A first approach to human biometeorology research in Brazil: a systematic review and meta-analysis

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Abstract
This systematic review aims to give an overview of the diversity of research areas related to human biometeorology in Brazil. The main focus of this paper addresses research trends, represented by published papers with national and international authorship, main contributions and shortcomings, as well as challenges and prospects of research in this area of study. An extensive literature search was conducted in the Scopus, Web of Science, and Science Direct databases so as to identify relevant publication output up to July 2021 related to the research area. The screening resulted in 96 studies chosen for full-text reading. Overall, results indicated a reduced amount of articles on the subject matter published internationally, with noticeable gaps in research in some regions of the country, such as the Amazon region and in the Brazilian Midwest region. Research gaps in relevant areas have been identified with limited output in the climate dimensions of tourism, vector-borne diseases, mortality and morbidity in urban centers. Such gaps should further encourage researchers to engage in research focused on those areas.

Keywords Brazil · Human biometeorology · Thermal comfort · Bioclimate · Disease · Contingency table · Chi-squared test · Correspondence analysis

Introduction
As put forth by Fdez-Arroyabe and Robau (2017), the study of the interactions between atmospheric processes and human health has become a major scientific topic in recent years. Noticeable impacts from various global crises we are facing today, among them climate change with weather extreme events, emerging diseases as the COVID-19 global pandemic and inequalities of different sorts require actions to be taken around the globe with regional specificities (Felsenthal 2021). In this context, many developing countries such as Brazil are lagging behind and will surely need a boost in scientific research in areas related to human biometeorology. In the Global South, climate change is likely to exacerbate heat loads, creating undesirable conditions for human performance and occupational health both in outdoor and indoor environments. Developing countries characterized by predominantly hot-humid conditions will be more vulnerable to climate change. Kjellstrom et al. (2016) show case two main negative consequences of such vulnerability, namely impacts on health and the economy. On one hand, we have outdoor occupations with potential heat-related risks
(such as in the construction, mining, and transportation sectors), on the other hand, a great part of human activities that take place indoors, generally in naturally-ventilated buildings with no running air-conditioning systems. Even though the penetration of air conditioners in such economies is growing faster than income growth (Santamouris 2019), the poor maintenance and the generalized use of split air-conditioning units with very limited air renewal in Brazil could potentially cause sick-building syndrome (SBS) and indoor air quality (IAQ) issues in the short term.

It takes at least 10 years of data to define the climate of a region, according to the World Meteorological Organization (WMO). In 1970, the ISB (International Society of Biometeorology) defined biometeorology as “the study of the direct and indirect effects (of an irregular, fluctuating, or rhythmic nature) of physical-, chemical-, physical–chemical-, micro-, and macro-environments, of both, the atmosphere of Earth and other similar extraterrestrial environments, in physicochemical systems in general, and in living organisms in particular (plants, animals, and humans)” (Tromp 1974). WMO and ISB decided to group bioclimatology with biometeorology due to the fact that modern climatology is part of meteorology. Biometeorology can be classified into six main groups: plant, animal, human, cosmic, space, and paleo-biometeorology. According to Tromp (1980) and the ISB, human biometeorology is the study of the influence of weather and climate on human beings for physiological and medicinal purposes and can be also subdivided into different approaches: (a) a physiological approach: dealing with meteorotropic relationships, that is, between meteorology and the physiology of healthy people; (b) a sociological approach: affecting tourism, cultural, behavioral and public health activities of the population in general; (c) a pathological approach: related to diseases in human beings; (d) an architectural and urban planning approach: outdoor urban and indoor microclimate, to which human thermal comfort belongs; (e) a nautical transportation approach: microclimate in humans and cargo transport at sea.

Human biometeorology is quite an old science: during the times of Hippocrates in ancient Greece, the influence of weather changes on physiological processes in humans was a subject of general interest (Höppe 1997). Nevertheless, it was only with advances in modern statistics, physics, and physiology in the last century that studies on human biometeorology could thrive.

Despite its longstanding history since the times of Hippocrates, considered to be the father of Medicine (King 2019), human biometeorology has gained visibility only more recently, mainly due to the potential climate change scenarios for the upcoming years, which will certainly cause enormous health risks to the population worldwide. The latest report of the Lancet Countdown on health and climate change presents indicators that highlight these impacts and emphasize the importance of mitigating actions to ensure a healthier future for all (Romanello et al. 2021).

Another pressing issue is the fact that large urban agglomerations generate and suffer from high levels of atmospheric pollution. This issue is severely amplified by meteorological factors that can hinder the dispersion of pollutants, such as in thermal inversions, absence of wind and precipitation, high levels of solar radiation, among others, and is also a focus of human biometeorology research. There are several episodes with such characteristics whose impacts on human health are considerable. In this respect, Munn (1970) coined the term “meteorotropism”, which represents a change in an organism (or in large populations) due to changes in atmospheric conditions.

Currently, research in the area of human biometeorology has greatly advanced, especially regarding the impacts of weather and climate variables on humans. Likewise, specific weather patterns, meteorological variables, and air pollutants that might contribute to an increase or decrease in respiratory and cardiovascular morbidity and mortality in the population have been widely researched in the specialized literature. Apart from the climate-related impact on diseases, there is also a clear influence of weather and climatic conditions on our well-being, hence, on human thermal comfort. To a great extent, the various factors that might contribute to enhancing human thermal comfort under certain exposure conditions are well researched. In particular, as in the case of vulnerable populations, cold and heatwaves can be extremely harmful to human health, especially in the case of children and the elderly. Another important impact of weather patterns and climate is observed in tourism, a fast-growing sector worldwide (albeit severely impacted by the COVID-19 pandemic in the last 2 years). Human biometeorology in this sector can support tourism management with the aim of ensuring the well-being and diminished health risks of tourists. As pointed out by McGregor in his progress report, the science of human biometeorology requires a truly interdisciplinary approach (McGregor 2012).

