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A systematic review on role of humidity as an indoor thermal comfort parameter in humid climates

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ABSTRACT

Thermal discomfort over time can lead to unproductivity and health issues for the occupants. Like operative temperature, humidity is an important parameter that affects thermal comfort and occupant health. This paper analyzed how humidity was incorporated into spatial and personalized thermal comfort assessments and models. In addition, the paper studied different indoor thermal comfort indices in terms of index type and time temporality. The study found that most standards and guidelines recommended a fixed upper and lower threshold for humidity for spatial assessment. For personalized assessments, the humidity was indirectly coupled through evaporative heat losses in most physiological and psychological models. In addition, transient processes like metabolic activities that changed in warm temperatures and humidities also influenced human comfort perception. The existing indoor thermal comfort indices used a point-in-time approach in terms of time temporality. Based on these findings, this paper suggested a spatial assessment for early-stage building design and a personalized assessment for the post-occupancy stage. In addition, this paper recommended a time-integrated and multizonal hygrothermal discomfort indicator that should incorporate both operative temperature and relative humidity in the future. Finally, the paper provides a set of suggestions and aspirations for practice and research based on the study findings.

Abbreviations

ABNT	Associação Brasileira de Normas Técnicas
AMS	American Meteorological Society
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEWARE	BElgian WAllonia REsearcher
BIS	Bureau of Indian Standards
BREEAM	Building Research Establishment Environmental Assessment Method
BSN	Badan Standardisasi Nasional
CEN	Comité Européen de Normalisation
CFD	Computational Fluid Dynamics
CIBSE	Charted Institution of Building Services Engineers

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EBC	Energy in Buildings and Communities
EN	European Norm
GB	Guobiao
IEA	International Energy Agency
IOD	Indoor Overheating Degree
ISO	International Organization for Standardization
LEED	Leadership in Energy and Environmental Design
LEHB	Law for Environmental Health in Buildings
MS	Malaysian Standards
MSCA	Marie Skłodowska-Curie Actions
NBC	National Building Code of India
NBR	Norma Brasileira Regulamentadora
NHBC	National House Building Council
NSW	New South Wales
OH&S	Occupational Safety and Health
PERENE	PERformances ENErgétiques
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RE	Règlementation Environnementale
SBD	Sustainable Building Design
SET	Standard Effective Temperature
SNI	Standar Nasional Indonesia
SS	Singapore Standard
UK	United Kingdom
USA	United States of America
WoS	Web of Science

1. Introduction

According to the ASHRAE Standard 55 [1], thermal comfort is ‘that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation’. Indoor thermal comfort is one of the most crucial factors influencing building occupant well-being, health, and productivity [2]. This is significant because people spend up to 90% of their time indoors, especially in developed countries [3]. Spatial thermal comfort can be assessed using two main approaches: PMV/PPD and adaptive thermal comfort models. The applicability of the comfort models in different types of buildings is under debate to date. The PMV/PPD indices are based on the widely accepted Fanger’s heat balance thermal comfort model and stand for Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) [4]. The thermal conditions are assessed by regulating the environmental parameters like the air temperature, air velocity, air humidity, and mean radiant temperature, and neglecting the adaptive opportunities taken by the occupants [5], except for the clothing insulation and metabolic rate levels, which are included as model inputs. The PMV/PPD indices have led to the definition of limits and ranges for the thermal comfort evaluation in the standards.

However, in the 1970s [6], new research results proposed that the human body is not a passive recipient of thermal stimuli as formulated in the PMV/PPD model. In contrast, occupants react through feedback loops between their thermal perception and adaptive thermoregulatory behavior in buildings. Due to these adaptive opportunities, they can tolerate a wider range of temperatures compared to the limits set by the PMV/PPD model. Adaptive models are based on surveys and monitoring data collected in real buildings and demonstrate that there is a direct correlation between indoor comfort temperature and outdoor temperature in naturally ventilated buildings. Among the reviews on thermal comfort models, the PMV/PPD and adaptive comfort from ASHRAE 55 and EN 15251 were reviewed in Ref. [7]. In this study, the main differences between the models were discovered to be the outdoor reference temperature, acceptable temperature ranges, and field study databases used to derive the models.

