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Review article

# A scoping review on the impact of ambient temperature on human infertility

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ABSTRACT

Ambient temperature is a well-known environmental factor affecting gamete production in mammals. Despite a growing interest in biological mechanisms and epidemiologic studies for ambient temperature and human reproductive outcomes, systematic evidence synthesis is limited. Mapping human infertility outcomes in relation to ambient temperature is important to inform public health and identify research gaps. This scoping review systematically searched (n = 21,332) and included eligible epidemiologic studies (n = 135) on temperature and fertility in human populations to identify the types of temperature metrics and outcomes examined. Included studies used a variety of temperature exposure metrics: ambient temperature measurements, thermal indices, extreme temperatures (e.g., heatwaves), season, occupational heat exposure, climate region, and outdoor activities. Seven types of outcomes were identified across various geographical regions: sperm parameters, outcomes of assisted reproductive technologies, pregnancy loss, population-level reproductive outcomes (e.g., birth rate), infertility diagnosis (yes/no), testicular torsion, and ovarian function. The largest number of studies was for sperm parameters, followed by outcomes of assisted reproductive technologies. Results consistently indicated that higher temperature exposure was associated with reduced sperm parameters (e.g., motility) and increased odds of infertility, while other outcome types showed heterogeneous exposure-response associations. While the methodologies vary by the type of exposures and outcomes, most studies lacked longitudinal or prospective study designs, detailed description of exposure assessments, and consideration for non-monotonic exposure-response associations. This review maps research on temperature and human infertility, highlighting methodological limitations and knowledge gaps to guide future epidemiologic studies and systematic evidence synthesis for evidence-based public health and clinical decision making.

## 1. Introduction

Fertility refers to the ability to produce offspring. The World Health Organization (WHO) defines infertility as the failure to achieve a pregnancy after 12 months or more of regular and unprotected intercourse (WHO, 2024). Globally, the prevalence of female infertility increased by

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86.4 %, rising from 65.66 million cases in 1990 to 122.37 million in 2019 (Yu et al., 2023). Additionally, decreasing sperm counts (De Jonge et al., 2024), declining fertility rates (live births among women of reproductive age within defined age groups) (Skakkebæk et al., 2022), and increasing rates of miscarriage have been observed over the past 50 years (Segal and Giudice, 2022).

While social (e.g., a global trend of delayed marriage and childbearing in urban populations) and behavioral (e.g., smoking) factors may contribute to these trends (Yu et al., 2023), environmental stressors such as air pollution, wildfires, and extreme heat events (e.g., heatwaves) are increasingly recognized as key influences for the molecular mechanisms for human reproductive health. Climate change has also gained increased public health significance as it may threaten human fertility through increases in these environmental stressors. Therefore, it is increasingly important to understand the relationship between climate-related factors and infertility from a public health perspective to improve reproductive health.

Ambient temperature, especially exposure to heat, is a well-known risk factor for reduced sperm generations and oocyte development in humans and animals (Boni, 2019). Human physiological thermoregulation maintains the temperature of the entire body and specific anatomical regions primarily through skin blood flow (Charkoudian and Stachenfeld, 2016). Human thermoregulatory functions may fail to dissipate increased body heat and maintain optimal temperatures (Miyake, 2013) in reproductive organs when heat production exceeds heat loss, resulting in impaired gamete production. Particularly, spermatogenesis occurs optimally at 2–4 °C below core body temperature. Elevated scrotal heat can disrupt this process and reduce sperm quality, potentially leading to male infertility or reduced reproductive function (Celeghini et al., 2024; Kumar and Singh, 2022). Increased temperature in female reproductive tracts (e.g., ovary, fallopian tubes, uterus) can influence ovulation and oocyte quality (Ng et al., 2018; Sammad et al., 2020). When ambient temperature exceeds the temperature range where reproductive tissues function, it can adversely affect reproductive functions via mechanisms of gonadal heat shock and oxidative stress (Jegasothy et al., 2021). High temperature may also reduce sexual desire and coital frequencies, potentially leading to reduced number of pregnancies (Cho, 2020; Hajdu and Hajdu, 2021a). Otherwise, recent evidence suggests that cold temperature may disrupt sex hormone levels and impair reproductive capacity through inflammatory responses in female reproductive organs (Sun et al., 2025).

While numerous epidemiologic studies have explored the relationship between ambient temperature and birth outcomes (e.g., preterm birth, low birth weight) (Chersich et al., 2020; Zhang et al., 2017), relatively little attention has been given to its impact on infertility or reproductive outcomes. A growing number of epidemiological studies have suggested that higher ambient temperature may negatively affect male and female infertility prevalence worldwide (Qian et al., 2025a, 2025b). Evidence from population-based cohort studies suggests ambient temperature variability can affect spermatozoa (Xiao et al., 2024). Yet the evidence is heterogeneous and fragmented across varied exposure metrics, outcome types, study designs, and populations, hindering comparability and limiting efforts to systematically synthesize findings and generate coherent public health recommendations. Moreover, the field of environmental epidemiology lacks an overview regarding the specific endpoints used to define infertility and how they have been measured in relation to ambient temperature. As this is a growing research area, a comprehensive summary of the variety of infertility-related outcomes examined in the literature, alongside the corresponding temperature exposure metrics, is critical for guiding future systematic reviews and synthesizing existing evidence for informing policy development and clinical guidance. Scoping reviews are particularly suited for this purpose, identifying the coverage of literature, examining emerging evidence and trends, and summarizing how research has been conducted before addressing a specific question in a systematic review (Munn et al., 2018).

This scoping review addresses this gap with specific aims to identify, summarize, and report findings from studies examining the associations between ambient temperature and human infertility, as well as to identify key methodological approaches and research gaps. Specifically, we analyzed previous literature to examine how ambient temperature exposure has been assessed, which infertility outcomes have been investigated, what associations have been reported, and what methodological features and improvements could strengthen causal inference in future research. Through narrative synthesis, we aimed to provide valuable insights on the current state of research on ambient temperature and human infertility. The findings can guide future research and inform evidence-based decision-making in public health and clinical practices.

## 2. Methods

This scoping review was conducted following JBI's guidelines (Aromataris and Munn, 2020), and results were reported following the checklist of PRISMA Extension for Scoping Reviews. The protocol was registered in the Open Science Framework (https://osf.io/) prior to conducting the review (Registration Number: czx2t).

### 2.1. Literature search

Literature published until 11 November 2024 was searched from PubMed/Medline, Scopus, and Web of Science, using the search terms for exposure, outcomes, and study types (Table S1). The search terms and phrases were developed based on MeSH terms in PubMed, search terms in relevant prior reviews, and consultation with librarians. We conducted forward citation chaining on 18 February 2025, using a website-based software (Haddaway et al., 2021), to identify newer articles that cited our included studies but were not captured through the initial search strategy.

### 2.2. Eligibility criteria

Eligibility for inclusion was defined using the PECOS (Population, Exposure, Comparison, Outcome, Study design) framework (Table S2). Regarding population, exposure, and study design, we included peer-reviewed, English-language human studies involving female or male participants that examined exposure to externally measured or defined temperature-related factors such as ambient temperature, occupational heat, season as a proxy for temperature, or climate categories (e.g., climate zones) in relation to infertility outcomes. Regarding outcomes, studies were eligible if they investigated any outcome related to human infertility and temperature exposure. While examples of such outcomes include time to pregnancy, causes of infertility, birth rate, success of reproductive treatments, pregnancy loss, and male or female reproductive function in our PECOS inclusion criteria (Table S2), we did not restrict inclusion based on a predefined list of outcomes. We excluded non-human studies (e.g., animal studies); studies focused solely on internal physiological temperature measures (e.g., core body temperature, fever); studies reporting only gestational complications or adverse but live birth outcomes (e.g., preterm birth, low birth weight); and non-original research such as commentaries, protocols, methodological papers, or review articles.

### 2.3. Study selection

All studies retrieved from the search were screened independently by two authors at the title/abstract and full-text review stages using Covidence. Studies reviewed and agreed upon by two authors were retained. Any disagreements were resolved by the first author. Studies deemed eligible after full-text review were included.

### 2.4. Data extraction

We generated a data extraction form involving relevant information for the included studies. A pilot test was conducted on five eligible studies to refine the form. The finalized data extraction form was uploaded to Covidence and used to extract information from the included studies. Two reviewers independently extracted data from each included study, capturing publication year, study location, participant inclusion/exclusion criteria, participant characteristics (e.g., age), temperature exposure metrics, infertility outcomes, statistical methods, direction and statistical significance of associations, and textual conclusions. Any discrepancies were resolved by the first author.