The most common definition of thermal comfort entails the feeling of well-being experienced by a person with respect to the thermal conditions of the environment (Auliciems 1976). In this research area, several researchers have proposed empirical indices of human thermal comfort, which consider the interaction of different meteorological variables on the human body and heat balance models, and which combine, in addition to environmental variables, also personal variables such as clothing and metabolism. Examples of such indices can be observed over time, from the studies of Yaglou and Minard (1957), with the proposition of the WBGT index, to those performed by Jendritzky and Höppe (2017), with the development of the UTCI, among many other indices. New demands generated by climate change, such as the severity of the impact of extreme
weather on human health, make clear that there is a strong dependency on physical meteorological parameters and the general health condition of a given population. A number of studies stress the linkages between heat waves and mortality in different regions of the world, in many cases with the call for heat-warning systems (McGregor et al. 2015). A related issue in this context is the aforementioned case of vulnerable populations. Research in the epidemiology of vulnerable populations, particularly the elderly, is paramount to help decision-makers to better conceive and implement heat-warning systems (Guo et al. 2021). In this regard, the joined efforts of the ISB Climate and Human Health Commission (CHC), which focused on the study of the relationship between atmospheric processes and human health, can be crucial.

In the case of Brazil, despite its predominantly tropical climate, heatwave episodes have become more frequent over recent years (Lopes and Fioravanti 2017). The study by Geirinhas et al. (2019) shows that the Brazilian cities of São Paulo, Manaus, and Recife had the most marked increase in the number of days per year with heatwaves for the period between 1961 and 2014. In that study, São Paulo stood out as the city with the highest number of heat wave days per year, reaching 50 days with heat waves in 2014.

The very first study on biometeorology in Brazil published in the international literature dealt with human thermoregulatory processes and was carried out by Japanese researchers, who analyzed differences between Japanese Brazilians and Japanese subjects (Katsuura et al. 1993). Subsequent work was focused on bioclimatic architecture and urban design (Labaki and Kowaltowski 1998; Sad de Assis and Barros Frota 1999). Later, Gonçalves et al. (2005) explored interactions between respiratory diseases and meteorological impacts in humans, with follow-up studies presented by Gonçalves et al. (2007), Nedel et al. (2009), and Gonçalves et al. (2009). In medical research, air pollution was usually the main focus, rather than meteorological impacts on humans. Studies in the areas related to architecture and urban planning generally focused on thermal comfort as the main approach. Thus, in general, study aims are not combined, so health-related aspects and human thermal comfort related to biometeorology remained separate areas of investigation. This is worrying when we examine the basic question posed to the field of biometeorology on the ISB website, “how do weather and climate impact the well-being of all living creatures?” In the coming years, we will surely witness a gradual demand for research focused on the well-being, morbidity, and mortality of humans due to climate change, extreme weather, and inadvertent microclimatic changes resulting from urbanization.

In the wake of the COVID-19 pandemic, human biometeorology in urban centers will need to tackle strategic actions in terms of pandemic resilience, such as natural ventilation in cities. As the COVID-19, similarly to the SARS (severe acute respiratory syndrome) pandemic that struck densely populated cities like Hong Kong in 2003, is airborne, ventilation strategies in cities will be amongst the main directives for pandemic resilience alongside the current needs to ensure environmental quality in urban locations. In this respect, an example to be followed is the series of initiatives taken by the Government of Hong Kong after the SARS pandemic in 2003 regarding air ventilation assessment guidelines for locations with increased urban density (Ng 2009). Particularly cities like São Paulo, both due to the extent of its built-up area and to urban density, will require in-depth analyses focused on climatic and pandemic resilience. The systematic review presented in this paper aims to curb the current limitations of research carried out on human biometeorology so as to guide future planning strategies, contingency plans, and risk assessments of two of the greatest crises facing humanity in the present day, namely global warming and pandemics. In Brazil, as in many centers of the Global South, this is a pressing matter due to the country’s ever-growing urbanization trends.

**Methods**

This systematic review was conducted taking into account the method proposed by Ahmad et al. (2019), which was employed here in order to understand the current state and future directions to be taken in research on human biometeorology in Brazil. Apart from the systematic review, we also conducted a meta-analysis, which is based on the use of statistical methods to summarize the results of independent studies. By combining data from several studies, the meta-analysis allowed us to conclude with more precise estimates of the observed effects of the whole than those derived from the individual studies. The systematic review attempted to answer a previously defined research question by collecting and summarizing all empirical evidence that fitted predefined eligibility criteria. The research question can be stated as: what is the state of the art of research on human biometeorology in Brazil?