The existing adaptive thermal comfort models rely on maintaining indoor thermal comfort primarily through adjusting the indoor operative temperature or sensible heat as in Ref. [1]. These adaptive models represent outdoor air temperature as an influential parameter for indoor thermal comfort. However, the outdoor humidity is also likely to have a bigger effect on the indoor humidity, and in turn on the building thermal comfort [8], like outdoor air temperature on adaptive thermal comfort models [1]. Studies from Refs. [9,10], have addressed humidity as an adaptive thermal comfort parameter but do not provide a clear explanation or formulation of its effect on adaptive thermal comfort, whereas the experiments from Ref. [11] suggested an adaptive model similar to ASHRAE 55 for Southeast Asia. The regression gradient analysis from Ref. [8] gives clear evidence that relative humidity has a measurable impact on the occupants’ thermal sensation. Furthermore, a second independent line of evidence emerges from the analysis using statistical methods like Random Forest, to explain the data from the ASHRAE RP-884 database.

Another important factor to consider while evaluating the effects of humidity on thermal comfort is the ability of the human body to self-regulate, which allows it to adapt to various thermal environments. For instance, the human body will adjust to the new environment through a series of complex physiological processes, such as vasoconstriction, shivering, and so forth, e.g., when someone

Table 1
A systematic literature review of existing scientific studies from Google Scholar, Scopus, and WoS based on defined keywords and criteria, that are classified based on methodology, location, climate zone, operation mode, building type, comfort model, and survey type.

No.	Authors	Citations	Methodology	Location and Climate	Operation mode and building type	Comfort models	Survey type
1	Indraganti et al. [41]	202	Observational - Monitoring and surveys	Hyderabad (0A), Chennai (0A), India	Naturally ventilated and air-conditioned buildings	BIS NBC PMV/PPD model ASHRAE 55 adaptive model EN 15251 adaptive model CIBSE Guide A adaptive model	Thermal sensation Thermal preference Thermal acceptance
2	Damiati et al. [42]	167	Observational - Monitoring and surveys	Kuala Lumpur (0A), Selangor (0A), Malaysia Bandung (0A), Indonesia Singapore (0A) Tokyo (3A), Yokohama (3A), Japan	Free running, mixed-mode, and mechanically cooled office buildings	ASHRAE 55 adaptive model ASHRAE Handbook estimating T_{mrt} and T_{op} EN 15251 adaptive model CIBSE Guide A adaptive model	Humidity feeling and preference Thermal sensation Thermal preference Air movement vote
3	Indraganti [20]	133	Observational - Monitoring and surveys	Hyderabad (0A), India	Naturally ventilated residential buildings	NBC India PMV/PPD model ASHRAE 55 adaptive model	Thermal sensation Thermal preference Thermal acceptance
4	D'Ambrosio Alfano et al. [43]	119	Modeling - Simulations	–	–	ISO 7730 PMV/PPD model	–
5	Mba et al. [44]	114	Observational - Monitoring Modeling - Simulations	Douala (0A), Cameroon	Cement hollow block residential building	–	–
6	Tablada, A. et al. [45]	110	Observational - Monitoring and surveys	Havana (1A), Cuba	Different types of courtyard buildings	ASHRAE 55 PMV/PPD model	Thermal sensation Comfort sensation
7	Djamila, H. et al. [46]	109	Observational - Monitoring and surveys	Kota Kinabalu (0A), Malaysia	Naturally ventilated residential buildings	–	Thermal sensation
8	Teodosiu et al. [47]	99	Experimental - Test room	Lyon (4A), France	Test room with mechanical ventilation	ISO 7730 PMV/PPD model ISO 7726 T_{mrt} calculation	–
9	Vellei et al. [8]	84	Modeling - Simulations	Liverpool (4A), Oxford (4A), UK Brisbane (2A), Melbourne (3A), Australia Singapore (0A) Jakarta (0A), Indonesia Athens (3A), Greece Bangkok (0A), Thailand	Naturally ventilated buildings	ASHRAE 55 adaptive model ASHRAE RP-884 database	Thermal sensation
10	Wijewardane et al. [48]	65	Observational - Monitoring and surveys	Colombo (3A), Sri Lanka	Free-running commercial factory buildings	ASHRAE 55 adaptive model	Thermal sensation
11	Nematchoua et al. [49]	64	Observational - Monitoring and surveys	Douala (0A), Nkongsamba (1A), Bafang (2A), Cameroon	Modern style built with the bond stones, traditional style with boards, and with mud buildings	ASHRAE 55 adaptive model ISO 7730 PMV/PPD model	Thermal satisfaction index Thermal wish index Thermal acceptability index Thermal tolerability index

