Heat Exposure during Pregnancy and Risk of Preterm Birth: A Systematic Review and Meta-Analysis

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Abstract

Background: Climate change is increasing the frequency, intensity, and duration of extreme heat events. Pregnant females represent a climate-vulnerable population, yet the relationship between heat exposure during pregnancy and preterm birth has not been consistently synthesized.

Objective: To synthesize and critically evaluate the available evidence regarding the association between heat exposure during pregnancy and preterm birth.

Methods: A systematic review and meta-analysis were conducted in accordance with PRISMA 2020 guidelines. PubMed and Google Scholar were searched from inception to December 2025 for studies examining the association between heat exposure during pregnancy and preterm birth. Eligible studies included cohort and time-series designs reporting quantitative effect estimates. A random-effects meta-analysis (DerSimonian-Laird model) was used to pool comparable effect estimates.

Results: A total of 2,635 records were identified; five studies met the criteria for qualitative synthesis, and four were included in the meta-analysis. The random-effects meta-analysis demonstrated a significant association between maternal heat exposure and preterm birth (pooled RR=1.04, 95% CI: 1.01-1.06; p=0.0119). Statistical heterogeneity was considerable (I^2=81.5%). Individual study effect estimates ranged from 1.01 to 1.08 and consistently indicated increased risk. Overall, the included studies were assessed as having low to moderate risk of bias.

Conclusion: Heat exposure during pregnancy is associated with a modest but statistically significant increase in the risk of preterm birth. Given the increasing frequency and intensity of extreme heat events associated with climate change, these findings highlight the importance of incorporating maternal health considerations into heat-health action plans, antenatal care guidance, and climate adaptation strategies.

Keywords: *Heat exposure, preterm birth, pregnancy, climate change, maternal health, systematic review.*

INTRODUCTION

Preterm birth has been identified as one of the most common causes of neonatal morbidity and mortality worldwide. It represents a significant contributor to long-term neurodevelopmental impairment and chronic disease throughout the life course [1-7]. Despite advances in obstetric and neonatal care, the global rate of preterm birth has declined only marginally, with low- and middle-income countries bearing a disproportionate burden. Identifying modifiable environmental risk factors is therefore essential for reducing preventable adverse birth outcomes and improving maternal-child health equity.

Concurrently, climate change has emerged as one of the most pressing public health challenges of the 21st century, driven by rising global temperatures and the increasing frequency, duration, and intensity of extreme heat events [8-11]. Heatwaves are now occurring more frequently across most regions of the world, a trend projected to worsen under continued emissions trajectories [12-15]. Although the health consequences of extreme heat are well documented in older adults and individuals with chronic illness, pregnant individuals remain a relatively overlooked climate-vulnerable group within climate-health frameworks [16].

There is mounting epidemiological evidence that exposure to elevated ambient temperatures or heatwave conditions during pregnancy is associated with an increased risk of adverse birth outcomes, particularly preterm birth [17-30]. Due to the widespread and growing prevalence of heat exposure globally, even modest relative increases in risk may translate into substantial population-level impacts, particularly as climate change continues to intensify thermal extremes.

Numerous observational studies have investigated the association between heat exposure and preterm birth across diverse geographic contexts; however, the findings have not been consistently synthesized. Previous reviews have frequently examined a broad range of reproductive outcomes, incorporated non-quantitative evidence, or addressed climate change in a general context without isolating heat exposure as a specific environmental risk factor [31, 32].

A major systematic review and meta-analysis by Chersich *et al.* (2020) synthesized evidence on high-

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temperature exposure during pregnancy and multiple adverse birth outcomes, including preterm birth, low birth weight, and stillbirth [13]. However, that review examined a broad range of reproductive outcomes rather than focusing specifically on preterm birth. Furthermore, additional epidemiological studies [33-36] evaluating maternal heat exposure and preterm birth have been published since the search period covered by Chersich *et al.* Given the continuing increase in extreme heat events associated with climate change and the clinical importance of preterm birth as a leading cause of neonatal morbidity and mortality, an updated review focusing specifically on preterm birth is warranted. The present study therefore makes a distinct contribution by providing an outcome-specific synthesis restricted exclusively to preterm birth, incorporating more recently published studies not captured by Chersich *et al.* (2020) [13], and applying predefined eligibility criteria to improve methodological rigor. Unlike the 2020 BMJ review, which pooled heterogeneous reproductive outcomes and did