**Identification**

An extensive literature search was conducted in the Scopus, Web of Science, and Science Direct databases in order to identify relevant publications up to July 2021 that are related to the research question. The employed online citation databases were chosen due to their extent and relevance of publications according to a predefined list of journals, publishers, or subject areas. Scopus is one of the largest databases of peer-reviewed abstracts and citations worldwide. It has search engines for tracking,
analyzing, viewing, classifying, and refining search results and covers approximately 77 million items from more than 5000 international publishers (https://www.scopus.com/). Web of Science is another large bibliographic database worldwide, covering 171 million records (https://clarivate.com/webofsciencegroup/solutions/web-of-science/) and has Clarivate (formerly Thomson Reuters) as its provider. ScienceDirect is the gateway to 18 million academic articles provided by Elsevier (https://www.elsevier.com/solutions/sciencedirect/). Different from the Scopus and the Web of Science databases, which can be accessed with an institutional subscription only, ScienceDirect allows free access to the database.

We deliberately did not use in our review free-to-use services such as Google Scholar (GS), as these search engines do not store citations within a specific database; instead, they regularly “crawl” the internet for information that appears to be a citation (Haddaway et al. 2015). Moreover, GS has a great percentage of grey literature (i.e. articles that were not formally published by commercial academic publishers) and, as noticed in a study aimed at investigating the utility of GS in systematic reviews, Google Scholar missed some important literature in five out of six case studies analyzed (Haddaway et al. 2015).

The search was conducted without limitation of the year of publication. Only research articles written in English were considered. The search was conducted using the search string: “Brazil” AND “human” AND “thermal comfort” OR “health climate” OR “weather disease.” Search results in the various databases were cross-checked in order to locate and eliminate duplicates using online software (Rayyan, from Qatar Computing Research Institute).

Finally, the identification of the studies that would potentially be included in our review was one of the most discussed issues in the first stages of this research. At first, discussions involved the choice of the most feasible keywords for the search, and several search terms were proposed, such as Brazil, human, thermal comfort, health climate, weather disease, thermal stress, tourism, and vectorial diseases, among many others. Upon testing a combination of different search terms, we observed that the articles that would indeed fit the objective of our review and answer the research question without creating redundancy would have the keywords that we ultimately used. It should also be stressed that the term “biometeorology” is quite new in Brazil, and only two out of the 96 papers that comprised our sample had included this term as a keyword and was thus not considered to be a relevant search term.

**Screening**

As an inclusion criterion, we considered all studies published in English on human biometeorology in Brazil from the aforementioned databases. The exclusion criteria were as follows: (a) working group meeting reports; (b) conference papers; (c) review articles; (d) books and book chapters. The reason for excluding books and book chapters is due to the difficulty we had to identify which books or chapters were peer-reviewed or not. The choice of English-only articles was justified as the main (most-cited) studies published in Brazil on human biometeorology were written in English. In addition, only a very limited number of journals address this subject matter with publications in Portuguese, and these journals are often not internationally indexed.

All titles and abstracts were independently reviewed by two authors of this article using Rayyan and selected for further review if they met the inclusion criterion and did not exhibit any of the exclusion criteria. Disagreements were resolved in a discussion between reviewers. If discrepancies remained, a third author of this manuscript was consulted. Cohen’s kappa index of agreement between reviewers was $K = 0.89$, which indicates a strong agreement.

**Data extraction**

Metadata was systematically extracted from eligible studies and categorized as follows: publication year, authors, authors’ affiliation, the title of article, journal, keywords, aim, study location, disease type (if applicable), number of citations (Scopus), method, main contributions, type of study (theoretical or experimental study), and human biometeorology research area (heat island/thermal comfort/disease/bioclimatic architecture/building simulation/climate change). Note that the terms given for the type of study and research area were identified after the full reading of the papers. These are not author keywords from the initial search but are terms attributed by us that most characterize the type of study conducted or the outcomes from individual studies.

**VOSviewer analysis**

As part of the bibliometric analysis, the VOSviewer software was used to perform a scientific mapping to assess the development of human biometeorology in Brazil. VOSviewer version 1.6.16 is a tool for bibliometric analysis that facilitates the creation of maps based on bibliographic data (available for free at http://www.VOSviewer.com/) (van Eck and Waltman 2010). VOSviewer’s co-occurrence function identifies features of various documents such as author keywords so that the distance between two analyzed terms can be interpreted as an indicator of the relationship between them. In general, the shorter the distance between two terms, the stronger the related terms are (van Eck and Waltman 2010).

In this study, we used VOSviewer to perform a cluster analysis on the recurrent main contributions of the selected articles so as to build a keyword map based on co-occurrence
data. In the case of our database generated from Scopus, Web of Science, and Science Direct, it was possible to identify clusters of the main findings obtained in individual papers of the sample using the VOSviewer’s functionality “co-occurrence of author keywords” (Apriliyanti and Alon 2017). The procedure used was as follows:

a) We first identified the main findings of each paper so as to generate a list of common terms that better describe the application of the study outcomes. Such a list was created with terms that more closely define the scope of application of the findings of individual papers;

b) As a second step, a revision of the terms was conducted in order to standardize common terms;

c) We then saved such a list of common terms as a replacement for author keywords (as informed by the authors of the respective papers) in a .csv file in the standard format generated by the Scopus database (so as to allow VOSviewer to read that file as a regular Scopus bibliographic database file);

d) Maps were created in VOSViewer from reading the modified bibliographic database file for the “co-occurrences of author keywords” analysis (in this case, our list of terms for main findings), with full counting and adopting as threshold a minimum number of three occurrences for a given keyword/common term;

e) From the list of common terms that were identified in VOSviewer as belonging to specific clusters, we assigned in a MS Excel® spreadsheet a respective cluster to each paper whenever there was a minimum match of terms for that paper, each belonging to a specific cluster according to VOSviewer.