(*continued on next page*)

Table 1 (*continued*)

No.	Authors	Citations	Methodology	Location and Climate	Operation mode and building type	Comfort models	Survey type
							Acceptable air movement index Acceptable vertical thermal gradient index
12	Singh et al. [50]	40	Observational - Monitoring and surveys	Cherrapunji (1A), Tezpur (1A), Imphal (2A), India	Vernacular households	ASHRAE 55 adaptive model	Thermal sensation
13	Nematchoua et al. [51]	30	Observational - Monitoring and surveys	Antsiranana (1A), Madagascar	Naturally ventilated buildings - hospitals, shopping centers	ASHRAE 55 adaptive model	Thermal sensation Humidity sensation Air movement sensation Thermal satisfaction Thermal Preference Thermal comfort
14	Nematchoua et al. [52]	26	Observational - Monitoring and surveys	Antsiranana (1A), Madagascar	Naturally ventilated buildings - hospitals, shopping centers, traditional buildings, and schools	ASHRAE 55 adaptive model	Thermal sensation Humidity sensation Air movement sensation Thermal satisfaction Thermal Preference Thermal comfort
15	Lenoir et al. [53]	24	Observational - Monitoring and surveys	Reunion Island (2A), France	Mixed-mode net-zero energy building	ISO 7730 PMV/PPD model	Thermal sensation
16	Buonocore et al. [54]	23	Observational - Monitoring and surveys	Sao Luis (0A), Brazil	Naturally ventilated and fan-assisted university building	ASHRAE 55 adaptive model	Thermal sensation Thermal preference Thermal acceptance Current opinion about air movement Preference for air movement Thermal comfort
17	Gamero-Salinas et al. [55]	19	Observational - Monitoring Modeling - Simulations	Tegucigalpa (2A), Honduras	Naturally ventilated residential buildings - apartments and single-family homes	EN 15251 adaptive model ASHRAE 55 adaptive model CIBSE TM52 overheating risk assessment	–
18	Pan et al. [56]	1	Observational - Monitoring	Singapore (0A) Tuxtia Gutierrez (1A), Mexico Guatemala City (2A), Guatemala Hong Kong (2A), China Colombo (3A), Sri Lanka Antananarivo (3A), Madagascar Blacksburg (4A), USA	Mixed-mode hospitals, offices, residences, and labs	–	–
19	Nedel et al. [57]	0	Observational - Monitoring	Pelotas (3A), Brazil	Naturally ventilated and mixed-mode residential houses	–	–
20	Payet et al. [58]	0	Observational - Monitoring and surveys	Reunion Island (2A), France	Naturally ventilated lecture theatre	–	Thermal, hygrometric, and air speed comfort

(*continued on next page*)

Table 1 (*continued*)

No.	Authors	Citations	Methodology	Location and Climate	Operation mode and building type	Comfort models	Survey type
							Thermal sensation Thermal Judgement

moves from a warm to a cold environment. The process of transferring heat from the human body to the surrounding thermal environment also involves conduction, evaporation, radiation, convection, and respiration [12]. The interaction between physiological signals and indoor environmental factors has huge significance in identifying human responses to environmental stressors [13]. The environmental parameters and physiological signals have a considerable effect on thermal comfort perception [13]. With a focus on the thermodynamic, metrological, and biomedical aspects of the occupants' physiological thermal comfort responses, the measurements using different wearable sensors and data analysis techniques using indices for assessing physiological thermal comfort metrics for field studies are provided in Ref. [14].

Acclimatization to humidity is sometimes endorsed as a solution to its effects on thermal comfort, but there is growing evidence that the amount of time required for acclimatization varies between different individuals. The rate of acclimatization depends highly on personal factors like age and gender, in addition to health factors like obesity, cardiovascular diseases, and alcohol abuse, among others. The ability of the human body to acclimatize is a long-term solution and depends on different individuals [15,16]. These constraints, taken together, will limit the role that acclimatization can play in human adaptation to thermal discomfort due to humidity [17]. The research articles listed in Table 1 revealed that there is a scarcity of scientific literature explaining the role of humidity as a thermal comfort parameter for spatial assessment. These studies focus on operative temperature as a primary parameter that influences thermal comfort, except in Ref. [8], which also considers relative humidity in addition to operative temperature.

