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Review

Global warming impacts on lactating mammalian milk: A systematic review

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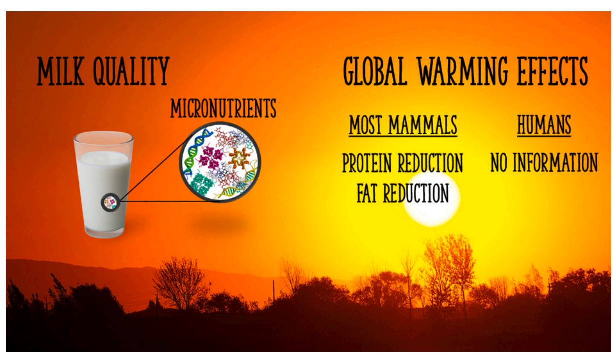
HIGHLIGHTS

- This systematic review aims to highlight the main findings of the impacts of global warming on the nutritional value of mammalian milk.
- Among 14 studies about the direct impact of climate change on milk protein content, about 86% reported a reduction in protein concentration.
- Among 13 studies on milk fat content, approximately 62% indicated a reduction in fat concentration.
- No paper discussing the effects of climate change on the nutritional quality of human milk was found.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change represents a significant loss of billions of dollars for the livestock sector, prompting researchers to investigate how global warming and heat stress impact dairy cow productivity. However, research on the effects of climate change on human health remains a knowledge gap. This systematic review aims to highlight the main findings of the impacts of global warming on the nutritional value of mammalian milk. We systematically reviewed seven databases from October 2024 to April 2025, excluding papers related to seasonal climate effects. Twenty-one eligible studies were selected in our literature review, revealing several contradictory research outcomes. Among 14 studies about the direct impact of climate change on milk protein content, about 86 % reported a reduction in protein concentration. Similarly, among 13 studies on milk fat content, approximately 62 % indicated a reduction in fat concentration. Such a finding suggests a trend but also indicates that further

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studies are necessary. No paper discussing the effects of climate change on the nutritional quality of human milk was found. Therefore, we emphasize the need for studies on this topic, given the rapid pace of climate change and the vulnerability of particular human groups, including women and newborns in developing countries.

1. Introduction

Climate change refers to long-term weather and temperature shifts due to natural and human factors, causing environmental and health impacts (UNDP Climate Promise, 2023; Cerceo et al., 2024; da Cunha Bustamante, 2024). According to the United Nations, climate change can cause extreme events such as very intense hurricanes, floods, and droughts (UNDP Climate Promise, 2023). However, punctual extreme events do not explain climate change. For example, the year of 1889 was particularly hot compared to the precedent and following years, as indicated in Fig. 1. Nevertheless, the Earth's average surface temperature of that period was stable for decades around −0.5 °C compared to the 1901–2000 average. On the other hand, starting from the year of 1979, there is a clear long-term trend of temperature increase, which clearly contrasts with the temperature stability of the 19th century.

Global warming specifically denotes Earth's rising surface temperature (NASA, n.d.), currently about 1 °C above pre-industrial levels, possibly exceeding 4 °C by the end of the century if no action is taken (UNDP Climate Promise, 2023; da Cunha Bustamante, 2024; IPCC, 2023; Chersich et al., 2024). Agriculture and livestock both affect and suffer from climate change (Astuti et al., 2024). Stringent policies can reduce emissions but may also raise food prices and worsen food insecurity, especially in developing countries (Hasegawa et al., 2018). Besides, overreliance on taxation can lead to emissions leakage, meaning that overtaxed producers end up importing livestock commodities and thus shifting pollution elsewhere (Herrero et al., 2016).

The livestock industry represents a significant global economic force, so extensive research has been conducted to elucidate the effects of climate change on dairy cattle. More specifically, most papers focus on heat stress, i.e., the inability of dairy cows and other mammals to dissipate heat when the temperature-humidity index (THI) exceeds a certain threshold (Zhao et al., 2020), which typically ranges from 68 to 75 (Zhao et al., 2020; Piscopo et al., 2024; Moore et al., 2024; Mbuthia et al., 2021; Cowley et al., 2015). Most studies link THI to milk yield (Moore et al., 2024; Mbuthia et al., 2021) or analyze milk properties experimentally (Zhao et al., 2020; Piscopo et al., 2024). While heat stress reduces food intake (Moore et al., 2024; Xiao et al., 2020), its effect on milk's nutritional quality remains debated (Cowley et al., 2015; Xiao et al., 2020).

In homeothermic animals, body temperature is kept constant despite variations in ambient temperature, as long as these variations fall within the thermoneutral zone of these animals. Under heat stress, the physiological mechanisms of these animals are no longer able to dissipate heat and the animal faces hyperthermia (Moore et al., 2024). One of the well-known physiological responses of mammals to heat stress is hypophagia. An experimental study involving laboratory rats indicates that hypophagia induced by heat stress is responsible for the underdevelopment of mammary glands during the final stage of pregnancy and partially responsible for low milk production (hypogalactia) in the early stages of breastfeeding (Xiao et al., 2020). This is an indirect effect of heat stress. However, these authors were able to demonstrate through experiments involving groups paired by food intake that there are also direct effects of heat stress on mammary gland metabolic functions in laboratory rats, regardless of food intake. According to these authors, laboratory rats react to heat stress similarly to dairy e hjspecies (Xiao et al., 2020). To the best of our knowledge, there is no similar study involving humans. However, the study conducted by Bottin et al. (Bottin et al., 2022) showed that food insecurity in humans is responsible for a reduction of oligosaccharides, retinol, fatty acids, and amino acids, as well as a surprising increase in lactose. Given that hypophagia is a well-known effect of heat stress in certain mammals species, results presented by Bottin et al. (Bottin et al., 2022) can provide hints about a potential indirect effect of heat stress on the nutritional composition of human milk. However, more studies in this regard are needed to confirm this hypothesis.

The connection between heat stress and mammalian health raises concerns about its impact on pregnant and breastfeeding women. Nutritionally, cow's milk and human milk share similarities. For example, concentrations of iron in cow's milk vary between 0.40 and 0.59 μg/mL, while in human milk these concentrations vary in a close range, between 0.20 and 0.69 μg/mL. (Fransson and Lönnerdal, 1983). In climate-affected areas, women and children face greater food insecurity, worsening social and gender inequalities (da Cunha Bustamante, 2024; Bottin et al., 2022; Rao et al., 2019). Identifying whether global warming affects human milk quality is crucial for health authorities.

This systematic review aims to critically examine the scientific

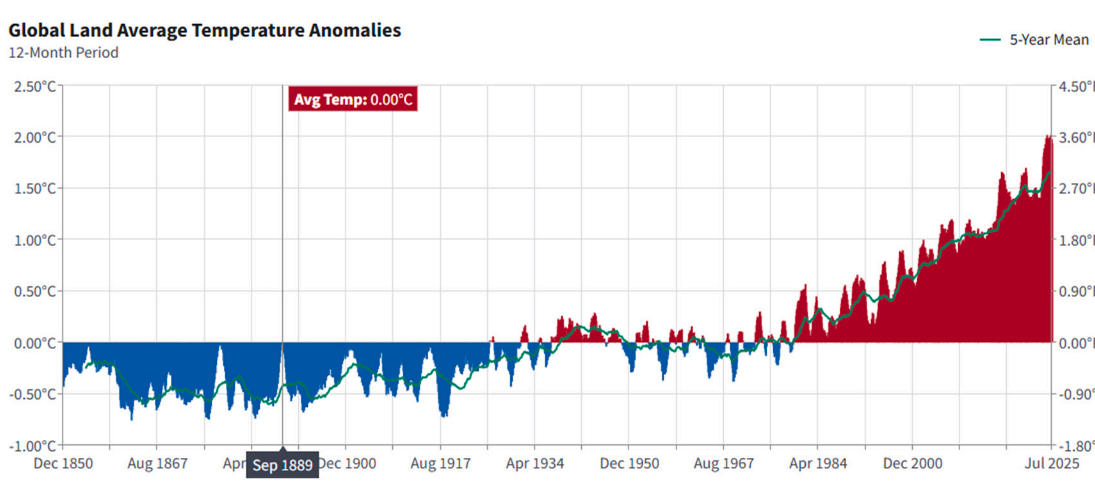


Fig. 1. Earth's surface temperature on a monthly basis since December 1850.
This curve was generated with the aid of the following US' National Oceanic and Atmospheric Administration platform: https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/global/time-series/globe/land/tavg/12/0/1850-2025?filter=true&filterType=running-mean.

evidence available on the effects of climate change on the biochemical composition of mammalian milk, addressing the primary research question: (i) Is there evidence of changes in milk biochemical components due to climate change?, and the following secondary questions: (ii) What type of sensing technology has been used to detect these changes?, (iii) Is there evidence of similar effects on human milk?.