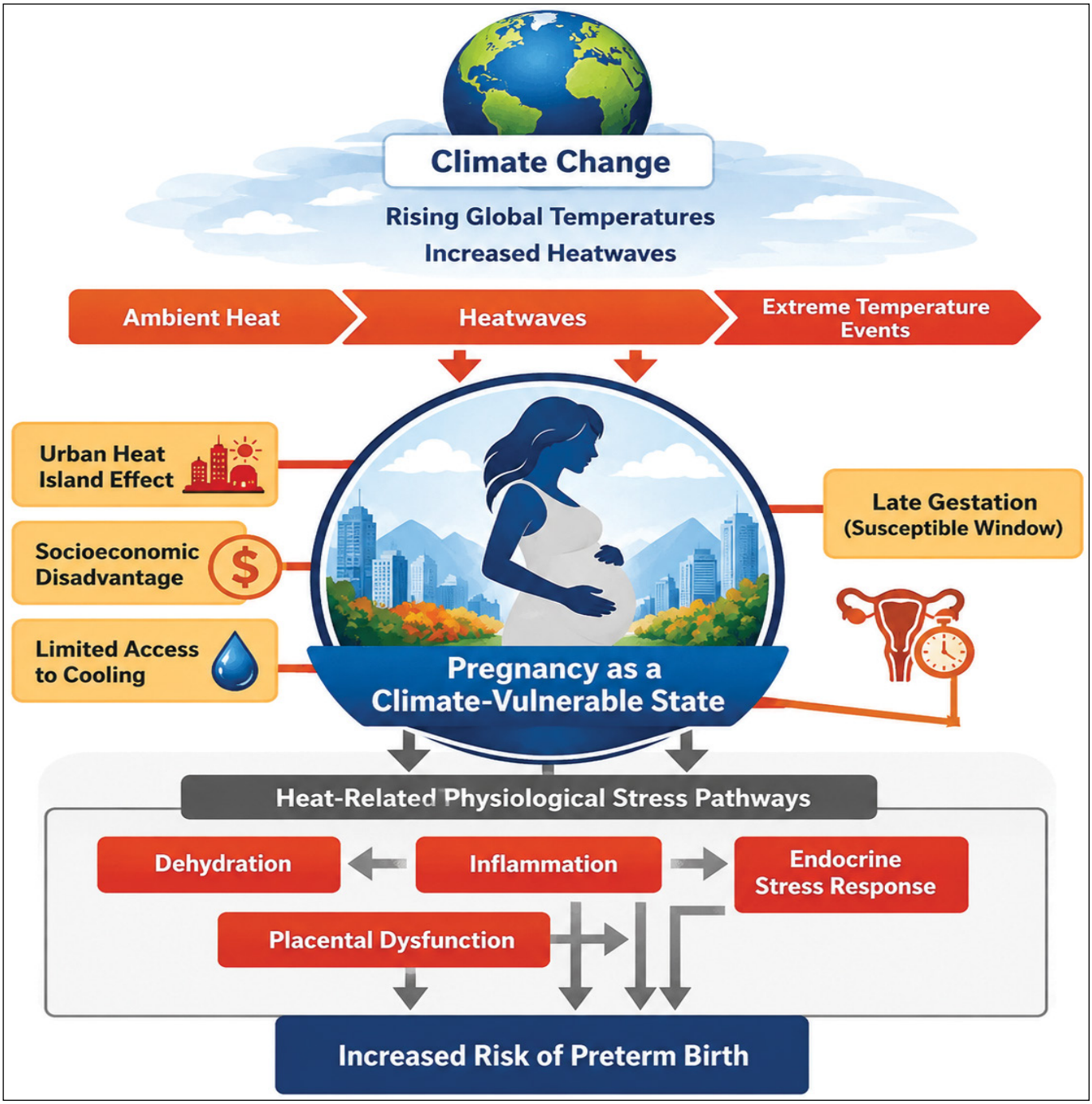


Fig. (1): A conceptual framework demonstrating the correlation between climate change-induced heat exposure during gestation and the risk of preterm birth. Increasing global temperatures and more frequent heatwaves may cause maternal heat stress, leading to dehydration, inflammation, endocrine stress responses, and placental dysfunction. Pregnancy is considered a climate-sensitive condition, with its relationship potentially influenced by socioeconomic, environmental, and gestational factors. This figure shows possible pathways, not the results of the study.

not restrict analysis to preterm birth alone, the current review offers a focused reassessment of the consistency and magnitude of the heat-preterm birth association in the context of accelerating climate change.

The objective of this systematic review and meta-analysis was therefore to synthesize and critically evaluate the available evidence regarding the association between heat exposure during pregnancy and preterm birth. Specifically, this review aimed to: (1) assess the consistency of reported associations across diverse geographic and climatic settings; (2) summarize study characteristics and methodological approaches; (3) evaluate the methodological quality of available evidence; and (4) provide an updated, outcome-specific synthesis relevant to maternal health in the context of climate change. Fig. **(1)** illustrates the potential biological pathways through which heat exposure during pregnancy may contribute to preterm birth.