This paper proposes a two-pronged approach to evaluate the effects of humidity on thermal comfort: (i) a spatial assessment for early-stage building design to help designers and engineers to evaluate building thermal comfort, and (ii) a comprehensive personalized assessment involving quantitative measurements and qualitative surveys involving the occupants during the post-occupancy stages. In this context, the current paper attempts to respond to the following research questions.

1. How do existing standards, guidelines, and codes couple humidity to thermal comfort assessment?
2. How do these standards, guidelines, and codes recommend humidity requirements?
3. How do existing indoor physiological and psychological thermal comfort models for personalized assessment account for humidity?
4. How do existing indoor thermal comfort indices incorporate humidity - a point-in-time or time-integrated approach?

This research has several originalities and innovative aspects as given below.

1. A qualitative two-pronged approach, without limiting the thermal comfort assessment to just spatial analysis for early-stage building design but also integrating personalized models for post-occupancy evaluations, thus covering both scenarios.
2. A qualitative and systematic literature review that covered:
   a. Twenty state-of-the-art articles cover twenty countries that cover five humid climatic zones according to ASHRAE 169 classification.
   b. Ten standards, four guidelines, and one code related to indoor thermal comfort from humid climates.
   c. Thermal comfort models included two spatial models and eight personalized models with four physiological and four psychological models.
   d. Eleven thermal comfort indices included seven spatial indices and four personal indices.
3. A detailed analysis of current thermal comfort assessment methodologies and research perspectives will provide a thorough thermal comfort analysis that will include a spatial thermal comfort analysis for early-stage building design and personalized thermal comfort analysis for post-occupancy evaluation.

This paper contributes to the advancement of hygrothermal comfort research by combining personalized thermal comfort from an occupant perspective with spatial thermal comfort from an environmental perspective. To the best of our knowledge, during our literature review, we did not find any qualitative studies that addressed this two-pronged approach that integrated spatial and personalized comfort evaluation. In addition, a set of recommendations can be used for a more comprehensive thermal comfort assessment that takes humidity into account.

This paper offers support for building professionals' and designers' decision-making in assessing indoor discomfort while taking humidity into account through humidity inclusive spatial assessment for early-stage design and personalized assessment based on physiological and psychological responses for post-occupancy stages. The findings of the study also provide policymakers with practical recommendations for improving discomfort evaluation methods toward a hygrothermal discomfort index.

2. Methodology

The methodology used a systematic and data-driven analysis to collect and investigate the data from numerous publications available in different scientific databases. This study was a systematic review that employs systematic and repeatable techniques to gather and analyze data from the studies within the study scope framework. To provide an in-depth review, the scope was defined as the role of humidity in indoor thermal comfort and humid climates, as shown in the study conceptual framework in Fig. 1.

This paper put forward a two-pronged approach based on spatial thermal comfort assessment for early stage building design and a personalized comfort assessment for the post-occupancy period. A practical implementation of this approach can be implemented as follows.

1. For spatial thermal comfort analysis, the modeling interfaces like DesignBuilder can be used for the building design and indoor thermal comfort parameters like operative temperature [%], relative humidity [%], etc. can be calculated by simulating the building model using EnergyPlus. The indoor spatial thermal comfort can be calculated using humidity-sensitive adaptive thermal comfort models like in Ref. [8] and humidity-inclusive spatial indices like effective temperature, etc., from Table 5.
2. For personalized comfort analysis, once the building is fully constructed and occupied for a while, quantitative monitoring can be performed using measurement equipment like Testo 400 and qualitative surveys as per standards like ISO 7730 for personal parameters like clothing [clo], and metabolic activities [Met]. The indoor personal thermal comfort can be then calculated using personalized indices like Predicted Mean Vote (PMV) from Table 5.

A practical implementation flowchart for this two-pronged approach is shown in Fig. 2.

2.1. Review methodology

The approach used in this study to review the existing literature was systematic. A three-step methodology was used to conduct the literature review [18,19].

