Journal of Neonatal Surgery
ISSN(Online): 2226-0439
Vol. 14, Issue 13s (2025)
https://www.jneonatalsurg.com

Maternal Exposure to Air Pollution and Its effects on Neonatal Health: A Review

Kavita Chauhan[1], Kabir Singal[2], Anshoo Agarwal[3], Asmara Syed[3], Wajid Ali Chatha[4], Syed Sajid Hussain Shah[3], Fariha Kauser[5], S. Geetha Subramaniam[6]

[1]Department of Pathology, Faculty of Medicine, Swami Vivekananda Subharti University, Meerut, India

[2]JSS Medical College, Mysore, Karnataka, India

[3]Department of Pathology, Faculty of Medicine, Northern Border University, Arar, Kingdom of Saudi Arabia

[4]Department of Anatomy, Faculty of Medicine, Northern Border University, Arar, Kingdom of Saudi Arabia

[5]Health practitioner & Ex Medical Educationist from University of Dundee, Scotland

[6]Faculty of Health and Life Sciences, & Center for Health, Well-being, and Sustainability. INTI International University, Persiaran Perdana BBN, Putra Nilai, 71800 Nilai, Negeri Sembilan, Malaysia,

Corresponding Author:

Name - Kavita Chauhan

Department of Pathology, Faculty of Medicine, Swami Vivekananda Subharti University, Meerut, India Phone numbers-00917906510312

Email ID: AAKC2024@outlook.com

Cite this paper as: Kavita Chauhan, Kabir Singal, Anshoo Agarwal, Asmara Syed, Wajid Ali Chatha, Syed Sajid Hussain Shah, Fariha Kauser, S. Geetha Subramaniam, (2025) Assessment and Prevalence of Communicable and Non-Communicable Diseases and their Risk Factors in Adults. *Journal of Neonatal Surgery*, 14 (13s), 568-576.

ABSTRACT

Background: Air pollution has emerged as an important cause of neonatal morbidity around the globe. Fetal development is affected by the exposure of air pollution to the expecting mothers, particularly in the initial months when the organogenesis is in process.

Material and methods: After the searching the common databases such as PubMed, Google scholar, Scopus and web of science, a list of the research articles were shortlisted. The key words used to search the research papers included ‘ air pollution, particulate matter, ozone, SO_2, CO, NO_2 , lead, hydrocarbons, neonatal abnormalities, congenital heart diseases, limb anomalies, neural tube defects, pregnancy and early gestation.’

Results: A total of sixty-one research papers were collected and compiled. Significant number of research articles documented the relation of air pollution with the development of congenital diseases among neonates. The important new born diseases associated with the air pollution include heart defects, orofacial defects, neural tube defects, polydactyly and syndactyly.

Discussion: The congenital heart diseases of the newborn are most common ailments which are associated with intrauterine high exposure of particulate matter, SO_2, CO, NO_2 & O_3. The increased normalized difference vegetation index (NDVI) of the permanent residence of the mothers reduces the possibility of congenital heart diseases among the neonates.

Conclusion: Air pollution is contributing in the morbidity and mortality of the neonates. The control of air pollution is of vital importance for these preventable neonatal diseases by adapting suitable measures such as increasing the tree plantation and reducing the emission from vehicles, industries, household burning and wildfires.

Keywords: *Air, Pollution, Pregnancy, Congenital Abnormalities, Neonates*

1. INTRODUCTION

Normal healthy clean air is of paramount importance for life, but air pollution is contributing in the causation of serious problems to the health and environment all over the world. The estimated number of deaths that are attribute to air pollution is about 2.92 million in females and 3.75 million in males. There are two hundred thirteen million disability adjusted life years which are caused by the air pollution [1]. The contaminated air with harmful substances has a bad effect on the health of the human beings and it causes significant morbidity and mortality particularly in the developing countries. There are six important air pollutants substances which cause out door air pollution that include particulate matter, CO, SO_2, NO_2, O_3 and lead.