METHODOLOGY

This systematic review and meta-analysis were conducted in accordance with the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [37].

A comprehensive literature search was conducted across PubMed and Google Scholar to identify studies examining the association between heat exposure during pregnancy and adverse birth outcomes. The search strategy employed controlled vocabulary terms (including MeSH headings in PubMed) and free-text keywords related to heat exposure, pregnancy, and birth outcomes. Search terms included combinations of: “heatwave,” “extreme temperature,” “heat exposure,” “climate change,” “pregnancy,” “pregnant,” “maternal,” “preterm birth,” “low birth weight,” and “stillbirth,” combined using Boolean operators (AND/OR). For PubMed, no date restriction was applied. For Google Scholar, a 20-year publication window (2005-2025) was applied to improve search relevance and manageability, consistent with the approach used in comparable climate-health systematic reviews. Reference lists of all eligible studies were also manually screened to identify additional relevant publications. The complete electronic search strategies, including MeSH terms, Boolean operators, and database-specific syntax, are provided in Supplementary Table **S1**.

This systematic review was not prospectively registered in PROSPERO or any other review registry before commencement, which is acknowledged as a methodological limitation. The review protocol, including eligibility criteria, study selection procedures, and data extraction methods, was developed by the authors before study selection began and was applied consistently throughout the review process. The review was conducted and reported in full accordance with PRISMA 2020 guidelines to mitigate the risk of selective reporting bias.

The following criteria were used to choose studies:

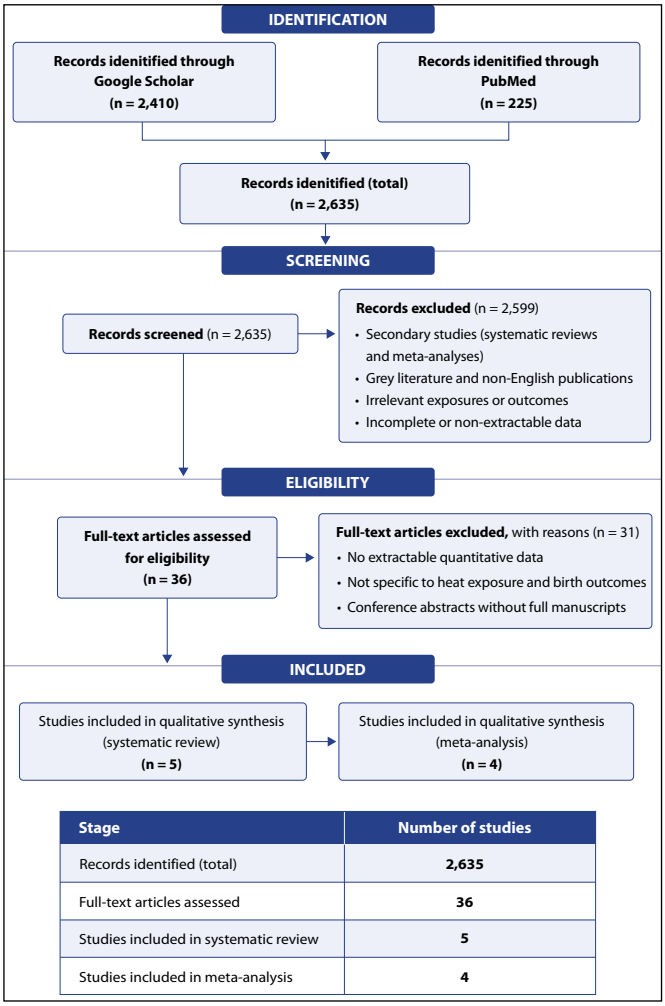
Population: Human populations of pregnant persons and their offspring.

Exposure: Weather data measures how much heat an individual is exposed to, such as outside temperature, a hot day, or a heatwave.

Comparator: The individual studies define it as periods of lower temperature or reference temperature ranges.

Outcomes: Preterm birth, defined as birth before 37 completed weeks of gestation. Only studies reporting a quantifiable association between heat exposure and preterm birth specifically were eligible for inclusion.

Study Design: Observational epidemiological designs, such as cohort and time-series designs.



Stage	Number of studies
Records identified (total)	2,635
Full-text articles assessed	36
Studies included in systematic review	5
Studies included in meta-analysis	4

Fig. (2): The PRISMA 2020 flow diagram shows how studies examining the link between exposure to heat during pregnancy and adverse birth outcomes were identified, screened, and included. We found records by searching Google Scholar and PubMed. We then removed secondary studies, grey literature, publications in languages other than English, and records with incomplete or non-extractable data in that order. The diagram shows the final number of studies that were used in the qualitative synthesis and the quantitative meta-analysis.