2. Methods

2.1. Protocol registration and reporting guideline

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The protocol used in this systematic review is registered in the protocols.io database (Nogueira de São José et al., 2024).

2.2. Search strategy

We conducted a systematic literature search on September 19, 2024, based on the following databases: MEDLINE (PubMed), Cochrane Library, Embase (Elsevier), Scopus (Elsevier), Web of Science, LILACS (BVS), and IEEE. The library of the *Faculdade de Medicina da Universidade Federal de Minas Gerais*, Belo Horizonte, Brazil, provided the search strategies. The search mechanisms are shown in Table 1.

The search mechanisms listed in Table 1 reveal that, not only we tried to search for specific information on human milk by means of keywords such as “Human Milk” and “Breastfeeding Women”, but we also considered mammals in general by means of more comprehensive keywords such as “Milk” and “Suckling Animals”. A complete description of the search strategies can be found in our published protocol (Nogueira de São José et al., 2024). Additionally, one extra reference was included in our database. This additional reference was taken from the bibliography list of one of the included studies. Once the papers' metadata were downloaded, the team used StArt (v. 3.3 Beta 03) software during the review's screening, selection and extraction process.

StArt stands for State of the Art through Systematic Review. It is a free software (download: https://www.lapes.ufscar.br/resources/tools-1/start-1)developedat the Universidade Federal de São Carlos, in Brazil, with the aim of helping researchers to deal with large datasets during the screening process in systematic reviews. Fig. 2(a) shows the software's main user interface. In this image, one can see the complete list of records retrieved from databases using search mechanisms, such as those presented in Table 1. This dataset is imported by means of.ris files which can be obtained directly from the digital libraries (PubMed, Cochrane, Embase etc). During the screening process, researchers evaluate each record individually, by taking notes and assigning it a status (Unclassified, Accepted, Rejected or Duplicated), as shown in Fig. 2(b). All information shown in Fig. 2(a) and (b) can be saved in.start files. One of the major limitations of this software is its incapacity to merge different.start files. So, given that the screening process is conducted by a group of researchers, if the coordinator decides to centralize all the reports in a single .start file, he must do it manually. Still, the software serves as a useful tool to accelerate the screening process with no bias, since it only helps researchers in managing the dataset while it gives absolutely no suggestion in terms of acceptance or rejection of a record.

2.3. Eligibility criteria

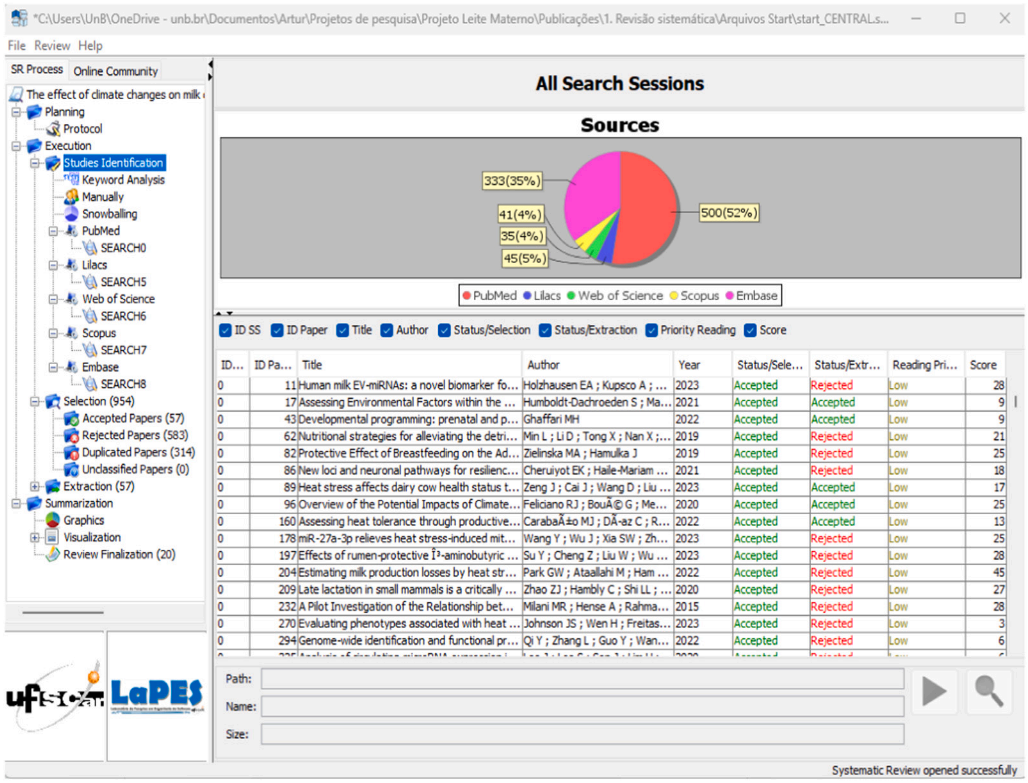
Studies were selected based on the following inclusion criteria: (i) Presence of adverse environmental effects that have been attributed to climate change, (ii) Studies on female lactating mammals (human or not), (iii) Studies that analyze fresh milk (collected during breastfeeding), and (iv) Studies with a clear definition of climate change. On the other hand, studies were excluded if they matched at least one of the following exclusion criteria: (i) The study reports adverse environmental effects that have not been attributed to climate change, (ii) The study reports effects on processed milk (e.g. freeze-dried milk, refrigerated milk, or milk samples stored in a milk bank) rather than raw milk, (iii) The study does not assess the effects of climate change on milk.

Table 1
Search mechanisms.

