

Review

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Eco-fertility: examining the climate change-total fertility rate nexus in the context of sustainable developmental goals in a systematic review approach

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Abstract: Sustainable Development Goals (SDGs) are paramount as the global community confronts the ramifications of climate alterations, especially its implications on population dynamics. Initial studies suggest an intricate relationship between environmental determinants and reproductive choices. This systematic review elucidates the complex interplay between climate-related challenges and observed global fertility rate variations. A comprehensive search and analysis of literature published in the last 10 years (2013–2023), available in the PubMed database, delineates the relationship between environmental changes and fertility patterns in both human and animal populations. The review highlighted significant effects of climatic fluctuations on reproductive health, manifested as either adaptive or maladaptive responses to environmental stressors. This relationship not only influences population trajectories but may also have complications for the SDGs, specifically those pertaining to health, well-being, and gender equality. The study emphasizes the importance of intertwining demographic insights with ecological considerations. A deeper understanding of the nexus between climate and fertility can augment strategies aimed at global sustainability. The synthesized evidence underscores the urgency for further research, which seeks to seamlessly incorporate

eco-fertility perspectives into wider climate and sustainability discussions.

Keywords: climate change; eco-fertility; environmental sustainability; sustainable development goals (SDGs); total fertility rate (TFR)

Background

Within the pressing challenges of the 21st century, both climate change and population trends have been highlighted as critical issues warranting urgent focus [1]. The complex interplay between environmental sustainability and human population expansion encompasses a broad spectrum of socio-economic and ecological factors [2]. Notably, the Total Fertility Rate (TFR), which denotes the average number of offspring a woman is anticipated to have throughout her lifespan, serves as a pivotal metric for understanding population growth trajectories [3]. Beyond being a marker of societal constructs, TFR can also provide insights into its implications for environmental sustainability [4]. This relationship paves the way for the term ‘Eco-Fertility’, which is an interdisciplinary approach to studying the nexus between TFR and ecological footprints [5].

The 2030 Agenda for Sustainable Development, unanimously backed by United Nations Member States, positions the Sustainable Development Goals (SDGs) as a global directive to abolish poverty, safeguard the environment, and guarantee well-being for all [6]. Under this agenda, SDGs underscore the vital importance of sustainable consumption and production patterns, coupled with cautious natural resource stewardship. Yet, a pertinent query emerges: how does population expansion, as delineated by TFR, integrate into this framework?

Emergent research posits that shifts in fertility rates could potentially be reciprocally linked with climate change impacts [7, 8]. Aspects such as resource limitations, migrations triggered by climatic events, and socio-economic

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resilience might weave fertility decisions with environmental shifts [9]. Therefore, this article highlights an essential yet frequently overlooked dimension of the climate change dialogue: its possible effects on the TFR and the subsequent repercussions for realizing the SDGs. In this communication, our objective is to clarify the complex interplay between these areas and suggest approaches to tackling the combined challenges they present.

Methods

To gain insights into the potential effects of climate change on fertility over the span of a decade (2013–2023), a comprehensive search was executed on the PubMed database. We oriented our search around the MeSH terms “Climate change” AND “Fertility”, emphasizing the goal to fetch articles that interlinked these two phenomena. The language preference was set to English, with the timeframe filtered to cover publications from 2013 to 2023. During the search, we maintained an inclusive stance, considering a

variety of article types including, but not limited to, full-text articles, clinical studies, reviews, and randomized trials. Both male and female subjects were deemed relevant for the scope of our research. A total of 839 records were initially identified through this database search. After the preliminary filter, 171 duplicate records were removed. The titles and abstracts of the remaining 668 records were screened for relevance based on specific inclusion criteria, such as publication years (2013–2023), English language, and full-text availability.