Systematic reviews, meta-analyses, scoping reviews, conference abstracts without full manuscripts, theses, non-English articles, animal or laboratory studies, and studies that did not contain quantifiable effect estimates were culled.

Records retrieved from database searches were screened in two sequential stages. In the first stage, titles and abstracts were evaluated to exclude studies that were obviously irrelevant. In the second stage, full-text articles of potentially eligible studies were assessed against the predefined inclusion and exclusion criteria.

Title and abstract screening was performed by the primary reviewer, with all decisions reviewed and verified by a second author. Full-text eligibility assessment and data extraction were similarly conducted by the primary reviewer and independently verified by co-authors. Any disagreements or uncertainties at either stage were resolved through discussion and consensus among all authors. A PRISMA 2020 flow diagram (**Fig. 2**) is used to demonstrate the process of study selection.

Data were extracted from included studies using a standardized data extraction form. Extracted information included: author and year of publication, country and study setting, study design and period, sample size, heat exposure definition and assessment method, outcome definition, effect estimates (hazard ratios, odds ratios, or relative risks) with 95% confidence intervals, and covariates included in adjusted models. Where multiple estimates were reported, the most fully adjusted estimate was selected for analysis.

Data extraction was performed by the primary reviewer and independently verified by co-authors. Discrepancies were resolved through discussion and consensus.

The Newcastle-Ottawa Scale (NOS) was used to evaluate the methodological quality and risk of bias of included observational studies (**Table 1**) [38]. This tool assesses studies across three domains: selection of study groups, comparability of groups, and outcome assessment. Newcastle-Ottawa Scale assessments were conducted independently by the primary reviewer and verified by a second author, consistent with the approach used for screening and data extraction (Section 2.3). Disagreements in scoring were resolved through discussion and consensus among all authors. Total scores were used to classify studies as low (7-9), moderate (5-6), or high risk of bias (below 5).”

Included studies reported effect estimates as hazard ratios (HRs), odds ratios (ORs), or relative risks (RRs). The comparability of these measures for pooled synthesis requires methodological justification. In epidemiological studies of binary outcomes, ORs approximate RRs when the outcome is relatively uncommon, and HRs approximate RRs when the follow-up period is short, or event rates are low. Preterm birth, with a prevalence of approximately 5-15% depending on the population, satisfies the rare-disease assumption sufficiently for this approximation to be reasonable. Furthermore, all included studies reported effect sizes of modest magnitude (range: 1.01-1.08), a range in which OR, HR, and RR converge numerically. On this basis, and consistent with the approach adopted by prior meta-analyses in this field, including Chersich *et al.* (2020) [13], these measures were treated as sufficiently comparable for quantitative pooling. It should be explicitly noted that no formal mathematical conversion between OR, HR, and RR was performed; each effect estimate was pooled in its originally reported form, and this remains an acknowledged methodological limitation of the analysis (see Section 4, Limitations).

Given anticipated clinical and methodological heterogeneity across studies arising from differences in study populations, exposure definitions, temperature thresholds, exposure windows, climatic settings, and analytical approaches, a random-effects model (DerSimonian-Laird method) was selected a priori to account for between-study variability and yield a more conservative summary estimate [39]. Statistical heterogeneity was quantified using the I^2 statistic and Cochran’s Q test. A sensitivity analysis was conducted by excluding the OR-based study (Sun *et al.,* 2019 [2]) to assess the robustness of the pooled estimate to the inclusion of different effect measures. All statistical analyses were conducted using R (version 4.3.2). Forest plots were generated using standard meta-analysis packages. AI-assisted tools supported figure design and formatting; however, all data extraction, analyses, and interpretations were performed and verified by the authors.

RESULTS

Study Selection

The database searches identified 2,410 records from Google Scholar and 225 from PubMed, for a combined total of 2,635. Following application of the 20-year

Table 1: Risk of bias assessment of included studies using the Newcastle-Ottawa Scale (NOS).

Study (Author, Year)	Selection (0-4)	Comparability (0-2)	Outcome (0-3)	Total Score (0-9)	Overall Risk of Bias
Wang *et al.*, 2019 [1]	4	2	3	9	Low
Sun *et al.*, 2019 [2]	4	2	3	9	Low
Mohammadi *et al.*, 2019 [3]	3	2	3	8	Low
Choi *et al.*, 2021 [5]	4	2	2	8	Low
Gordon *et al.*, 2023 [4]	3	1	2	6	Moderate

Abbreviations: NOS, Newcastle-Ottawa Scale. The Newcastle-Ottawa Scale assesses observational studies across three domains: selection of study groups (maximum 4 points), comparability of groups (maximum 2 points), and outcome assessment (maximum 3 points). Studies scoring 7-9 points were considered low risk of bias, 5-6 moderate risk, and below 5 high risk.