1. Data collection

The keyword string used for the search *was* ***"Indoor thermal comfort (and) Humidity (and) Humid climates"***. The development of the search string was based on the aim of the study to map the scientific landscape of publications that concerned the role of humidity in thermal comfort assessments in humid climates. This approach makes it possible to conduct a qualitative analysis of the humidity research. The search was carried out by using the keywords mentioned above. We chose scientific databases and reliable websites that included complete bibliographic information. The following major databases were used in the analysis.

a. Google Scholar
b. Scopus
c. Web of Science (WoS)

On November 10, 2021, the search string was applied to different scientific databases and the existing literature was collected. The results of the literature review are given in section 3.1. This step was followed by data filtering process to screen the larger dataset in terms of the inclusion criteria of this study as given below.

2. Data screening

The initial data filtering procedure was completed in three steps.

a. Document type: only includes journal or conference articles in the records.
b. Language: only includes articles written in English.

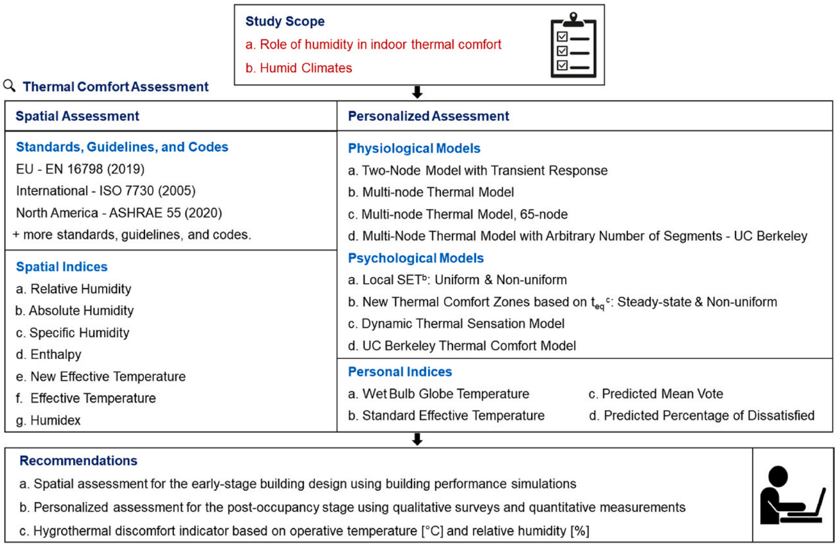

Fig. 1. Proposed workflow of role of humidity as a thermal comfort parameter in humid climates.