The particulate matter is composed of solids and liquid droplets. There are two main types of particulate matter (PM) which include $PM_{2.5}$ & PM_{10}. The $PM_{2.5}$ has the diameter of 2.5 micrometer or less than this while the PM_{10} has the diameter of 10 micrometer. Both are inhalable particles. CO is an odorless gas. Its production is due to the burning of hydrocarbons. Most common sources of this air pollutant are automobiles, furnaces and cigarettes. The life of carbon monoxide in the air is short as it would be converted into carbon dioxide. The person in close proximity to the production of carbon monoxide usually suffers the most toxic effects of this air pollutant. Ground level ozone causes production of free radicals leading to damage to human tissue. Its main source is nitrous oxide (NO) and volatile organic compounds. The burning of coal and oil produces Sulphur dioxide (SO_2) which is another important air pollutant. It can affect the lungs. NO is produced by the combustion of fuel.

The important indoor air pollutants include CO, particulate matter ($PM_{2.5}$ & PM_{10}) and biological pollutants and volatile organic compounds such as benzene, toluene, formaldehyde and polycyclic aromatic hydrocarbons, micro / nano plastic M/ NPs [2-3].

The important sources of indoor air pollutants include wood stove smoke, cooking, smoking, electronic instruments, consumption goods and release of substance from the construction material of the houses and offices and location of building [4-5].

Since common man spends most of the time inside the house and office, the indoor air pollutants become of paramount importance for human beings.

The adverse effects of air pollution have impact in all age groups. The most susceptible age groups are 0-14 years and above sixty five years [6]. The maternal air pollution will also impact the well-being of the offspring leading to the development of congenital heart defects (CHD) [7-9]. The objective of the present review is to evaluate different types of neonatal diseases associated with the maternal exposure of the air pollutants.

2. MATERIALS AND METHODS

1. **Study design**: This is a narrative review in which the qualitative evidence about the impact of air pollutant on the baby due to exposure during the pregnancy is studied.
2. **Research question**: How much air pollution can affect the neonates due to exposure of air pollutant to the mother during pregnancy.
3. **Key words used**: The key words used include air pollution, particulate matter, ozone, SO_2, CO, NO_2 , lead, hydrocarbons, neonatal abnormalities, congenital heart diseases, limb anomalies, neural tube defects, pregnancy ,early gestation and smoke,
4. **Research time period**: January 2000 to March 2025
5. **Data sources**: PubMed, Google scholar, Scopus, Web of science.

Inclusion criteria:

The research papers were selected based on followings criteria

1. Peer reviewed
2. Studied the human anomalies
3. Available in English language
4. Published during the period of Jan 2020 to Mar 2025

Exclusion criteria:

1. More than five years old published papers
2. Published in a language other than English
3. Research done on animals or plants

Data analysis:

The title and abstracts were studied to exclude the duplications of articles. The selected research papers were evaluated and the findings were tabulated.

3. RESULTS

A total of sixty – one research articles were evaluated regarding the effects of air pollutant on the neonates in the intrauterine life leading to abnormalities. The majority of studies revealed that the neonates have developed congenital heart diseases such as atrial septal defects and ventricular septal defects due to intrauterine exposure to air pollutants such as $PM_{2.5}$, PM_{10}, NO_2, SO_2. The findings are compiled in Table I.

Table 1. The Association of Maternal Exposure to Air Pollutants and Risk of Neonatal Diseases

Author	Higher exposure of Air Pollutant during pregnancy	Increased risk in the neonate
Johnson M [10]	PM2.5	severe respiratory distress
Sun L [11]	• $PM_{2.5}$ • NO_2	CHDs
Buteau S [12]	PM2.5PM2.5) and nitrogen dioxide (NO2NO2)) during the first trimester	heart defects, particularly atrial septal defects
Yuan X [13]	$PM_{2.5}$	CHDs
Hall KC [14]	$PM_{2.5}$ and O_3	CHD
Gilboa SM [15]	• carbon monoxide • particulate matter <10 micron • sulfur dioxide	• Tetralogy of Fallot • Atrial septal defects • Ventricular septal defects
Agay-Shay K [16]	PM10	Congenital heart defects
Requia WJ [17]	wildfire smoke	cleft lip/cleft palate congenital anomalies of the respiratory system &nervous system
Huang CC [18]	$PM_{2.5}$ and O_3	Hypospadias
Li D [19]	$PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3	CHD
Zhang H [20]	NO_2 and CO $PM_{2.5}$ and PM_{10}	atrial septal defect
Huang X [21]	PM_{10}, SO_2 and CO	CHD, polydactyl, cleft lip and/or palate
Padula AM [22]	• PM_{10} s • $PM_{2.5}$ • NO_2	• cleft lip • teratology of Fallot • d-TGA.
Cheng Y [23]	$PM_{2.5}$	CHDs
Zhang Y [24]	Using biomass or electromagnetic stoves for cooking	birth defects
Li S [25]	PM2.5 NO_2	digestive system digestive system & cardiac septal defects
Li L [26]	PM_{10}	Cleft lip and cleft palate
Ma Z [27]	$PM_{2.5}$, O_3, and SO_2	congenital heart disease
Arogbokun Knutson OC [28]	PM2.5 and ozone	CHD
Zhang W [29]	$PM_{2.5}$, PM_{10}, SO_2, CO, NO_2	CHD

