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Review

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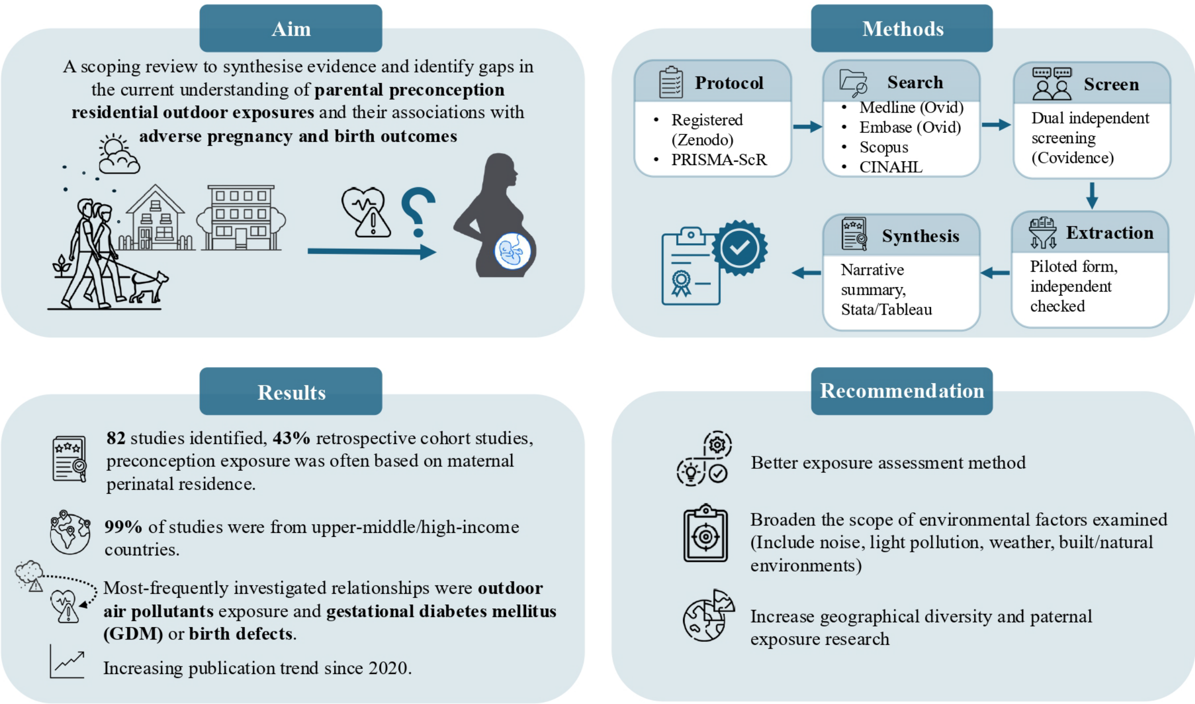
Graphical Abstract



Highlights:

- First scoping review on preconception outdoor environmental exposures and perinatal health outcomes.
- Few studies examined exposures beyond air pollution.
- Lack of studies on paternal preconception exposures and in low-middle income countries.
- Preconception exposure was often based on maternal perinatal residence.

Parental preconception exposure to residential outdoor neighbourhood environments and adverse pregnancy and birth outcomes: a scoping review

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Abstract: **Background:** Preconception exposure to residential outdoor neighbourhood environments can influence perinatal outcomes by influencing fertility, gamete quality and foetal development through mechanisms such as oxidative stress, epigenetics and inflammation. Following our published protocol, this scoping review aims to synthesize the available evidence and identify gaps in the current understanding of this topic. **Methods:** We searched four databases (Cumulative Index to Nursing and Allied Health Literature, Ovid Medline, Ovid Embase and Scopus) for peer-reviewed publications on 20 December 2023. The search was restricted to English, without other restrictions. Two reviewers independently screened titles, abstracts and full texts. Findings were narratively synthesised. **Results:** We identified 82 eligible studies since 2010, all but one from upper-middle-or high-income countries. The largest proportion (43%) comprised retrospective cohort studies, with number of studies published since 2020 trending upwards. Although preconception was usually defined as the three months before pregnancy, most studies assigned these exposures using pregnancy or birth addresses, assuming residential stability since preconception. Among included studies, exposure to PM2.5 was associated with an increased risk of gestational diabetes mellitus (GDM), while PM10 was linked to birth defects. However, most exposure-outcome associations were inconsistent across included studies. The literature suggested the strongest consistency for PM10-birth defects associations, while evidence for O_3-GDM associations was inconclusive. Research on other outdoor environmental factors, such as noise, light pollution, weather, built and natural environments, was lacking. **Conclusions:** Our review found that the existing evidence base is geographically skewed, concentrated on air pollution exposures, and notably lacking in research on paternal exposures. To advance the field, future studies should adopt more precise exposure assessments and expand the range of environmental factors, geographical diversity, and paternal exposure research.

Keywords: preconception; outdoor environments; neighbourhood; pregnancy and birth outcomes; perinatal; scoping review

1. Introduction

The preconception period is critical in shaping pregnancy and birth outcomes. Adverse pregnancy and birth outcomes are significant public health challenges, contributing substantially to the global disease burden [1–3]. In 2021, preterm birth (PTB) and low birth weight (LBW) together ranked as the fourth leading contributors to this burden, accounting for 5.6% of total disability-adjusted life-years [1]. These outcomes have lifelong consequences for both mothers and their children [4–7].