### 2.5. Data synthesis

We synthesized the extracted data using narrative synthesis methods, following the Centre for Reviews and Dissemination's (CRD's) guidance for undertaking reviews in health care (Akers, 2013). Given the heterogeneity in study settings, exposure metrics, and infertility outcomes, this approach was appropriate. We organized the results by key themes including types of temperature exposure (e.g., ambient, occupational) and categories of infertility-related outcomes. A Sankey diagram was used to visually summarize the volume of studies and the connections between specific exposure types and infertility outcomes, providing an overview of research coverage. The findings of each study were summarized in tabular form for each infertility outcome, with studies grouped by the type of temperature metric. Color coding was applied to indicate the direction and significance of exposure–outcome associations: dark green = positive and significant (PS), light green = positive and not significant (PN), dark orange = negative and significant (NS), light orange = negative and not significant (NN), and no color = null or non-linear. Tabulation and color coding visually identify patterns and inconsistencies in associations across exposure–outcome pairs. Color coding shows the direction of the associations. A positive association means that higher exposure increases the likelihood of the outcome. For example, a positive association indicates higher incidence of male reproductive disease with greater temperature exposure. In contrast, for outcomes based on reproductive cell counts, a positive association indicates higher cell counts with increased exposure. Therefore, the direction of the association should be interpreted in the context of each specific outcome. Then, the overall consistency of associations across studies was summarized in a table for each exposure–outcome pair, using vote counting (i.e., number of studies) for positive, negative, non-linear and null associations. As an individual study can include multiple exposure metrics, the total number of vote counting represents the number of associations for temperature metrics and outcomes, not the total number of included studies. Further, a bar plot analysis was used to illustrate the consistency and direction of associations for each outcome. We did not assess risk of bias as scoping reviews are intended to map the existing literature rather than critically appraise study findings (Munn et al., 2018). Methodological characteristics of the included studies were described narratively, focusing on research gaps related to study design limitations affecting causal inference, variability or limitations in exposure assessment, representativeness of study populations, and potential sources of bias (e.g., selection bias), both within each infertility outcome and across all outcomes.

## 3. Results and discussion

### 3.1. Overview of included studies

Among the identified 21,332 unique references, 135 studies were eligible for inclusion (Fig. S1). During the title/abstract screening, 17,440 studies were excluded. The primary reasons for exclusion during the full-text review were ineligible exposure (n = 35) and ineligible outcomes (n = 29).

The earliest included study was published in 1983, with a notable increase in publication volume beginning around 2014 (Fig. 1). The included studies originated from 35 countries (Fig. S2). There was a heterogeneous geographical distribution of included studies. The largest numbers of studies were conducted in East Asia (n = 31), the Middle East (n = 22), and European countries (n = 19). Fewer than ten studies were included from Africa, Oceania, South America, South Asia, and Southeast Asia. Six studies included data from multiple countries.

### 3.2. Identified exposure metrics

The included studies utilized various metrics for temperature. These were categorized into seven groups: ambient temperature, thermal indices, temperature extremes (e.g., heatwaves, coldwaves), season, occupation or occupational heat exposure, climate region, and outdoor activity (Table 1). These exposure metrics were analyzed in relation to the various infertility outcomes identified in this review (summarized in 3.3. Identified human infertility outcomes), as illustrated in Fig. 2.

#### 3.2.1. Ambient temperature

The most employed metric was ambient temperature levels (°C, °F) found in 80 studies (Table 1). These studies used this metric as a continuous variable in their risk estimating model. The temperature metric used varied across studies (daily minimum, average, or maximum temperature). Diurnal Temperature Range (DTR), a measure of the difference between daily maximum and minimum temperature, was also used in three studies (Chen et al., 2013; Cheng et al., 2024; Ma et al., 2024).

Generally, exposure periods ranged from several weeks to one year before the outcome event, capturing both short- and long-term effects. Exposure periods varied by infertility outcome and are detailed in the following outcome-specific sections. Approximately half of the studies examining temperature assessed exposure levels using the data from station-based monitors, while approximately one third of the studies used modeled data at a high spatiotemporal resolution (such as ERA5, PRISM) integrating multiple strategies such as station-based or satellite-based temperature observations, topographic information, advanced statistical interpolation, and physical atmosphere simulation. The remaining studies used interpolated temperature data, applied satellite-only measurements, or did not specify their data sources. The increasing use of modeled temperature data since 2016 in included studies is noteworthy given its utility for assessing exposures in future large-scale studies involving populations in areas lacking monitoring networks.

#### 3.2.2. Thermal indices

Various thermal indices were found from nine studies: Universal Thermal Climate Index (UTCI) (Brimicombe et al., 2025; Nyadanu et al., 2022, 2023), Wet-bulb Globe Temperature (WBGT) (Asamoah et al., 2018; Brimicombe et al., 2025; Rekha et al., 2024; Sarfraz et al., 2024; Verón et al., 2021), Temperature-Humidity Index (THI) (Kabukçu et al., 2020), Apparent Temperature (AT) (Basu et al., 2016), Humidity Index (Verón et al., 2021), and Heat Index (HI) (Savitz and Hu, 2021). These thermal indices represent perceived temperature by combining multiple meteorological factors such as air temperature, humidity, wind speed, and solar radiation. Unlike simple ambient temperature measures, these metrics better capture the overall thermal stress experienced by the human body.

Exposure periods of several weeks to one year before the outcome event, as used for ambient temperature, were similarly applied to thermal indices. Approximately half of the studies for thermal indices used modeled data sources (e.g., ERA5, PRISM) to assess exposure levels.

#### 3.2.3. Temperature extremes

Temperature extremes (i.e., heatwave, coldwave), defined as a period with ambient temperature exceeding a certain threshold

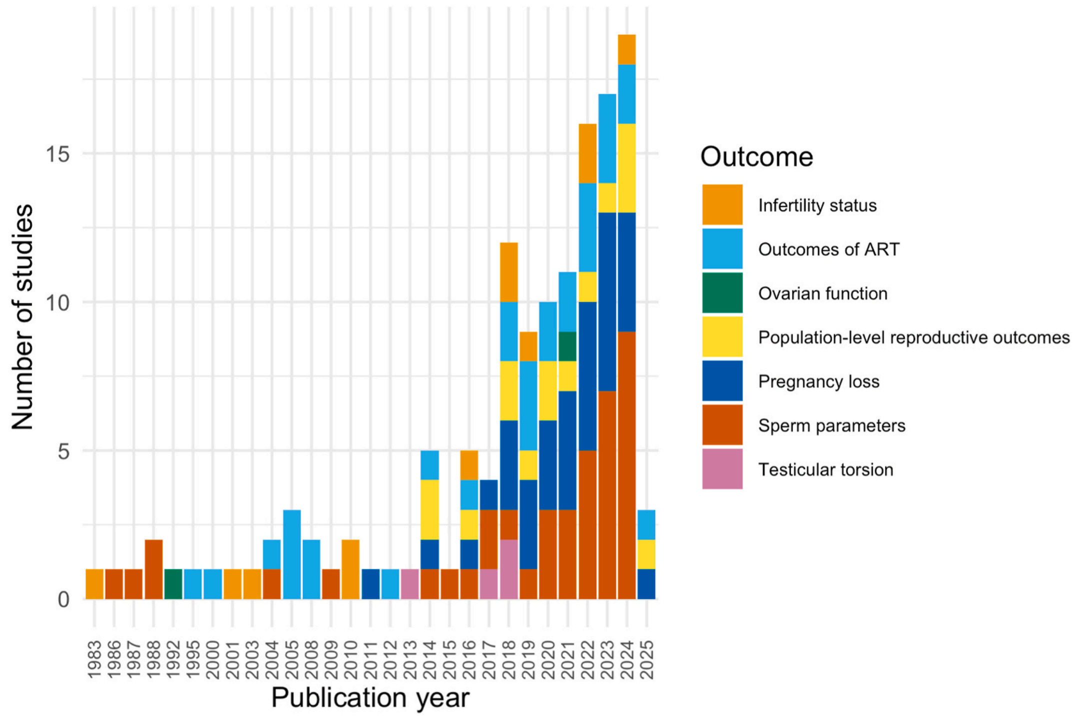


**Fig. 1.** Publication year of the included studies, by type of infertility outcomes. Note. 2025 is a partial year.

temperature, were assessed in relation to infertility in nine studies (Table 1). These studies analyzed the effects of sustained exposure to extreme temperatures over an extended period. For example, Verón et al. (2024) (Verón et al., 2024) defined heatwaves as a period of at least three consecutive days with daily maximum temperature >32.3 °C or daily minimum temperature >22 °C, considering both intensity and duration. However, heatwave definitions varied across these studies. Moodley et al. (2024) defined extreme heat exposures based solely on the intensity of temperature without duration (e.g., minimum number of consecutive days with intensified temperature) and defined days with a daily mean temperature >26.6 °C as extreme heat exposures. Some studies compared the infertility risk among days with different temperature categories, presenting extremely hot days. For example, Cho (2020) (Cho, 2020) grouped the study periods based on the daily maximum temperature in six strata (<22 °C, 22–24 °C, 24–26 °C, 26–28 °C, 30–32 °C, and ≥32 °C) as a categorical variable in their statistical model. While heatwaves were considered in most studies, one study analyzed coldwaves (Zhang et al., 2024).