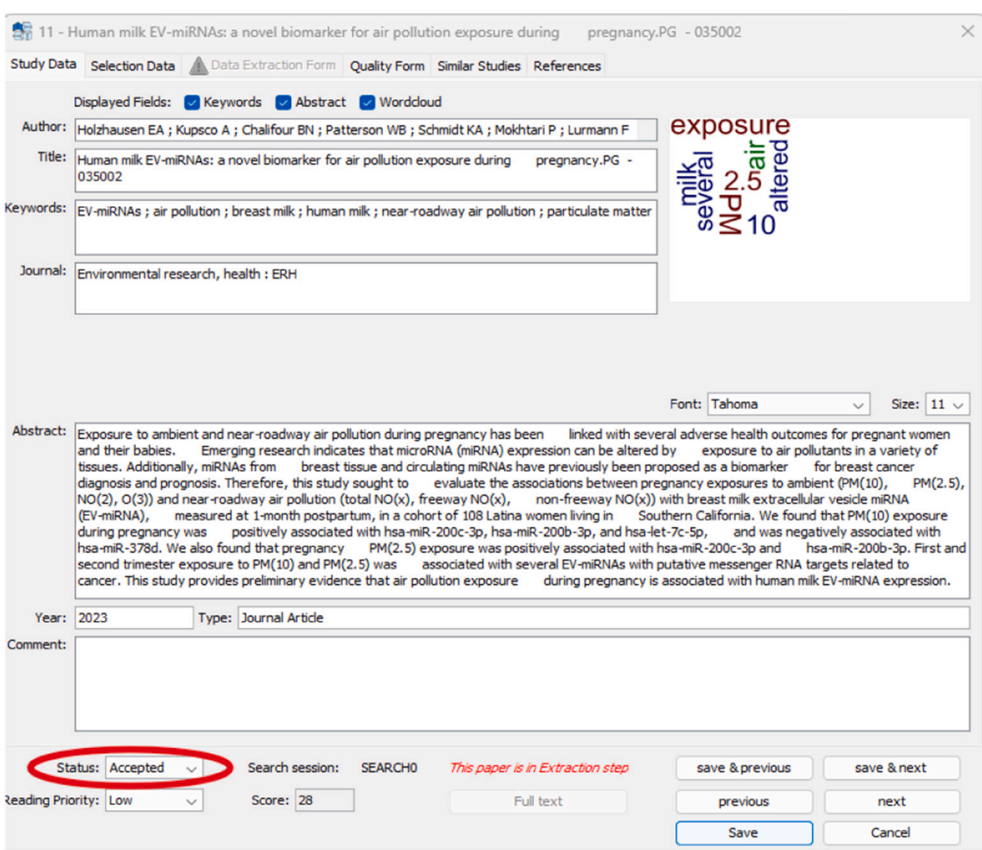
Database	Search mechanism
MEDLINE (PubMed)	Milk[Title/Abstract] OR “Human Milk”Title/Abstract] OR Lactation[Title/Abstract] OR “Breastfeeding Women”Title/Abstract] OR “Breast Feeding”Title/Abstract] OR “Suckling Animals”Title/Abstract])) AND (((“Climate Change”Title/Abstract] OR “Global Warming”Title/Abstract] OR “Sea Level Rise”Title/Abstract] OR “Air Pollutants”Title/Abstract])))
Cochrane Library	Milk OR “Human Milk” OR Lactation OR “Breastfeeding Women” OR “Breast Feeding” OR “Suckling Animals”) AND (“Climate Change” OR “Global Warming” OR “Sea Level Rise” OR “Air Pollutants”)
Embase (Elsevier)	(milk:ab,ti OR ‘breast milk’:ab,ti OR lactation:ab,ti OR ‘breastfeeding women’:ab,ti OR ‘breast feeding’:ab,ti OR ‘suckling animal’:ab,ti) AND (‘climate change’:ab,ti OR ‘greenhouse effect’:ab,ti OR ‘sea level rise’:ab,ti OR ‘air pollutant’:ab,ti)
Scopus (Elsevier)	Milk OR “Human Milk” OR Lactation OR “Breastfeeding Women” OR “Breast Feeding” OR “Suckling Animals”) AND (“Climate Change” OR “Global Warming” OR “Sea Level Rise” OR “Air Pollutants”)
Web of Science	Milk OR “Human Milk” OR Lactation OR “Breastfeeding Women” OR “Breast Feeding” OR “Suckling Animals”) AND (“Climate Change” OR “Global Warming” OR “Sea Level Rise” OR “Air Pollutants”)
LILACS (BVS)	((“Mudança Climática” OR “Climate Change” OR “Cambio Climático” OR “Changement climatique” OR “Alterações Climáticas” OR “Aquecimento Global” OR “Global Warming” OR “Calentamiento Global” OR “Réchauffement de la planète” OR “Elevação do Nível do Mar” OR “Sea Level Rise” OR “Elevación del Nivel del Mar” OR “Élévation du niveau de la mer” OR “Impactos da Poluição na Saúde” OR “Impacts of Polution on Health” OR “Impactos de la Polución en la Salud” OR “Impacts sur la Santé” OR “Poluentes Atmosféricos” OR “Air Pollutants” OR “Contaminantes Atmosféricos” OR “Polluants atmosphériques”)) AND ((“Mulheres Lactantes” OR “Breastfeeding Women” OR “Madres Lactantes” OR “Femmes allaitantes” OR “Animais Lactentes” OR “Animals, Suckling” OR “Animales Lactantes” OR “Animaux allaités” OR “Aleitamento Materno” OR “Breast Feeding” OR “Lactancia Materna” OR “Allaitement naturel” OR “Animais Lactentes” OR “Animals, Suckling” OR “Animales Lactantes” OR “Animaux allaités” OR leite OR milk OR leche OR lait OR “Leite Humano” OR “Milk, Human” OR “Leche Humana” OR “Lait humain” OR lactação OR lactation OR lactancia OR lactation)) AND (db:(“LILACS” OR “WPRIM” OR “BINACIS” OR “CUMED” OR “IBECS” OR “LIPECS”))
IEEE	(“All Metadata”:(“All Metadata”Milk) OR “All Metadata”:(“All Metadata”Human Milk) OR “All Metadata”:(“All Metadata”Lactation) OR “All Metadata”:(“All Metadata”Breastfeeding Women) OR “All Metadata”:(“All Metadata”Breast Feeding) OR “All Metadata”:(“All Metadata”Suckling Animals)) AND (“All Metadata”:(“All Metadata”Climate Change) OR “All Metadata”:(“All Metadata”Global Warming) OR “All Metadata”:(“All Metadata”Sea Level Rise) OR “All Metadata”:(“All Metadata”Air Pollutants))

2.4. Study selection and data extraction

The team was divided into four pairs of reviewers: ANSJ and PJHN, MCFB and HOM, MGPM and SLMA, and UCR and ZSNR. The revision process consisted of two steps: the first was the screening of titles and abstracts, and the second was the full-text analysis. Both reviewers analyzed the same papers separately. Then, they discussed until reaching a consensus on whether to include or exclude the papers. After all reviewers provided the coordinator, ANSJ, with their decisions about the documents, he double-checked all papers eligible for full-text analysis and, in some cases, changed the reviewers' decisions.



(a)



(b)

Fig. 2. StArt user interface. (a) Complete list of records. (b) Information about one specific record, with a red circle highlighting its status as given by the user.

2.5. Quality assessment

Two independent investigators (SLMA and ZSNR) conducted the quality analysis of the primary studies, both randomized and non-randomized animal studies. Any disagreements were resolved through consensus-oriented discussion meetings. We presented methods and results in the supplementary file.

3. Results

3.1. Search results

The literature search initially yielded 954 records, of which 314 were duplicates. Therefore, only 640 were screened. A selection based on titles and abstracts resulted in 584 records being excluded, leaving 56 reports effectively selected for complete reading. At this point, we highlight the significant difference between the number of articles retrieved from the databases and those assessed for eligibility. Such contrast reflects the lack of studies specifically addressing our primary research question. Although various authors have investigated the decrease in milk production on dairy farms due to global warming, only a limited number of authors seem to engage in in-depth analyses of the micronutrient composition of milk. Another reason for this discrepancy resides in our strict climate change definition, which excludes seasonal climate fluctuation patterns and environmental conditions which are not proven to be extreme (e.g. air pollution) during data collection. As a consequence, all papers whose titles and abstracts did not include a clear definition for climate change or did not refer to extreme climate conditions were excluded. Finally, we also excluded those studies which consider the milk production activity as the cause (and not the victim) of global warming. All 56 reports were thoroughly peer-reviewed, and 37 of them were subsequently excluded. In terms of exclusion criteria, 11 papers were excluded due to the first exclusion criterion ("The study reports adverse environmental effects that have not been attributed to climate change"), one paper was excluded due to the second exclusion criterion ("The study reports effects on processed milk (e.g. freeze-dried milk, refrigerated milk, or milk samples stored in a milk bank) rather than raw milk"), and 25 papers were excluded due to the third exclusion criterion ("The study does not assess the effects of climate change on milk"). Nineteen papers met the eligibility criteria to be included in the review. An additional study, identified through citation tracking, underwent the same screening process and was also included. Therefore, a total of 20 studies were incorporated into the final review. A flowchart summarizing this process was generated using the tool described by Haddaway et al. (Haddaway et al., 2022) and is presented in Fig. 3.

3.2. Study characteristics

During the screening process, we selected studies (Table 2) that report both direct effects and indirect effects of climate change on milk quality. The definition of direct and indirect effects is as follows:

- Direct effects: when the impact of climate change directly affects animals or humans, affecting their physiology or behavior.
- Indirect effects: when the impact of climate change affects the environment in which the animal or human lives, which somehow affects their physiology or behavior.