To ensure proper quality assessment, post-search, we adopted a two-phased approach to select relevant articles. Initially, titles and abstracts were screened to determine alignment with our criteria. A total of 53 records were excluded because they were deemed irrelevant from their titles and abstracts. Those shortlisted underwent a thorough full-text review to ascertain their pertinence to our study. A further 36 reports were excluded after a detailed full-text review. All the included articles underwent a quality assessment using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

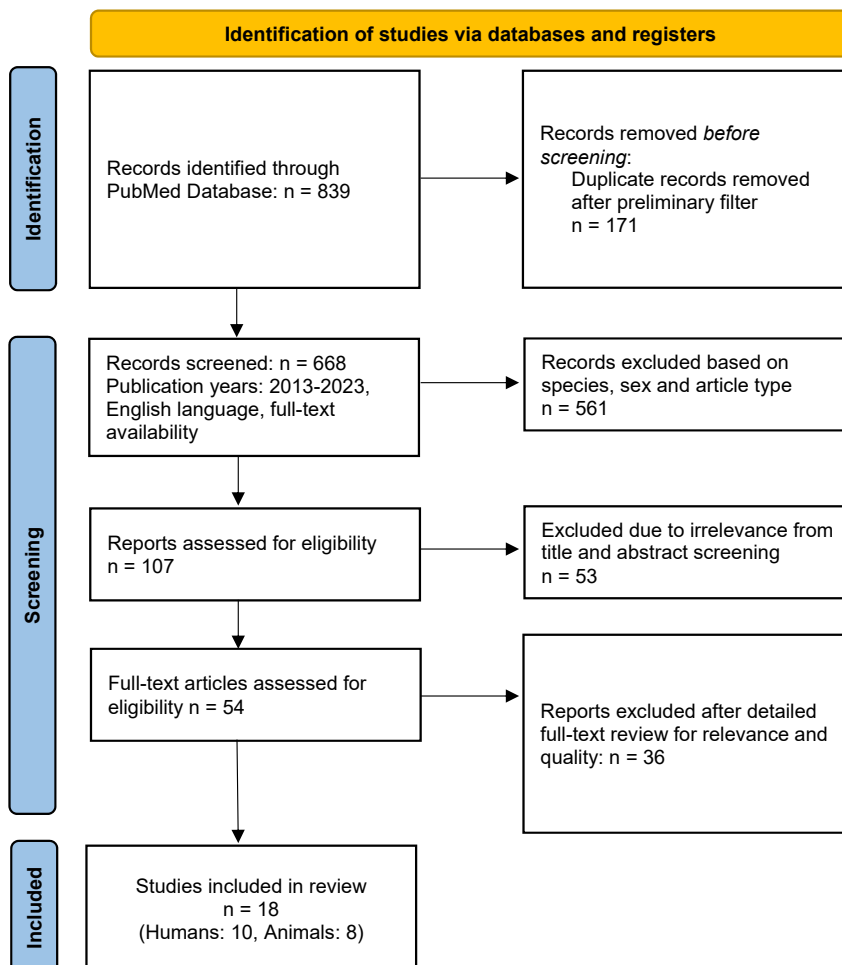


Figure 1: PRISMA flowchart for article selection Process.

Table 1: Decadal review of key publications on climate change and fertility (2013–2023).