### 3.2.4. Season

Season was used as an indirect assessment of temperature in 28 studies (Table 1). Most compared infertility risk across seasons, commonly grouped into four calendar-based categories: spring, summer, fall, and winter. Season was examined with various infertility outcomes (e.g., sperm parameters, birth rate, pregnancy loss, and pregnancy after assisted reproductive technologies [ART] described in Section 3.3). The associations for these outcomes were generally heterogeneous with both worsened and improved results in warmer seasons. For instance, while some studies showed increased sperm counts during warm seasons (e.g., summer), others showed decreased sperm counts. While these studies often discussed temperature as a potential reason for the seasonal trends in infertility outcomes, few analyzed ambient temperature levels, introducing uncertainty about exposure differences within studies and limiting the ability to directly associate temperature with infertility. For instance, Malathi et al. (2023) (Malathi et al., 2023) observed significant seasonal differences in motile sperm percentages in semen samples but did not measure temperature levels.

The included studies defined seasons based on monthly changes. The temperature exposure considered in these studies reflected long-term rather than short-term variations occurring over days or weeks, since the included studies defined seasons based on monthly changes and applied them to the timing of diagnosis or examination for each infertility outcome.

### 3.2.5. Climate region

We identified one cross-sectional study that assessed the impact of temperature on infertility status by comparing the risks between different climate regions as a proxy to capture variation in temperature (Afroughi and Pouzesh, 2019). In this study, higher odds of infertility status was observed in couples living in hot climate regions compared to those living in cold or moderate climate regions in Kohgiluyeh and Boyer-Ahmad Province, Iran (Afroughi and Pouzesh, 2019).

### 3.2.6. Occupation or occupational heat

Occupation, another potential indirect measure of temperature, was found in 25 individual studies. These studies grouped participants by occupation, categorizing occupations such as oven workers or firefighters as involving occupation-related heat exposure compared to other occupations. For example, a study in Pakistan reported that oven workers/bakers had the lowest percentage of active sperm and the highest percentage of sperm head defects compared to farmers, gardeners, and industrial workers (Shah et al., 2021). Some studies collected data on occupational heat exposure through surveys or interviews asking participants about their work conditions. For example, Wong et al. (2003) (Wong et al., 2003) grouped male participants as exposed or unexposed based on self-reported occupational heat exposure (yes/no) from a questionnaire and compared the odds of infertility status between these groups. Some studies surveyed occupational heat exposure over specific periods, such as 1–3 months or several prior years before recruitment into the study (Cong et al., 2016; De Fleurian et al., 2009; De La Calle et al., 2001; Effendy and Krause, 2009; Eisenberg et al., 2015; El-Helaly et al., 2010; Me et al., 2010; Rachootin and Olsen, 1983; Wong et al., 2003), while others did not specify exposure timing (Ali et al., 2014; Pokhrel et al., 2019). While most studies focused on a

**Table 1**
Classification of exposure metrics and included studies.

| Exposure | Study Region | Author-publication year |
|---|---|---|
| Ambient temperature | Africa | Brimicombe et al. (2025) |
| | East Asia | (Cao et al., 2021; Chang et al., 2005; Chen et al., 2013; Cheng et al., 2024; Chu et al., 2022; Du et al., 2023; Geng et al., 2023; Jiang et al., 2025; Liu et al., 2019; Ma et al., 2024; Mao et al., 2017; Matsumoto et al., 2022; Sun et al., 2020; C. Wang et al., 2024; L. Wang et al., 2024; Wang et al., 2020; Weng et al., 2017; Wu et al., 2025, 2023; Xiao et al., 2024, 2022; Yang et al., 2022; Zhang et al., 2023; Zhao et al., 2019, 2022; Zhou et al., 2020) |
| | Europe | (Bruckner et al., 2014; Conte Keivabu et al., 2024; Garcia-Grau et al., 2022; Hajdu and Hajdu, 2021a, 2023; Karlsson et al., 2021; Künzle et al., 2004; Medyannikova and Klinyshkova, 2012; Miloradović et al., 2022; Santi et al., 2016, 2018; Schumann et al., 2019; Vandekerckhove et al., 2016) |
| | Middle East | (Bogan et al., 2021; Ekici et al., 2018; Kabukçu et al., 2020; Khajavi et al., 2016; Ranjbaran et al., 2020; Reiner-Benaim et al., 2024; Rojansky et al., 2000; Roshan et al., 2008; Shabani et al., 2014a, 2014b) |
| | North America | (Auger et al., 2016; Barreca et al., 2018; Barreca and Schaller, 2019; Castañeda-Sánchez et al., 2017; Correia et al., 2022; Farland et al., 2020; Gaskins et al., 2021; Kanner et al., 2020; Rammah et al., 2019; Richards et al., 2022; Shupler et al., 2024; Tong et al., 2023; Wesselink et al., 2024) |
| | Oceania | (Li et al., 2018; Strand et al., 2011) |
| | South America | (Cabral Dias Filho and Gonçalves de Oliveira, 2018; Marteleto et al., 2023; Ramírez et al., 2023; Verón et al., 2021) |
| | South Asia | (Das et al., 2023; Dogra et al., 2022; Padmanabhan et al., 2023; Rameshkumar et al., 1992) |
| | Southeast Asia | Sellers and Gray (2019) |
| | Multiple countries | (Boland, 2018; Hajdu, 2024; Hanson et al., 2024; Jensen et al., 2021; McElroy et al., 2022; Thiede et al., 2022) |
| Thermal index | Africa | (Asamoah et al., 2018; Nyadanu et al., 2023) |
| | North America | (Basu et al., 2016; Savitz and Hu, 2021) |
| | Oceania | Nyadanu et al. (2022) |
| | South Asia | (Rekha et al., 2024; Sarfraz et al., 2024) |
| | South America | Verón et al. (2021) |
| Temperature extremes (heatwaves, coldwaves) | Africa | Moodley et al. (2024) |
| | East Asia | (Chen et al., 2013; Cho, 2020; Ma et al., 2024; Zhang et al., 2024) |
| | Europe | Hajdu and Hajdu (2021b) |
| | North America | (Mancuso et al., 2022; Richards et al., 2022; Wesselink et al., 2024) |
| | Oceania | Wang et al. (2019) |
| | South America | Verón et al. (2024) |
| Season | East Asia | (Cao et al., 2021; Chu et al., 2022; Du et al., 2023; Liu et al., 2019; C. Wang et al., 2024; Xiao et al., 2018; Zhang et al., 2021; Zhao et al., 2019) |
| | Europe | (Revelli et al., 2005; Vlachadis et al., 2024; Wunder et al., 2005) |
| | Middle East | (Kabukçu et al., 2020; Khafri et al., 2008; Korkmaz et al., 2023; Mehrafza et al., 2020; Pakmanesh et al., 2024; Pekcan et al., 2019; Rojansky et al., 2000; Vahidi et al., 2004; Yazdanpanah Ghadikolaei et al., 2023; Yucel and Kozacioglu, 2019) |
| | North America | (Chamoun et al., 1995; Correia et al., 2022; Farland et al., 2020; Levine et al., 1988; Patel et al., 2022) |
| | South America | Cho et al. (2024) |
| | South Asia | Malathi et al. (2023) |
| Occupation group or occupational heat | Africa | (Ali et al., 2014; Daoud et al., 2017; El-Helaly et al., 2010; Me et al., 2010) |
| | East Asian | (Cong et al., 2016; Pokhrel et al., 2019; Yang et al., 2024) |
| | Europe | (De Fleurian et al., 2009; De La Calle et al., 2001; Effendy and Krause, 1987; Jurewicz et al., 2014; Laven et al., 1988; Petersen et al., 2019; Rachootin and Olsen, 1983; Wong et al., 2003) |
| | Middle East | (Al-Otaibi, 2018; Caliskan et al., 2023; Yazdanpanah Ghadikolaei et al., 2023) |
| | North America | (Eisenberg et al., 2015; Levine et al., 1988) |
| | Oceania | Henderson et al. (1986) |
| | South America | Ramírez et al. (2022) |
| | South Asia | Shah et al. (2021) |
| Climate region | Middle East | Afroughi and Pouzesh (2019) |
| Outdoor activity | Southeast Asia | Melinawati et al. (2023) |

binary classification of occupational heat exposure (exposed vs. unexposed), one study assessed the frequency of the current exposure at work (e.g., often vs. rarely) (Yang et al., 2024). However, reliance on occupational categories and self-reported exposure without direct temperature measurements could lead to exposure misclassification and limit the accuracy of estimated associations.

#### 3.2.7. Outdoor activities

Outdoor activities involving exposure to high ambient temperature was found in one study (Melinawati et al., 2023). This cross-sectional study of 60 men in Surakarta, Indonesia used a portable device to track weekly minutes spent riding bicycles to assess time spent outdoors in high-temperature conditions and found a negative association with sperm quality (concentration, motility, morphology) (Melinawati et al., 2023).