Table 2 reveals a clear predominance of dairy species among the selected studies and a complete absence of wild mammals and humans. This trend may be explained by the significant economic value of dairy species to the milk and meat industries. Only articles in which the effects of climate change were clearly reported were accepted. The employed strategy was to identify critical numerical values for climate indices, with the THI being the most commonly used index. Based on these critical values, it is possible to determine if and when an abnormal climatic condition indicative of climate change actually occurred. In articles lacking this information, we had to conduct an analysis to assess

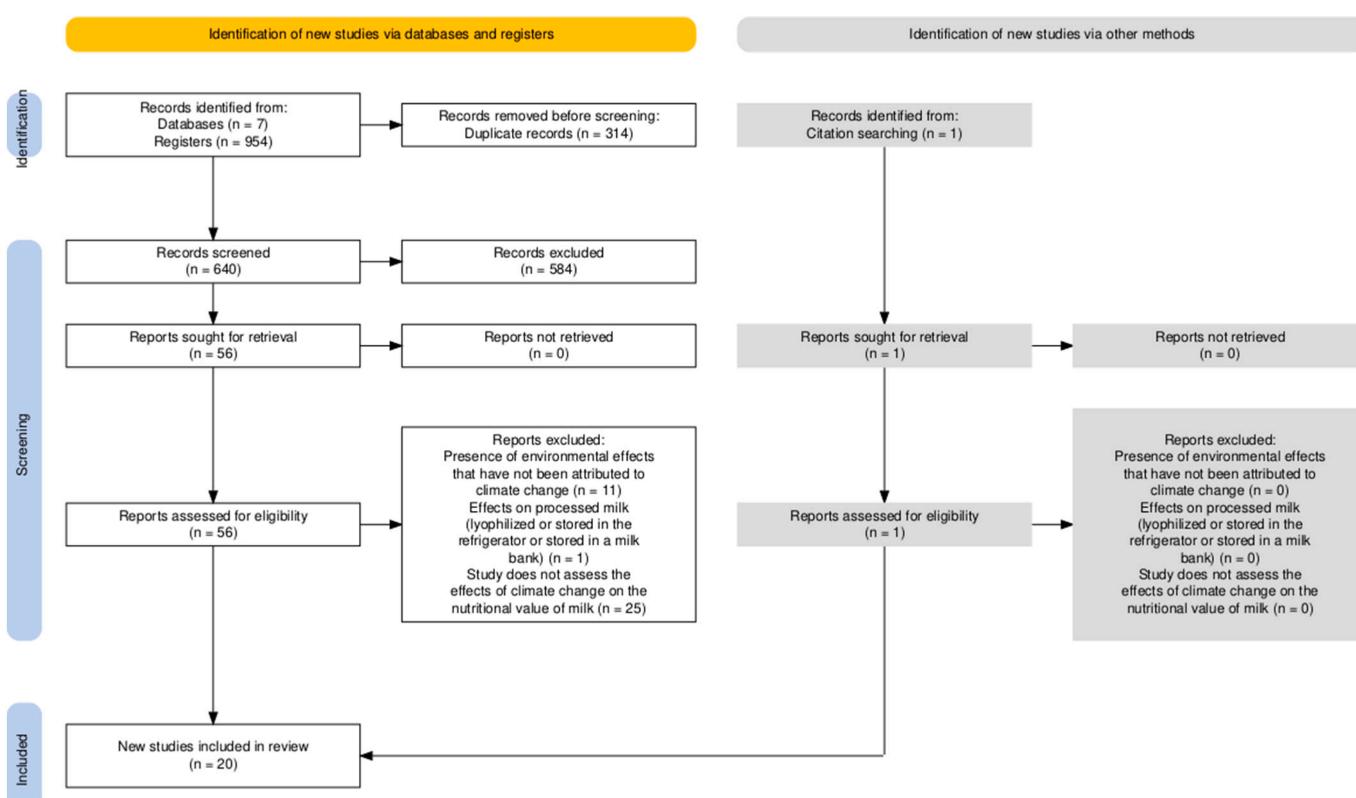


Fig. 3. Flowchart describing the search, screening, and selection processes.

Table 2
Characteristics of studies included in the review.

Authors	Geographical scope of the study	The main objective of the study	Lactating mammal	Study design	Authors' definitions of climate change
Ghaffari, 2022	Multicenter	Review the literature about pre- and post-natal hyperthermia in cows caused by HS	Cow	Review	A daily THI > 68
Zeng et al., 2023	China	Investigate the role of oxygen metabolism in the health of dairy cows under HS	Cow	Experimental	THI > 68
Feliciano et al., 2020	Multicenter	Provide an overview of the climate change effects on the whole farm-to-fork process of milk production and distribution	Cow	Review	THI > 69
Stefanska et al., 2024	Poland	Evaluate how HS affects dairy cow productivity, fertility, and blood biochemistry	Cow	Cohort	THI > 68
Summer et al., 2018	Multicenter	Review the literature about the HS impacts on the livestock sector	Cow	Review	THI > 75 (authors seem to consider this value as the threshold)
Koch et al., 2024	Germany	Evaluate the HS effects on cows' mammary gland proteome, and ruminal short-chain fatty acid concentrations	Cow	Experimental	A daily THI > 76
Habimana et al., 2024	Tanzania	Evaluate the HS effects on cows' physiological parameters and milk properties	Cow	Experimental	A daily THI > 79
Bokharaeian et al., 2023	Iran	Investigate possible correlations between environmental variables and milk properties	Cow	Experimental	THI > 22.2
Ahmad et al., 2019	Pakistan	Test the effectiveness of shade, fan, and sprinklers to mitigate HS in cows	Buffalo	Experimental	THI > 72
Humboldt-Dachroeden and Mantovani, 2021	Italy and Denmark	Investigate the role played by the environment in the spread of infectious diseases between humans and animals	Ruminant	Review	An environmental factor severely impacting wild and domestic animal populations, food chains and human health
Carabaño et al., 2022	Spain	Investigate possible correlations between HS, milk production and physiological indicators of dairy sheep	Sheep	Experimental	THI > 72
Han et al., 2019	China and Canada	Understand, at a molecular level, the poor lactation performance of animals under HS	Mice	Experimental	HS: response of an organism to the thermal environment when it is unable to cool itself enough to maintain a healthy temperature
Carabaño et al., 2016	Multicenter	Propose statistical models for the HS effects on milk production based on geographically diverse dairy cattle populations	Cattle	Cohort	Increased temperatures and frequencies of extreme weather events
Chhaya et al., 2023	France and Ireland	Propose probabilistic models to predict the contamination of milk with AFM1	Cow	Cohort	Two IPCC's scenarios: 2–4.5 (moderate effects) and scenario 5–8.5 (worst-case scenario)
Kos et al., 2024	Serbia	Investigate the occurrence of aflatoxins in maize, milk, and dairy products and how they relate to climate change	Cow	Surveillance study	An increase of up to 2.7 °C in air temperature and a reduction of up to 90 % in rainfall during data collection compared with the historical average (1981–2010)
Chhaya et al., 2024	Ireland	Rank different types of mycotoxins, potentially present in milk, according to their potential human health hazards	Cow	Transverse study	Four IPCC's scenarios: baseline, best-case, worst-case, and most likely, corresponding to 1.2 °C, 0.7 °C, 2.0°,C and 4.0 °C of mean temperature changes, respectively.
Petrocchi Jasinski et al., 2023	Multicenter	Review the literature about the HS effects on buffalo and the various mitigation strategies already proposed.	Buffalo	Review	HS: when the ambient temperature is above the thermoneutral zone
Mylostyvyi et al., 2023	Ukraine	Determine the relationship between environmental parameters and milk productivity	Cow	Experimental	THI > 68
Feliciano et al., 2021	Saudi Arabia	Develop probabilistic models to predict *E. coli* concentration in contaminated milk	Cow	Transverse study	Two RCP's scenarios: 4.5 and 8.5
Liu et al., 2017	Australia	Investigate the HS effects on the lipid composition of milk in dairy cattle	Cow	Experimental	THI > 72

AFM1: Aflatoxin M1.
HS: Heat Stress.
IPCC: Intergovernmental Panel on Climate Change.
RCP: Representative Concentration Pathways.
THI: Temperature-Humidity Index.

whether the meteorological database encompassed days, weeks, or months of extreme events. For example, Kos et al. (Kos et al., 2024) reported an increase of up to 2.7 °C in air temperature and a reduction of up to 90 % in rainfall during data collection compared with the historical average (1981–2010). In Mylostyvyi et al. (Mylostyvyi et al., 2023), although the data collection period was relatively short (May to September 2017–2018), the authors reported significant variability in climate indicators, which is practically observed in the same season of the year (summer). These authors report that in July 2018, 74.7 % of the days were clear (i.e., without clouds or rain), while in the following month, this percentage increased to 98.1 %. They also reported significant climatic differences compared to the same period in the previous year, with an average temperature increase of 3.4 °C. Feliciano et al. (Feliciano et al., 2021), on the other hand, use meteorological data from

Saudi Arabia obtained in 2019 to infer about France in a future climate change scenario. This strategy, based on climate diversity between the two countries, proved to be reasonable, as the average temperature in Saudi Arabia (AlKharj) was 15 °C higher than the average temperature in France (based on an average of 30 locations) during the same period (August 2019). Carabaño et al. (Carabaño et al., 2016) also take advantage of the climatic diversity of the European continent to evaluate the effects of different levels of THI, noting that the difference between the average THI in Belgium and Spain is 10 units.