Title	Summary	Publication year	Reference
Publications on human fertility			
Indices of methylation in sperm DNA from fertile men differ between distinct geographical regions	Investigates the determinants of sperm DNA methylation levels. Geographical region was identified as a significant factor affecting methylation in repetitive DNA sequences. However, methylation levels seemed independent from semen quality parameters, marking it as a potential biomarker in fertility studies.	2014	Consales et al. [11]
Reproductive science and the future of the planet	Reproductive sciences play pivotal roles in human health, livestock production, and environmental management. Joint efforts can shape policies on fertility, livestock breeding, and climate. Continued advocacy is vital for global welfare.	2019	Findlay et al. [12]
Human health and ocean pollution	Details the significant effects of ocean pollution on human health. Land-based ocean pollutants threaten marine life and humans. Health impacts from plastics, toxic metals, and chemicals include neurological issues and disease risks. Advocates for pollution prevention and intervention.	2020	Canelón and Boland [14]
A systematic literature review of factors affecting the timing of menarche: The potential for climate change to impact women's health	Climate change can influence the timing of menarche through environmental disturbances, which might increase future health risks for women, including mental health and cardiovascular issues.	2020	Landrigan et al. [13]
Environmental impact on reproductive health and risk mitigating strategies	Environmental elements, like industrial toxins and climate change, jeopardize reproductive health. Factors including air pollution and endocrine disruptors lead to reproductive disorders. Emphasis on risk mitigation and healthier alternatives is vital.	2021	D'Angelo et al. [16]
Challenges for midwives' healthcare practice in the next decade: COVID-19 – global climate changes – aging and pregnancy – gestational alcohol abuse	Midwives confront diverse challenges in the upcoming decade: Infectious disease risks, menstrual waste pollution, aging-related fertility issues, teen pregnancies, and gestational alcohol consumption. Enriching the role of midwifery, particularly in education and prevention, is essential.	2021	Giudice [15]
Pollutants and sperm quality: a Systematic review and meta-analysis	A systematic review connecting environmental and occupational pollutants to decreased sperm quality in humans. The study found that these pollutants may influence various sperm parameters, emphasizing the need to understand pollutants' impact on health and environment.	2021	Pizzol et al. [17]
Systematic review of climate change effects on reproductive health	Emphasizes the detrimental effects of climate change on reproductive health. Rising temperatures lead to threats like pollution, wildfires, and vector-borne diseases, impacting fertility, fetal development, and obstetric outcomes. Calls for education by health providers.	2022	Segal and Giudice [18]
Climate and environmental change: A generation at risk	Identifies pregnant women and children as populations vulnerable to climate and environmental changes. These changes affect maternal and newborn health through heat, extreme weather, and pollution. Reviews impacts on reproductive health and suggests interventions.	2023	Chalupka et al. [19]
The minderoo-monaco commission on plastics and human health	Plastics present both benefits and threats to health and environment. Issues arise from unsustainable practices causing environmental damage, health risks,	2023	Landrigan et al. [20]

Table 1: (continued)

Title	Summary	Publication year	Reference
	and societal injustices. Global intervention, especially against single-use plastics, is crucial.		
Publications on animal reproduction			
Do hormone-modulating chemicals impact on reproduction and development of wild amphibians?	Reviews evidence of endocrine-disrupting contaminants (EDCs) affecting wild amphibians, contributing to population declines. While some chemicals showed hormone system alterations in amphibians, their impact on fertility and breeding remains inconclusive. Requires better assessment methods for clearer impacts.	2015	Egger-Danner et al. [23]
Overview of new traits and phenotyping strategies in dairy cattle with a focus on functional traits	Highlights the shifting breeding goals in dairy from milk production to include functional traits due to health and sustainability concerns. Suggests using existing data sources and advanced tools like mid-infrared spectroscopy for efficient trait measurement, pushing for a balanced and sustainable approach.	2015	Orton and Tyler [22]
Dairy cow reproduction under the influence of heat stress	Highlights global warming's challenge to dairy farming, especially heat stress (HS) impacts on cow fertility in tropical climates. HS affects reproduction stages, due to hyperthermia, oxidative stress, and physiological changes. Recommends strategies like cooling and improved breeding.	2020	Sammad et al. [24]
Moving towards sustainable breeding objectives and cow welfare in dairy production: a south african perspective	Emphasizes the need to reconsider dairy breeding objectives for sustainable production and cow welfare in South Africa. Despite past focus on milk production, the inclusion of genomic information can benefit cow welfare and sustainable dairy production traits.	2021	Erasmus and van Marle-Köster [25]
History, insights, and future perspectives on studies into luteal function in cattle	Reviews the corpus luteum's role in bovine fertility, focusing on its formation, function, and destruction. Highlights pivotal research while proposing future study areas regarding ruminant fertility.	2022	Bishop et al. [26]
Reproductive consequences of whole-body adaptations of dairy cattle to heat stress	Heat stress impacts dairy cattle's reproductive performance due to physiological changes, such as altered metabolism. This review delves into the effects and potential remedies for fertility challenges during heat stress.	2023	Rhoads [21]

checklist [10] to ensure the reliability and validity of the data presented in this review. Records were excluded based on irrelevant species, sex-specific studies not applicable to the broader research question, and article types that did not contribute to the research objectives. After the rigorous screening and exclusion processes, 18 studies were included in the review, with 10 focusing on humans and eight on animals (Figure 1). The selection procedure adhered to a structured and transparent methodology, employing the PRISMA guidelines to ensure the inclusion of studies relevant to the complex interplay between climate change and fertility rates within the context of SDGs. Key

data such as study title, findings summary, publication year, and reference were tabulated in Table 1.