Mapping

The geographic information system (GIS) was used to manipulate the quantitative data from the tabulation in an electronic spreadsheet in MS Excel® for spatial values. Quantitative information was scaled using the “color ramp” and transforming the visual variable into choropleth maps in the ArcGIS® 10.1 software.

The cartographic database used was from the Brazilian Statistics Institute (IBGE) and from GISCO – Eurostat (2020) (GISCO 2020; IBGE 2020). These are vectors of the country borders and limits between Brazilian states, available in Shapefile (SHIP). Furthermore, the Mercator projection system was adopted for the latitude/longitude information, with the datum SIRGAS 2000 for Brazil.

Meta-analysis

A statistical meta-analysis was adopted to summarize the results of the independent studies. From the main keywords of the selected studies, the meta-analysis evaluated the effects of a given variable on another variable, always considering binary outcomes (2 × 2 contingency tables). Correspondence analysis was performed for the association of given variables.

Results

The search strategy identified 213 potentially relevant records, excluding duplicates. The screening conducted according to inclusion and exclusion criteria resulted in 96 studies selected for full-text reading. Figure 1 shows a flow chart that summarizes the selection process of the study.

Publication trends

Figure 2 shows the number of articles published in the area of human biometeorology in Brazil, departing from the search string used in the study. The 96 papers evaluated are distributed over the years starting in 1993, with a considerable increase from 2015 onwards. Between 1994 and 1997, there were no publications, as well as between 2000 and 2004 and in 2008. The absence of publications in these years is possibly due to the specific terms defined in the search for this systematic review, as well as to the exclusion criteria adopted here.

It should be stressed that the number of studies in the area of interest may not fully correspond to the research output of Brazilian researchers in this field, as several papers have been published in Portuguese and, in many cases, in journals that are not indexed in the databases considered relevant at the identification stage (cf. Figure 1).

The increase in the number of papers published from 2005 onwards may be associated with the epistemological evolution of research in biometeorology, especially with regard to thermal comfort and the greater transdisciplinarity of studies from the early 2000s with collaborative work between researchers in architecture, geography, and meteorology, for example.

Authors’ overview

The locations of the authors, co-authors, and study groups of the evaluated papers are represented in Fig. 3, which shows that they are distributed in practically the whole Brazilian territory, with a higher concentration in the south/southeast, and mainly in the state of São Paulo. In the world map, some detached countries represent the places of origin of the collaborating international authors. Main contributions outside Brazil came from the US, Australia, and Germany.

Regarding the international partners in research and in publications, it should be noted that, as we adopted “Brazil” as a required keyword in our search, either the field study...
was carried out in Brazil and analyzed jointly with international colleagues, or the paper presents a comparative study between Brazil and another foreign country. In simulation studies, the same applies.

Among the areas of human biometeorology categorized for this review, six of them can be highlighted as areas per se: heat island/thermal comfort/disease/bioclimatic architecture/building simulation/climate change. Within each of these categories, it is possible to differentiate between indoor and outdoor studies (or both), which frequently point to the scope of the research study, whether it is more related to indoor environments and architecture or to outdoor environments, with stronger linkages to urban planning, climate change scenarios, and weather vulnerability. Evidently, the same study can be classified in more than one area, as illustrated in Table 1. In a first analysis, the articles considered in this review were classified within these areas, and the results shown in Fig. 4 indicate a marked thermal comfort approach for research developed in Brazil.

The reviewed papers were published in forty-one different journals, and those with the most publications were: building and environment (22 papers), energy and buildings

*Exclusions: did not belong to biometeorology (n=77); conference papers (n=12); non-English main text (n=1); book chapter (n=2); did not focus on human biometeorology (n=24); review paper (n=1)

Fig. 1 Workflow of literature search and selection criteria – identification of studies via databases and registers (Page et al. 2021)
(10 papers), urban climate (9 papers), and the international journal of biometeorology (7 papers). The remaining journals published three or less of the selected papers during the period.

The maps of Brazil, shown in Fig. 5, present the most studied Brazilian states in relation to each research area. For example, papers that address urban heat islands concentrate their studies in the states of Mato Grosso do Sul, Minas Gerais, São Paulo, Paraná, and Santa Catarina. Thermal comfort is a subject area that covers almost the whole country. Disease and bioclimatic architecture research covered several states. Building simulation is represented only in the Brazilian states of Santa Catarina, São Paulo, Maranhão, Pernambuco, and Alagoas. Finally, climate change research was carried out in almost the entire northeast and in São Paulo. Some of these studies have been conducted in the indicated areas, while others were carried out within international collaboration, especially in the case of comparative analyses.

A closer inspection of the Brazilian states with identified studies on human biometeorology shows that a few inland states and in the north part of the country have still not published relevant studies in the consulted databases and are lagging behind in this respect.

**VOSviewer output and cluster analysis for main findings**

VOSviewer was a useful tool to identify at first sight the clusters that emerge from the sample. For the subset of found papers on the surveyed topic, exemplified by the outcomes of the Scopus database, we could identify the main co-occurrences of common author keywords (full counting, minimum occurrence of three keywords) as well as the co-authorship (with a minimum number of documents per author of two) (Fig. 6).