Among which 11 were based on a single location and nine were multicentric. Regarding the study design, 45 % consisted of experimental work, including five reviews, 9 experimental studies, three cohorts, one surveillance study, and two transverse studies. The vast majority of these studies analyzed the response of cows to climate change (cows: 15 studies; ruminating animals in general: 1 study; buffaloes: 2 studies; sheep: 1 study; mice: 1 study).

Table 3
Reported effects on milk components.

Authors	Fat	Proteins	SCC	Urea	Lactose	Total solid percentage	Mineral content	Presence of bacteria, toxins, and other pathogens	Direct or indirect effects of climate change
Ghaffari, 2022	NI	Reduction	NI	NI	NI	NI	NI	NI	Direct
Zeng et al., 2023	Reduction	Reduction	Increase	NI	NI	NI	NI	NI	Direct
Feliciano et al., 2020	Reduction	Reduction	NI	NI	NI	NI	NI	Potential increase	Direct and indirect
Stefanska et al., 2024	Increase	Reduction	Increase	NI	NI	NI	NI	NI	Direct
Summer et al., 2018	NI	Reduction	Unaffected	NI	Unaffected	NI	Little is known	NI	Direct
Koch et al., 2024	Reduction	Reduction	Unaffected	Increase	NI	NI	NI	NI	Direct
Habimana et al., 2024	Increase	Reduction	NI	NI	Reduction	Reduction	NI	NI	Direct
Bokharaeian et al., 2023	Reduction	Reduction	Increase	NI	NI	Reduction	NI	Increase in TBC	Direct
Ahmad et al., 2019	Reduction	Reduction	NI	NI	Reduction	Reduction	NI	NI	Direct
Humboldt-Dachroeden and Mantovani, 2021	NI	N/A	NI	NI	NI	NI	NI	Increase in AFM1	Indirect
Carabaño et al., 2022	Reduction	Reduction	NI	Reduction	Unaffected	Reduction	NI	NI	Direct
Han et al., 2019	Increase	Increase	NI	NI	Slight reduction	NI	Reduction in calcium	NI	Direct
Carabaño et al., 2016	Reduction	Reduction	NI	NI	NI	NI	NI	NI	Direct
Chhaya et al., 2023	NI	N/A	NI	NI	NI	NI	NI	AFM1 concentration may be affected but it does not exceed EU's limits under IPCC 5–8.5 (worst case)	Indirect
Kos et al., 2024	NI	N/A	NI	NI	NI	NI	NI	Increase in AFM1	Indirect
Chhaya et al., 2024	NI	N/A	NI	NI	NI	NI	NI	Increase in AFB1	Indirect
Petrocchi Jasinski et al., 2023	Unaffected: 1 report Reduction: 6 reports Increase: 1 report	Unaffected: 4 reports Reduction: 2 reports Increase: 1 report	Unaffected: 4 reports Increase: 1 report	Unaffected: 1 report Increase: 1 report	Unaffected: 1 report Reduction: 1 report Increase: 1 report	NI	Mineral balances are affected	TBC: Unaffected (1 report), and increase (1 report)	Direct
Mylostyvyi et al., 2023	Reduction	Reduction	NI	NI	NI	NI	NI	NI	Direct
Feliciano et al., 2021	NI	N/A	NI	NI	NI	NI	NI	Increase in *E. coli* contamination	Indirect
Liu et al., 2017	Reduction and increase (varying according to TAG and polar lipid profiles)	N/A	NI	NI	NI	NI	NI	NI	Direct

AFB1: Aflatoxin B1.
AFM1: Aflatoxin M1.
EU: European Union.
N/A: Not Applicable.
NI: Not Informed.
SCC: Somatic Cell Count.
TAG: Triacylglycerol.
TBC: Total Bacterial Count.

3.2.1. Primary outcomes

Studies were also categorized in terms of specific components of milk and the way they were affected by climate change (i.e., concentration increase, concentration reduction, or no change), as shown in Table 3. A total of seven components naturally present in milk were listed, plus a set of possible pathogens present in contaminated milk, allowing a better comparison between the research results. In some instances, comparison was not possible because the milk components being analyzed differed. Among the 14 studies on direct climate change effects on the milk protein content, approximately 86 % ($n = 12$) reported protein concentration reduction (Ghaffari, 2022; Zeng et al., 2023; Feliciano et al., 2020; Stefanska et al., 2024; Summer et al., 2018; Koch et al., 2024; Habimana et al., 2024; Bokharaeian et al., 2023; Ahmad et al., 2019; Carabaño et al., 2022; Carabaño et al., 2016; Mylostyvyi et al., 2023), while 7 % (n = 1) reported protein increase (Han et al., 2019), and 7 % (n = 1) presented mixed results (Petrocchi Jasinski et al., 2023). Six studies did not analyze this milk component (Humboldt-Dachroeden and Mantovani, 2021; Chhaya et al., 2023; Kos et al., 2024; Chhaya et al., 2024; Feliciano et al., 2021; Liu et al., 2017). Among the 13 studies on direct climate change effects on the milk fat content, approximately 62 % ($n = 8$) pointed a reduction of fat concentration as a direct effect of climate change (Zeng et al., 2023; Feliciano et al., 2020; Koch et al., 2024; Bokharaeian et al., 2023; Ahmad et al., 2019; Carabaño et al., 2022; Carabaño et al., 2016; Mylostyvyi et al., 2023), 23 % ($n = 3$) reported an increase (Stefanska et al., 2024; Habimana et al., 2024; Han et al., 2019), 15 % ($n = 2$) presented mixed results (Petrocchi Jasinski et al., 2023; Liu et al., 2017). The remaining studies did not analyze this milk component (Ghaffari, 2022; Summer et al., 2018; Humboldt-Dachroeden and Mantovani, 2021; Chhaya et al., 2023; Kos et al., 2024; Chhaya et al., 2024; Feliciano et al., 2021). Some changes in milk components were still reported as SCC increase (Petrocchi Jasinski et al., 2023), as well as alterations in urea concentration (Carabaño et al., 2022; Petrocchi Jasinski et al., 2023), lactose (Ahmad et al., 2019; Han et al., 2019; Petrocchi Jasinski et al., 2023), and minerals (Summer et al., 2018; Han et al., 2019). Additionally, an increase in pathogens in the raw milk was observed (Feliciano et al., 2020; Petrocchi Jasinski et al., 2023; Feliciano et al., 2021), and presence of aflatoxin (Humboldt-Dachroeden and Mantovani, 2021; Chhaya et al., 2023; Kos et al., 2024) as abnormal milk components indirectly associated with climate change.

The anomalies reported in Table 3 may compromise the health and well-being of mammals in general. Although the reported studies refer to non-human mammals, it is possible to make a prediction of the consequences if similar effects are observed in humans. Changes in the composition of breast milk can bring different clinical repercussions for infants. The reduction of fats, proteins, lactose, minerals, urea and somatic cells compromises growth, immunity and metabolism, favoring infections, low weight, rickets and delay in development. On the other hand, increased levels of these components can cause renal overload, gastrointestinal discomfort, risk of future obesity, metabolic imbalances and, in cases of maternal inflammation, altered acceptance of milk. Thus, the natural balance of milk composition is essential to ensure proper nutrition and immune protection for the baby (Mazur et al., 2024).

