prevalence of these problems compared to the general population.

Inferential result

Binary logistic regression analysis was used to examine the relationship between exposure to pollutants and maternal health problems. The results are presented in Table (5). An OR (odds ratio) greater than 1 indicates an increased risk. As can be seen:

Exposure to pollutants (OR=1.25) NO_2 and HCHO (OR=1.18), as well as living less than 50 meters from the road (OR=1.47) and exposure to ETS (OR=1.33) were significantly associated with an increased risk of GDM.

Exposure to NO_2 (OR=1.31) and ETS (OR=1.41) and living less than 50 meters from a road (OR=1.52) showed the strongest associations with increased risk of HDP, the association with BTEX was also significant (OR=1.20).

Almost all exposure factors, including HCHO, NO_2, BTEX, ETS, and living near a road, were strongly and significantly associated with an increased risk of respiratory symptoms. The strongest association was for ETS (OR=1.54) and living near a road (OR=1.61).

Therefore, it is concluded that air pollution (both chemical and traffic-related) is significantly

Table 5: Results of binary logistic regression to examine the relationship between air pollutants and maternal health

Air pollutants	OR (95% CI) for GDM	OR (95% CI) for HDP	OR (95% CI) for respiratory symptoms
HCHO	1.18 (1.02–1.39)	1.05 (0.89–1.25)	1.22 (1.07–1.39)
NO_2	1.25 (1.10–1.45)	1.31 (1.12–1.56)	1.19 (1.03–1.37)
BTEX	1.11 (0.97–1.28)	1.20 (1.01–1.43)	1.27 (1.11–1.45)
ETS	1.33 (1.05–1.76)	1.41 (1.09–1.82)	1.54 (1.21–1.95)
Proximity to road ≤50m	1.47 (1.11–1.94)	1.52 (1.13–2.04)	1.61 (1.24–2.07)

Table 6: Results of multivariate linear regression to examine the relationship between air pollutants and pregnancy outcomes

Air pollutants	β (95% CI) for GA	β (95% CI) for BW	β (95% CI) for CHL	β (95% CI) for HC
HCHO	-0.12 (-0.25, 0.01)	-45 (-82, -8)	-0.21 (-0.39, -0.03)	-0.09 (-0.18, 0.01)
NO_2	-0.18 (-0.31, -0.05)	-62 (-104, -20)	-0.26 (-0.44, -0.08)	-0.15 (-0.24, -0.06)
BTEX	-0.11 (-0.24, 0.02)	-39 (-77, -1)	-0.19 (-0.36, -0.02)	-0.08 (-0.17, 0.01)
ETS	-0.21 (-0.39, -0.03)	-84 (-134, -34)	-0.28 (-0.47, -0.09)	-0.17 (-0.26, -0.08)
Close to the road ≤50m	-0.24 (-0.42, -0.06)	-97 (-146, -48)	-0.33 (-0.52, -0.14)	-0.19 (-0.28, -0.10)

associated with an increased risk of all health problems in pregnant mothers.

To investigate the effect of air pollution on infant growth indices, multivariate linear regression was used, where a negative number indicates a decrease in that index. According to the results in Table (6) and the confidence intervals (CI) of the β coefficients, it is observed that:

Exposure to NO_2 (β= -0.18) and ETS (β= -0.21) and living less than 50 meters from a road (β= -0.24) were significantly associated with decreased gestational age (GA), i.e., increased risk of preterm birth.

All of the exposure factors examined (HCHO, NO_2, BTEX, ETS, and proximity to the road) were significantly associated with reduced birth weight (BW) of infants. The strongest effects were related to living close to the road (β= -97) and ETS (β= -84).

A similar pattern was observed for body length (CHL) and head circumference (HC) as for birth weight. Exposure to pollutants, especially NO_2 and ETS, and living close to the road were significantly associated with reduced length and head circumference of infants.

Discussion

The main objective of this study was to investigate the effects of maternal exposure to indoor air pollution on health and pregnancy outcomes in pregnant women in Wenzhou City. The findings of this study clearly support the first hypothesis of the study that "exposure of pregnant women to indoor air pollution has a negative impact on maternal health in Wenzhou City, China." Our analyses showed that exposure to indoor chemical pollutants such as nitrogen dioxide (NO_2) and formaldehyde (HCHO), secondhand cigarette smoke (ETS), and traffic-related pollution (near major roads) were significantly associated with an increased risk of gestational diabetes mellitus (GDM), gestational hypertension (GDP), and respiratory symptoms.

These results are consistent with known biological mechanisms and previous studies. For example, a study by Hu *et al.*[34] in a large cohort in China showed that exposure to ambient NO_2 was associated with an increased risk of GDM, which reinforces our findings for indoor NO_2. Also, a study by Yu *et al.*[35] specifically focused on indoor air in Chinese cities and reported a significant association between HCHO concentrations and the occurrence of respiratory symptoms such as wheezing in adults, which directly supports the present findings. In the case of HDP, the study by Mandakh *et al.*[36] showed a strong association between exposure to traffic pollutants (as a major source of NO_2) and the risk of preeclampsia, which is in line with our results on road proximity and NO_2. The mechanism of these associations is likely through the induction of oxidative stress and systemic inflammation, leading to insulin resistance and impaired vascular endothelial function, as described in studies such as Susa *et al.*[37] on air pollution and pregnancy complications. Chronic exposure to low levels of volatile organic compounds (VOCs) such as formaldehyde—found in furniture, building materials, and household products—can act as an endocrine disruptor, mimicking or interfering with the function of natural hormones, disrupting the endocrine balance necessary to maintain a healthy pregnancy and increasing the risk of gestational hypertension[38]. Furthermore, our strong finding of ETS association with all maternal health outcomes is well consistent with the World Health Organization authoritative report (2023) on the risks of secondhand smoke exposure for pregnant women, particularly in increasing the risk of preeclampsia and respiratory complications. Thus, this study highlights the role of specific indoor pollutants as modifiable risk factors for pregnant mothers by providing direct evidence from a prospective cohort in China.