Based on the Developmental Origins of Health and Disease (DOHaD) theory, exposure to different aspects of neighbourhood environment in the preconception period could affect maternal and child health and development [8–11]. Neighbourhood environments are a ubiquitous feature of daily life and can shape health and well-being [12–15]. These environments encompass a range of exposures including pollution (e.g., air, noise and light pollution), weather conditions (e.g., temperature and humidity), natural features (e.g., green and blue spaces), and built features (e.g., access to facilities and services and walkability). These preconception exposures could influence fertility, gamete quality, foetal development and long-term maternal and child health through mechanisms such as gametogenesis timing, oxidative stress, epigenetic remodelling, hormonal disruption and inflammation [8,16]. Preconception exposure to these neighbourhood environments has been associated with longer-term child health, including childhood obesity, respiratory and allergic outcomes (e.g., respiratory disease syndrome, asthma, eczema, allergic rhinitis) and infectious diseases (e.g., pneumonia, otitis media) [17,18]. The definition of the preconception period varies, it refers to: days to weeks before embryo development and maturation from a biological perspective; weeks to months before pregnancy at the individual level; and months to years prior to pregnancy from a public health perspective [19].

Emerging evidence shows that exposure to outdoor neighbourhood environment may act as risk or protective factors for pregnancy and birth outcomes. For example, exposure to higher levels of ambient air pollution during pregnancy are associated with increased risk of PTB, GDM and suboptimal measures of foetal growth [14,20,21]. A comprehensive review identified that exposure to particulate matter with an aerodynamic diameter of 2.5 µm or less (PM2.5) during the entire pregnancy (not including the preconception period) was associated with a higher risk of PTB (pooled effect estimate 1. 95% CI: 1.08–1.41 per 10 µg/m^3 increase) [20]. On the other hand, greenspace has been found to mitigate the adverse cognitive effects of air pollution in adolescents [22]. Similarly, multiple systematic reviews show that noise [23,24], heat [25], humidity [26], outdoor artificial light [27,28], green space, and blue space [29,30] exposures during pregnancy are associated with pregnancy and birth outcomes. As such, neighbourhood environments represent a potentially modifiable mechanism to improve pregnancy and birth outcomes at the population level. Although pregnancy is widely recognised as a critical window of susceptibility, exposures before conception may also affect pregnancy and birth outcomes in ways consistent with DOHaD.

Blanc *et al.* synthesised evidence on preconception air pollution and children's health and found that maternal preconception exposure to air pollution (e.g., particulate matter with an aerodynamic diameter ≤ 2.5 µm or ≤ 10 µm (PM2.5 or PM10), ozone (O_3) and sulfur dioxide (SO_2) increases the risk of birth defects, PTB and LBW, underscoring the relevance of the preconception period [17]. There are even fewer studies on paternal preconception exposures, despite growing recognition of the importance of their influence in the health and developmental path of offspring, for example, through DNA methylation and histone changes [8,31]. Identifying and mitigating environmental hazards, such as pollution, and promoting good health and nutrition during the preconception period for both parents can support lifelong health for mothers and their offspring [32]. Additionally, it remains unclear how the wider range of outdoor environmental factors beyond air pollution during preconception relates to pregnancy and birth outcomes.

Given rising concern about environmental determinants of health and improved methods for measuring the exposome, a scoping review is both timely and necessary to clarify what is known, identify gaps and inform research, surveillance and policy. This scoping review addresses the research gap identified in our published protocol [33]. Within this context, we conducted a systemic scoping review that aimed to: (1) identify the existing evidence on the relationships between parental preconception residential exposure to outdoor neighbourhood environments and adverse pregnancy and birth outcomes; and (2) summarise evidence gaps, present evidence maps and narratively summarise the findings.

2. Material and methods

2.1. Protocol and registration

The study protocol of this scoping review has been published [33] and registered in Zenodo (zenodo.org/records: 15645421). This manuscript followed version 3 of the protocol. As per our published protocol [33], this scoping review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines and Checklist [34].

2.2. Search strategy

We conducted systematic searches for peer-reviewed published literature in four major databases including Medline (Ovid), Embase (Ovid), Scopus and Cumulative Index to Nursing and Allied Health Literature (CINAHL). Our search strategy was divided into three key concepts: (1) the outdoor neighbourhood environment, (2) the preconception period, and (3) adverse pregnancy and birth outcomes. The detailed search strings for each database and search results are in Tables S1–S4. An initial search was conducted on 22 August 2021 following the search terms documented in version 2 of the protocol. An updated search was then developed in consultation with an expert librarian from Deakin University and conducted on 20 December 2023 following the search strings detailed in Tables S1–S4. We restricted the search to English language. There was no restriction on the publication date. Other sources of literature were not considered in this review. While indoor environmental risk factors may also contribute to adverse pregnancy and birth outcomes, they were outside the scope of this review.

2.3. Study selection

Two reviewers independently screened each title and abstract according to the inclusion and exclusion criteria (Table 1) (drawn from YW, SM, M Marzan, M Moslehi, MC, RT, DK, KL, KC). Eligible articles were entered into full-text screening and each was independently screened by two of the reviewers (drawn from YW, SM, M Marzan, M Moslehi, RT). Discrepancies were resolved by a third reviewer or consensus. The screening approach was piloted by each reviewer before the formal screening started to identify potential questions, reach consensus and ensure consistency. The screening process was conducted in Covidence [35].

The inclusion and exclusion criteria were determined based on the Populations, Exposures, Comparators and Outcomes statement (PECOs) and are listed in Table 1.