Although Table 3 does not include information on anomalies in the volume of milk produced by mammals, it is possible to predict certain consequences in a climate change scenario. In hot climate regions, many women may face challenges related to adequate fluid intake, which can lead to a decrease in breast milk production. Hydration is crucial for maintaining lactation, and a lack of fluids can negatively impact both the volume and quality of milk. To monitor this situation, the weight gain of the baby becomes an important indicator of how the mother's nutrition is influencing breastfeeding. Healthy weight gain in the baby suggests that, despite reduced fluid intake, the quality of the milk may be adequate; however, close monitoring is necessary to ensure that the baby's nutritional needs are fully met. Thus, mothers in hot climates should be encouraged to increase their fluid intake to promote healthy lactation that supports their children's growth.

3.2.2. Secondary outcomes

Regarding the analysis of the milk, sensing technology for detecting anomalies included spectroscopy (Ghaffari, 2022; Feliciano et al., 2020; Koch et al., 2024; Carabaño et al., 2022; Liu et al., 2017), specialized machine dedicated to milk analysis (Habimana et al., 2024; Bokharaeian et al., 2023; Ahmad et al., 2019), chemical assays (Han et al., 2019; Kos et al., 2024), and colorimetric approach (Feliciano et al., 2021). None of the 20 accepted papers analyzed human milk.

3.2.3. Excluded papers

Details about the excluded papers can be found in the Supplementary File.

4. Discussion

4.1. Research questions

Regarding the primary research question on the influence of climate change on the biochemical components of milk, we found that most studies focus on the analysis of fat and protein. More specifically, most eligible studies, such as those conducted by Zeng et al. (Zeng et al., 2023), Petrocchi et al. (Petrocchi Jasinski et al., 2023), and Mylostyvyi et al. (Mylostyvyi et al., 2023), indicate fat and protein reduction trends as the THI increases. Therefore, results reported in the scientific literature suggest that climate change may affect the fat and protein contents and, consequently, the nutritional value of mammalian milk. Other milk properties (SCC, urea, lactose, total solid percentage, and mineral content) were also studied on a smaller scale. However, the reported results are insufficient for us to establish a trend.

To understand how heat stress affects milk synthesis at a physiological level, some authors analyzed the physiological response of these animals to heat stress. In a study involving mice under heat stress, Han et al. (Han et al., 2019) report the apoptosis of cells in the epithelial tissue of the mammary glands. These authors studied rats' neuroendocrine system response to heat stress. This understanding is essential since the neuroendocrine system is related to milk synthesis. One of the known consequences of heat stress in dairy cows is a reduction in appetite, commonly referred to as hypophagia. A reduced feed intake can affect the nutritional value of milk. Han et al. (Han et al., 2019) explore the mechanisms behind heat stress-induced hypophagia, focusing on the endocrine and nervous systems. These authors associate hypophagia with a down-regulated appetite-related peptide, with neuropeptide Y playing the opposite role (i.e. attenuating reduced food intake).

Concerning the second research question on the sensing technology used to measure the concentration of milk components under heat stress, we found a variety of technologies. The reported sensing solutions ranged from classical techniques based on chemical assays (Han et al., 2019; Kos et al., 2024), colorimetric approach (Feliciano et al., 2021), and spectroscopy (Ghaffari, 2022; Feliciano et al., 2020; Koch et al., 2024; Carabaño et al., 2022; Kos et al., 2024; Liu et al., 2017) to specialized machines dedicated to milk analysis (Habimana et al., 2024; Bokharaeian et al., 2023; Ahmad et al., 2019). The choice for a given technology may be influenced by the type of milk component to be detected and other factors such as the costs and the required accuracy. Finally, we found no evidence regarding the third research question on the effects of heat stress on human milk.

In our literature search, we found studies exploring other aspects of heat stress in mammals. While most studies analyze the concentrations of substances naturally present in milk, others investigate the presence of harmful substances (e.g., mycotoxins and *E. coli*) due to climate change. Mycotoxins can be found in corn and other types of cattle feed. Under heat stress, these toxins proliferate more easily, are consumed by cows, and pass through their digestive systems, eventually infecting the milk (Humboldt-Dachroeden and Mantovani, 2021; Chhaya et al., 2023; Kos et al., 2024; Chhaya et al., 2024). On the other hand, *E. coli* may be present in the feces of other cows that share the same farm environment. These bacteria reproduce more in heat stress scenarios and can be transferred to milk (Feliciano et al., 2020; Feliciano et al., 2021). Heat stress can also negatively impact a cow's mammary gland, increasing the number of microorganisms that may be transferred to the milk (Han et al., 2019).

Some papers that were excluded after the full-text analysis provide complementary information on the heat stress in mammals. These papers explore various topics, including the different levels of thermotolerance among mammals and the impact of diverse microclimates within a specific geographical region on the thermal discomfort thresholds of cows. A more detailed discussion can be found in the Supplementary File.

4.2. Limitations

One important limitation of most eligible studies is the lack of a formal definition of climate change. Only three eligible studies, namely Chhaya (Chhaya et al., 2023), Chhaya et al. (Chhaya et al., 2024), and Feliciano et al. (Feliciano et al., 2021), were based on clear climate change scenarios as defined by IPCC, the United Nations body for assessing the science related to climate change. In several cases, the climate change definition was implicit in the threshold THI levels. These are THI levels above which the weather conditions are no longer classified as normal. However, comparing different reported threshold THI levels is not straightforward and sometimes impossible. Indeed, different threshold THI levels for the same mammal can be found in the literature. For instance, dairy cows from tropical regions tend to be more resilient to heat stress, presenting a higher threshold THI level than those from mild-climate regions. In addition to these inherent differences, we observed varying methodological approaches among the studies regarding the calculation of THI. Among the eligible studies, different mathematical formulas were used to calculate the THI, which makes it impossible, in some cases, to compare different reported threshold THI levels.

In our review, we gathered information about the sensing technology used to detect anomalies in milk composition. However, we noticed that not all experimental studies provided details about the milk collection, storage, processing, and sensing, as shown in Table 4, which compromises the reproducibility of these works.

The reported discrepancies among the eligible studies in terms of climate change definition and THI calculation, as well as the lack of information about the methodologies and technologies used to collect, store, process and analyze milk samples bring an extra difficulty not only to researchers but also to decision-makers. On one hand, researchers may not be able to replicate the experimental conditions reported by their peers, which prevents them from checking the reported results and proposing improvements. On the other hand, the fact that the main indicator for the global warming effects on mammals (threshold THI levels) is calculated in several different ways makes it very difficult for researchers to compare the different studies. In such a scenario, the evolution of climate change research becomes limited. Ultimately, Governments may face challenges in identifying geographical areas, animal species and human groups most in need of investment for climate impact mitigation. So, we hope this systematic review will encourage researchers engaged with climate change issues to establish common metrics and to include in their reports sufficient information for the replication of their experiments.

Among the articles evaluated in this systematic review, we did not find any studies analyzing the effects of climate change on human milk. There is a clear predominance of studies focused on animal milk, mainly bovine. This fact can be explained by climate change's significant economic impact on the highly profitable livestock industry - a loss that reached US$1.2 billion in 2013 (Cowley et al., 2015). In addition, climate change can also affect the cheese production processes (Summer et al., 2018), as well as other business activities related to the livestock industry.

Generalization of the results of the review should be viewed with caution considering different species of animals, breed and geographic location where they were exposed to climate change. Regarding primary reports from animals, we observed a large variability in sample size and sampling between studies, ranging from 15 animals (Ahmad et al., 2019) to 1566 cows from 10 different herds (Bokharaeian et al., 2023), as well as studies using databases with 350,664 records (Carabaño et al., 2022).

5. Conclusion

This systematic review revealed trends in the reduction of fat and protein content in the milk of animals (specially cows) subjected to heat stress and a lack of scientific papers relating climate change to the nutritional value of human milk. We hope this work will encourage more studies elucidating the real effects of climate change on the nutritional value of milk. In particular, we hope to foster research linking climate change to the health of women and newborns, as evaluated through the nutritional value of human milk.