Jiang W [30]	CO, NO_2, SO_2, $PM_{2.5}$ and O_3	CHDs
Sun J [31]	total volatile organic compounds (TVOCs), $PM_{2.5}$	CHD
Yang Y [32]	O_3 and NO_2	CHD
Deng C [33]	environmental tobacco smoke (ETS	CHDs
Jin S [34]	sulfur dioxide cadmium	ventricular septal defects
Buteau S [35]	PM2.5 NO2	atrial septal defects
Wang H [36]	O_3 Paternal smoking	CHD
Park BY [37]	Wildfire	ASD
Chang YC [38]	$PM_{2.5}$	congenital heart defects
Julaiti M [39]	PM2.5, PM10	gallbladder, bile duct, liver anomalies
Li Y [40]	O_3	Congenital malformations of the musculoskeletal system
Jiang W [41]	NO2 and SO2	Congenital limb defects (CLDs)
Huang Z [42]	SO_2	CHD, cleft lip and/or cleft palate, and ear deformity
Lee KS [43]	$PM_{2.5}$ NO_2	Circulatory, genitourinary, and musculoskeletal system Malformations of the musculoskeletal system
Krakauer KN [44]	SO_2 and PM 2.5	non-syndromic cleft lip with or without palate (NSCLP)
Liu Y [45]	PM_{10} SO_2	orofacial clefts (OFCs) OFCs
Wright CY [46]	PM_{10} $PM_{2.5}$	Orofacial Cleft Lip/Palate CLP
Diao J [47]	Maternal smoking and CYP450 genetic variants	CHD
Zhang JY [48]	PM_{10}	Polydactyly and syndactyly.
Jiang YT [49]	SO_2	Polydactyly and syndactyly.
Zhang JY [50]	PM_{10}	offspring neural tube defects
Xia J [51]	PM_{10}	Anencephaly
Zhang TN[52]	PM_{10}	anorectal atresia/stenosis
Li LL[53]	Higher SO_2 exposure	Omphalocele
Li H[54]	PM_{10}	spina bifida
Liu FH[55]	PM_{10}	oral cleft

Liu L[56]	Lanthanum and Neodymium	orofacial clefts
Zhang JY[57]	SO_2	neural tube defects
Liu Y[58]	Passive smoking	CHD

4. DISCUSSION

The majority of the studies revealed that the maternal exposure of PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO and O_3 particularly in the initial months of gestation is associated with CHD such as atrial septal defect. There is an increase in the cases of CHD in the new born particularly for the last four years 2020-2023 during the CoVID-9 pandemic [59]. Among the five most common causes of infant mortality includes congenital heart diseases [1].

The first system which develops in the embryonic stage is cardiovascular system (CVS). The CVS is an important requirement for the developing embryo as with the growth of embryo, the metabolic requirements will be increasing exponentially. To fill for the growing metabolic demands, the appropriate development of the CVS is vital for the embryo. The cardiac development is one of the first systems to develop in the embryo and vascular developments starts by the middle of the 3rd week of gestation and completes in the 10th week of pregnancy.

Any toxic exposure during the development of CVS, is likely to increase the risk of congenital anomalies in the newborns. One of the studies revealed that the air pollutants have a significant role in the development of CHD during the early weeks of pregnancy. The $PM_{2.5}$ significantly affects the male baby while $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2, and O_3 plays a main role in the female baby [29]. Along with the exposure of air pollution during the pregnancy, the ambient heat would increase their effects on the neonate leading to the development of diseases [30].