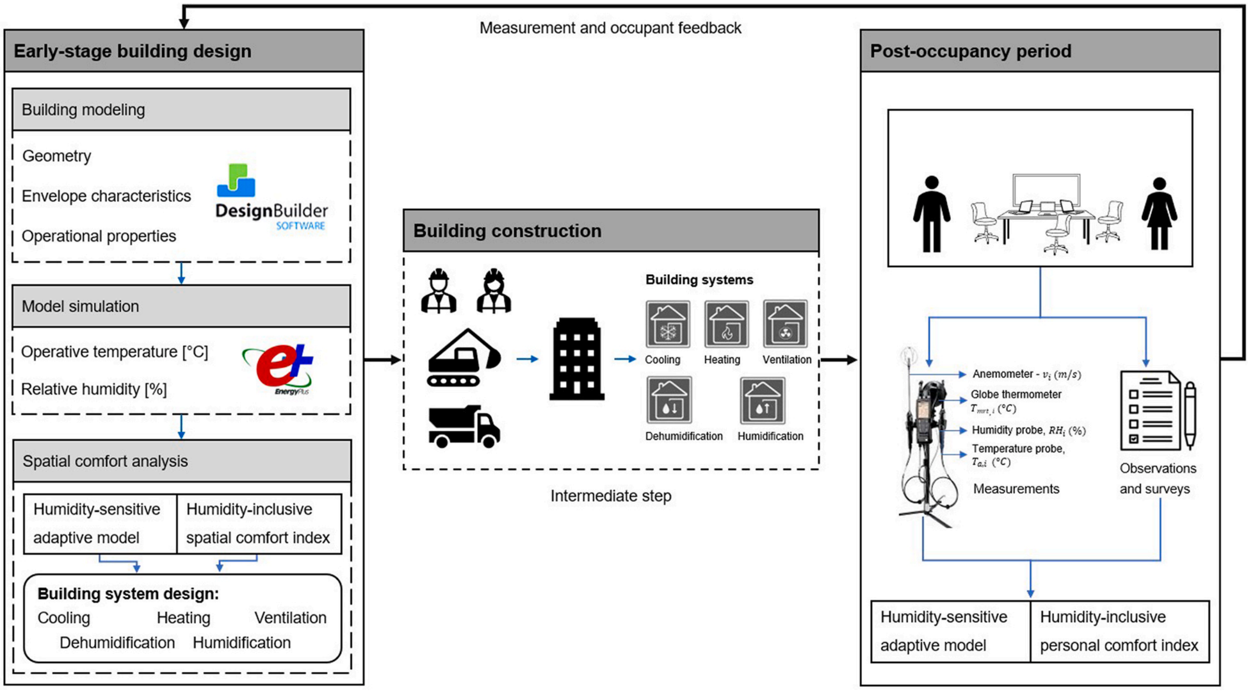

Fig. 2. A flowchart for the two-pronged approach based on spatial thermal comfort assessment for early stage building design and a personalized comfort assessment for the post-occupancy period.

c. Duplicates: duplicates from the dataset are removed.

The inclusion and exclusion parameters used in the study are shown in Fig. 2. The inclusion criteria were composed of the keywords like indoor thermal comfort, humidity, and humid climates. If the study analyzed satisfied these keywords it was selected for the study. The subsequent analysis was focused on studies that addressed spatial comfort, personalized comfort, and humidity indices. The inclusion criteria are shown in the area in blue in Fig. 3. The exclusion criteria were twofold.

1. To eliminate publications that defined comfort in terms of the outdoor environment, visual, acoustic, e.g., if a study defined thermal comfort in humid areas but for an outdoor environment, it was excluded from the study. Terms such as “outdoor thermal comfort”, “acoustic comfort”, “visual comfort”, and/or “indoor air quality” were used as exclusion criteria here,
2. To eliminate publications that defined the effects of humidity on building composition and structure, e.g., if a study defined humidity in humid areas, but focused on corrosion and decay in the building structure, it was excluded from the study. Terms such as

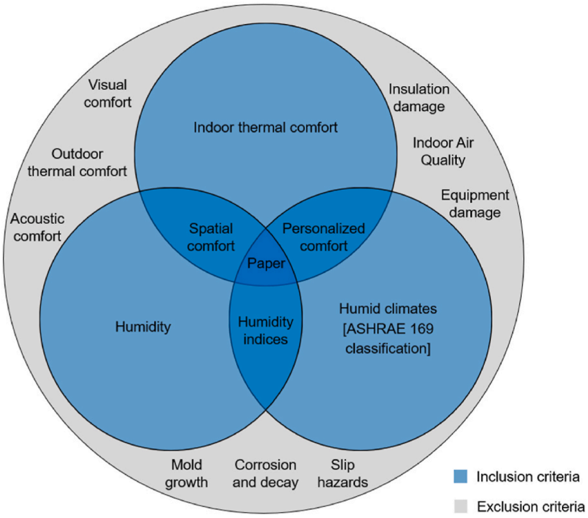

Fig. 3. Inclusion and exclusion criteria used in the study.

"mold growth", "corrosion and decay", "insulation damage", "equipment damage", and/or "slip hazards" were used as exclusion criteria here.

An extensive identification of the literature was necessary before the data analysis. The relevant studies were found by screening the titles, keywords, and abstracts for the dataset obtained. Irrelevant records were manually filtered out. This procedure was designed to make the dataset smaller so that the field's research could be examined. If the research presented findings that were outside the inclusion criteria of the study, they were removed from the dataset and subsequent analysis. The publications from the year 2000–2021 were considered for the review. This was because the data filtering process returned only very few publications in Scopus and WoS before the year 2000 and these publications were outside the inclusion criteria of the study.

3. Data analysis

The data analysis was conducted in four parts.

a. Literature that provided information about the knowledge structure and existing research in the context of humidity and indoor thermal comfort in humid climates. The relevant articles that satisfied the inclusion criteria during the data screening process were subjected to a full-text review and discussion.
b. The entire text of the full article was read by most of the authors and followed up with a focus group for further discussions on the selected literature. The follow-up discussions took place between the first author and the co-authors via teleconference and emails.
c. The literature reviewed for relevant articles was categorized into the following research methodologies: (a) observational including monitoring and surveys, (b) modeling including simulations, (c) experimental including test rooms and climate chambers, and (d) qualitative included scientific reviews.
d. Thematic analysis of the formulated research questions was based on the knowledge gaps identified from the literature review in section 3.1. This was based on a full-text examination of each publication.