Table 1. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
(1) Original empirical studies investigating the relationship between one or more of the specified outdoor environment exposures and one or more adverse birth outcomes. (2) Exposures during preconception period for one or both parents. Studies will be included even if they used pregnancy or birth address as a proxy for preconception exposure. (3) At least one objectively assessed feature of the physical outdoor neighbourhood environment. Included environ-mental features were pollution (e.g., sulphur dioxide, nitrogen oxides, particulate matter, noise and light pollution), weather (e.g., temperature, humidity), built environment (e.g., dwelling density, walkability), and natural environment (e.g., green space, blue space). The exposures could be individual exposures or aggregate indices. (4) The outdoor environment was within the residential neighbourhood. (5) At least one adverse pregnancy or birth outcome (see keywords used in search strings for details, Tables S1–S4) including: Maternal (during all trimesters of pregnancy): gestational diabetes mellitus, gestational hyperglycaemia, pre-eclampsia, eclampsia, gestational hypertension, pregnancy complications, mental health, *etc*. Neonate (assessed at/immediately following birth): low or large birth weight, large or small for gestational age, preterm birth, premature rupture of membranes, congenital anomalies, birth complications, macrosomia, macrosomic, intrauterine growth retardation, fetal growth restriction, dystocia, stillbirths, *etc*. (6) Study published in English.	(1) Not an original study, such as reviews, commentaries, non-research letters, editorials, not human studies, not a full article (e.g., conference abstract) or full text not available. (2) Study did not separately assess exposure during preconception period. (3) Study did not analyse an environmental exposure listed in the inclusion criteria. (4) Study only included environmental exposures relating to organic and inorganic chemicals, radiation, and heavy metals. (5) Study measured indoor environment only or the measured outdoor environment was not in the residential neighbourhood (e.g., workplace or occupation exposure). (6) Study did not have an analysis with a pregnancy or birth outcome (during pregnancy or at or just after birth). Childhood asthma, mental health, autism spectrum disorder (ASD) or any other conditions/diseases that can only be diagnosed some time after birth were excluded.

2.4. Data extraction

The data extraction form was developed by YW and SM. All authors involved in the data extraction piloted the data extraction as a group during a research meeting. Questions and uncertainties were raised and resolved during the meeting. Data from the included articles were then extracted by multiple authors independently (YW, M Marzan, M Moslehi, ZY). The lead author (YW) reviewed 25% of studies extracted by other team members to ensure consistency. Information extracted from each study included bibliographic information; study characteristics and context (study type, study period, geographic region, study participants information, sample size); exposure information (paternal and/or maternal exposure, preconception period definition, location data, outdoor environment exposure type/s, data source, measurement methods), outcome information (outcome variables, definition, data source, measurement methods); covariates and results (whether exposures were risk or promotive factors and a narrative summary of findings). Data extraction was conducted in covidence.

2.5. Synthesis of results

As a scoping review, our synthesis focuses on mapping the volume, characteristics and distribution of studies across regions, exposure domains, outcomes and study results (including count of studies) rather than on quantitative pooling (such as meta-analysis) of effect estimates. In line with PRISMA-ScR and JBI scoping review guidelines [34,36], a formal critical appraisal of included studies was not conducted. Data extracted from the included studies were exported to Stata (StataCorp LLC, SE/18.0) and Tableau Desktop (2024.3) for cleaning and data visualisation.

2.6. Ethics

The scoping review did not require ethics approval since it consists of collecting and reviewing publicly available publications.

3. Results

3.1. Study selection

The search results, article screening and final number of included studies are reported in Figure 1. We identified

7621 original references from 4 databases after removing duplicates. Title and abstract screening excluded 7378 articles as they did not meet the inclusion criteria. A remaining 243 articles underwent full-text screening. A total of 82 articles were included in this review (Figure 1).