### 3.3. Identified human infertility outcomes

We categorized the identified outcomes into seven groups: sperm parameters ($n = 43$ studies), testicular torsion ($n = 4$), ovarian function ($n = 2$), infertility status ($n = 12$), population-level reproductive outcomes ($n = 15$), pregnancy loss ($n = 33$), and outcomes of ART ($n = 30$) (Fig. 2). The observed associations for each identified outcome were presented across exposure metrics in Fig. 3, highlighting patterns of positive, negative, non-linear, or null associations. The following text summarizes outcome types, consistency of observed associations, and key study characteristics, including population, exposure period, and study design.

#### 3.3.1. Sperm parameters

Sperm parameters, assessments of male fertility, included total sperm count, semen volume, semen concentration, sperm motility, sperm morphology, sperm DNA fragmentation, sperm velocity, and sperm vitality. Sperm parameters have been examined in relation to temperature, thermal index, temperature extremes, season, and occupation (Fig. 2).

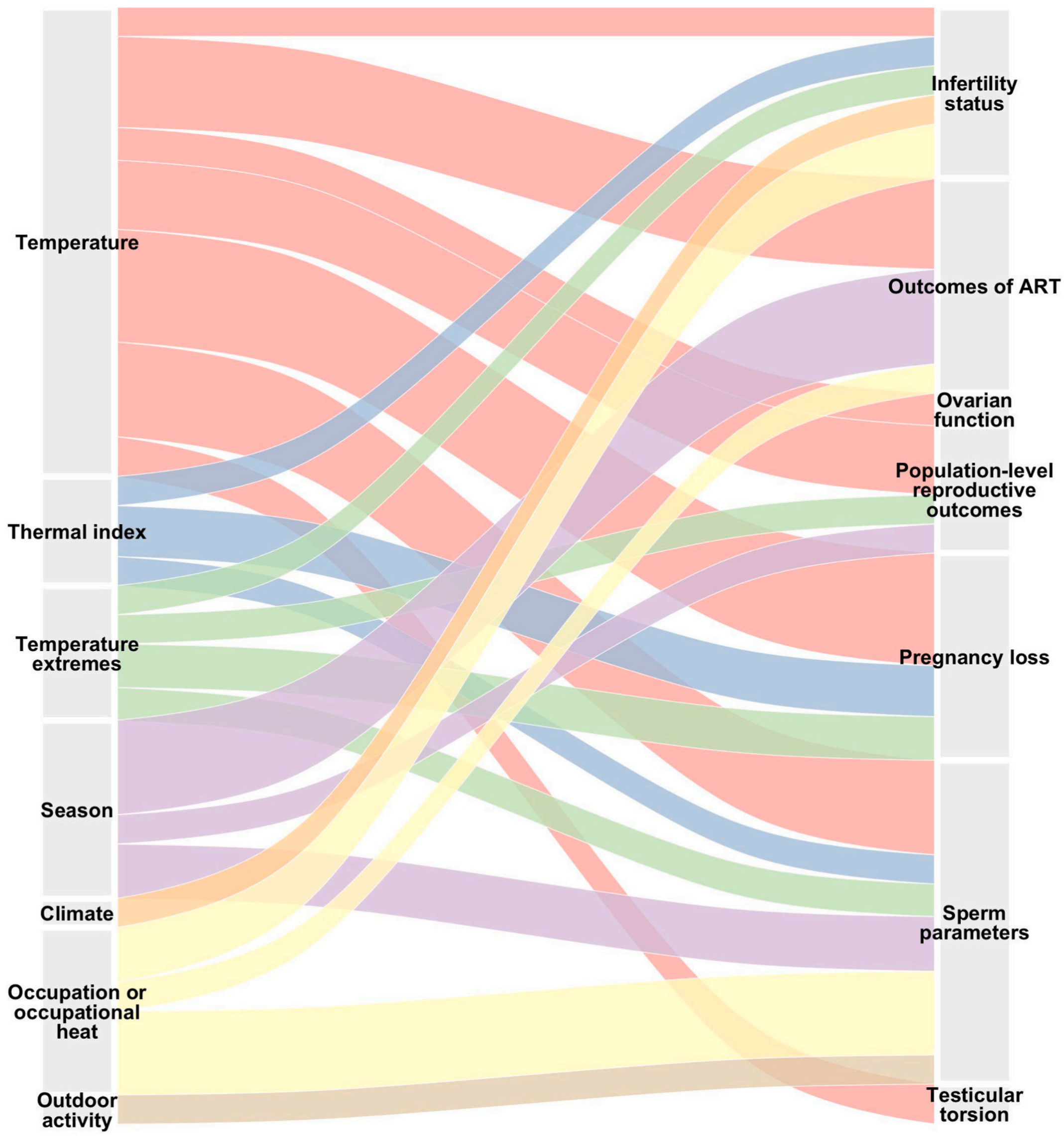


**Fig. 2.** Sankey diagram showing connections between exposure metrics and infertility outcomes.

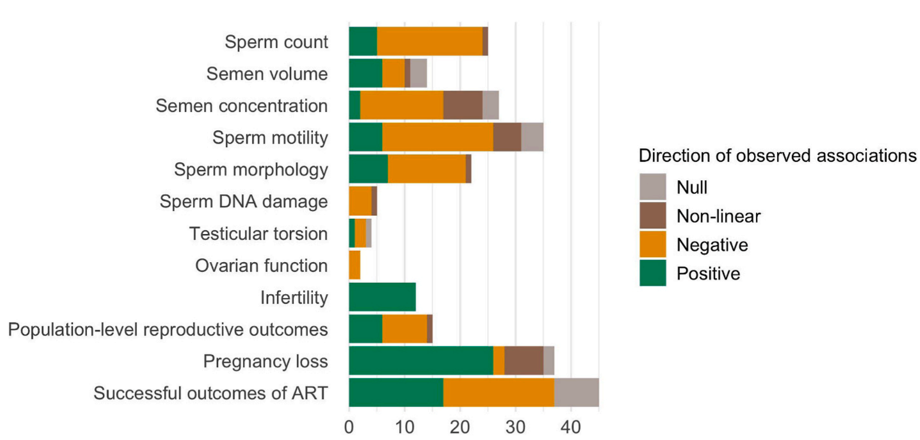


**Fig. 3.** Frequency of observed association directions between exposure and infertility outcomes among included studies.

We found 25 associations from 21 studies for sperm count. Seven analyses reported a negative association between temperature and sperm count (Table S3), although three analyses observed positive associations (Padmanabhan et al., 2023; Reiner-Benaim et al., 2024; Xiao et al., 2024). Oligozoospermia, a condition of low sperm count in semen (<15 million/mL), was more frequent in men exposed to occupational heat in the included studies. Considering all association analyses of different types of exposure metrics, we found five positive, 19 negative, and one non-linear association for sperm count (Table 2). Study results of 14 analyses from 13 studies for semen volume and temperature, season, or occupational heat exposure were mixed: six showed positive, four negative, one non-linear, and three null associations (Table S4). While eight associations reported negative directions between temperature and sperm concentration (Table S5), five associations identified non-linear patterns, including inverted U-shaped (C. Wang et al., 2024; Wang et al., 2020; Zhou et al., 2020) and U-shaped (Ma et al., 2024; L. Wang et al., 2024) relationships.

Sperm motility is the ability of spermatozoa to move efficiently and properly through the female reproductive tract. The included studies performed sperm motility analysis according to the WHO standardized manual, which is updated regularly. The 6th-edition WHO manual (WHO, 2021) defines sperm motility as the percentage of rapidly progressive (actively moving with a minimum speed 25 μm/s), slowly progressive (5 to <25 μm/s), non-progressive (showing movement but without forward progression or <5 μm/s), and immotile (no movement) sperms, assessed from at least 200 spermatozoa within 60 min of ejaculation at 37 °C. The total sperm motility is calculated as the percentage of rapidly progressive, slowly progressive, and non-progressive motile sperms. Most included studies reported the percentage of total motile sperm (often referred to as total sperm motility), but some examined the percentage of progressive sperm, count of total motile sperm, and count of progressive sperm.

There were 36 association analyses from 35 studies for sperm motility. Findings on sperm motility with ambient temperature were inconsistent, with eight analyses reporting negative associations, three reporting null, one reporting positive, and five reporting non-linear relationships (Table S6). Four studies for season showed relatively consistent results of lower motility in summer than other seasons (Levine et al., 1988; Malathi et al., 2023; Patel et al., 2022; Zhang et al., 2021), but two studies showed higher motility in summer (Pakmanesh et al., 2024; Vahidi et al., 2004). Results were inconsistent for occupation, with seven associations showing negative and three showing positive directions. While cutoff values of motile sperms indicating asthenozoospermia (e.g., <40 % motile sperm based on the 6th WHO standards) varied slightly across studies, asthenozoospermia was more frequently observed in men exposed to occupational heat, indicating an association with lower sperm motility (De Fleurian et al., 2009; Ramírez et al., 2022).