The co-occurrence map suggests that four clusters are present, with some degree of redundancy in the terms, namely, studies on thermal comfort (red bubbles), studies dealing with urban conditions and urban planning (in green), studies on outdoor thermal comfort (in blue), and other studies, here represented by air quality and morphological attributes (in yellow). There are marked interactions between study areas, with “thermal comfort” standing out. The network map for authors shows that groups of authors are usually not connected except for two groups of co-authors that show an interaction (the red and the blue bubbles). Noteworthy is that some of the authors in the graph are coincidently authors of this review paper.

The cluster analysis was another way to gauge the contributions of the sampled papers to human biometeorology in Brazil. Advancing from the simple categorization into six major areas as shown in Fig. 4, the advantage of this analysis was, first, to standardize contributions of particular papers according to a more comprehensive and authors-tailored list of common terms (in order to reduce redundancy in author keywords as noticed in Fig. 6a), and then to visualize newly generated clusters in VOSviewer.

In the course of the cluster analysis conducted in VOSviewer, the minimum number of occurrences of a given term was determined by aiming at a reasonable distribution of terms in each cluster, yet with a workable number of identified clusters. The higher the minimum number of co-occurrences, the lower the number of clusters and items is (Table 2). As a consequence, a too high set minimum of co-occurrences leads to a diminished part of the sample that can be divided into clusters. In turn, adopting the minimum possible of one occurrence of a given term leads to a high number of clusters that have no actual significance. When post-processing the sample in an MS Excel® spreadsheet, the minimum match of terms in order to assign a given cluster to a paper has a direct consequence on the percentage of the total sample that is classified into clusters. The higher the match score of terms, the lower the percentages of the sample for each cluster are.

From these considerations, we decided for, again, a minimum occurrence of three keywords in VOSviewer and a minimum match score of two terms in MS Excel® for categorizing most parts of our sample. The co-occurrence network map generated in VOSviewer shows the representation of the five clusters obtained for such a setup (Fig. 7).

The harmonization of terms expressed as keywords in VOSviewer from a close inspection of paper outcomes leads to a more defined identification of main clusters. Thermal comfort still stands out, but the obtained ramifications and interactions between papers became more evident, with new
relevant terms emerging, such as climate change, heat stress, and the built environment.

In post-processing, each individual paper, according to the obtained clusters in MS Excel®, the unclassified (i.e. non-clustered) part of the dataset amounted to a third of the studies in the sample. Whenever a paper was classified as belonging to two different clusters, the relative match score in each cluster was weighed against the amount of common terms in that particular cluster (e.g., 2 terms/12 items in cluster 1 versus 2/6 in cluster 2 leading to the classification of the paper as pertaining to cluster 2 (Rupp and Ghisi 2017). Table 3 presents the clusters obtained, terms that characterize each cluster, the number of papers, and the corresponding percentage of the total.

The most meaningful and largest cluster (cluster 1) has a strong linkage to indoor thermal comfort in the built environment. The common terms “thermal comfort,” “indoor,” and “built environment” exhibit indeed the three
highest link strengths of the 106 items (common terms), namely 125, 79, and 50, respectively. In other words, “thermal comfort” is connected to 125 other common terms in the case of the threshold of three occurrences of a given term, “indoor” to 79 items and “built environment” to 50 items. “Outdoor” falls into another cluster (cluster 3), with significantly less participation of the sample, and is more strongly related to “thermal comfort index” as many papers have attempted to calibrate existing comfort indices for outdoor spaces, in particular the PET index and the UTCI, while others present predictive models (“prediction model”). Also, cluster 1 belongs to papers related to climate change research, energy consumption in buildings and ventilation strategies in naturally ventilated (NV) buildings, which reflect the dichotomy present in tropical areas between NV buildings, and the extensive use of HVAC (heating, ventilation, and air conditioning) systems.