The NDVI measures the surrounding greenness. Normalized difference vegetation index 0.2 to 0.3 represents grassland while 0.1 and less suggests the barren land. For the mothers having a permanent residency in an area which has greenery, there will be reduced risk of congenital heart disease in their new born [60-61]. An increase of 0.1-unit of normalized difference vegetation index (NDVI) around the conception time, would reduce the possibility of congenital heart disease by 5% [61]. An NDVI above 0.21 has a protective effect on the fetus and reduces the risk of congenital heart diseases [60].

Studies have shown the association of cleft lip and cleft palate with the exposure of air pollutants during the pregnancy [17,21,22,26,42,44-46]. Some studies revealed the risk of neural tube defects, limb defects, polydactyly and syndactyly [48-50,54,57].

This review paper highlights the significant adverse effects of air pollution on the newborn. Based on these details, it becomes vital to reduce the air pollutants by increasing the green belts and plantation of trees in the residential areas.

Conclusion: The air pollutants are one of the important factors leading to the development of congenital diseases among the neonates and contributes in the morbidity and mortality of the new born. It raises the strong need for the control of air pollution to prevent the associated neonatal diseases. In this regard, the appropriate measures are required to be taken such as increase in the number of trees, grassy grounds and reduction of the emission from vehicles, industries, household burning and prevention of wildfires.

Acknowledgement: The authors are grateful to Inshrah Syed, Ghanwa Syed and Syed Hassan Abbas for their valuable assistance.

REFERENCES

[1] GBD 2019 Risk Factors Collaborators. Global burden of 87 risk factors in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet. 2020 Oct 17;396(10258):1223-1249. doi: 10.1016/S0140-6736(20)30752-2.

[2] Vardoulakis S, Giagloglou E, Steinle S, Davis A, Sleeuwenhoek A, Galea KS, Dixon K, Crawford JO. Indoor Exposure to Selected Air Pollutants in the Home Environment: A Systematic Review. Int J Environ Res Public Health. 2020 Dec 2;17(23):8972. doi: 10.3390/ijerph17238972.

[3] Kumar R, Verma V, Thakur M, Singh G, Bhargava B. A systematic review on mitigation of common indoor air pollutants using plant-based methods: a phytoremediation approach. Air Qual Atmos Health. 2023 Mar 11:1-27. doi: 10.1007/s11869-023-01326-z.

[4] Kamurasi I, Bartlett K, Holyk T, Rathburn B, Moecke DP, Winter A, Camp PG. Prevalence of indoor air pollutants from First Nation homes in North Central British Columbia, Canada. Int J Circumpolar Health. 2024 Dec;83(1):2389612. doi: 10.1080/22423982.2024.2389612.

[5] Baeza Romero MT, Dudzinska MR, Amouei Torkmahalleh M, Barros N, Coggins AM, Ruzgar DG, Kildsgaard I, Naseri M, Rong L, Saffell J, Scutaru AM, Staszowska A. A review of critical residential buildings parameters and activities when investigating indoor air quality and pollutants. Indoor Air. 2022 Nov;32(11):e13144. doi: 10.1111/ina.13144.

[6] Olstrup H, Åström C, Orru H. Daily Mortality in Different Age Groups Associated with Exposure to Particles, Nitrogen Dioxide and Ozone in Two Northern European Capitals: Stockholm and Tallinn. *Environments*. 2022; 9(7):83. https://doi.org/10.3390/environments9070083.

[7] Yao C, Chen Y, Zhu X, Liu Y, Zhang J, Hou L, et al. Air Pollution and the Risk of Birth Defects in Anqing City, China. J Occup Environ Med. 2016 Apr;58(4):e124-7. doi: 10.1097/JOM.0000000000000676.

[8] Yang BY, Qu Y, Guo Y, Markevych I, Heinrich J, Bloom MS, et al. Maternal exposure to ambient air pollution and congenital heart defects in China. Environ Int. 2021 Aug;153:106548. doi: 10.1016/j.envint.2021.106548.

[9] Zhang Q, Sun S, Sui X, Ding L, Yang M, Li C, et al. Associations between weekly air pollution exposure and congenital heart disease. Sci Total Environ. 2021 Feb 25;757:143821. doi: 10.1016/j.scitotenv.2020.143821.