CRediT authorship contribution statement

Artur Nogueira de São José: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation. **Maria Cândida Ferrarez Bouzada Viana:** Writing – review & editing, Investigation. **Márcia Gomes Penido Machado:** Writing – review & editing, Investigation. **Sophia Livas de Morais Almeida:** Writing – review & editing, Investigation. **Ursula do Carmo Resende:** Writing – review & editing, Investigation. **Hilton de Oliveira Mota:** Writing – review & editing, Investigation. **Marcelo Lopes Pereira Júnior:** Writing – review & editing, Investigation. **Adson Ferreira da Rocha:** Writing – review & editing, Investigation. **Daniel Orquiza de Carvalho:** Writing – review & editing, Investigation. **Paulo de Jesus Hartmann Nader:** Writing – review & editing, Investigation. **Zilma Silveira Nogueira Reis:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Ethics approval and consent to participate

Not applicable.

Author contributions

ANSJ and ZSNR were responsible for the conceptualization of this work and for writing the first draft of this manuscript. ANSJ, MCFB, MGPM, SLMA, UCR, HOM, PJHN, and ZSNR conducted literature search, screening, and data synthesis. MLPJ, AFdR, and DOC contributed to the conceptualization, investigation, and editing. All authors read, contributed and approved the final version of the manuscript.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Copilot, ChatGPT, and online translation services such as https://www.reverso.net/in order to either translate some sentences from Brazilian Portuguese to English or to improve certain English constructions. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Table 4
Reported techniques to collect, store, process and measure milk properties.

Authors	Milk sample collection strategy	Milk storage procedure	Technique used to process the milk sample	Milk properties under analysis	Sensing technology for detecting anomalies in milk samples
Ghaffari, 2022	NI	NI	NI	Alpha-, beta-, kappa-, and gamma-casein	NI
Zeng et al., 2023	Milk samples were collected three times a day using the APOLLO milking system	NI	The collected milk samples were premixed at a ratio of 4:3:3 in a 50-mL centrifuge tube for later analysis	Protein, fat, lactose, milk urea nitrogen, and SCC	Infrared analysis using a spectrophotometer
Feliciano et al., 2020	NI	NI	NI	Protein, casein, fat, fatty acid, and some pathogens	NI
Stefanska et al., 2024	Milk samples were collected once a month, in the morning and afternoon	NI	NI	Fat, protein, lactose, casein, milk urea, SCC, and milk fatty acid	Fourier transform infrared spectroscopy method
Summer et al., 2018	NI	NI	NI	Fat content, lactose, protein, casein, and casein fractions, minerals, pH, and titratable acidity, milk coagulation properties, and SCC	NI
Koch et al., 2024	Milk samples were collected twice a day before and during the experimental phase	Use of Bronopol and storage at 4 °C	NI	Fat, protein, lactose, milk urea, and SCC	Mid-infrared spectroscopy
Habimana et al., 2024	Milk samples were manually collected twice a day and weighted with calibrated milking cups	Samples were stored in falcon tubes and stored in cool boxes	NI	Protein, fat, lactose, and SNF	Milk analysis device (Lactoscan)
Bokharaeian et al., 2023	Milk samples were collected daily from the bulk storage tanks of individual herds	For TBC, samples were kept in a controlled greenhouse environment for 72 h at a temperature of 32 °C.	For TBC, each sample underwent eight consecutive dilutions, with the plated surfaces placed on two SPC medium plates and cultured for a specific duration	Fat, protein, SNF, pH, SCC, and TBC	SCC: NucleoCounter® SCC-100™. Protein, fat, SNF: Milkoscan 134 model. pH: HI981034 Milk pH Tester
Ahmad et al., 2019	Milk samples were collected twice a day and weighed with an electrical balance	NI	Milk samples collected in the morning and evening were mixed	Fat, protein, SNF, and lactose	Milk analysis device (Lactoscan)
Humboldt-Dachroeden and Mantovani, 2021	N/A	N/A	N/A	AFM1	N/A
Carabaño et al., 2022	Milk samples were collected twice a day on a biweekly basis	NI	NI	Fat, protein, lactose, casein, milk urea content, total solid percentage	IR spectrophotometry
Han et al., 2019	Milk samples were collected from lactating dams on postnatal days 4, 8, and 12. After separating the pups, dams were injected with oxytocin, and milk was obtained by hand massaging	NI	The collected milk samples were diluted 100 times with deionized water.	Protein, triglyceride, and lactose	BCA Protein Assay Kit, Triglyceride Assay Kit; authors did not inform about the lactose measurement system
Carabaño et al., 2016	Milk samples were collected from official milk recording programs	N/A	N/A	Fat, and protein	N/A
Chhaya et al., 2023	N/A	N/A	N/A	AFM1	N/A
Kos et al., 2024	Milk samples were obtained from small producers	NI	Milk underwent thermal processing; reagents included 7 AFM1 standards, enzyme conjugate, and extraction buffer, washing buffer, developing solution, stop solution, and sample diluent; methanol, dichloromethane, and hexane and distilled water were used for sample extraction and preparation	AFM1	ELISA
Chhaya et al., 2024	N/A	N/A	N/A	AFB1, zearalenone, T-2 and HT-2 toxin, and other mycotoxins	N/A
Petrocchi Jasinski et al., 2023	N/A	N/A	N/A	Fat, protein, lactose, MUN, electrical conductivity, pH, SCC, and TBC	N/A

(*continued on next page*)

Table 4 (*continued*)

Authors	Milk sample collection strategy	Milk storage procedure	Technique used to process the milk sample	Milk properties under analysis	Sensing technology for detecting anomalies in milk samples
Mylostyvyi et al., 2023	NI	NI	NI	Fat, and protein	Although authors do not mention the sensing technology, they refer to the DairyComp 305 herd management system
Feliciano et al., 2021	Milk samples were collected from a bulk milk tank	Milk tank temperature ≤ 4 °C	A 1 mL raw milk sample was placed in Petri dishes with 10–12 mL of VRBA, cooled to 45 ± 1 °C, as a base layer. An additional 3–5 mL of VRBA was overlaid, then the plates were incubated at 37 ± 1 °C for 24 h.	*E. coli*	Colorimetric analysis based on the NF ISO 4832 standard
Liu et al., 2017	Cows were milked twice a day at five different times, covering different climatic conditions	Milk samples were transported on ice and stored at −80 °C.	Raw milk samples were diluted with Milli-Q water, followed by the addition of solvents using the one-phase method. The samples then underwent chromatographic separation	Lipid composition of milk, explicitly focusing on TAG and polar lipid profiles.	Mass spectrometry aided by the LipidSearch software.

AFB1: Aflatoxin B1.
AFM1: Aflatoxin M1.
ELISA: Enzyme-Linked Immunosorbent Assay.
FFA: Free Fatty Acids.
MUN: Milk Urea Nitrogen.
MFG: Milk Fat Globule.
N/A: Not Applicable.
NI: Not Informed.
SCC: Somatic Cell Count.
SNF: Solids-Not-Fat.
SPC: Standard Plate Count.
TAG: Triacylglycerol.
TBC: Total Bacterial Counts.
TAG: Triacylglycerol.
VRBA: Violet Red Bile Agar.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.180757.

Data availability

No data was used for the research described in the article.

References

Ahmad, M., et al., 2019. Different ambient management intervention techniques and their effect on milk production and physiological parameters of lactating Nili-Ravi buffaloes during hot dry summer of subtropical region. Trop. Anim. Health Prod. 51, 911–918. https://doi.org/10.1007/s11250-018-1774-5.
Astuti, P.K., et al., 2024. Climate change and dairy farming sustainability; a causal loop paradox and its mitigation scenario. Heliyon 10, e25200. https://doi.org/10.1016/j.heliyon.2024.e25200.
Bokharaeian, M., et al., 2023. Quantitative associations between season, month, and temperature-humidity index with milk yield, composition, somatic cell counts, and microbial load: a comprehensive study across ten dairy farms over an annual cycle. Animals 13, 3205. https://doi.org/10.3390/ani13203205.
Bottin, J.H., et al., 2022. Food insecurity and maternal diet influence human milk composition between the infant's birth and 6 months after birth in Central Africa. Nutrients 14, 4015. https://doi.org/10.3390/nu14194015.
Carabaño, M.J., et al., 2016. Modeling heat stress under different environmental conditions. J. Dairy Sci. 99, 3798–3814. https://doi.org/10.3168/jds.2015-10212.

Carabaño, M.J., Díaz, C., Ramón, M., 2022. Assessing heat tolerance through productive vs physiological indicators. Data from dairy sheep under on-farm conditions. Animal 16, 100662. https://doi.org/10.1016/j.animal.2022.100662.