Sperm morphology refers to the size and shape of spermatozoa and is expressed as the percentage of sperm with normal forms based on detailed assessment of structural abnormalities in sperm head, neck and midpiece, tail, and excess residual cytoplasm (WHO, 2021). This measure was reported in many included studies examining sperm morphology (Table S7) and results for association directions were heterogeneous (Fig. 3, Table 2). We found 22 associations from 18 studies. Lower percentages of sperm with normal morphology were observed in warmer seasons (two associations) or men with occupational heat exposure or heat-related jobs (six associations). However, 12 analyses from nine studies for ambient temperature exposure showed five negative, six positive, and one non-linear association. Four observed higher incidence of teratozoospermia (e.g., high percentage of abnormal sperm in semen) in men exposed to occupational heat than unexposed men (Daoud et al., 2017; De Fleurian et al., 2009; Melinawati et al., 2023; Yang et al., 2024).

Detailed abnormality indicators may be more useful than the simple total percentage of normal spermatozoa. The multiple anomalies index (MAI) is the mean number of defects divided by the total number of abnormal spermatozoa, reflecting how many parts (head, midpiece, tail, or cytoplasm) are affected in each abnormal cell. One included study used correlation analysis to examine semen samples from male patients diagnosed with infertility or andrological diseases and the average temperature during the sample collection month was not correlated with

**Table 2**
Summary of exposure, outcome, and the number of association analyses by direction.

| Outcome | Exposure | Number of associations by direction |
|---|---|---|
| Sperm count | Temperature | Positive (3)<br>Negative (7)<br>Non-linear (1) |
| | Thermal index | Negative (1) |
| | Temperature extremes | Negative (2) |
| | Season | Positive (2)<br>Negative (2) |
| | Occupation & occupational heat | Negative (7) |
| Semen volume | Temperature | Positive (2)<br>Negative (2)<br>Non-linear (1)<br>Null (2) |
| | Thermal index | Positive (1) |
| | Temperature extremes | Null (1) |
| | Season | Positive (1)<br>Negative (2) |
| | Occupation & occupational heat | Positive (2) |
| Semen concentration | Temperature | Negative (7)<br>Non-linear (6)<br>Null (1) |
| | Thermal index | Negative (1) |
| | Temperature extremes | Negative (2) |
| | Season | Negative (3)<br>Non-linear (1)<br>Null (1) |
| | Occupation & occupational heat | Positive (2)<br>Negative (2)<br>Null (1) |
| Sperm motility | Temperature | Negative (8)<br>Positive (1)<br>Non-linear (5)<br>Null (3)<br>Direction not reported (1) |
| | Temperature extremes | Negative (1)<br>Null (1) |
| | Season | Positive (2)<br>Negative (4) |
| | Occupation & occupational heat | Positive (3)<br>Negative (7) |
| Sperm morphology | Temperature | Positive (6)<br>Negative (5)<br>Non-linear (1) |
| | Thermal index | Positive (1) |
| | Temperature extremes | Negative (1) |
| | Season | Negative (2) |
| | Occupation & occupational heat | Negative (6) |
| Sperm DNA damage | Temperature | Non-linear (1) |
| | Season | Negative (1) |
| | Occupation & occupational heat | Negative (3) |
| Sperm velocity | Occupation & occupational heat | Positive (1) |
| Sperm vitality | Temperature | Negative (1) |
| Testicular torsion | Temperature | Positive (1)<br>Negative (2)<br>Null (1) |
| Ovarian function | Temperature | Negative (2) |
| Infertility status | Temperature | Positive (1) |
| | Thermal index | Null (1) |
| | Temperature extremes | Positive (1) |
| | Climate region | Positive (1) |
| | Occupation & occupational heat | Positive (9) |

(continued on next page)

**Table 2** (*continued*)

| Outcome | Exposure | Number of associations by direction |
|---|---|---|
| Population-level reproductive outcomes | Temperature | Positive (4)<br>Negative (8)<br>Non-linear (1) |
| | Season | Positive (2) |
| Pregnancy loss | Temperature | Positive (18)<br>Negative (2)<br>Non-linear (5)<br>Null (2) |
| | Thermal index | Positive (4)<br>Non-linear (2) |
| | Temperature extremes | Positive (4) |
| Outcomes of artificial reproductive technologies (ART) | Temperature | Positive (10)<br>Negative (8)<br>Null (4) |
| | Season | Positive (7)<br>Negative (10)<br>Null (4) |
| | Occupation & occupational heat | Negative (2) |

MAI ($r = 0.072$, $p$-value $= 0.757$) (Mao et al., 2017). The sperm deformity index (SDI), the number of defects divided by the total number of spermatozoa, did not show a significant correlation coefficient for the monthly average temperature ($r = 0.085$, $p$-value $= 0.714$) in the same study. The teratozoospermia index (TZI), included in the 6th WHO standards and defined as the total number of defects in a spermatozoa (up to four across four anatomical regions) divided by the number of abnormal spermatozoa, was not examined in the included studies.

Sperm DNA fragmentation is a common form of DNA damage and may provide additional diagnostic value, as morphologically normal sperm can exhibit fragmented DNA. The DNA Fragmentation Index (DFI) is calculated as the percentage of sperm cells with fragmented DNA among the total number of sperm counted, reflecting DNA integrity. Five studies examined this index and observed decreased DNA integrity (i.e., higher DNA fragmentation) in relation to exposure to temperature, warm seasons, or heat-related occupations (Caliskan et al., 2023; Eisenberg et al., 2015; Yang et al., 2024; Yazdanpanah Ghadikolaei et al., 2023) (Table S8). Among these, four analyses showed negative associations and one showed a non-linear association (Table 2).

Sperm velocity and sperm vitality were less examined compared to other parameters. A few studies examined sperm vitality based on Eosin Y staining, distinguishing immotile live sperm from dead sperm (Verón et al., 2021). Sperm velocity measures the distance and pattern of sperm movement to better indicate motility quality, and were examined in relation to occupational heat exposure in a study (Pokhrel et al., 2019).

Regarding study characteristics, sperm parameters were usually measured using collected semen samples, and male participants were recruited from hospitals or clinics for health checkups, sperm donation, or reproductive treatments for couples. Some studies reported that they excluded men with specific infertility factors, such as azoospermia, vasectomy, anatomical anomalies, genetic or endocrine disorders, varicocele, and genitourinary inflammation or infection.

Studies had varying exposure period before or at the semen collection timing (Tables S3–S8). To assess exposure to ambient temperature, occupational heat, and temperature extremes, many studies considered conditions during the 70–90 days prior to semen collection, reflecting the duration of spermatogenesis and sperm maturation. Seasonal analysis of sperm parameters roughly reflected temperature exposure in the preceding three months, as most studies used four seasonal categories.

Among the included 43 studies, 17 studies used a univariate statistical analysis (e.g., $t$-test, chi-square test, analysis of variance) (Appendix) and therefore did not consider confounding effects when examining the associations between exposure and semen parameters. Other studies using multivariable analyses considered confounders effects from abstinence period (before semen collection), temporal variables (e.g., year, season), individual-level characteristics (e.g., age, body mass index [BMI], drinking/smoking status, drug use, underlying health condition, race/ethnicity, marital status, education, fertility status), and atmospheric factors (air pollution levels, humidity, sunshine hour) despite varying data availability.

**Summary**

Despite heterogeneous results, studies suggest potentially adverse impacts of temperature on male reproductive potential. Although many studies reported associations between temperature and sperm parameters, the use of continuous outcome variables in most studies without defining abnormal status (e.g., based on established cutoff points) limits our understanding of the clinical relevance of the temperature effects. The absence of clear clinical guidance or changes in the definition of abnormal sperm parameters may challenge the interpretation and comparison of findings across studies. Study findings were from the Americas (USA, Argentina), Africa (Tunisia), Europe (Italy, Netherlands, France, Poland, Germany, Switzerland, Spain), Middle East (Iran, Israel, Turkey), Oceania (Australia), and Asia (China, India, Indonesia, Pakistan), using varied methods (design, analysis, confounders). This highlights the need for future in-depth quantitative synthesis and critical appraisal to evaluate strength of evidence, bias, and heterogeneity for informing decision-making.