Results

The collected articles offered valuable insights into the nexus between climate change and fertility for both humans and animals. For clarity, articles were grouped under 'Human Fertility' [11–20] and 'Animal Reproduction' [21–26] in Table 1. The review of the published literature from 2013 till present, highlighted a growing body of evidence

connecting climate change with fertility challenges in both humans and animals over the past decade. While a comprehensive discussion is presented in the subsequent sections, it is clear that climate change has multifaceted impacts on reproductive health, warranting further exploration and research.

Discussion

Climate change and TFR nexus

Over the past decade, a growing body of research has illustrated the intricate relationship between climate change and fertility, both in humans and animals [27, 28]. Studies from past decade, such as the 2014 investigation into the determinants of sperm DNA methylation levels, highlighted geographical variations in methylation, potentially serving as a biomarker in fertility studies [11]. By 2019, the conversation had expanded to emphasize the significant roles reproductive sciences play in human health, livestock production, and environmental management [29]. The intersection of these fields can shape global policies to address issues exacerbated by climate change [12].

The subsequent years continued to underscore the importance of understanding the role of the environment in fertility. For instance, a 2020 study showcased the implications of ocean pollution on human health, marking the perils posed by land-based pollutants to marine life and humans alike [13]. The same year, researchers probed into the potential influence of climate change on the timing of menarche in women, suggesting that climate-related disturbances might affect long-term health of women [14].

By 2021, the narrative shifted to a comprehensive exploration of various environmental threats to reproductive health. Notably, studies started to consistently highlight the detrimental effects of industrial toxins, pollutants, and other climate change outcomes on reproductive health [15]. Sperm quality, often regarded as a crucial parameter in fertility studies, was found to be compromised by environmental and occupational pollutants [17]. A systematic review in 2022 further emphasized the threats that rising temperatures pose to reproductive health, pointing to challenges like pollution, wildfires, and vector-borne diseases, which directly affect fertility and obstetric outcomes [18]. Meanwhile, in 2023, research reiterated the vulnerabilities of pregnant women and children to climatic and environmental changes, emphasizing the repercussions of these changes on maternal and newborn health [19]. Concurrently, the Minderoo-Monaco Commission delved into the multifaceted issue of plastics, underscoring the

potential detrimental impact of plastics to human health, including reproductive wellness. The report delineates concerns stemming from unsustainable plastic practices leading to environmental degradation, health hazards, and societal inequities. There is an expressed urgency for global action, predominantly against the pervasive use of single-use plastics, given their environmental accumulation and consequent threats [20].

Turning our attention to animal reproduction, the investigation of fertility, particularly in the context of external stressors such as climate change and endocrine-disrupting chemicals (EDCs), has garnered increasing attention and concern. In 2015, a paper explored the potential effects of hormone-disrupting substances on the reproductive and developmental processes of wild amphibians. Although evidence was presented indicating the influence of EDCs on amphibians, there was an ambiguous link between these chemicals and direct repercussions on amphibian fertility and reproduction. This underscores the need for refined methodologies and comprehensive research frameworks to conclusively ascertain the hazards posed by EDCs [22]. Simultaneously, in the same year, research highlighted a significant transition within the dairy cattle breeding sector. Traditionally, the primary breeding objective in the dairy sector was focused on milk yield. However, the 2015 study depicted an evolutionary shift prioritizing not only productivity but also sustainable and functional traits, driven by both health and ecological considerations. The adoption of advanced techniques, such as mid-infrared spectroscopy for trait assessment, was advocated as a progressive approach [23]. Moreover, in 2021, a study on sustainable dairy farming with a distinctive spotlight on South Africa, accentuated the need to reconfigure dairy breeding goals and championed the integration of genomic data, positing its potential to bolster both cow well-being and sustainable dairy production [25].