Table 2: Characteristics of included studies.

Author (Year)	Country / Region	Study design	Study period	Sample size	Exposure definition	Outcome
Wang *et al.* (2019) [1]	Australia (Brisbane)	Population-based cohort	2000-2010	277,133 births	Heatwave defined as ≥2 consecutive days with daily mean temperature above the 95th percentile	Preterm birth, stillbirth
Sun *et al.* (2019) [2]	United States (nationwide)	Retrospective cohort	1969-1988	~32 million singleton births	Ambient temperature assessed as daily mean temperature and percentile-based extremes	Preterm birth
Mohammadi *et al.* (2019) [3]	Iran (Sabzevar)	Time-series analysis	2007-2014	Population-based daily births	Extreme temperature defined using high and low temperature thresholds	Preterm birth
Choi *et al.* (2021) [5]	United States (North Carolina)	Population-based cohort	2004-2016	546,441 births	Daily mean temperature; heat exposure assessed per 1 °C increase	Preterm birth
Gordon *et al.* (2023) [4]	United States (Chicago)	Ecological time-series	July 1995	City-level births	Extreme heatwave event	Preterm birth

Abbreviations: °C, degree Celsius. Heat exposure definitions varied across studies, including percentile-based heatwave thresholds, ambient temperature increments, and extreme temperature events. Where a study reported stillbirth in addition to preterm birth, only the preterm birth estimate was extracted for this review.

publication filter in Google Scholar and removal of secondary studies, grey literature, non-English articles, and records with incomplete or non-extractable data, 11 full-text articles from Google Scholar were assessed for eligibility. Of these, two met the criteria for inclusion in the quantitative synthesis.

From PubMed, the majority of records were excluded at the title and abstract screening stage as they comprised review articles, commentaries, non-original research, or studies that did not measure heat exposure in relation to pregnancy outcomes. Following title, abstract, and full-text evaluation, three studies from PubMed were incorporated into the systematic review based on the predefined eligibility criteria.

In total, five studies were included in the qualitative synthesis and four studies in the quantitative meta-analysis. The restriction to four studies in the meta-analysis reflects a deliberate methodological decision: one of the five qualitatively reviewed studies [4] was excluded from pooling because it reported a rate ratio describing changes in preterm birth rates following a heatwave event, rather than a directly comparable HR/OR/RR estimate suitable for synthesis alongside the other four studies. This approach prioritized methodological consistency and validity of the pooled estimate over a larger but less homogeneous pool of studies. Fig. **(2)** presents a complete overview of the study selection process.

Characteristics of Included Studies

Table **2** summarizes the characteristics of the included studies. The articles were published between 2014 and 2023 and comprised population-based cohort studies and time-series analyses conducted in Australia, the United States, and Iran [1-5].

Sample sizes varied considerably, ranging from regional population-based counts of daily births to a national cohort of over 32 million singleton births [2]. Heat exposure was operationalized across studies using several approaches, including percentile-based heatwave definitions, daily mean ambient temperature, and extreme temperature thresholds. The primary outcome across all included studies was preterm birth, defined as delivery before 37 completed weeks of gestation.

Qualitative Synthesis of Findings

Heat Exposure and Preterm Birth

Across all included studies, preterm birth was consistently and positively associated with exposure to elevated ambient temperatures or heatwave conditions during pregnancy [1-4]. The adjusted effect estimates in all four studies included in the meta-analysis were above the null, with hazard ratios, odds ratios, or relative risks ranging from 1.01 to 1.08 (**Table 3**).

Population-based cohort studies conducted in Australia and the United States demonstrated an elevated risk of preterm birth associated with heatwave exposure or rising ambient temperatures [1, 2]. Consistent findings were observed in time-series analyses reporting short-term effects of extreme temperatures on daily preterm birth counts [3]. The consistency and magnitude of these associations across study designs and geographic settings are illustrated in the forest plot (**Fig. 3**).

Susceptible Exposure Windows

Four studies examined the relationship between heat exposure during pregnancy and preterm birth across different gestational exposure windows [1-4]. Among these, late pregnancy emerged as a potentially susceptible period, with some studies reporting stronger associations during the final weeks of gestation [1, 5]. In time-series analyses, short-term exposure to extreme temperatures over lag periods of several days was associated with increases in daily preterm birth counts [3]. However, the evidence on critical exposure windows remains limited and inconsistent across studies, and firm

Table 3: Summary of quantitative findings of included studies.