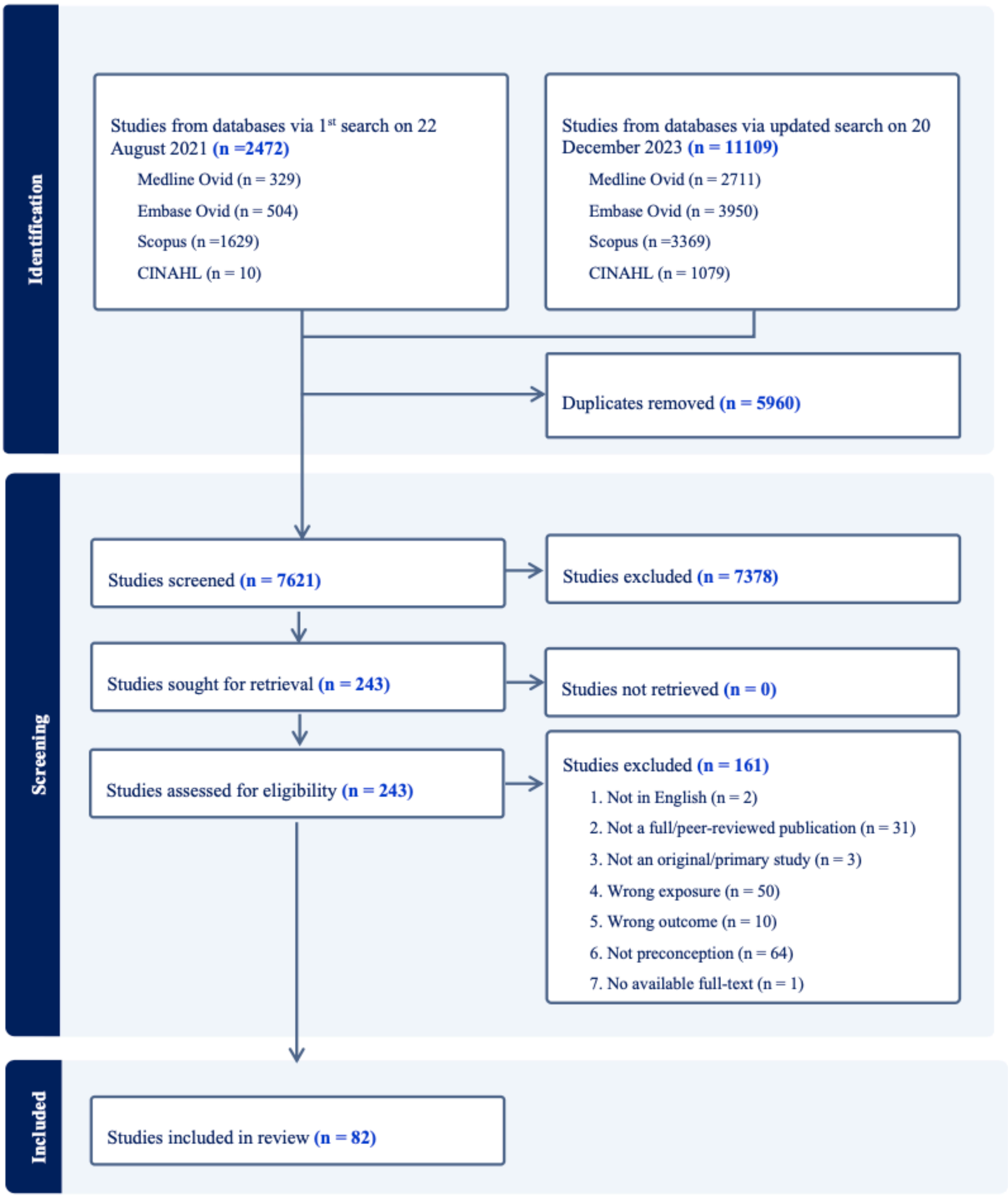

Figure 1. Study flowchart.

3.2. Study characteristics

The main descriptive characteristics of the included studies are listed in Table 2. Study designs included retrospective cohort (n = 35%, 43%), prospective cohort (n = 23%, 28%), and case-control studies (n = 20%, 24%). The sample size of the included studies ranged from 77 to 2,093,185 people. Air pollutants were the main environmental exposure reported (n = 74%, 88%), followed by weather conditions (n = 95%, 11%). Supplement Table S5 summarises the characteristics of the included studies in more detail.

Table 2. Main descriptive characteristics of the included studies (N = 82).

Characteristics	Number of studies	Percentage
Study type/design		
Retrospective cohort	35	43%
Prospective cohort	23	28%
Case control	20	24%
Cross-sectional	2	2%
Time-series	2	2%
Study location region		
East Asia	53	65%
Europe	2	2%
North America	24	29%
South America	1	1%
South Asia	1	1%
West Asia	1	1%
Study location (2023 World Bank Income group)		
High-income	28	34%
Upper-middle-income	53	65%
Lower-middle-income	1	1%
Location used to represent residence		
Birth hospital	16	20%
Residential address	61	74%
Residential and workplace addresses	3	4%
Other: Not clearly reported	2	2%
Location resolution#		
Address	41	50%
Area unit-city/county	19	23%
Area unit-hospital referral region	12	15%
Area unit-postcode	5	6%
Other	2	2%
Unknown-did not report	3	4%
Timing of location data^		
Birth	25	30%
Preconception	19	23%
Pregnancy	26	32%
Unknown-did not report	12	15%
Environmental exposure*		
Air pollutants	72	88%
Weather condition	9	11%
Built environment	3	4%
Natural environment	1	1%
Outcome category		
Birth	49	60%
Pregnancy	32	39%
Both	1	1%

Note: # This is the resolution of the location data that was used to estimate the environmental exposure. ^ This is the time period of the location data which was used to estimate the environmental exposure. * The number of studies was more than 82 as included studies contain more than one category.

3.2.1. Study region map

The included studies were mainly from East Asia (n = 53%, 65%) and North America (n = 24%, 29%). These studies were predominately (98%) from upper-middle-income or high-income countries defined by the 2023 World Bank income group [37] and were primarily from China and the USA (Figure 2).

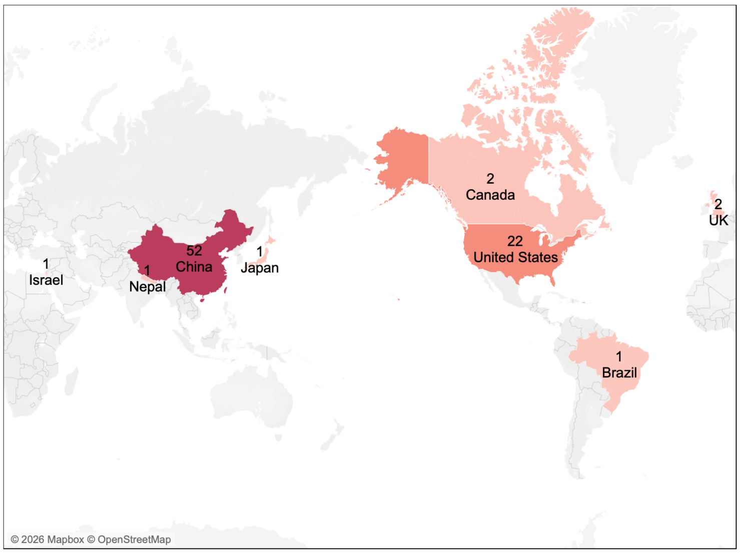

Figure 2. Number of included studies by country.

3.2.2. Time trends of included studies

The time trends for the publication year of the included studies between 2010 and 2024 are presented in Figure 3. Since 2020, there has been a dramatic increase in the number of studies with most (72%) of studies published since then.

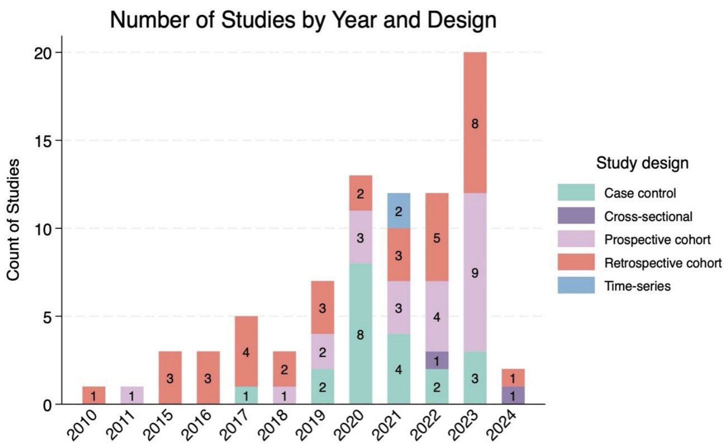

Figure 3. Number of included studies by publication year and design.