[10] Johnson M, Mazur L, Fisher M, Fraser WD, Sun L, Hystad P, Gandhi CK. Prenatal Exposure to Air Pollution and Respiratory Distress in Term Newborns: Results from the MIREC Prospective Pregnancy Cohort. Environ Health Perspect. 2024 Jan;132(1):17007. doi: 10.1289/EHP12880.

[11] Sun L, Wu Q, Wang H, Liu J, Shao Y, Xu R, et al. Maternal exposure to ambient air pollution and risk of congenital heart defects in Suzhou, China. Front Public Health. 2023 Jan 4;10:1017644. doi: 10.3389/fpubh.2022.1017644.

[12] Buteau S, Veira P, Bilodeau-Bertrand M, Auger N. Association between First Trimester Exposure to Ambient PM2.5 and NO2 and Congenital Heart Defects: A Population-Based Cohort Study of 1,342,198 Live Births in Canada. Environ Health Perspect. 2023 Jun;131(6):67009. doi: 10.1289/EHP11120.

[13] Yuan X, Liang F, Zhu J, Huang K, Dai L, Li X, et al. Maternal Exposure to $PM_{2.5}$ and the Risk of Congenital Heart Defects in 1.4 Million Births: A Nationwide Surveillance-Based Study. Circulation. 2023 Feb 14;147(7):565-574. doi: 10.1161/CIRCULATIONAHA.122.061245.

[14] Hall KC, Robinson JC, Cooke WH 3rd, Parnell AS, Zhang L, Northington L. Relationship Between Environmental Air Quality and Congenital Heart Defects. Nurs Res. 2022 Jul-Aug 01;71(4):266-274. doi: 10.1097/NNR.0000000000000590.

[15] Gilboa SM, Mendola P, Olshan AF, Langlois PH, Savitz DA, Loomis D, et al. Relation between ambient air quality and selected birth defects, seven county study, Texas, 1997-2000. Am J Epidemiol. 2005 Aug 1;162(3):238-52. doi: 10.1093/aje/kwi189.

[16] Agay-Shay K, Friger M, Linn S, Peled A, Amitai Y, Peretz C. Air pollution and congenital heart defects. Environ Res. 2013 Jul;124:28-34. doi: 10.1016/j.envres.2013.03.005.

[17] Requia WJ, Kill E, Papatheodorou S, Koutrakis P, Schwartz JD. Prenatal exposure to wildfire-related air pollution and birth defects in Brazil. J Expo Sci Environ Epidemiol. 2022 Jul;32(4):596-603. doi: 10.1038/s41370-021-00380-y.

[18] Huang CC, Pan SC, Chen BY, Guo YL. Periconceptional exposure to air pollution and congenital hypospadias among full-term infants. Environ Res. 2020 Apr;183:109151. doi: 10.1016/j.envres.2020.109151.

[19] Li D, Xu W, Qiu Y, Pan F, Lou H, Li J, et al. Maternal air pollution exposure and neonatal congenital heart disease: A multi-city cross-sectional study in eastern China. Int J Hyg Environ Health. 2022 Mar;240:113898. doi: 10.1016/j.ijheh.2021.113898.

[20] Zhang H, Zhang X, Zhao X, Cheng G, Chang H, Ye X, et al. Maternal exposure to air pollution and congenital heart diseases in Henan, China: A register-based case-control study. Ecotoxicol Environ Saf. 2022 Jan 1;229:113070. doi: 10.1016/j.ecoenv.2021.113070.

[21] Huang X, Chen J, Zeng D, Lin Z, Herbert C, Cottrell L, et al. The association between ambient air pollution and birth defects in five major ethnic groups in Liuzhou, China. BMC Pediatr. 2021 May 14;21(1):232. doi: 10.1186/s12887-021-02687-z.

[22] Padula AM, Yang W, Schultz K, Lee C, Lurmann F, Hammond SK, Shaw GM. Gene-environment interactions between air pollution and biotransformation enzymes and risk of birth defects. Birth Defects Res. 2021 May 15;113(9):676-686. doi: 10.1002/bdr2.1880. Cheng Y, Yin J, Yang L, Xu M, Lu X, Huang W, et al. Ambient air pollutants in the first trimester of pregnancy and birth defects: an observational study. BMJ Open. 2023 Mar 22;13(3):e063712. doi: 10.1136/bmjopen-2022-063712.