Author (Year)	Exposure contrast	Effect measure	Effect estimate (95% CI)	Exposure window	Key covariates adjusted
Wang *et al.* (2019) [1]	Heatwave *vs* non-heatwave days	HR	1.08 (1.00-1.18)	Whole pregnancy; strongest in late gestation	Maternal age, parity, seasonality, long-term trends
Sun *et al.* (2019) [2]	Extreme ambient temperature *vs* reference	OR	1.05 (1.03-1.07)	Whole pregnancy	Maternal characteristics, temporal trends, geographic region
Mohammadi *et al.* (2019) [3]	Extreme temperature days *vs* non-extreme days	RR	1.04 (1.01-1.07)	Short-term exposure (lag days)	Seasonality, long-term trends, meteorological factors
Choi *et al.* (2021) [5]	Per 1 °C increase in daily mean temperature	HR	1.01 (1.00-1.02)	Late pregnancy (final weeks)	Maternal age, socioeconomic status, urbanicity, greenness
Gordon *et al.* (2023) [4]	Extreme heatwave event *vs* non-event period	Rate ratio	Increased preterm birth rates following heatwave (estimate not pooled)	Heatwave period	Area-level demographic factors

Abbreviations: HR, hazard ratio; OR, odds ratio; RR, relative risk; CI, confidence interval; °C, degree Celsius. Studies reporting comparable measures of heat exposure and preterm birth were included in the quantitative synthesis.

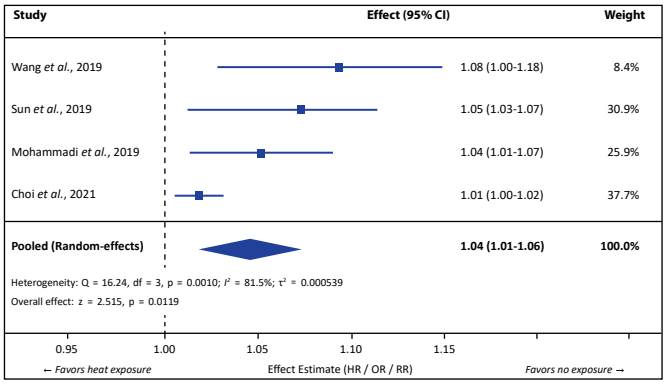


Fig. (3): Random-effects meta-analysis (DerSimonian-Laird model) of the association between maternal heat exposure and preterm birth. The pooled effect estimate was RR = 1.04 (95% CI: 1.01-1.06). Statistical heterogeneity was considerable (I^2 = 81.5%; Q = 16.24, p = 0.0010). Square sizes represent study weights and the diamond represents the pooled effect estimate.

conclusions regarding the most vulnerable gestational period cannot be drawn from the available data.

Population Characteristics and Contextual Factors

Several studies have reported heterogeneity in the risk of heat-related preterm birth across population subgroups. Differences were observed across socioeconomic characteristics, residential contexts, and geographic locations, with higher risks reported among socioeconomically disadvantaged populations in certain settings [4, 5]. However, subgroup analyses were not uniformly conducted across all included studies, limiting the generalizability of these observations. Table **2** presents the full characteristics of the included studies, while Table **3** summarizes the quantitative findings and individual study effect estimates.

Quantitative Synthesis (Meta-Analysis)

Only four studies were eligible for inclusion in the quantitative synthesis. Although five studies met the criteria for qualitative review, one [4] was excluded from pooling because it reported a rate ratio describing changes in preterm birth rates following a heatwave event, rather than a directly comparable HR/OR/RR estimate suitable for synthesis alongside the other four studies. To maintain methodological consistency and avoid inappropriate pooling of heterogeneous exposures and outcomes, the quantitative synthesis was restricted to studies reporting comparable measures of the association between maternal heat exposure and preterm birth. While this restriction resulted in a small number of studies in the meta-analysis, it strengthens the internal validity of the pooled estimate. The effect estimates included in the quantitative synthesis are presented in Table **3**.

Main Meta-Analysis

The random-effects meta-analysis using the DerSimonian-Laird model demonstrated a statistically significant association between maternal heat exposure and preterm birth. The pooled effect estimate was RR = 1.04 (95% CI: 1.01-1.06; z = 2.515, p = 0.0119). Although the magnitude of effect was modest, all four included studies reported effect estimates above the null value, indicating a consistent positive direction of association across diverse geographic and methodological contexts. Fig. **(3)** presents the individual study estimates and the pooled effect estimate.