3.2.3. Study participants' recruitment methods of included studies

Most of the included studies were recruitment-based studies (n = 54%, 66%), while the rest involved the entire targeted population. Among the recruitment-based studies, 81% recruited participants from a birth or maternity service, and the rest were secondary data analyses from existing datasets such as data registries, administrative databases, and existing cohorts.

3.3. Outdoor environment features

3.3.1. Type of outdoor environments

Outdoor neighbourhood environments were classified into four categories: air pollution (e.g., SO_2, nitrogen oxides (NO_x), nitrogen dioxide (NO_2), carbon monoxide (CO), PM2.5, PM10, O_3, volatile organic compounds (VOCs)), weather conditions or weather events (e.g., ambient temperature, humidity, drought, excess rain, wildfire), built environment (e.g., residential proximity measures to major roads/wells) and natural environment (e.g., vegetation measured with the Normalised Difference Vegetation Index (NDVI)).

Only one study investigated paternal exposures, all the rest only assessed maternal exposures. The frequency of outdoor environments reported by the included studies is presented in Figure 4 of the outdoor neighbourhood environments, air pollution was the most reported environmental exposure (72/82, 88%). Among air pollutants, PM2.5 was the most reported (55/72, 76%). Nine studies also reported PM2.5 constituents such as sulphate, nitrate, ammonium, organic matter and black carbon. Ambient temperature was the most studied weather condition (7/9, 78%) and distance to roads was the most studied built environment feature (2/3, 67%). Only one study examined the natural environment feature (*i.e.*, NDVI).

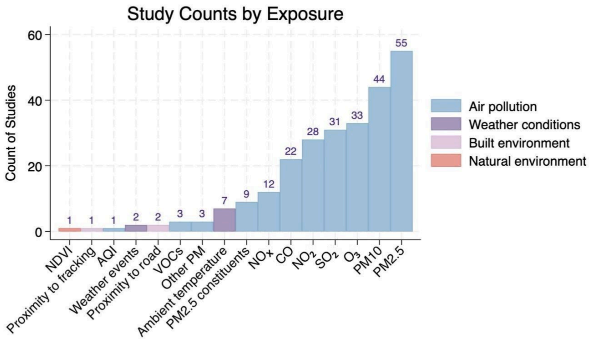

Figure 4. Frequency of outdoor environments reported by the included studies. Note: many papers reported more than one exposure and are represented more than once in the figure; AQI: air quality index; NDVI: normalised difference vegetation index; VOCs: Volatile Organic Compounds; Proximity to fracking: proximity to hydraulic fracturing sites.

3.3.2. Preconception period definition

The included studies have varying definitions of the preconception period, which ranged from weeks to years before pregnancy. The most common preconception period used was 12 weeks or three months before pregnancy (n = 63%, 77%). Many studies (n = 33%, 40%) did not report how they defined the conception date or how the pregnancy period was calculated. The last menstrual period was most often used (n = 47%, 57%) to calculate gestational age and estimate the preconception period.

3.3.3. Location for estimating exposure

The location used to estimate environmental exposure is an important factor to account for residential mobility and ensure accurate exposure estimates. Maternal residential address was the predominant location used to estimate the neighbourhood outdoor environment exposure (n = 64%, 78%). Half of the included studies estimated environmental exposure at the residential address level by linking the geocoded addresses to model exposure grids or to the nearest monitor. More than half (62%) of the studies used maternal location during pregnancy or at birth, with only 23% reporting the location during the preconception period. Only 23% of studies considered location changes during the preconception period and/or time-activity patterns. Maternal location was obtained from data linkage from medical/birth records or registries (57%) and study-collected measures from surveys, questionnaires and interviews (29%).

3.4. Adverse pregnancy and birth outcomes

More than half of the studies examined birth outcomes focusing on the offspring (60%) while the rest examined pregnancy outcomes (39%), and one study (1%) examined both pregnancy and birth outcomes (Figure 5). Birth defect or congenital abnormality was the most reported birth outcome, followed by PTB and abnormal growth and size issues (e.g., small for gestational age (SGA), large for gestational age (LGA) and LBW). Six studies included a total of 24 types of birth defects or congenital abnormalities based on International Classification of Diseases (ICD) codes. Twelve studies investigated a single type of birth defect (e.g., anorectal atresia/stenosis, gastroschisis, neural tube defect, orofacial defect, polydactyly/syndactyly). GDM and hypertensive disorders of pregnancy were the most reported adverse pregnancy outcomes. Mental health problems during the perinatal period and premature rupture of membranes (PROM) were in one study each.

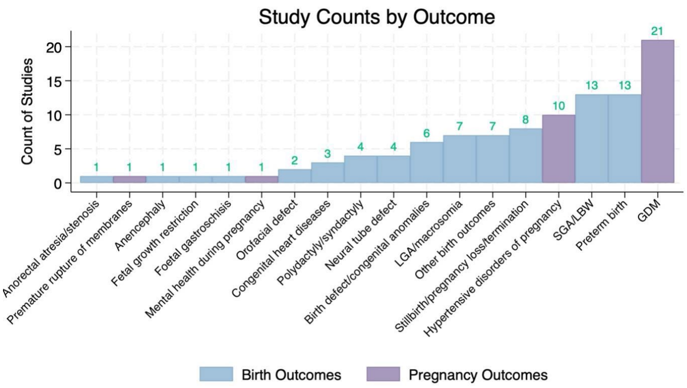

Figure 5. Frequency of adverse pregnancy and birth outcomes reported by the included studies. Note: papers that reported more than one outcome are represented more than once in the figure; SGA: small for gestational age; LGA: large for gestational age; LBW: low birth weight; GDM: gestational diabetes mellitus.