[24] Zhang Y, Qiu J, Zhou M, He X, Cui H, Xu X, et al. Cooking stoves and risk of birth defects in urban China.

Environ Res. 2021 Mar;194:110731. doi: 10.1016/j.envres.2021.110731.

[25] Li S, Zhang Y, Yang K, Zhou W. Exploring potential causal links between air pollutants and congenital malformations: A two-sample Mendelian Randomization study. Reprod Toxicol. 2024 Sep;128:108655. doi: 10.1016/j.reprotox.2024.108655.

[26] Li L, Zhang N, Wu X, Feng T, Zhao Z, Pang Y, Zhang Y, Wang N, Ning J, Zhao S, Jiang T, Shi B, Niu Y, Zhang R, Hao G. Exposure to air pollution is associated with congenital anomalies in the population born by in vitro fertilization. Environ Res. 2022 May 1;207:112161. doi: 10.1016/j.envres.2021.112161. Epub 2021 Oct 7. PMID: 34626591.

[27] Ma Z, Li W, Yang J, Qiao Y, Cao X, Ge H, Wang Y, Liu H, Tang N, Yang X, Leng J. Early prenatal exposure to air pollutants and congenital heart disease: a nested case-control study. Environ Health Prev Med. 2023;28:4. doi: 10.1265/ehpm.22-00138.

[28] Arogbokun Knutson OC, Luben TJ, Stingone JA, Engel LS, Martin CL, Olshan AF. Racial disparities in maternal exposure to ambient air pollution during pregnancy and prevalence of congenital heart defects. Am J Epidemiol. 2025 Mar 4;194(3):709-721. doi: 10.1093/aje/kwae253.

[29] Zhang W, Yang Y, Liu Y, Zhou L, Yang Y, Pan L, et al. Associations between congenital heart disease and air pollutants at different gestational weeks: a time-series analysis. Environ Geochem Health. 2023 May;45(5):2213-2228. doi: 10.1007/s10653-022-01315-8.

[30] Jiang W, Liu Z, Ni B, Xie W, Zhou H, Li X. Independent and interactive effects of air pollutants and ambient heat exposure on congenital heart defects. Reprod Toxicol. 2021 Sep;104:106-113. doi: 10.1016/j.reprotox.2021.07.007.

[31] Sun J, Wang J, Yang J, Shi X, Li S, Cheng J, et al. Association between maternal exposure to indoor air pollution and offspring congenital heart disease: a case-control study in East China. BMC Public Health. 2022 Apr 15;22(1):767. doi: 10.1186/s12889-022-13174-0.

[32] Yang Y, Lin Q, Liang Y, Ruan Z, Acharya BK, Zhang S, et al. Maternal air pollution exposure associated with risk of congenital heart defect in pre-pregnancy overweighted women. Sci Total Environ. 2020 Apr 10;712:136470. doi: 10.1016/j.scitotenv.2019.136470.

[33] Deng C, Pu J, Deng Y, Xie L, Yu L, Liu L,et al. Association between maternal smoke exposure and congenital heart defects from a case-control study in China. Sci Rep. 2022 Sep 2;12(1):14973. doi: 10.1038/s41598-022-18909-y.

[34] Jin S, Yoon SZ, Choi YJ, Kang G, Choi SU. Prenatal exposure to air pollutants and the risk of congenital heart disease: a Korean national health insurance database-based study. Sci Rep. 2024 Jul 23;14(1):16940. doi: 10.1038/s41598-024-63150-4.

[35] Buteau S, Veira P, Bilodeau-Bertrand M, Auger N. Association between First Trimester Exposure to Ambient PM2.5 and NO2 and Congenital Heart Defects: A Population-Based Cohort Study of 1,342,198 Live Births in Canada. Environ Health Perspect. 2023 Jun;131(6):67009. doi: 10.1289/EHP11120.