Heterogeneity Assessment

Statistical heterogeneity was considerable (I^2 = 81.5%; Cochran's Q = 16.24, df = 3, p = 0.0010; τ^2 = 0.000539). The observed heterogeneity most likely reflects variation in exposure definitions, temperature thresholds, exposure windows, study populations, climatic settings, and the mix of effect measures (HR, OR, RR) across studies. Given the small number of studies included in the analysis, heterogeneity estimates should be interpreted with caution, as I^2 values are known to be unstable with fewer than five studies. A sensitivity analysis excluding the OR-based study (Sun *et al.,* 2019 [2]) yielded a pooled RR of 1.03 (95% CI: 1.00-1.06; I^2 = 65.5%), confirming that the direction and approximate magnitude of the association remained stable. This stability suggests that the overall pooled estimate is

not disproportionately driven by a single study or effect measure, supporting the robustness of the observed association despite the small number of included studies. The considerable heterogeneity (I^2 = 81.5%) most plausibly arises from three overlapping sources: (i) differences in how heat exposure was operationalized (percentile-based heatwave definitions *vs.* continuous daily temperature *vs.* discrete extreme-temperature thresholds); (ii) differences in study design (population-based cohort *vs.* ecological time-series), which capture different exposure windows and confounding structures; and (iii) differences in climatic and geographic setting (temperate Australia and the US *vs*. arid Iran), which affect baseline heat adaptation and thresholds for physiological heat stress.

DISCUSSION

This systematic review and meta-analysis synthesized evidence from five observational studies examining the association between maternal heat exposure during pregnancy and preterm birth, four of which were eligible for quantitative pooling. The random-effects meta-analysis yielded a statistically significant pooled effect estimate of RR = 1.04 (95% CI: 1.01-1.06), indicating a modest but consistent positive association between heat exposure and preterm birth across diverse geographic and methodological contexts. This finding is consistent with the broader literature on temperature and adverse birth outcomes, including the seminal review by Chersich *et al.* (2020) [13], which reported similarly modest but significant associations across multiple reproductive outcomes. The present review extends that evidence base by focusing exclusively on preterm birth and incorporating more recently published studies not captured in prior syntheses.

The consistency of positive associations across studies conducted in Australia, the United States and Iran [1-5] strengthens the plausibility of a genuine association between heat exposure and preterm birth, despite methodological differences across studies. All four studies included in the meta-analysis reported effect estimates above the null, with individual estimates ranging from 1.01 to 1.08 (**Table 3**), and the overall direction of association was maintained in the sensitivity analysis (pooled RR = 1.03; 95% CI: 1.00-1.06; I^2 = 65.5%) following exclusion of the OR-based study [2].

Several biological mechanisms have been proposed in the literature to explain a plausible pathway linking maternal heat exposure and preterm birth, including maternal dehydration, altered placental perfusion, systemic inflammatory responses, and activation of endocrine stress pathways. However, it is important to emphasize that none of these mechanisms were directly evaluated in the observational studies included in this review. These pathways therefore represent biologically plausible explanations drawn from the broader physiological literature and should not be interpreted as findings of the present synthesis.

The findings also indicate that late pregnancy may represent a particularly susceptible exposure window, with some studies reporting stronger associations during the final weeks of gestation [1, 5]. However, the evidence on critical gestational exposure windows remains limited and inconsistent across studies, and firm conclusions cannot be drawn from the available data. This represents an important area for future investigation.

Variation in exposure definitions, temperature thresholds, climatic settings, and analytical approaches across studies underscores the need for greater methodological standardization in this field. The considerable statistical heterogeneity observed (I^2 = 81.5%) reflects this diversity and limits the precision and generalizability of the pooled estimate. These methodological differences also highlight the challenges inherent in synthesizing evidence across studies conducted in climatically and demographically distinct settings.

This review has several notable strengths. Adherence to PRISMA 2020 reporting guidelines ensured methodological transparency throughout. The use of predefined eligibility criteria minimized the risk of selective inclusion. Systematic quality assessment using the Newcastle-Ottawa Scale provided a structured evaluation of study-level risk of bias. The inclusion of studies from multiple countries and geographic regions adds breadth to the synthesized evidence base. Finally, the outcome-specific focus on preterm birth, rather than on a composite of adverse reproductive outcomes, improves the interpretive precision of the findings compared with broader prior reviews.

Several limitations must be considered when interpreting the findings of this review. First, only four studies were eligible for quantitative synthesis, substantially limiting statistical power, the precision of the pooled estimate, and the reliability of heterogeneity statistics. With fewer than five studies, I^2 values are known to be unstable and should be interpreted cautiously. The sensitivity analysis (excluding Sun *et al.,* 2019 [2]) produced a pooled RR of 1.03 (95% CI: 1.00-1.06; I^2 = 65.5%), indicating directional stability, but the lower confidence interval boundary approaching 1.00 underscores the fragility of the estimate given the small study pool.