3.5. Associations between outdoor environments and adverse pregnancy and birth outcomes

Figure 6 presents the number of papers examining associations between each outdoor environment factor with each pregnancy and birth outcome. Associations could be protective (green), null (blue) or risk (red). The current literature is dominated by studies of air quality, especially those considering GDM and birth defects. Further, for most outcomes some papers reported risk and/or no effect, while beneficial effects were less common.

	Exposure category	Adverse birth outcomes																		Adverse pregnancy outcomes											
		Birth defect			PTB			SGA/LBW			LGA/ macrosomia			Pregnancy loss/			Stillbirth			PROM			GDM			Hypertensive disorder			Mental health		
Air pollution	PM2.5	3	3		2	4	2	2	6		3	2		1	1		2	2			1		14	7		2	6		1		
	PM10	12	2		1	3	1	1	3			1		3	1								7	6		1	4		1		
	NO2/NOx	1	4		2	1		1	5			2		1	1		1				1		6	8			5		1		
	O3	1	2		3	1	1	1	2	2	1	1		1	1								5	4	5	1	3	2			1
	SO2	3	4		1		2	2	2		1			1	1								7	4		2	3		1		
	CO	1	2		2	1		1	3			1		1	1								1	5		1	2	2			1
	PM2.5 Constituents							1									1			1			3		1		2				
	PM1					1																				1					
	VOCs																									3		1			
	AQI																							1							
Weather	Temperature				3	1	1		2			1						1								1		1			
	Drought/rain								1																						
	Wildfire	1																													
Built	Proximity measure	1	1												1																
Nat	NDVI								1			1																			

Count of studies	0	5	10	15
Risk factor				
Null				
Protect factor				

Figure 6. Heatmap of studies by adverse outcomes across environmental exposures and directionality of findings.

3.5.1. Associations between air pollutants and outcomes

We found evidence of associations between preconception exposure to six air pollutants (*i.e.*, PM2.5, PM10, NO_2/NO_X, SO_2, O_3, CO) and adverse pregnancy and birth outcomes. Each air pollutant was associated with a range of adverse outcomes, most commonly, GDM, birth defects and abnormal growth and size issues.

(1) Particulate matter and adverse outcomes

PM2.5 and PM10 were the most studied air pollutants in the included studies (Figure 6). Exposure to both PM2.5 and PM10 during the preconception period was associated with an increased risk of a range of adverse pregnancy and birth outcomes. Multiple studies linked higher levels of PM2.5 with GDM ($n = 14$), and higher levels of PM10 with birth defects ($n = 12$). Across the included studies, the association between PM10 and birth defects showed the strongest consistency. More than half of the studies reported non-statistically significant findings for the associations between PM2.5, PM10 and PTB, SGA/LBW and hypertensive disorders of pregnancy. Nine studies explored individual PM2.5 constituents (e.g., sulphate, nitrate, ammonium, organic matter, and black carbon) and reported that some of the constituents were associated with an increased risk of GDM, stillbirth and PROM. PM1 was examined in two studies, and one found it was associated with an increased risk of hypertensive disorders of pregnancy (HDP).

(2) Gaseous air pollutants

Exposure to higher levels of NO_2/NO_X, SO_2 and CO during the preconception period was associated with an increased risk of a range of adverse pregnancy and birth outcomes such as GDM and PTB (Figure 6). Contrary to other air pollutants, a mix of positive and negative associations between O_3 exposure and adverse outcomes was reported. The association between O_3 and GDM showed the weakest consistency.

(3) Other air pollutants

In addition to the air pollutants mentioned above, three studies reported that exposure to volatile organic compounds (VOCs) was associated with an increased risk of HDP. One of these studies also reported that two (N-hexane and o-xylene) of the VOCs were associated with reduced risk of gestational hypertension [38]. No other air quality measures were assessed by the included studies.

3.5.2. Associations between weather conditions and outcomes

Seven of the nine studies that investigated the effects of weather conditions or extreme weather events assessed ambient temperature. Exposure to hotter ambient temperatures was associated with an increased risk of PTB. In contrast, exposure to lower temperatures in hot areas was associated with a decreased risk of PTB [39]. Exposure to colder temperatures was associated with an increased risk of HDP such as preeclampsia, eclampsia and gestational hypertension [40]. Few studies assessed other aspects of weather. One study in Nepal found null association between drought/excess rainfall exposure during preconception and birthweight [41]. One study from the USA found that wildfire exposure before pregnancy was associated with an increased risk of gastroschisis (a congenital defect in the abdominal wall that allows intestines to exit the abdominal cavity) [42].

3.5.3. Associations between built and natural environments and outcomes

Few studies investigated preconception exposure to built and natural environments. Residential proximity to roadways, which is often used as a proxy for air pollution, was investigated by two studies. One reported that it was associated with an increased risk of congenital heart diseases (CHDs) [43] and the other found no association with spontaneous abortion risk [44]. Residential proximity to hydraulic fracturing sites (fracking) was assessed by one study, but it found no evidence of a link with adverse birth outcomes [45].

Only one of the included studies evaluated the association between urban residential surrounding greenness (measured as Normalised Difference Vegetation Index (NDVI) with adverse birth weight outcomes but found no evidence of an association).

4. Discussion

4.1. Principal findings

Our scoping review of 82 studies provides a comprehensive overview of empirical evidence examining the relationship between preconception exposure to residential outdoor neighbourhood environments and adverse pregnancy and birth outcomes. We found that air pollutants, particularly PM2.5, were the most frequently studied exposures, while GDM and birth defects were the most examined outcomes. Most studies (65%) were conducted in East Asia, with nearly all (99%) from upper-middle-income or high-income countries. Since 2020, there has been a substantial increase in the volume of published relevant studies. Maternal residential addresses during pregnancy or at birth were the commonly used location and timing for the environmental exposure estimate. The preconception period was usually defined as the three months before pregnancy. Among the included studies, exposure to PM2.5 was associated with an increased risk of GDM, while PM10 was linked to a higher risk of birth defects. However, most exposure-outcome associations were inconsistent across included studies. The literature suggested the strongest consistency for PM10–birth defects associations, while evidence for O_3–GDM associations was inconclusive. Notably, there was lack of research into other aspects of outdoor environments beyond air pollution, such as noise and light pollution, weather, built or natural features.