The publications included scientific journal and conference articles during the initial literature review in section 3.1. This was followed by the analysis of existing standards, guidelines, and codes that satisfied the inclusion criteria from Fig. 3.

3.1. Study scope

As the first study scope, we focus on the role of humidity in indoor thermal comfort since there is still a knowledge gap in this area [8,20]. The second study scope was that the study focused on the humid climatic zones since the impact of humidity is more visible in humid areas. In warmer environments, discomfort is caused by too much moisture on the skin due to high humidity levels. Experimental studies have shown that skin humidity is a major reason for discomfort in highly humid zones [21–23]. Non-humid climatic zones were not considered since the effect of humidity is negligible in these zones.

The study scope in this paper can be divided into: (i) spatial thermal comfort assessments, (ii) personalized thermal comfort assessments, and (iii) indoor thermal comfort indices including humidity. In addition to the literature identified from the scientific databases, universally accepted standards, like EN 16798 [24], ISO 7730 [25], and ASHRAE 55 [1]. These are some of the most well-cited standards within the subject area of thermal comfort. In addition, we review the guidelines from countries like the UK – CIBSE Guide A [26], and standards from India – BIS NBC [27], Singapore – SS 554 [28], Brazil – ABNT NBR 16401–2 [29], Indonesia – BSN SNI 6390 [30], Malaysia – MS 1525 [31], China – GB/T 50,785 [32], codes from Japan – LEHB [33], and regional standards from Réunion Island, France – PERENE [34].

These countries together entail zones from extremely hot humid (0A) to mixed humid (4A) according to ASHRAE 169 climate zone classification [35]. Many countries like India [27] have a national climatic classification, which divides the country into 5 different climatic zones. In this paper, we use ASHRAE 169 as a tool to identify humid climates around the globe and in no way assert that the studied locations follow this classification. In addition, the guidelines like ASHRAE Handbook [36], OH&S [37], and SafeWork New South Wales (NSW) [38] are also selected for the study. The effect of humidity on thermal comfort is complex. The study also studies different indoor thermal comfort models and indices, measurable physically for spatial assessment, and through observation and experiments for a personalized assessment.

Since the scientific literature is based on existing best practices like standards, guidelines, and codes, the analysis was extended to these documents. Indoor thermal comfort models and indices were also studied as part of this paper. The existing best practices and spatial comfort models are also formulated directly based on operative temperature limits. Some existing literature that studies standards, guidelines, and codes are [39,40].

4. Results

This review was carried out by describing the role of humidity as a thermal comfort parameter for spatial and personalized thermal comfort assessment and its relevance in available literature along with an analysis of the existing standards, guidelines, and codes, physiological and psychological models, and indoor thermal comfort indices incorporating humidity.

4.1. Literature review

The dataset from Scopus recorded 179 publications and WoS records 156 publications for the period from 2000 to 2021 for the chosen string of keywords, which was "***Indoor thermal comfort (and) Humidity (and) Humid climates***". The countries and geographic locations covered in these publications are shown in Fig. 4. The relevance of the existing literature was selected during the data filtering step by screening the titles, keywords, and abstracts for the initial dataset obtained. Only existing literature that was within the scope of the study defined in section 2.2 were considered relevant. The scope of the study was: (i) the study evaluated humidity as a thermal comfort parameter, and (ii) was the study from a humid climatic zone.

A detailed review of these existing studies considering the methodology, location, climate zone as per ASHRAE 169, operation mode, building types, comfort models, and survey type is listed in Table 1. The research from Ref. [42] suggested that relatively high average humidity influences the occupants' thermal comfort. According to the findings of this study, comfort operative temperatures are significantly correlated with humidity feeling and humidity perception of the occupants. Furthermore, during the field studies conducted in Japan, the highest mean comfort temperature was recorded when the occupants felt less humid.