Second, substantial heterogeneity in exposure across studies was evident in heatwave definitions, temperature thresholds, exposure windows, and assessment methods. This variability directly limits the comparability of effect estimates across studies and is a primary driver of the high I^2 value observed. The inability to conduct subgroup analyses by exposure type or gestational window due to the small number of eligible studies means that exposure-specific effects cannot be disentangled

from the pooled estimate. Future reviews with a larger study base should prioritize subgroup analyses stratified by exposure definition and gestational timing.

Third, residual confounding cannot be ruled out despite covariate adjustment in most of the included studies. Factors such as ambient air pollution, socioeconomic disadvantage, access to cooling resources, occupational heat exposure, indoor thermal environment, and comorbidities may independently influence the risk of preterm birth. They may be correlated with exposure to ambient temperature. The observational design of all included studies means that causal inference cannot be established from these findings alone.

Fourth, the pooling of different effect measures hazard ratios, odds ratios, and relative risks introduces potential methodological heterogeneity. Although the rare-disease approximation and modest effect sizes justify this approach as a reasonable analytical decision (as detailed in Section 2.6), this remains a limitation that may affect the precision of the pooled estimate.

Fifth, the majority of included studies were conducted in high-income countries (Australia, United States), with only one study from a lower-resource setting (Iran). This geographic imbalance substantially limits the generalizability of findings to low- and middle-income countries, which may face greater heat exposure, have less access to cooling infrastructure, and experience different baseline rates of preterm birth and healthcare access. This represents perhaps the most important gap in the current evidence base given that these populations are simultaneously the most climate-vulnerable and the least represented in existing research.

Despite these limitations, the consistency of positive associations across diverse geographic settings and study designs strengthens the overall evidence supporting an association between maternal heat exposure and increased risk of preterm birth.

Future research should prioritize standardized definitions of heat exposure and heatwave events to improve cross-study comparability. Improved spatial and temporal exposure assessment, including individual-level rather than area-level temperature data, would reduce exposure misclassification. Greater representation of low- and middle-income countries and climate-vulnerable populations is urgently needed. Prospective cohort studies incorporating biological markers of heat stress, such as inflammatory biomarkers or hormonal indicators, may help clarify the mechanisms linking maternal heat exposure to preterm birth. Finally, intervention studies evaluating the effectiveness of heat-mitigation strategies, including access to cooling, behavioral guidance, and early warning systems during pregnancy, are needed to translate epidemiological evidence into actionable public health policy.

CONCLUSION

This systematic review and meta-analysis provides evidence suggestive of an association between heat exposure during pregnancy and an increased risk of preterm birth, with a pooled RR of 1.04 (95% CI: 1.01-1.06). As all included studies were observational, these findings should be interpreted as associations rather than evidence of causal effects. The association was consistent in direction across all four studies included in the quantitative synthesis and across the five studies included in the qualitative review, spanning diverse geographic settings and study designs. Although the observed effect size was modest, the widespread and growing prevalence of extreme heat exposure globally driven by accelerating climate change means that even small relative risks may translate into substantial population-level burdens of preterm birth.

Given the observational nature of the evidence, these findings are best framed as evidence-informed considerations rather than definitive policy directives. They suggest that maternal health may merit greater consideration within heat-health action plans, antenatal care guidance, and climate adaptation strategies, and that protecting pregnant individuals from extreme heat exposure could be a reasonable public health priority as global temperatures rise and heatwave frequency and intensity increase. Continued investment in epidemiological research, standardized exposure assessment, and heat-mitigation interventions targeted at pregnant populations is warranted to reduce the preventable burden of preterm birth in a warming world.

DISCLOSURE

A preprint version of this manuscript is available on Research Square (DOI: https://doi.org/10.21203/rs.3.rs-8455131/v1). The current submission represents a substantially revised and restructured version of the original preprint, with updated analysis, improved interpretation, and reduced textual overlap in accordance with journal requirements.

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None.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Declared none.

AUTHORS' CONTRIBUTION

AS conceptualized the study; AS, MN & AZS conducted the literature search and performed data extraction and analysis; MN & AZS drafted the initial manuscript; AS critically reviewed and revised the draft.

All authors read and approved the final version.

GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

The authors acknowledge the use of AI-assisted tools for figure design and language refinement.

SUPPLEMENTARY MATERIAL

Supplementary material is available on the journal's website.

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