Our literature search has also found studies that specifically emphasized several challenges introduced by climate change, notably the implications of heat stress on dairy cow fertility [21, 30]. A 2020 paper unambiguously identified global warming as a formidable challenge for dairy farming, accentuating the adverse effects of heat stress on bovine fertility, predominantly in tropical zones. This was linked to factors like hyperthermia, oxidative stress, and associated physiological alterations resulting from elevated temperatures [24]. In 2023, a study delved into the systemic physiological adaptations in dairy cattle arising from heat stress, and an exhaustive analysis provided perspectives on how shifts in metabolic processes could influence reproductive outcomes [21]. Infertility in cattle not only causes significant economic loss but also exacerbates climate change [31, 32]; more cattle are needed to meet global

protein demands, increasing greenhouse gas emissions. The Northeast Multistate Project has extensively studied ovarian processes in ruminants, enhancing understanding of “maternal recognition of pregnancy”. The study highlighted the regulation of the ruminant corpus luteum, revealing roles of prostaglandins and immune cells in fertility. Such insights can guide future climate-friendly fertility research, promoting sustainable livestock production [26].

Thus, the trend in publications on climate change and fertility reflects an evolving understanding of the profound impact of environment upon reproductive health. This understanding underscores the urgency of implementing multidisciplinary solutions to safeguard both human and animal reproductive health in the face of a changing climate.

Climate change TFR: comprehensions and future perspectives

Climate change is prominently transforming the global ecosystem, exerting profound effects on both natural and anthropogenic systems [33] (Figure 2). Such alterations exert both direct and indirect effects on the determinants of TFR, denoting the mean number of offspring a female is projected to produce during her lifespan [34]. Resource scarcity is one of the major challenges. Environmental changes prompted by climate fluctuations, like extended droughts or alterations in precipitation regimes, can lead to diminished access to crucial resources [35]. As a result, in many societies

that value large families for their agricultural or economic contributions, a decreased resource base might indirectly promote increased reproductive rates. Moreover, migration and displacement are another concern. The amplification in the intensity and frequency of climatic disturbances is compelling populations to relocate, and the adverse conditions associated with such migrations often have a positive correlation with heightened fertility rates. These demographic transitions present significant challenges for governmental bodies in ensuring appropriate healthcare, education, and other vital services [36]. Additionally, the escalation in the prevalence of vector-transmitted diseases, undernutrition, and related health risks due to climate transformations can also impact reproductive behaviors. In locales where the mortality rate of children is elevated due to these issues, families may opt to birth more offspring, foreseeing that a portion might not reach maturity [37].

TFR and SDGs: implications and measures

The intricate relationship between TFR and the SDGs is significantly influenced by climate change, which impacts fertility patterns through factors such as agricultural failure, water scarcity, and disaster-driven displacement [38]. As economic and environmental uncertainties prompt families to have fewer children, lowering fertility rates, it becomes crucial to integrate responses with specific SDGs to mitigate these effects (Table 2). For instance, climate-induced poverty can influence family planning decisions, necessitating

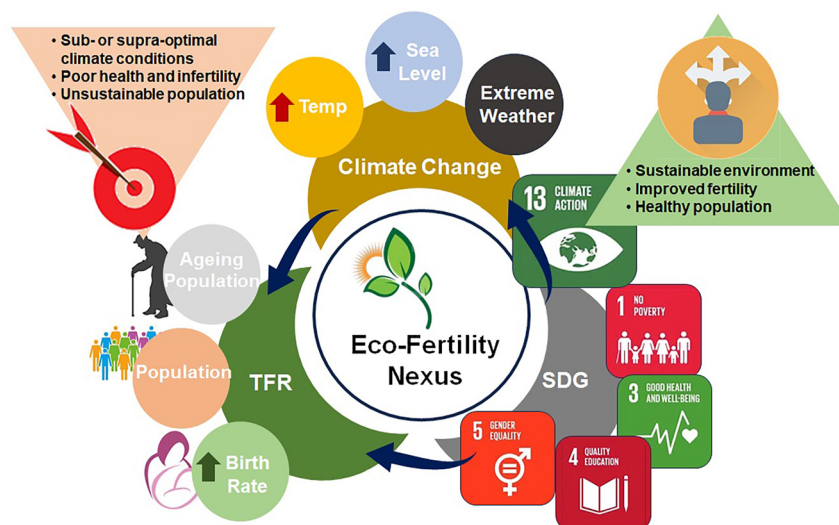


Figure 2: Interplay among climate change, sustainable development goals (SDGs), and total fertility rate (TFR). This figure highlights the impact of climate change factors, namely increased temperatures, rising sea levels, and extreme weather events. These factors directly affect SDG 13 (climate action) and consequently influence SDG 1 (poverty), SDG 3 (good health and well-being), SDG 4 (quality education), and SDG 5 (gender equality). The SDGs may ameliorate the impact of climate changes on the TFR determinants, influencing birth rates, overall population growth, and shifting age demographics, while the related.