Table 1 Brazilian human biometeorology papers published up to July 2021

| Research area                                      | References                                                                 | N(% of total) |
|---------------------------------------------------|---------------------------------------------------------------------------|---------------|
| Heat island                                       | Dorigno et al. 2019; Anjos et al. 2020; Ortiz Porangaba et al. 2021        | 3 (3.1%)      |
| Thermal comfort                                   | Freire et al. 2006; Krüger and Rossi 2011; De Souza 2007;                  | 46 (47.9%)    |
|                                                   | Nedel et al. 2009; Cândido et al. 2011; Bröde et al. 2012; Bröde et al. 2013; Chase et al. 2014; Abreu-Harbich et al. 2014; de Abreu-Harbich et al. 2015; Greca and Moreira 2015; González Cruz and Krüger 2015; Nedel et al. 2015; Pinto et al. 2015; da Silva and de Alvarez 2015; Hirushima et al. 2016; Krüger et al. 2017a, b; Krüger et al. 2017a, b; Krüger and Drach 2017; Rupp and Ghisi 2017; Krüger 2017; Caetano et al. 2017; Lucena et al. 2017; Buonocore et al. 2018; Hirashima et al. 2018; de Abreu-Harbich et al. 2018; Saraiva et al. 2018; (Gobo et al. 2018a); Rupp et al. 2018b; Gobo et al. 2018b; Buonocore et al. 2019; Marçal et al. 2019; Pacífici et al. 2019; Cóstola et al. 2019; Chen et al. 2020b; da Silva Júnior et al. 2020; Buonocore et al. 2020; Resende et al. 2020; Krüger et al. 2020; Schettino et al. 2021; Chen et al. 2021; Pereira et al. 2021; Silva and Hirashima 2021; Castiglia Feitosa et al. 2021; Nedel et al. 2021; Teixeira 2021 |   |
| Disease                                           | Gonçalves et al. 2007; de Sousa Zanotti Stagliorio Coelho et al. 2010; Pimenta and Assunção 2015; Segalin et al. 2017; Leal Filho et al. 2018; Geirinhas et al. 2019; Machado-Silva et al. 2020a, b; Da Silva et al. 2020a, b; de Oliveira Lemos et al. 2021 | 10 (10.2%) |
| Bioclimatic architecture                         | Labaki and Kowaltowski 1998; Maciel et al. 2007; Borgstein et al. 2018; Chen et al. 2020a; Morishita et al. 2020 | 5 (5.1%)      |
| Building simulation                               | Oliveira et al. 2015                                                     | 1 (1%)        |
| Heat island, thermal comfort                      | Katsuura et al. 1993; Sad De Assis and Barros Frota 1999; Johansson et al. 2013; Portela et al. 2020 | 4 (4.1%)      |
| Heat island, disease                              | Sobral 2005                                                              | 1 (1%)        |
| Thermal comfort, disease                          | Vieira et al. 2016; De Souza et al. 2018; Mazzone 2020; de Paula Corrêa et al. 2021 | 4 (4.1%)      |
| Thermal comfort, bioclimatic architecture        | Freire et al. 2005; Guimarães et al. 2013; Moreno et al. 2017; Wilkinson et al. 2017; Castiglia Feitosa and Wilkinson 2018; Sant’Anna et al. 2018; Costa et al. 2019; Celuppi et al. 2019 | 8 (8.2%)      |
| Thermal comfort, building simulation             | Camargo et al. 2005; Rackes et al. 2016; Barbosa and Ip 2016; Rupp et al. 2018a; dos Santos et al. 2019; Muniz-Giá et al. 2020 | 6 (6.1%)      |
| Thermal comfort, bioclimatic architecture, building simulation | Cândido et al. 2010; Sorgato et al. 2016 | 2 (2.1%) |
| Thermal comfort, climate change                   | Alves et al. 2016; Silva et al. 2018; Costa et al. 2021                 | 3 (3.1%)      |
| Building simulation, climate change               | Invidiata and Ghisi 2016                                                 | 1 (1%)        |
| Heat island, bioclimatic architecture, building simulation | Rupp et al. 2021 | 1 (1%) |
| Heat island, thermal comfort, building simulation, climate change | Alves et al. 2021 | 1 (1%) |
| Bioclimatic architecture, building simulation     | Bavaresco et al. 2021                                                   | 1 (1%)        |
Two papers are particularly representative of the relationship between common terms in cluster 1. Findings from the paper presented by Invidiata and Ghisi (2016) reached a high match score for the set of 12 common terms that define that cluster (5/12, namely “energy consumption,” “indoor,” “artificial cooling,” “climate scenarios,” “climate change,” and “built environment”). The paper analyzed energy consumption and thermal comfort in buildings resulting from climate change projections (IPCC’s Scenario A2) for Brazil. The method employed computer simulations in EnergyPlus, thereby investigating which passive design strategies would potentially counteract negative impacts from global warming on building energy demand. Cóstola et al. (2019) evaluated the long-term thermal performance of naturally-ventilated buildings based on hourly data of occupant thermal discomfort and introduced a novel performance indicator termed “seasonal thermal sensation vote” (S-TSV) (Cóstola et al. 2019). S-TSV and its capabilities were listed as the main contributions of that paper. Again, 5 of the 12 common terms of cluster 1 were identified in the attributed terms that best describe the main findings (“thermal sensation,” “thermal performance,” “built environment,” “environmental variables,” and “ventilation”). Common to these two papers is only the term “built environment.”

Cluster 2 consists of papers whose main findings are related to human thermal perception and primarily tend to be human-centered. The three most prominent papers in this cluster in terms of match score for common terms (4 out of 6 items, namely “natural ventilation,” “thermal adaptation,” “thermal comfort,” “thermal perception,” “thermal preference,” and “thermal tolerance”) are the ones by Cândido et al. (2010), Krüger and Rossi (2011), and Hirashima et al. (2016). All three papers are human-centered thermal comfort studies, dealing with subjective thermal perception indoors and outdoors. Cândido et al. (2010) analyzed the effectiveness of natural ventilation to ensure thermal comfort conditions in buildings by means of surveys testing air movement acceptability levels in NV buildings. Krüger and Rossi (2011) and Hirashima et al. (2016) draw conclusions from surveys conducted with pedestrians in outdoor spaces in terms of thermal perception, biometrical influences on thermal perception, thermal acceptability, and tolerance.

Cluster 3 entails five common terms: “index adjust,” “index adjustment,” “outdoor,” “prediction model,” and “thermal comfort index.” The main findings in this cluster can be best exemplified by the three most representative papers with a match score of 4 out of 5 items. One of them concerns the thermal comfort index for air-conditioned indoor spaces PMV and proposes algorithms for automated thermal control for buildings equipped with HVAC systems (Freire et al. 2005). The two other papers promote the use of the outdoor thermal comfort index UTCI (Bröde et al. 2012, 2013). The three papers have thus a strong linkage to predictive models of human thermal comfort.

Cluster 4 entails research on urban heat islands, heat stress, and urban morphology, whose findings are more pertinent to urban planning. This cluster comprehends 5 common terms: “heat island,” “heat stress,” “thermal field,” “urban morphology,” and “vegetation.” Both Abreu-Harbich et al. (2014) and Dorigon et al. (2019) scored 3 out of the 5 common terms, and both present findings related to bioclimatic urban planning (Abreu-Harbich et al. 2014; Dorigon et al. 2019).