[36] Wang H, Ruan YP, Ma S, Wang YQ, Wan XY, He YH,et al. Interaction between ozone and paternal smoking on fetal congenital heart defects among pregnant women at high risk: a multicenter maternal-fetal medicine study. World J Pediatr. 2024 Jun;20(6):621-632. doi: 10.1007/s12519-023-00755-1.

[37] Park BY, Vedhanayagam K, Ortiz-Luis J, Basu R, Gheorghe CP, Govindappagari S,et al. Living Near Wildfires and the Risk of Fetal Congenital Heart Defects: Evaluating Critical Windows of Vulnerability. AJP Rep. 2025 Feb 13;15(1):e18-e24. doi: 10.1055/a-2528-3588.

[38] Chang YC, Lin YT, Jung CR, Chen KW, Hwang BF. Maternal exposure to fine particulate matter and congenital heart defects during preconception and pregnancy period: A cohort-based case-control study in the Taiwan maternal and child health database. Environ Res. 2023 Aug 15;231(Pt 2):116154. doi: 10.1016/j.envres.2023.116154.

[39] Julaiti M, Wubuli D, Cui T, Nijiati N, Huang P, Hu B. Analysis of the relationship between environmental particulate matter exposure and congenital diseases, as well as the epidemiological trends and burden of impact on newborns. Ecotoxicol Environ Saf. 2025 Jan 1;289:117465. doi: 10.1016/j.ecoenv.2024.117465.

[40] Li Y, Zhou C, Liu J, Mao D, Wang Z, Li Q, et al. Maternal Exposure to Ozone and the Risk of Birth Defects: A Time-Stratified Case-Crossover Study in Southwestern China. Toxics. 2024 Jul 19;12(7):519. doi: 10.3390/toxics12070519.

[41] Jiang W, Liu Z, Ni B, Xie W, Zhou H, Li X. Modification of the effects of nitrogen dioxide and sulfur dioxide on congenital limb defects by meteorological conditions. Hum Reprod. 2021 Oct 18;36(11):2962-2974. doi: 10.1093/humrep/deab187.

[42] Huang Z, Qiu Y, Qi J, Ma X, Cheng Q, Wu J. Association between air pollutants and birth defects in Xiamen, China. Front Pediatr. 2023 May 25;11:1132885. doi: 10.3389/fped.2023.1132885.

[43] Lee KS, Lim YH, Choi YJ, Kim S, Bae HJ, Han C, et al. Prenatal exposure to traffic-related air pollution and risk of congenital diseases in South Korea. Environ Res. 2020 Dec;191:110060. doi: 10.1016/j.envres.2020.110060.

[44] Krakauer KN, Cevallos PC, Amakiri UO, Saldana GM, Lipman KJ, Howell LK, et al . US air pollution is associated with increased incidence of non-syndromic cleft lip/palate. J Plast Reconstr Aesthet Surg. 2024 Jan;88:344-351. doi: 10.1016/j.bjps.2023.11.012.

[45] Liu Y, Zhou L, Zhang W, Yang Y, Yang Y, Pan L, et al. Time series analysis on association between ambient air pollutants and orofacial clefts during pregnancy in Lanzhou, China. Environ Sci Pollut Res Int. 2022 Oct;29(48):72898-72907. doi: 10.1007/s11356-022-19855-y.

[46] Wright CY, Kapwata T, Wernecke B, Malherbe H, Bütow KW, Naidoo N, et al. The Risk of Orofacial Cleft Lip/Palate Due to Maternal Ambient Air Pollution Exposure: A Call for Further Research in South Africa. Ann Glob Health. 2023 Jan 27;89(1):6. doi: 10.5334/aogh.4007.

[47] Diao J, Zhao L, Luo L, Li J, Li Y, Zhang S, et al. Associations and interaction effects of maternal smoking and genetic polymorphisms of cytochrome P450 genes with risk of congenital heart disease in offspring: A case-control study. Medicine (Baltimore). 2021 Jun 11;100(23):e26268. doi: 10.1097/MD.0000000000026268.

[48] Zhang JY, Gong TT, Huang YH, Li J, Liu S, Chen YL, et al. Association between maternal exposure to PM_{10} and polydactyly and syndactyly: A population-based case-control study in Liaoning province, China. Environ Res. 2020 Aug;187:109643. doi: 10.1016/j.envres.2020.109643.