Table 2: Total fertility rate, government policies and SDGs achieved of some mostly affected countries by climate change.

Country	Climate change indicators	Total fertility rate	Government policies	SDG progress
USA	Rising sea levels, increased frequency and intensity of hurricanes, heat-waves, and wildfires.	1940: ~2.3 1950: ~3.5 2000: ~2.1 2020: ~1.7	Clean air act, clean water act, Paris agreement participation (though there was a brief withdrawal), multiple state-level renewable energy incentives.	The USA had made progress on many SDGs but faced challenges on SDGs like 10 (reduced inequalities), 13 (climate action), and 14 (life below water).
India	Changing monsoon patterns, rising sea levels affecting coastal regions, increased heatwaves, and glacial retreat in the himalayas.	1940: ~5.9 1950: ~5.9 2000: ~3.3 2020: ~2.2	National action plan on climate change, jawaharlal nehru national solar mission, afforestation efforts, commitment to increase renewable energy production.	India made progress in several SDGs but faced challenges particularly in SDGs like 2 (zero hunger), 6 (clean water and sanitation), and 11 (sustainable cities and communities).
Brazil	Increased deforestation rates in the amazon, altered rainfall patterns, and rising temperatures.	1940: ~6.2 1950: ~6.2 2000: ~2.3 2020: ~1.7	Forest code, Brazil's national policy on climate change, commitments to reduce deforestation and increase reforestation.	Brazil made progress on many SDGs but faced challenges particularly in SDGs like 12 (responsible consumption and production), 13 (climate action), and 15 (life on land).
China	Increased temperatures, altered precipitation patterns, rising sea levels, increasing frequency of extreme weather events.	1950: ~6.1 2000: ~1.6 2020: ~1.7	One-child policy (later changed to two-child and then to three-child), extensive reforestation programs, push for renewable energy sources, carbon neutral by 2060 pledge, etc.	Variable depending on the specific SDG, but China has made significant progress in SDG1 (no poverty), SDG2 (zero hunger), and others. SDG numbers would need to be cross-referenced with up-to-date sources for exact percentages.
South Africa	Increasing droughts, water scarcity, shifts in rain patterns, increasing temperatures, and loss of biodiversity.	1950: ~6.5 2000: ~2.9 2020: ~2.3	National climate change response policy, push for renewable energy, commitment to reduce greenhouse gas emissions by 34 % by 2020 and 42 % by 2025 relative to the 'business as usual' scenario.	Variable. South Africa has made strides in various SDGs, especially SDG4 (quality education) and SDG7 (affordable and clean energy), but challenges remain in SDG10 (reduced inequalities) and SDG16 (peace and justice strong institutions).
Germany	Rising temperatures, increased risk of flooding, altered precipitation patterns, and forest die-offs.	1950: ~2.2 2000: ~1.4 2020: ~1.6	Energiewende (energy transition) focusing on renewable energies, exit from coal by 2038, green deal, and commitment to achieve carbon neutrality by 2050.	Germany has shown substantial progress in SDGs such as SDG3 (good health and well-being) and SDG11 (sustainable cities and communities). However, specific percentages would require up-to-date sources.
Japan	Rising sea levels, increased frequency of natural disasters (e.g., typhoons), temperature increases.	1950: ~4.3 1980: ~1.8 2020: ~1.3	Japan's strategic energy plan (a shift towards renewable energy), reduction in greenhouse gas emissions, coastal protection measures.	Significant efforts and progress in SDG 13 (climate action)
Russia	Melting permafrost, increased temperatures, changing precipitation patterns, forest fires.	1940: ~2.9 1980: ~2.2 2020: ~1.5	Ratified the Paris agreement in 2019, various initiatives to increase forest cover, efforts to reduce industrial greenhouse gas emissions.	Significant efforts and progress in SDG 13 (climate action)
Bangladesh	Rising sea levels, increased flooding, changing monsoon patterns, saltwater intrusion.	1980: ~6.0 2020: ~2.0	Bangladesh climate change strategy and action plan, relocation of at-risk populations, construction of embankments and storm shelters.	Bangladesh is particularly proactive in SDG 13 (climate action) due to its vulnerability to climate change