Cluster 5 is the less representative one and contains only two papers with two common terms (“air pollution” and “mortality”). Both papers discuss the issue of establishing clear relationships between air pollutants and health issues and mortality in São Paulo (Gonçalves et al. 2007; Segalin et al. 2017) and coincidentally have in their authorship one of the authors of the present paper.

Thus, it is suggested that the classification obtained in VOSviewer with respect to main findings, expressed as common terms and fed into VOSviewer as keywords, is corroborated by a close inspection of sampled papers.

**Meta-analysis**

The meta-analysis was carried out based on the following classifications of the selected studies: “thermal comfort,” “indoor,” “outdoor,” “observational,” “simulation,” “experimental,” and “numerical simulation.” The keywords “heat island,” “health” or “disease,” “bioclimatic architecture,” “building numerical simulation,” and “climate change” was not included in the meta-analysis since they were not associated with a consistent number of articles for statistical analysis.
Table 4 shows the association measures of the contingency tables between two dichotomous categorized variables. The outcome (dependent variable or target variable) is the characteristic that is assumed to be the result of the effect of a factor. The classifications “indoor,” “outdoor,” “empirical,” and “simulation studies” were considered the outcome. The exposure (covariate, independent variable, or predictor variable) is the factor that precedes the outcome. In this study, the covariate considered was the keyword “thermal comfort” as the most representative term for human biometeorology in Brazil (Figs. 4 and 5, Table 1).

In the analysis of the contingency table, the hypotheses tested were: $H_0$: the variables are independent; versus $H_1$: the variables are not independent. The chi-square test evaluates whether there is a significant association between the categories of the two variables. Considering a significance level of 5%, it can be seen in Table 4 that when $p > 0.05$, $H_0$ is not rejected, i.e., there is no association between the thermal comfort approach and indoor studies, as well as between thermal comfort and outdoor studies. In these cases, since the $H_0$ hypothesis is not rejected, it is not necessary to proceed with the correspondence analysis.

It is important to note that, with $p$-values $< 0.05$, $H_0$ is rejected and an association is considered to exist between the keyword thermal comfort and empirical studies as well as between thermal comfort and numerical simulation studies. In these cases, in the correspondence analysis, the standard symmetric representation of the simple correspondence
The results of the Correspondence Analysis indicate that within the studies selected for this review, the studies in human biometeorology in Brazil that involve empirical data consider the variable thermal comfort, but this variable is not considered in numerical simulation studies (the contingency table is auto-explanatory). The main approach of the studies in numerical simulations aims at optimizing or describing energy consumption in buildings. In this case, considering that the energy load depends directly on the expected thermal comfort levels of the occupant, it would be interesting that future studies on numerical simulations also consider the thermal comfort approach in an interdisciplinary way.
Discussion

The systematic literature review has revealed limitations of research in Brazil regarding human biometeorology and pointed to deficiencies that could be starting points for future investigations. The review had the benefit of making clear which areas should primarily receive research funding in the short term. This way, gaps in publication output may encourage the expansion of research in particular areas and regions of the country. Regardless of the topic studied, São Paulo remains the Brazilian state with the highest output in research on human biometeorology.

From the findings obtained in this review, we can highlight the following bullet-point assumptions:

- Overall, there are a small number of articles on the subject matter;
- There are a limited number of papers published internationally, with noticeable gaps in some regions of the country, such as the Amazon region and in the Brazilian Midwest region;
- Studies on urban heat islands, tourism, and vector-borne disease in connection to human biometeorology are still lacking.

| Minimum number of occurrences | Items | Clusters | Maximum number of items in the largest cluster | Minimum number of items in the smallest cluster |
|-------------------------------|-------|----------|-----------------------------------------------|-----------------------------------------------|
| 1                             | 106 (all) | 20 | 13 | 2 |
| 2                             | 45 | 6 | 10 | 5 |
| 3                             | 30 | 5 | 12 | 2 |
| 4                             | 25 | 4 | 9 | 4 |
| 5                             | 20 | 4 | 6 | 3 |

Table 2  Impact of minimum number of occurrences of a keyword (i.e. common term as defined for the main findings of each paper)

![Fig. 7 VOSviewer network map for co-occurrence of author keywords (common terms)](image)

| Cluster | Terms | N | % of total |
|---------|-------|---|------------|
| 1       | Built environment, climate change, climate scenarios, energy consumption, environmental variables, health, individual variables, indoor, thermal performance, thermal satisfaction, thermal sensation, ventilation | 23 | 24 |
| 2       | Natural ventilation, thermal adaptation, thermal comfort, thermal perception, thermal preference, thermal tolerance | 17 | 18 |
| 3       | Index adjust, index adjustment, outdoor, prediction model, thermal comfort index | 10 | 10 |
| 4       | Heat island, heat stress, thermal field, urban morphology, vegetation | 10 | 10 |
| 5       | Air pollution, mortality | 2 | 2 |
| Miscellaneous | Remaining 76 terms | 34 | 35 |

Table 3  Obtained clusters, terms that best characterize each cluster, number of papers, and corresponding percentage of the sample
As regards the search string, it was first and foremost a group decision by the authors of the article, and the exclusion criteria adopted by us further limited the obtained sample. Perhaps this might indicate the need for establishing a list of standard keywords, some sort of thesaurus for studies published in the area of human biometeorology. The need for standardization was also noticed in the list of author keywords with a variety of terms that were not compatible. In this sense, the exercise done for standardizing common terms performed in this paper in preparation for the cluster analysis in VOSviewer was crucial for the identification of main clusters.