4.2. Interpretation in light of existing evidence

Our review reveals several key gaps in the literature, identifying areas for future research. First, we observed geographic imbalances, with a disproportionate number of studies from higher-income countries such as China and USA. Other regions are underrepresented. This highlights the need for more locally focused research to understand the effects of preconception environmental exposures in diverse global contexts, especially in the low/middle-income countries.

Second, while much of the literature focused on air pollution, there is a lack of evidence regarding other important environmental factors, such as noise, artificial light, humidity, and green and blue space. Yet these factors have known links to health outcomes [27,28,46], and potentially modifiable and therefore, are potential intervention targets. Similarly, there is a concentration of research on specific outcomes such as birth defects, PTB, abnormal growth and size outcomes, GDM and HDP. However, other important pregnancy/birth outcomes, particularly maternal mental health during pregnancy, have received limited attention. Given the long-lasting effects of maternal mental health on both mother and child [47,48], further research on preconception exposure and mental health outcomes is warranted. While there is evidence of neighbourhood environments exposures on mental health during other life stages, few studies focus specifically on the preconception period [47,48].

Third, despite an intention to include both maternal and paternal exposure, only one study assessed paternal exposure-highlighting a clear gap in the literature on paternal periconception exposures and adverse pregnancy and birth outcomes. Although paternal data were rarely reported, increasing evidence suggests that paternal environmental exposure can influence offspring health through sperm-mediated pathways, including gamete quality, DNA methylation and histone changes [8,31], supporting the importance of considering paternal exposures in future studies.

Estimating and quantifying neighbourhood environment exposures is key for studies aiming to examine their health effects. Accurate estimation of neighbourhood environment exposure requires careful consideration of three critical factors: (1) the location used for the study participant (to be linked with spatial environmental data), (2) the timing for the study participant exposed to the exposure at the location (to be linked with temporal environmental data), and (3) changes in residence or activity that could affect exposure classification.

In our scoping review, we found that most included studies (75%) used maternal residential address to estimate outdoor neighbourhood environmental exposure, which is preferable to birthing hospitals (used in 20% of included studies). However, less than a quarter of studies used preconception period as the timing of the location. Most of the studies used the location data at the time of birth or during pregnancy and assumed that participants remained in the same residence without verifying this. Residential mobility during pregnancy has been shown to range from 9%–32%, and is particularly high in the second trimester, introducing potential misclassification [49]. Future studies should use more accurate exposure estimate and any planned meta-analyses should also account for this factor. Less than a quarter of studies considered mobility or time-activity patterns, despite individuals spending more than 60% of their time at home [50]. Exposure at work or during transit is also relevant. Therefore, considering time-activity patterns would enhance exposure assessment accuracy.

Furthermore, the resolution of environmental data impacts the accuracy of the estimated environmental exposure. In our review, half of the studies linked data at large geographic scales (e.g., postcode, hospital referral region or city), which may compromise precision compared to address-level (e.g., geocoded residential or work address) linkages. Though direct measures (e.g., personal monitoring or biomonitoring devices) provide the most accurate data, indirect measurements are more feasible for large cohort studies. In most studies, the period of the linked environmental exposure data was not clearly reported, making it difficult to determine alignment with the preconception window. It is, therefore, important for future studies to follow best-practice reporting guidelines, such as those outlined in the spatial life course epidemiological studies [51].

Consistent with previous reviews, three months before pregnancy was the most common definition used of preconception period [17]. However, the included studies varied in their methods to calculate the preconception period, as some used the date of conception, while most studies used the last menstrual period date. The date of conception should be around 14 days after the last menstrual period date, assuming a woman's cycle is exactly 28 days, which will be more accurate as the cut point between preconception and pregnancy compared to the last menstrual period date [52]. Notably, all these calculations (estimated due date, conception date) are estimates and can vary based on individual circumstances.

Additionally, most studies averaged environmental exposures over the preconception period. This may introduce bias, as different patterns (e.g., consistent exposure *vs.* occasional peaks) may have distinct different biological effects [13]. Both short-term and long-term exposure prior to conception can impact health and development of mothers and babies [17,53], and therefore the pre-determined preconception length (e.g., three months) may not capture critical exposure windows. Very few studies employed distributed lag models to identify the critical time window of exposure and assess the daily/weekly effects. Where possible, future research should apply such models to better understand exposure timing.

Our review found that preconception exposure to particulate matter was positively associated with adverse pregnancy and birth outcomes, aligning with earlier systematic reviews. For instance, Ren *et al.* reported an increased GDM risk with PM2.5 exposure during the preconception period (OR = 1.09, 95% CI: 1.05–1.14) [21]. While we did not conduct a meta-analysis, 14 out of 21 studies examining this association reported similar findings. PM10 was most commonly examined in relation to birth defects, similar to the results from a systematic review by Feng *et al.* [54]. They found that exposure to PM10 during the three months prior to pregnancy was significantly associated with nervous system anomalies. Preconception exposure to air pollution was also associated with increased risk of stillbirth, pregnancy loss or termination, which aligns with findings in other studies [55].