### 3.3.2. *Testicular torsion and ovarian function*

Testicular torsion is a twisting of the spermatic cord. If not promptly treated, it can cause testicular damage or loss, potentially impairing sperm production and quality (e.g., motility, morphology). This was examined in relation to ambient temperature in four included studies, showing inconsistent association directions: one positive, two negative, and one null association (Table 2, Table S9). It is notable that these studies were patient-only analyses including patients admitted due to testicular torsion incidence. For instance, one of the four studies compared temperature on the diagnosis day between severe cases (requiring testicle removal) and milder cases (moving testicles into the scrotum), finding no significant exposure differences (Castañeda-Sánchez et al., 2017). One time-series analysis observed a significantly increasing risk at cold temperatures below 21 °C, indicating potential cold effects (Cabral Dias Filho and Gonçalves de Oliveira, 2018). The other three studies used a bivariate statistical analysis (e.g., Chi-square test) comparing exposure levels by severity of conditions or examining frequency of all incidences at different exposure levels (Castañeda-Sánchez et al., 2017; Chen et al., 2013; Ekici et al., 2018). Varying exposure periods were examined across these studies to reflect both short-term (e.g., same day or within a week) and long-term (e.g., over months) exposures.

Ovarian function refers to the activities of ovaries. Diminished ovarian function is reduced quantity and quality of oocytes in ovaries and can be examined by antral follicle scan, measuring the number of antral follicles, fluid-filled sacs containing immature eggs. Two studies were identified, one analyzing the incidence of ovulation and the other one analyzing antral follicle counts. The study for ovulation investigated women undergoing infertility evaluation and found that incidence of ovulatory cycles in infertile women tested by endometrial biopsies were more frequent during months with lower monthly temperatures, resulting in a negative association (Rameshkumar et al., 1992) (Table 2, Table S10). A correlation analysis on the other study about antral follicle counts found that each 1 °C increase in temperature during the prior 1–3 months or 2 weeks before antral follicle scan was significantly associated with lower antral follicle counts, showing a negative association and indicating reduced fertility potential (Gaskins et al., 2021) (Table 2, Table S10).

**Summary**

Study results of testicular torsion were from the US (Castañeda-Sánchez et al., 2017), Turkey (Ekici et al., 2018), Brazil (Cabral Dias Filho and Gonçalves de Oliveira, 2018), and China (Chen et al., 2013), while the results for ovarian functions were from the US (Gaskins et al., 2021) and India (Rameshkumar et al., 1992). Due to the limited number of studies, ovarian function and testicular torsion were examined with fewer exposure metrics, presenting a limited scope of exposure assessments. Exposure periods varied across studies. While ovarian function can be assessed in diverse populations, testicular torsion is limited to diagnosed cases, and included studies often lacked appropriate control or references groups. Most included studies used bivariate statistical methods without addressing confounding or causality.

While these two conditions are important male and female factors for reproductive functions, the impact of temperature on them remains understudied. There is a need for more well-designed studies with appropriate control groups to minimize potential bias in risk estimation. Future studies should also examine a broader range of reproductive disorders to clarify mechanisms and identify more vulnerable populations.

### *3.3.3. Infertility status*

We refer to infertility based on the WHO definition, which classifies male or female reproductive system as infertile when pregnancy is not achieved after 12 months of regular, unprotected intercourse (WHO, 2024). This binary status (fertile vs. infertile) was analyzed in relation to temperature, thermal indices, occupational heat, season, and climate region, with occupational heat being the most frequently studied (Table S11). We found 13 associations out of 12 studies. All nine studies about occupational heat consistently found positive associations between exposure and increased risk of infertility (Table 2).

Although infertility is defined at the couple level, included studies focused on females, males, or both, mostly using case-control designs and comparing exposure between fertile and infertile groups. Controls often were couples or individuals who attended hospitals for their prenatal care (El-Helaly et al., 2010; Me et al., 2010). Other study designs also examined associations between temperature and infertility. We found one cohort study, which followed eligible participants across three occupational groups (firefighters, military personnel, and non-firefighters) in Denmark and found that firefighters had a higher risk of receiving an infertility diagnosis (Petersen et al., 2019). Other studies used cross-sectional designs, either population-based or with recruited participants. One study found that exposure to monthly temperature higher than average in women was associated with significantly reduced probability of achieving pregnancy in the following year in populations in multiple African countries (Thiede et al., 2022). A cross-sectional study comparing recruited tandoor workers and bankers in Attock City, Pakistan defined infertility as having no children at recruitment and reported a higher crude odds of infertility among tandoor workers (Sarfraz et al., 2024). Another study in Suizhong, China found that ale participants reporting high-temperature occupational exposure had approximately four times the prevalence of infertility compared to others (Cong et al., 2016).

**Summary**

The findings for exposure and infertility were notably consistent across the included studies (Fig. 3), which may be partially attributable to the use of a binary classification of infertility. Limitations of existing studies include reliance on self-reported occupational heat exposure and a lack of research on ambient temperature effects across both workers and the general population. Despite the highest consistency of the exposure–response associations among all identified outcomes, more scrupulously designed studies can help reduce potential biases. Future cohort studies with participant follow-up and improved exposure assessment are needed to more rigorously evaluate causality in this area.

### *3.3.4. Population-level reproductive outcomes*

We categorized birth rate, fertility rate, conception rate, pregnancy history, and number of births in populations as population-level reproductive outcomes. While these metrics do not directly assess individual-level fertility, they are used to evaluate the impact of environmental exposures on population-level reproductive patterns. Birth rate is typically calculated as the number of live births per total population during a given time frame (e.g., daily, monthly, or annually), while fertility rate is the number of live births per women of reproductive age (typically 15–49 years) (Barreca and Schaller, 2019). This type of outcome was examined most frequently with temperature followed by temperature extremes and season. A negative association indicates worsened outcome due to exposure for this type of outcomes. Eight associations from the included studies were negative, indicating that higher temperature exposure was linked to lower birth or fertility rates, while four associations were positive (Table 2, Table S12).

Regarding study characteristics, these studies commonly used aggregated temperature data at city, county, or national levels, assigning temperature exposures to the outcomes based on monitoring or modeled datasets. Exposure windows varied widely, focusing on narrow windows such as the exact date of birth or the conception week (Barreca and Schaller, 2019; Hajdu and Hajdu, 2021a). Other studies considered broader windows such as each month between the birth month to 25 months prior to assess long-term effects (Cho, 2020; Conte Keivabu et al., 2024; Hajdu, 2024; Wu et al., 2025). Many of the included studies applied distributed lag models to account for multiple exposure lags across the analysis period (Barreca et al., 2018; Barreca and Schaller, 2019; Conte Keivabu et al., 2024; Hajdu, 2024; Hajdu and Hajdu, 2021a). However, some studies aggregated exposures into fixed time windows, which limited the ability to model lagged effects flexibly (Jensen et al., 2021; Marteleto et al., 2023; Sellers and Gray, 2019).

Although 11 studies focused on a single country, three conducted multi-country analyses (Boland, 2018), offering broader insight into regional differences. Birth rate is influenced not only by environmental conditions but also by socioeconomic factors such as income, education, and access to reproductive healthcare (Shabani et al., 2014b). However, only five studies accounted for individual- or community-level socioeconomic factors, such as income (e.g., GDP) and education, in their statistical models (Boland, 2018; Cho, 2020; Conte Keivabu et al., 2024; Khajavi et al., 2016; Marteleto et al., 2023). This limitation may lead to bias in association estimates.

Notably, one study in the US (Barreca and Schaller, 2019), one in Spain (Conte Keivabu et al., 2024), and a multi-country analysis (Barreca et al., 2018) suggested that the negative association between temperature and birth rate may be stronger in colder regions, possibly due to greater population vulnerability to heat. However, there was a lack of reported effect modification analyses, indicating a key area for future research.

**Summary**

Given the varying directions in the observed associations (Fig. 3), methodological heterogeneity, particularly in exposure windows and lag structures, may challenge quantitative evidence synthesis on this topic. For instance, studies on sperm parameters typically examined exposure windows of the 90 days preceding semen collection. In contrast, studies on population-level reproductive outcomes, such as birth rates, assessed temperature over both short periods (e.g., 30 days before birth) and longer periods (approximately 25 months prior), without indicating a consistently applied exposure window across studies. Future review studies for evidence synthesis should consider this modeling aspect for exposures as a source of heterogeneity for observed study results. Furthermore, given that the results are focused on population-level outcomes, it is imperative for future studies to account for potential confounding by socioeconomic factors and to examine whether socioeconomic factors modify the exposure-outcome associations.

### *3.3.5. Pregnancy loss*

Some studies define subfecundity as prolonged time-to-pregnancy and difficulty in carrying the pregnancy to a live birth (Cong et al., 2016). While pregnancy loss is a different outcome from infertility, as it occurs after pregnancy is achieved, it was included in this review because it can also result in a childless status. We identified 33 studies on pregnancy loss, including spontaneous abortion (loss before 20 weeks of gestation) and stillbirth (loss at or after 20 weeks of gestation) in relation to temperature, thermal indices, and temperature extremes, with ambient temperature being the most frequently studied exposure (Table S13).