strategies under *Goal 1 (No Poverty)* to enhance economic resilience and support sustainable family planning [39]. Similarly, environmental changes can strain healthcare systems under *Goal 3 (Good Health and Well-being)*, impacting reproductive health services and necessitating comprehensive healthcare access [40]. In the face of changing climate and declining TFR, there is need for proper

family planning so as to allow significant investment in each child's education, aligning with *Goal 4 (Quality Education)* to ensure universal access to quality education [41]. Finally, the pressures of climate change offer a pivotal moment to advance *Goal 5 (Gender Equality)* by empowering women in decision-making including family planning, thus challenging traditional roles and expanding opportunities [42]. These

adaptive strategies underscore the need for proactive policy and planning to address the interlinkages between climate change, fertility, and sustainable development.

Appreciating the interrelatedness of climate change, TFR and SDGs empower us to develop holistic approaches. Recommended measures encompass enhancing climate resilience, empowering women, strengthening health infrastructure, promoting sustainable agricultural practices, educational outreach and integrated policies. In this context, it is imperative for governments and institutions to allocate resources towards adaptive measures, ensuring communities can effectively cope with challenges instigated by climate fluctuations [43]. This, in turn, can equilibrate fertility rates. Potential adaptive measures include the establishment of sustainable water systems, advancement in agrarian methodologies, and the development of durable infrastructure [44]. Moreover, rectifying gender imbalances is of utmost importance. Ensuring equitable access to education and job opportunities for women frequently results in preferences for smaller family sizes. Enhancing access to family planning tools and education on reproductive health further facilitates well-informed choices concerning family dimensions [45]. Furthermore, augmenting access to high-caliber health-care, with an emphasis on maternal and child well-being, is crucial to mitigate high child mortality rates and the consequent elevated TFRs [46]. Also, in light of the correlation between TFR and agricultural output in numerous societies, transitioning to ecologically sustainable agricultural methodologies can guarantee consistent crop yields, thereby reducing the necessity for expansive families as agricultural labor [47]. It is also essential for communities to be cognizant of the enduring advantages of sustainable reproductive planning within the framework of a shifting climatic paradigm. Educational initiatives are instrumental in reshaping societal perspectives on optimal family dimensions [48]. Finally, policymaking should account for the intertwined dynamics of climate alteration, TFR, and SDGs. A comprehensive approach ensures that initiatives in one sphere augment, rather than impede, aims in another.

Conclusions

The intricate interplay between climate change, TFR, and SDGs calls for an urgent exploration to mitigate the adverse effects and directs towards a resilient, sustainable future. Our review reveals significant insights into the eco-fertility nexus, underscoring multifaceted impacts of climate change on human and animal reproductive health. This

understanding opens avenues for future research, emphasizing the need for a deeper investigation into the direct and indirect mechanisms through which environmental stressors affect fertility. Specific future research questions that emerged include: How do specific climate-induced environmental stressors, such as air pollution and extreme weather events, directly impact reproductive health metrics in diverse populations? What are the adaptive reproductive strategies in animal species facing rapid environmental changes, and what can they teach us about resilience and sustainability? Additionally, the role of socio-economic and cultural factors in shaping fertility responses to climate change warrants further exploration to identify targeted, effective interventions. There is also a pressing need to develop and evaluate the effectiveness of policy and public health interventions aimed at mitigating climate change's negative impacts on fertility while promoting sustainable development. Lastly, investigating the potential of technological and scientific advancements in mitigating the adverse effects of environmental stressors on reproductive health will be crucial. This roadmap for subsequent investigations aims to not only advance our understanding of the eco-fertility nexus but also to inform holistic, sustainable strategies that address the intertwined challenges of climate change, fertility, and global development.

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Informed consent: Not applicable.

Author contributions: PS and SD both have equally participated in the conceptualization of the study, data curation, literature search and extraction, resources writing – original draft, writing – review and editing. Both the authors have read and agreed to the published version of the manuscript.

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