The lack of papers focusing on the Amazon Region is a cause for alarm. This region is a natural carbon sink; however, due to progressing deforestation and climate change, its important planetary climate-regulating function seems to be in decline in recent years (Gatti et al. 2021). The combined effect of deforestation with the incidence of man-made and wildfires can be extremely hazardous to human health and deteriorate bioclimatic conditions in inhabited areas in the region, bringing about negative impacts on human biometeorology (Kim 2019; Bell et al. 2018).

Similar environmental impacts can be noticed in inland regions of the country that, likewise did not present any publications on human biometeorology in our search. Brazil has been frequently hit by drought and associated wildfire episodes in recent years (Cunha et al. 2019), and studies aimed at improving human biometeorological conditions in these hotspots can be crucial for ensuring the resilience of public health to extreme weather events in the future. In this respect, there is a need for drought risk management in order to identify population vulnerability as recommended by UNISDR (2009), and matters related to human biometeorology should be divulged in peer-reviewed international publications.

Heat island studies are also in great need when we take into account the prominent urbanized character of Brazil, with over 84% of the population living in urban areas and all its regions having most of their population in cities (IBGE 2010). Many cities in the country are in a permanent state of population growth with compact building schemes in downtown areas and a large urban sprawl with informal housing in peripheral areas. In diverse Brazilian cities, a loss of urban vegetation coverage is generally accompanied by diminished ecosystem services (De Carvalho and Szlafsztein 2019; De Faria Peres et al. 2018), resulting in deleterious impacts on urban climate.

The consequences of urbanization on the increase of urban heat island intensity are well documented (Oke 2002; Chen et al. 2006; Rizwan et al. 2008; Oke et al. 2017). Taking into consideration the current urbanization trends in Brazil, with a more pronounced population growth rate in major cities in the northern and central parts of the country (IBGE 2010), where unfortunately research gaps have been identified, research on human biometeorology will be needed to guide and monitor urbanization schemes in those areas. In this framework, the implementation of heat warning systems or early warning systems in the largest cities in Brazil is still lacking, and such could potentially foster active international collaborations with ISB-CHC members.

In our sample, research on the impact of climate and extreme weather on tourism has not been identified. Even though recent episodes of floods in touristic regions in the country have affected tourism to some extent and such events are highly dependent on weather patterns, the linkage to human biometeorology is not a direct one. Considering the growth of the tourism industry (with a 150% rise in e-commerce sales in the wake of the COVID-19 pandemic and vaccination roll-outs observed in September 2021 relative to 2020 -https://www.gov.br/), the impacts of the increase in the frequency of heat waves and extreme weather events on tourism and mobility in Brazil can open up a new avenue of research.

The ISB proposition for studies in human biometeorology goes “how do weather and climate impact the wellbeing of all living creatures?” (https://uwm.edu/biometeorology/what-is-biometeorology/). In his progress report on human biometeorology, McGregor (2012) points to the need for investigating the weather and climate dimensions of vector-borne disease. In our review, such dimensions are still little explored in international literature by Brazilian researchers. As pointed out by McGregor, this is an emerging field in human biometeorology in the relationship between climate and health, in which geographers, epidemiologists, and other human health researchers should join forces in interdisciplinary work. The dependence of
the spread of the COVID-19 pandemic on climate and seasonality is an example of such a relationship that has been recently explored in the literature. A very recent article, not part of our review and not conducted by Brazilian researchers, investigates the influence of climate and seasonality on COVID-19 transmission (Yin et al. 2022).

Conclusions

Wrapping up, the systematic literature review conducted for Brazil served as an initial approach to understanding the broad areas of human biometeorology in the country, limitations, and knowledge gaps that may encourage researchers to start research initiatives on the matter in areas and regions that are still precarious.

Whereas the area of Biometeorology as science started worldwide as an interdisciplinary area in the 1960s, in Brazil, the area was formally explored in this connotation (interaction between man and meteorological parameters) in international publications in the early 1990s. However, the reasons for this time lag are in great part related to the fact that publications so far had been published only in Portuguese. Important contributions to the formal establishment of the human thermal comfort area such as the Handbook of Thermal Comfort (Frota and Schiffer 1987) and the series of Biannual Meetings on Environmental Comfort (Encontro Nacional de Conforto no Ambiente Construído—ENCA), had started a few years before that, with the first meeting being held in 1990. Work related to human biometeorology and architecture, such as the promotion of more adequate dwellings, had been carried out in Brazil many decades before, in the first half of the twentieth century. To a greater extent, the issue of ensuring adequate sanitation in dwellings in the tropics belongs to the beginnings of studies aimed at human well-being and human thermal comfort, and thus, human biometeorology in Brazil. Those studies, albeit not scientifically oriented from the outset, were important for defining early building codes in the country (Segawa 2003). In its initial stage, thermal comfort in the early stage of the area was inaugurated by the pioneering engineer Paulo Sá, with a strong linkage to bioclimatic architecture. Unfortunately, documentation related to these developments is mostly found in Portuguese, and the seminal works were not captured in our review.

A more complete overview of studies conducted in the area should include search engines that are able to capture publication output in Portuguese, and this is a limitation of this study.

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