Considering the analyses using various exposure metrics, a total of 37 association estimates were obtained from 33 included studies. Of these association, 22 associations reported a positive direction, indicating increased risk of stillbirth or spontaneous abortion with higher exposure, while two reported negative, seven reported non-linear, and two reported null associations (Table 2). Along all identified infertility-related outcomes in this review, pregnancy loss was the most frequently examined for non-linear associations, reflecting more complex modeling approaches. For example, a study in the US reported that average daily temperature over the seven days preceding spontaneous abortion showed a U-shaped relationship, indicating both cold and heat effects (Wesselink et al., 2024). Another study examining average monthly temperature during the three months preceding stillbirth also reported a U-shaped relationship (Yang et al., 2022). Exposure periods also varied considerably across studies. Many assessed lagged temperature over the same day and previous two weeks to capture short-term effects, while a few examined longer periods, such as the incident month, year, or entire gestational period. Exposure levels were assigned to individuals using average exposure aggregated at larger spatial units (e.g., city, county) or from a single station, indicating potential exposure misclassification. We identified one study assigning exposure to geocoded residence of participants (Sun et al., 2020) and another assigning exposure averages aggregated at the postal code area level (Shupler et al., 2024).

The included studies largely depended on the population-level vital statistics data or medical data from hospitals to identify spontaneous abortion and stillbirth incidents. Most studies used case-crossover designs with conditional logistic regression or time-series analysis with distributed lag non-linear models, estimating risk ratios (e.g., relative risks, odds ratios, hazards ratios) for pregnancy loss per unit change in exposure while adjusting for temporal trends of outcome and time-varying covariates.

**Summary**

Findings indicate the need for refined exposure assessments. The variability in examined exposure periods may contribute to heterogeneous results; however, future quantitative evidence synthesis can help identify critical exposure windows for the risk of pregnancy loss related to temperature exposures by leveraging findings from these numerous studies. Also, future studies can further investigate community- or population-level factors influencing the non-linear exposure response-associations. Furthermore, investigating risk disparities by individual-level or community-level factors would be important to identify more vulnerable populations to the impact of temperature on the risk of pregnancy loss.

*3.3.6. Outcome of assisted reproductive technologies (ART)*

ART encompasses several procedures such as intrauterine insemination (IUI), which introduces sperm into the uterus; in vitro fertilization (IVF), where eggs are retrieved and fertilized outside the body; intracytoplasmic sperm injection (ICSI), a specialized IVF technique injecting sperm directly into an egg; and frozen egg or embryo thawing, which allows previously preserved gametes or embryos to be used for transfer. We identified 30 studies incorporating 46 analyses investigating how outcomes of ART were associated with ambient temperature, season, and occupational heat exposure (Table S14).

Included studies examined several outcomes indicating the success of ART including maturity of oocytes, fertilization rate, number of embryo transfers, implantation rate, biochemical pregnancy rate, clinical pregnancy rate, and live birth rate. Implantation rate is the proportion of transferred embryos resulting in a gestational sac seen on ultrasound. Biochemical pregnancy is identified by hormonal tests (elevated human chorionic gonadotropin levels) in early pregnancy, whereas clinical pregnancy is confirmed by ultrasound visualization around 5–7 weeks of gestation. The most frequently observed success outcome was clinical pregnancy rate and live birth rate after the ART procedures (Table S14). For instance, a study found that every interquartile range increase in the average temperature from the first cycle day to the day of oocyte retrieval was significantly associated with 1.04 times higher probability of pregnancy per IVF cycle (95 % CI: 1.01–1.07) (Zhao et al., 2019).

Included studies for the outcomes of ART showed substantial heterogeneity in the direction of observed association, with a slightly lower portion of associations reporting decreased successes of ART for increased temperature exposures ($n = 8$) than the associations reporting increased successes of ART ($n = 10$) (Table 2). Substantial heterogeneity was also observed for season, with 10 analyses reporting negative, seven reporting positive, and four reporting null associations.

Temperature effects may vary depending on the timing or stage of exposure during the ART process. For example, overall impacts of temperature on live birth outcome may depend on which specific phase of ART such as oocyte development, oocyte retrieval, conception, and implantation is affected. While the most frequently used outcome of ART success was live birth rate among the included studies, the use of various other outcomes (e.g., number of retrieved oocytes, fertilization, implantation) in the analyses may have led to the heterogeneous directions of associations as these studies were grouped into one outcome category.

This heterogeneity may also be partially explained by various research designs and analytic strategies. Recruited patients in these studies may differ in infertility duration, underlying causes, and ART procedures used, contributing to heterogeneity in the observed outcomes. In particular, infertility causes leading to severe or irreversible reproductive dysfunctions, rather than milder or temporary conditions, might influence both the baseline success of ART and its association with temperature. Some studies reported outcomes only for female participants as ART success is often defined by pregnancy, while others included couples undergoing treatment. Thus, the availability of patient information often varied depending on the recruited participant groups. For instance, many included ART studies did not report or clearly specify whether infertility was due to female, male, or unknown causes, which may be important for understanding potential pathways between temperature and ART outcomes. These study characteristics highlight an important insight that the underlying cause of infertility may contribute to the heterogeneity of study results, which future systematic evidence syntheses should carefully consider.

Among temperature exposure studies, the exposure period varied: some measured exposure at the start of ovulation induction (administration of follicle-stimulating hormones such as gonadotropins), others at oocyte retrieval, and some averaged temperature between these dates (Table S14). A few studies assessed multiple exposure windows, such as the three months before oocyte retrieval, from ovarian stimulation to retrieval, from retrieval to embryo transfer, from embryo transfer to chemical pregnancy test, from chemical test to ultrasound, and from ultrasound to delivery, to capture the most biologically relevant exposure windows (Cheng et al., 2024; Geng et al., 2023). Given the potentially different temperature effects depending on the stage of ART processes, assessing multiple exposure windows throughout each cycle (i.e., the full sequence of procedures in a single ART attempt) would be ideal and informative for identifying critical exposure windows. Among the 30 included studies, 16 examined ambient temperature as the exposure. Of these, 11 used ambient monitoring data, two used modeled data (Geng et al., 2023; Wu et al., 2025), one used satellite-derived data (Cheng et al., 2024), and three (Liu et al., 2019; Medyannikova and Klinyshkova, 2012; Rojansky et al., 2000) did not report the type of exposure data source (Appendix). Of these 16 studies, 12 reported the spatial resolution of exposure, typically assigning city-level aggregated values to all participants within the same city (Appendix).

While studies for seasonality of ART success often lacked consideration of confounders, studies for temperature considered various potential confounders including female age, infertility cause, number of embryos transferred, ovarian stimulation methods, infertility type (primary, secondary infertility), previous ART attempts, female BMI, sexual hormone levels during procedures, year, season, sunshine duration, and air pollution levels.

**Summary**

Existing studies indicate potential associations between temperature-related exposures and ART outcomes, though differences in study design, exposure assessment, outcome definitions, and confounder adjustment contribute to heterogeneity. Results also showed high heterogeneity likely due to differences in treatment, infertility causes, and geographic contexts. Our scoping review did not explore sources of heterogeneity in depth, and this remains an important question for future systematic reviews and evidence synthesis.

While our review included pregnancy loss, it primarily focuses on the ability to maintain a pregnancy rather than the ability to conceive. In this context, studying ambient temperature exposures during or before ART treatments may offer insights into key biological processes such as ovarian reserve, oocyte release, sperm quality, fertilization, and implantation. Clearer reporting baseline participant characteristics would strengthen the interpretability and appraisal of these studies and improve evidence synthesis to support informed decision-making on exposure-outcome associations. Furthermore, findings on ART outcomes were based on participants from single clinics. With growing interest, more research across diverse patient groups and ART methods is expected. Future multi-center studies may be helpful to investigate this topic with larger sample sizes, reducing selection and clinic-specific biases.

## 4. Conclusions

This scoping review highlights a growing field of temperature and human infertility outcomes, with 18 more published studies in 2024 compared to one in 1983. Our findings highlight a diverse and expanding field investigating the relationship between ambient temperature and a range of human infertility outcomes across populations and study designs. Despite the heterogeneity in exposure types, outcomes, populations, and study designs, numerous studies reported associations between higher ambient temperature or temperature extremes and reduced reproductive health outcomes, which can be plausibly explained by potential biological mechanisms such as disrupted thermal regulation in reproductive organs and behavioral changes (e.g., reduced coital frequency).

This scoping review mapped the existing epidemiologic landscape by exposure–outcome pairs and summarized the direction of observed associations for each outcome. Studies on sperm parameters generally suggested that elevated temperature may impair sperm quality, contributing to infertility. Due to the large number of studies and relatively consistent research designs, a systematic review and quantitative data synthesis (e.g., meta-analysis) on this outcome would be feasible and provide comprehensive evidence. The existing meta-analysis for ambient temperature and human sperm parameters supports this feasibility. For instance, a previous meta-analysis reviewed nine studies published in 1992–2017 and reported significant decreases in sperm volume, concentration, count, motility, or morphology due to heat exposure (Hoang-Thi et al., 2022). We assume that an updated meta-analysis incorporating these sperm parameters along with the latest evidence on sperm DNA damage would be useful.