Cerceo, E., Saxer, K., Grossman, L., Shapley-Quinn, K., Feldman-Winter, L., 2024. The climate crisis and breastfeeding: opportunities for resilience. J. Hum. Lact. 40, 33–50. https://doi.org/10.1177/08903344231216726.

Chersich, M.F., et al., 2024. A WHO-led global strategy to control greenhouse gas emissions: a call for action. Glob. Health 20, 4. https://doi.org/10.1186/s12992-023-01008-6.

Chhaya, R.S., Membré, J.M., Nag, R., Cummins, E., 2023. Farm-to-fork risk assessment of aflatoxin M1 in milk under climate change scenarios – a comparative study of France and Ireland. Food Control 149, 109713. https://doi.org/10.1016/j.foodcont.2023.109713.

Chhaya, R.S., Nag, R., Cummins, E., 2024. Quantitative risk ranking of mycotoxins in milk under climate change scenarios. Environ. Res. 245, 117979. https://doi.org/10.1016/j.envres.2023.117979.

Cowley, F.C., et al., 2015. Immediate and residual effects of heat stress and restricted intake on milk protein and casein composition and energy metabolism. J. Dairy Sci. 98, 2356–2368.

da Cunha Bustamante, M.M., 2024. Climate change and children's health: resilience challenges for Brazil. J. Pediatr. https://doi.org/10.1016/j.jped.2024.11.002.

Feliciano, R.J., Boué, G., Membré, J.M., 2020. Overview of the potential impacts of climate change on the microbial safety of the dairy industry. Foods 9, 1794. https://doi.org/10.3390/foods9121794.

Feliciano, R., Boué, G., Mohssin, F., Hussaini, M.M., Membré, J.M., 2021. Probabilistic modelling of *Escherichia coli* concentration in raw milk under hot weather conditions. Food Res. Int. 149, 110679. https://doi.org/10.1016/j.foodres.2021.110679.

Fransson, G.B., Lönnerdal, B., 1983. Distribution of trace elements and minerals in human and cow's milk. Pediatr. Res. 17, 912–915. https://doi.org/10.1203/00006450-198311000-00015.

Ghaffari, M.H., 2022. Developmental programming: prenatal and postnatal consequences of hyperthermia in dairy cows and calves. Domest. Anim. Endocrinol. 80, 106723. https://doi.org/10.1016/j.domaniend.2022.106723.

Habimana, V., et al., 2024. Heat stress effects on physiological and milk yield traits of lactating Holstein Friesian crossbreds reared in Tanga Region, Tanzania. Animals 14, 1914. https://doi.org/10.3390/ani14131914.

Haddaway, N.R., Page, M.J., Pritchard, C.C., McGuinness, L.A., 2022. PRISMA2020: an R package and shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and open synthesis. Campbell Syst. Rev. 18, e1230. https://doi.org/10.1002/cl2.1230.

Han, J., et al., 2019. Transcriptional changes in the hypothalamus, pituitary, and mammary gland underlying decreased lactation performance in mice under heat stress. FASEB J. 33, 12588–12601. https://doi.org/10.1096/fj.201901045R.

Hasegawa, T., Fujimori, S., Havlík, P. *et al.* Risk of increased food insecurity under stringent global climate change mitigation policy. Nat. Clim. Change 8, 699–703 (2018). doi:https://doi.org/10.1038/s41558-018-0230-x, Nat. Clim. Chang..

Herrero, M., Henderson, B., Havlík, P., et al., 2016. Greenhouse gas mitigation potentials in the livestock sector. Nat. Clim. Chang. 6, 452–461. https://doi.org/10.1038/nclimate2925.

Humboldt-Dachroeden, S., Mantovani, A., 2021. Assessing environmental factors within the One Health approach. Medicina 57, 240. https://doi.org/10.3390/medicina57030240.

IPCC, 2023. Summary for policymakers. In: Core Writing Team, Lee, H., Romero, J. (Eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, pp. 1–34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001.

Koch, F., et al., 2024. Novel perspective on molecular and cellular adaptations of the mammary gland-regulating milk constituents and immunity of heat-stressed dairy cows. J. Agric. Food Chem. 72, 20286–20298. https://doi.org/10.1021/acs.jafc.4c03879.

Kos, J., et al., 2024. Aflatoxins in maize, milk and dairy products from Serbia. Food Addit. Contam. Part B Surveill. 17, 296–307. https://doi.org/10.1080/19393210.2024.2335656.

Liu, Z., et al., 2017. Heat stress in dairy cattle alters lipid composition of milk. Sci. Rep. 7, 961. https://doi.org/10.1038/s41598-017-01120-9.

Mazur, D., Rekowska, A.K., Grunwald, A., Bień, K., Kimber-Trojnar, Ż., Leszczyńska-Gorzelak, B., 2024 Oct 31. Impact of maternal body composition, hydration, and metabolic health on breastfeeding success: a comprehensive review. Med. Sci. Monit. 30, e945591. https://doi.org/10.12659/MSM.945591. PMID: 39478297; PMCID: PMC11536699.

Mbuthia, J.M., Mayer, M., Reinsch, N., 2021. Modeling heat stress effects on dairy cattle milk production in a tropical environment using test-day records and random regression models. Animal 15, 100222. https://doi.org/10.1016/j.animal.2021.100222.

Moore, S.S., et al., 2024. Effects of different temperature-humidity indexes on milk traits of Holstein cows: a 10-year retrospective study. J. Dairy Sci. 107, 3669–3687.

Mylostyvyi, R., Izhboldina, O., Midyk, S., Gutyj, B., Marenkov, O., Kozyr, V., 2023. The relationship between warm weather and milk yield in Holstein cows. World Vet. J. 13, 134–143. https://doi.org/10.54203/scil.2023.wvj14.

NASA. What is Climate Change? https://science.nasa.gov/climate-change/what-is-climate-change/ (accessed 8 Feb 2025).

Nogueira de São José, A., et al., 2024. The Effect of Climate Change on Lactating Mammalian Milk: A Systematic Review Protocol v1. https://doi.org/10.17504/protocols.io.4r3l2qxxxl1y/v1(protocols.io.

Petrocchi Jasinski, F., Evangelista, C., Basiricò, L., Bernabucci, U., 2023. Responses of dairy buffalo to heat stress conditions and mitigation strategies: a review. Animals 13, 1260. https://doi.org/10.3390/ani13071260.

Piscopo, N., et al., 2024. Investigation of climate effects on the physiological parameters of dairy livestock (cow vs. buffalo). Sensors 24, 1164. https://doi.org/10.3390/s24041164.

Rao, N., et al., 2019. A qualitative comparative analysis of women's agency and adaptive capacity in climate change hotspots in Asia and Africa. Nat. Clim. Chang. 9, 964–971. https://doi.org/10.1038/s41558-019-0638-y.

Stefanska, B., et al., 2024. The effect of heat stress on performance, fertility, and adipokines involved in regulating systemic immune response during lipolysis of early lactating dairy cows. J. Dairy Sci. 107, 2111–2128. https://doi.org/10.3168/jds.2023-23804.

Summer, A., Lora, I., Formaggioni, P., Gottardo, F., 2018. Impact of heat stress on milk and meat production. Anim. Front. 9, 39–46. https://doi.org/10.1093/af/vfy026.

UNDP Climate Promise, 2023. The Climate Dictionary: An Everyday Guide to Climate Change [online] Available at: https://climatepromise.undp.org/news-and-stories/climate-dictionary-everyday-guide-climate-change [Accessed 4 Sep. 2025].

Xiao, Y., et al., 2020. Feed intake–dependent and –independent effects of heat stress on lactation and mammary gland development. J. Dairy Sci. 103, 12003–12014.

Zeng, J., et al., 2023. Heat stress affects dairy cow health status through blood oxygen availability. J. Anim. Sci. Biotechnol. 14, 112. https://doi.org/10.1186/s40104-023-00915-3.

Zhao, Z., Hambly, C., Shi, L., Bi, Z., Cao, J., Speakman, J.R., 2020. Late lactation in small mammals is a critically sensitive window of vulnerability to elevated ambient temperature. Proc. Natl. Acad. Sci. U. S. A. 117, 24352–24358. https://doi.org/10.1073/pnas.2008974117.