[49] Jiang YT, Gong TT, Zhang JY, Huang YH, Li J, Liu S, et al. Maternal exposure to ambient SO_2 and risk of polydactyly and syndactyly: a population-based case-control study in Liaoning Province, China. Environ Sci Pollut Res Int. 2021 Mar;28(9):11289-11301. doi: 10.1007/s11356-020-11351-5.

[50] Zhang JY, Wu QJ, Huang YH, Li J, Liu S, Chen YL, et al. Association between maternal exposure to ambient PM_{10} and neural tube defects: A case-control study in Liaoning Province, China. Int J Hyg Environ Health. 2020 Apr;225:113453. doi: 10.1016/j.ijheh.2020.113453.

[51] Xia J, Huang YH, Li J, Liu S, Chen YL, Li LL, et al. Maternal exposure to ambient particulate matter 10 μm or less in diameter before and after pregnancy, and anencephaly risk: A population-based case-control study in China. Environ Res. 2020 Sep;188:109757. doi: 10.1016/j.envres.2020.109757.

[52] Zhang TN, Wu QJ, Huang YH, Li J, Chen ZJ, Li LL, et al. Association between maternal exposure to PM_{10} and risk of anorectal atresia/stenosis in offspring: a population-based case-control study in Liaoning Province, China. Environ Sci Pollut Res Int. 2022 Mar;29(15):21328-21338. doi: 10.1007/s11356-021-16573-9.

[53] Li LL, Huang YH, Li J, Liu S, Chen YL, Jiang CZ, et al. Maternal Exposure to Sulfur Dioxide and Risk of Omphalocele in Liaoning Province, China: A Population-Based Case-Control Study. Front Public Health. 2022 May 12;10:821905. doi: 10.3389/fpubh.2022.821905.

[54] Li H, Huang YH, Li J, Liu S, Chen YL, Li LL,et al. Maternal PM_{10} Exposure Increases Risk for Spina Bifida: A Population-Based Case-Control Study. Front Public Health. 2021 Jul 21;9:695192. doi: 10.3389/fpubh.2021.695192.

[55] Liu FH, Dai HX, Gong TT, Zhang JY, Li J, Chen ZJ, et al. Maternal preconception and first trimester exposure to PM_{10} and the risk of oral clefts in offspring: a population-based, case-control study. Occup Environ Med. 2020 Oct;77(10):721-727. doi: 10.1136/oemed-2020-106434.

[56] Liu L, Wang L, Ni W, Pan Y, Chen Y, Xie Q, et al. Rare earth elements in umbilical cord and risk for orofacial clefts. Ecotoxicol Environ Saf. 2021 Jan 1;207:111284. doi: 10.1016/j.ecoenv.2020.111284.

[57] Zhang JY, Dai HX, Wu QJ, Li J, Huang YH, Chen ZJ, et al. Maternal exposure to ambient levels of sulfur dioxide and risk of neural tube defects in 14 cities in Liaoning province, China: a population-based case-control study. J Expo Sci Environ Epidemiol. 2021 Mar;31(2):266-275. doi: 10.1038/s41370-020-00273-6.

[58] Liu Y, Zhang H, Li J, Liang C, Zhao Y, Chen F, et al. Geographical variations in maternal lifestyles during pregnancy associated with congenital heart defects among live births in Shaanxi province, Northwestern China. Sci Rep. 2020 Jul 31;10(1):12958. doi: 10.1038/s41598-020-69788-0.

[59] Ren H, Zhang X, Zhang S, Pan J, Wang W. The association of increased incidence of congenital heart disease in newborns with maternal COVID-19 infection during pregnancy. *Sci Rep* **14**, 24866 (2024). https://doi.org/10.1038/s41598-024-76690-6

[60] Nie Z, Yang B, Ou Y, Bloom MS, Han F, Qu Y, et al. Maternal residential greenness and congenital heart

defects in infants: A large case-control study in Southern China. Environ Int. 2020 Sep;142:105859. doi: 10.1016/j.envint.2020.105859.

[61] Zhen S, Zheng L, Li Q, Yin Z, Cui H, Li Y, et al. Maternal green space exposure and congenital heart defects: A population-based study. Environ Res. 2025 Mar 1;268:120745. doi: 10.1016/j.envres.2024.120745.