We also found a mix of positive and negative associations between environmental exposures and adverse outcomes, led by O_3 and GDM. Most of these studies (79%, 11/14) have examined the effects of a single type of residential environmental exposure (O_3) in isolation, without accounting for the potential influence of other exposures. This limitation may partly explain the mixed findings observed. Emerging evidence suggests that different types of environmental exposures can interact to influence health outcomes. For instance, greenspace has been found to mitigate the adverse cognitive effects of air pollution in adolescents [22], and the health effects of greenspace may vary depending on co-exposure to biogenic volatile organic compounds and O_3 [56]. Therefore, it is crucial for future research and systematic reviews to account for the interplay between multiple environmental exposures when assessing their impact on health. Inconsistent findings for O_3 could also arise from its seasonal variability and the use of exposure metrics that inadequately capture concentration variations, leading to misclassification in exposures [57]. Additionally, as a secondary pollutant, O_3 formation depends on sunlight and precursor chemistry, and its oxidative potential may plausibly influence inflammatory or oxidative-stress pathways in ways that vary with timing of exposure and population susceptibility [57,58].

Climate change related factors, including rising temperatures, heat waves, extreme weather events and climate-driven changes in air pollution, are likely to influence the intensity and spatial distribution of neighbourhood-level exposures such as air pollution patterns, green spaces and ambient temperature and exacerbate existing environmental and health inequities [59]. Therefore, it is also crucial to consider climate factors in future studies.

4.3. Strengths and limitations

To our knowledge, this is the first scoping review to comprehensively evaluate the effects of parental preconception exposure to a broad range of outdoor residential neighbourhood environment features on all potential adverse pregnancy and birth outcomes. We followed a strict protocol adhering to the PRISMA-ScR guidelines of conducting a systematic scoping review with a systematic search strategy, preregistered our protocol and undertook a dual screening process.

However, several limitations should be noted. First, data extraction was completed by one reviewer. Although the lead author checked 25% of entries for consistency, potential oversights cannot be fully ruled out so are a potential source of error. Second, only peer-reviewed, English language studies were included. We did not conduct supplementary searching and search for grey literature in the interest of feasibility. These exclusions might have led us to overlook additional insights, especially relevant findings from government reports. The exclusion of non-English and grey literature may omit relevant data from underrepresented regions. Third, we excluded studies focusing solely on chemicals, heavy metals or cigarette/vape smoking during the preconception period. The main focus of this scoping review is outdoor neighbourhood natural and built environments, but chemicals (e.g., pesticides), heavy metals and smoking are all environmental toxins in extreme scenarios. Health hazards of certain chemicals have been reviewed separately [10] and are another priority topic [60]. Finally, a formal critical appraisal of included studies was not conducted, which should be considered when interpreting the findings of this scoping review.

We also identified limitations in the existing literature rather than in our approach to reviewing it. For example, some studies used time-invariant exposures (e.g. distance to major roads) across preconception and pregnancy periods, making it difficult to isolate preconception effects [43].

4.4. Implications and future direction

Although this is a scoping review and as such does not support causal inference or direct clinical recommendations, it identifies consistent associations between preconception residential outdoor exposures, particularly particulate matter and adverse pregnancy and birth outcomes. These findings highlight the potential value of earlier identification of high-risk pregnancies, particularly among those living in high-pollution areas, to enable enhanced prenatal monitoring and reduce the risk of adverse pregnancy and birth outcomes. In addition, raising public awareness of the importance of the residential outdoor environment before conception may support risk reduction efforts at the population level.

At the same time, major heterogeneity in study design, outcomes and exposure assessment limits synthesis and translation. Future studies should use exposure measures that are spatially and temporally aligned with the preconception period, account for residential mobility and time-activity patterns and follow standardised reporting guidelines to enable quantitative synthesis.

The evidence gaps identified by this scoping review provide clear direction for future research. Research is scarce in low- and middle-income countries, few studies examine environmental exposures beyond air pollution, and paternal preconception exposures are rarely considered. Addressing these gaps will be essential to build a more complete and policy-relevant understanding of how outdoor environments before conception shape pregnancy and birth outcomes. A parallel focus on impacts of indoor environments, which were out of scope for this review, may also be warranted, as these remain relatively under-investigated.

5. Conclusions

Our scoping review highlights growing interest in the health impacts of preconception exposure to outdoor neighbourhood environments, with air pollution, particularly PM2.5, being the most frequently studied factor. However, the evidence remains geographically skewed, methodologically varied, and limited in scope beyond air pollution. This review provides a valuable foundation for future research. To advance the field, future studies should adopt more precise exposure assessments, expand the range of environmental factors examined, ensure greater geographical diversity, and address the gap in paternal environmental exposure research. These efforts will be critical to support healthy lifecourse outcomes from the earliest stages of life.

Supplementary data

The authors confirm that the supplementary data are available within this article.

Data availability statement

No new data were created or analysed in this study.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools only to improve language and readability. The authors take full responsibility for the content of the manuscript.

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Conflicts of interest

Suzanne Mavoa holds the position of Associate Editor for *International Journal of Environmental Epidemiology* and has not peer reviewed or made any editorial decisions for this paper.

Authors' contribution

Yichao Wang: conceptualization, methodology, software, formal analysis, investigation, project administration, data curation, writing—original draft and visualization. Melvin Marzan: methodology, investigation, visualization and writing—review and editing. Zhengyu Yang: methodology, investigation and writing—review and editing. Mallery Crowe: conceptualization, methodology, investigation and writing—review and editing. Maryam Moslehi: methodology, investigation, visualization and writing—review and editing. Rachel Tham: methodology, investigation and writing—review and editing. Daniel Keevers: methodology, investigation and writing—review and editing. Stefan C. Kane: methodology, investigation and writing—review and editing. Melissa Wake: methodology, investigation and writing—review and editing. Kate Lycett: conceptualization, methodology, investigation, writing—review and editing and supervision. Yen Ting Wong: methodology, investigation and writing—review and editing. Katherine Chong: methodology, investigation and writing—review and editing. Suzanne Mavoa: conceptualization, methodology, investigation, resources, project administration, writing—review and editing and supervision.

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