Although limited in number, studies using a binary classification of infertility status showed the most consistent associations. Population-level reproductive outcomes such as birth rate showed inconsistent findings, with both positive and negative associations reported. Similarly, the findings were not consistent for successful outcomes of ART. Studies on pregnancy loss (e.g., stillbirth, spontaneous abortion) reported mixed results, possibly reflecting underlying non-linear relationships which some studies quantified using flexible statistical models.

Given that there were relatively more studies for semen parameters and pregnancy loss than the other identified outcomes, important research gaps remain for understudied outcomes. In particular, there were few studies addressing reproductive diseases (e.g., testicular torsion, diminished ovarian reserve), underscoring the need for a broad scope of male and female diseases and conditions that can lead to infertility status. It is noteworthy that evidence is limited for female reproductive outcomes other than achieving pregnancy after ART treatments. There are various measures for ovarian functions such as anovulation, menstrual irregularity, ovarian volume, antral follicle count, menopause, premature ovarian failure, endometrial thickness, or hormone levels indicating ovarian reserve and follicle development. Studying the impact of temperature on these outcomes would strengthen biological plausibility and contribute to a more consistent body of evidence.

For stronger causal inferences, large cohort or population-based studies can be helpful to evaluate broader temperature effects on population-level reproductive health and identify vulnerable subpopulations based on sociodemographic factors. Improvements in study designs are also needed in general across all outcomes. There is a need for more prospective studies with follow-up of participants to evaluate temperature effects on infertility outcomes while ensuring clear temporal precedence. For example, studies for sperm analysis mainly relied on a cross-sectional design and lacked the ability to assess causal associations, highlighting the need for prospective evidence. Given that studies on binary infertility classification were primarily based on case-control studies, there remains scope for study designs incorporating participant follow-up and longitudinal data to enable a more rigorous evaluation of causality. On the other hand, improving the consideration of confounders in statistical models is also required to strengthen causal inference. For example, outcomes such as birth rates are observed at the population levels and failing to consider important contextual confounders may affect the estimated associations, to which future research should pay particular attention.

Improvement in exposure assessments can also contribute to stronger causal inferences. Although many studies focused on various exposure periods (e.g., past weeks, past months) reflecting historical exposure levels, the exposure assessment was often performed cross-sectionally (i.e., performed at the same time as outcome diagnosis) or retrospectively, leading to some uncertainty in the temporality assessments. Additionally, exposure assessments can be improved by using more consistent exposure data across study participants. The use of self-reported heat exposure or heat-related tasks during work may introduce misclassification due to recall bias and subjective perceptions. This highlights a key research gap in more ubiquitous and non-occupational temperature exposures and the need for population-level evidence. Common data sources for ambient temperature are modeled or monitored data that can be used to estimate exposure levels for a given area. We acknowledge that these data sources are helpful in reflecting exposure variability across regions but also have limitations in capturing variations in personal exposure levels arising from different time-activity patterns. Personal exposure measurements can help assess more accurate heat stress in individuals and more precise estimates of temperature-outcome associations. We did not identify studies examining personal exposure levels among the included studies except for one study measuring the time spent outdoors under hot conditions doing physical activities (Melinawati et al., 2023). Therefore, data on non-occupational temperature exposures are lacking for certain outcomes and personal exposure measurements remain scarce across all outcomes. This important research gap should be addressed in future studies to improve understanding of the impact of individual-level heat stress on reproductive health.

Although we identified studies from various regions (e.g., North and South America, Europe, Oceania, Asia, and Africa), most evidence came from high-income countries, with limited research from low- and middle-income countries. Resources for exposure and infertility assessments may vary by country income, and the lack of data from more vulnerable populations, who face greater risks from temperature extremes due to limited infrastructure and healthcare, may limit our understanding of temperature's impacts on infertility. Further research focusing on socioeconomic and regional disparities is needed to inform equitable public health interventions and guide policy development.

In addition, based on our findings, evidence on effect modification by climate zone or geographic region in the temperature–infertility relationship is limited. Due to population differences in acclimatization to climate, physiological and behavioral responses to extreme temperatures may differ across regions. Future studies should account for climatic characteristics, in addition to socioeconomic factors, when examining heterogeneity in temperature–infertility associations.

Another important knowledge gap is the lack of epidemiologic assessments of potential behavioral mechanisms (e.g., sexual behavior). None of the included studies examined coital frequency as an intermediate factor that could help explain and differentiate plausible mechanisms underlying the observed associations. Future studies investigating these pathways could be useful to understand direct and indirect effects, strengthen causal inference, and identify interventions.

A strength of this scoping review is its comprehensive mapping of studies on temperature and human infertility, an area lacking systematic or quantitative synthesis. We identified the types and definitions of infertility outcomes examined with ambient temperature, revealing emerging evidence and understudied areas. Previous reviews, such as Kumar and Singh (2022) focused primarily on potential biological mechanisms linking temperature to spermatogenesis and summarized observational studies in occupational settings, where scrotal temperature was a key exposure metric. Similarly, Krzastek et al. (2020) (Krzastek et al., 2020) discussed lifestyle factors increasing scrotal temperature which can contribute to male infertility. Another review identified a few epidemiologic studies for heat and infertility within climate-focused search strategies (Segal and Giudice, 2022). Also, another review focused on temperature extremes and birth rates (Ahmed et al., 2024). We did not find prior review studies with meta-analysis for temperature and female reproductive functions in humans except for those focusing on birth outcomes or pregnancy loss. Our study adds to these findings by presenting observational evidence on ambient temperature exposures and infertility in human populations, adding a broader epidemiologic perspective. By summarizing the observed associations and the methodological characteristics of included studies, we identified knowledge gaps and priorities to guide future research, including systematic reviews and meta-analysis.

This review has limitations. Our aim was to map the current evidence for temperature and human infertility, and this wide scope identified various study designs but hindered an in-depth data synthesis. Despite our summary of association directions by outcome and exposure metric, this is not a quantitative synthesis and further research is needed to guide preventive decision-making. Even though we included study results from various regions and populations, we excluded grey literature or non-English references, which may contain relevant findings. Also, we did not include region-specific databases (e.g., Bielefeld Academic Search Engine, LILACS), potentially limiting the capture of all relevant evidence. We did not conduct a critical appraisal of individual studies, which limits assessment of study quality and potential bias. Therefore, the identified studies may differ in terms of their bias and limitations. Although we identified various types of exposure metrics, we did not critically summarize details such as spatial resolution or exposure assignment methods in the included studies. Similarly, while we summarized the observed exposure-response associations for each type of exposure metric, we did not explore in depth how the use of thermal indices rather than ambient temperature might influence observed associations with infertility outcomes. For instance, some studies suggest that broader use of such indices could improve exposure assessment and understanding of the temperature impacts on reproduction (Brimicombe et al., 2024). While this may be an interesting question for future research, it was beyond the primary scope of our review, which aimed to map the epidemiological evidence in this area. Last, this review may have missed studies published after our search date. Nonetheless, because our study is not a critical quantitative synthesis, the potential omission of recent studies is unlikely to significantly affect our overall data summarization.

In conclusion, this scoping review maps current evidence linking ambient temperature to human infertility. Our findings highlight key research gaps and offer direction for future studies to strengthen causal inference and expand evidence for various populations. Furthermore, our findings can inform reproductive healthcare of the potential influence of ambient temperature on infertility and the importance of exposure reduction. The findings can also support occupational health strategies to reduce heat stress among workers and prevent harmful reproductive effects. Environmental health and climate adaptation policies should consider infertility as a temperature-related public health concern in measures to mitigate its burden.

## CRediT authorship contribution statement

**Seulkee Heo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Garam Byun:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Yongsoo Choi:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Yimeng Song:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Mercedes Bravo:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Tian Ma:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Rory Stewart:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Audrey Amezcua-Smith:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Ji-Young Son:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Leo Goldsmith:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Kate Burrows:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Hayon Michelle Choi:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Chen Chen:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Damien Foo:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Sera Kim:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Nicholaus P. Johnson:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Nicole C. Deziel:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Yichen Wang:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Honghyok Kim:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Michelle L. Bell:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michelle L. Bell reports was provided by Yale University. Michelle L. Bell reports a relationship with National Institutes of Health that includes: funding grants. Michelle L. Bell reports a relationship with Wellcome Trust that includes: funding grants. Michelle L. Bell reports a relationship with Health Effects Institute that includes: funding grants. Michelle L. Bell reports a relationship with Institute of Physics that includes: consulting or advisory. Travel reimbursement from Boston University, Brown University, Harvard University, Columbia University, University of Connecticut, University of Texas, Colorado School of Public Health, University of Pennsylvania, and Duke University. Chen Chen reports a relationship with California Air Resources Board that includes: funding grants. Honghyok Kim reports financial support was provided by National Institutes of Health.

Other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.123641.

## Data availability

All data analyzed in this study are included in this published article and its supplementary information.

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