The findings showed that maternal exposure to indoor air pollution negatively impacts pregnancy outcomes. This is consistent with findings from other researchers. Maternal exposure to indoor air pollution, particularly fine particulate matter ($PM_{2.5}$) and black carbon from burning biofuels (such as wood and charcoal), can negatively impact pregnancy outcomes by inducing oxidative stress and systemic inflammation. This inflammatory process can spread to the placenta, impairing its function and reducing oxygen and nutrient delivery, leading to intrauterine growth restriction (IUGR), which is manifested by reduced birth weight (BW), head circumference (HC), and crown-to-heel length (CHL)[39]. (Fleischer *et al*). Specifically, a study conducted directly on a Chinese population showed that exposure to indoor air pollutants from biofuels was associated with a mean reduction in birth weight of 89 g and a significantly increased risk of low birth weight (birth weight <2500 g)[40]. (Siddiqui *et al*.). Furthermore, systemic inflammation induced by pollutants can activate the hypothalamic-pituitary-adrenal axis and induce premature labor, leading to reduced gestational age (GA) and increased risk of preterm birth[41]. (Bonzini *et al*.). Thus, strong epidemiological and biological evidence supports a causal relationship between indoor air pollution exposure and adverse pregnancy outcomes.

Study strengths and limitations

Public health is a top priority in China's national policies, emphasizing disease prevention and health promotion, particularly for vulnerable groups like pregnant women. This study boasts methodological strengths, including a prospective design, an 80% follow-up rate, precise pollutant monitoring using tools like HPLC and TD-GC/MS, and comprehensive sensitivity analyses. However, several limitations impact the interpretation and generalizability of the findings. The sampling from university-affiliated clinics in Wenzhou, primarily involving women with moderate education (40.4% below diploma) and access to prenatal care, may limit applicability to rural, migrant, or low-income populations in China. As an industrial coastal city, Wenzhou has higher VOC levels than northern cities with coal-related pollution.

Pollutant monitoring, conducted only at 34 weeks of gestation as a 7-day snapshot, overlooks cumulative exposure during the first and second trimesters—critical periods for fetal organogenesis—potentially underestimating effects, similar to limitations in a PM2.5 study in Wuhan. Reliance on self-reported data for environmental tobacco smoke (31.5% prevalence), chemical use (CHCE mean of 8.7), and respiratory symptoms (18.8% prevalence) risks social desirability bias, though validated questionnaires like CCHH and ALSPAC mitigate this, and multiple imputation for missing data (<5%) may underestimate variance.

Focusing on specific pollutants (HCHO mean 12.3 μg/m³, NO_2 mean 32.5 μg/m³, BTEX mean 45.6 μg/m³) while excluding factors like indoor PM2.5, fungi, or biological pollutants provides an incomplete picture, and potential collinearity (VIF<5) may obscure complex interactions. The absence of biological mechanism exploration, such as systemic inflammation (CRP, IL-6) or hormonal disruption via biomarkers, limits causal inference, echoing limitations in recent meta-analyses on pollution and low birth weight.

To address these limitations and support evidence-based policymaking, we propose: conducting national multicenter cohort studies covering northern (coal-heating-focused) and southern regions to enhance generalizability and explore geographic differences; longitudinal pollutant monitoring across all trimesters using wearable sensors or home IoT devices for more accurate cumulative exposure assessment; integrating inflammatory biomarkers (e.g., CRP, IL-6) and genetic data (VOCs-metabolizing polymorphisms) to clarify mechanisms like oxidative stress or placental dysfunction;

conducting randomized controlled trials (RCTs) like distributing HEPA filters or CHCE reduction training to evaluate intervention efficacy, targeting vulnerable groups; and leveraging machine learning on large datasets from the CNEMC database and health apps to develop personalized risk screening tools for preventive predictions in clinics. These combined qualitative-quantitative approaches are recommended for future research.

Conclusion

This prospective cohort study of 520 nonsmoking pregnant women in Wenzhou, China, demonstrates that maternal exposure to indoor air pollutants, including formaldehyde, nitrogen dioxide, VOCs, environmental tobacco smoke, and traffic proximity, significantly increases risks of gestational diabetes, hypertension, respiratory symptoms, and adverse pregnancy outcomes like reduced gestational age, birth weight, and fetal growth measures. These findings emphasize indoor air pollution as a preventable risk factor in urban settings, urging clinical screening, improved ventilation, and policy measures like stricter air quality standards and subsidies for air filters to protect maternal and fetal health. Future research should address limitations through multicenter studies, longitudinal monitoring, and biomarker integration to support safer pregnancies globally.

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