The studies from Ref. [50] offered a methodology that considers four variables like indoor temperature, outdoor temperature, relative humidity, and clothing pattern, as opposed to other available models, which only consider two variables like indoor temperature and outdoor temperature. The study results indicate that except for April, the relative humidity profile is consistent across the 3 different study locations in the northeast regions of India. This occurs since April is a presummer month for the study locations, and the outdoor temperature begins to rise, followed by low precipitation, implying that higher humidity leads to higher temperatures. However, to validate the model developed in the study to predict neutral temperatures with reasonable accuracy, more extensive monitoring and comfort survey at multiple locations is required.

On the contrary, the results from Ref. [47] proposed that humidity has very little effect on the indoor environment when the air temperature and velocity values ensure an acceptable microclimate for sedentary activity and light clothing. However, the enclosed indoor environment in this study was perceived as cooler when the hot air was supplied because the hot jet was mounted on the ceiling, and thus it's mixing with the indoor air in the occupancy zone is imperfect. In addition, the model lacks proper humidity integration and does not consider the air heat balance via evaporation or condensation of water vapor in indoor air condensation phenomena on enclosure surfaces. The comfort models, monitoring, and surveys performed in the reviewed papers considered operative temperature as a paramount parameter except for [8,42].

The review indicates that most publications with a thermal comfort related approach neither consider humidity as an influential parameter even in humid climates, except for [8,42]. The literature review points towards the need for an assessment framework that will include spatial thermal comfort assessment during the initial stages of building design for better HVAC design, which should be followed up with a comprehensive personalized thermal comfort assessment considering the physiological and psychological aspects that influence the occupant's thermal comfort perception during the post-occupancy evaluation.

Table 1 summarizes the literature review of existing studies. This table was created after the full-text review and discussion of articles that satisfied the inclusion criteria from Fig. 3. Each publication was analyzed for.

1. Methodology: Out of the 20 most relevant publications chosen for data analysis in this article through the data collection and filtering process, 15 were observational, 2 were modeling, 1 was experimental, and 2 were both observational and modeling based studies.
2. Location and climate: The review table covered 6 continents and 20 countries. The table also covered existing studies from 0A – extremely hot humid, 1A – very hot humid, 2A – hot humid, 3A – warm humid, and 4A – Mixed humid climatic zones as per ASHRAE 169 classification.
3. Operation mode and building: The table consist of information on the type of building evaluated from existing studies like residential or commercial, and mode of operations like free running, mixed-mode, and/or active cooling.
4. Thermal comfort models: Existing studies used comfort models that were based on standards like ASHRAE 55, EN 15251, ISO 7730, etc. These standards are based primarily on operative temperature limits and ignore the direct influence of humidity on spatial thermal comfort.

Fig. 4. Summary of countries and climatic zones reviewed in the scientific literature.

5. Thermal comfort survey: The studies used thermal comfort surveys like thermal sensation votes from the occupants. These results were then used to correlate the thermal sensation votes and measured temperature, thereby ignoring the effects of humidity in most of the studies except for [8].

The main results from Table 1 indicated that only a few qualitative reviews and field studies examine the role of humidity as an indoor thermal comfort parameter. The concept of incorporating humidity into thermal comfort assessments is still relatively rare except for a few studies that address it [8–10]. Even though [8] proposes a humidity-sensitive thermal comfort model, it is not currently capable of a practical formulation that practitioners can use for a variety of climatic zones, different buildings, and categories. The methodologies used in the previous studies were also developed based on current best practices such as standards, guidelines, and codes. Hence, it is important to investigate how humidity is coupled to thermal comfort in these existing best practices.

4.2. How do the existing standards, guidelines, and codes couple humidity to thermal comfort assessment?

Several documents like standards, guidelines, and codes covering the subject of indoor thermal comfort were chosen based on the humid climates. The scope of these standards was then determined by whether they are: (i) international standards like ASHRAE 55, EN 16798, ISO 7730, etc., which are universally accepted in multiple countries, (ii) national standards like BIS NBC, which is accepted on a country level, in this case in India, or (iii) regional like PERENE Reunion, which is accepted in a region within a country, in this case in Reunion island, France. The main research question investigated here was the coupling between humidity and thermal comfort in these standards and guidelines. The results of this research question are listed in Table 2.

The existing standards, guidelines, and codes propose PMV/PPD model for a static environment and an adaptive model for dynamic environments. However, these limits are primarily based on operative temperature limits, which are absolute for PMV/PPD model, and based on mean outdoor air temperature for the adaptive model. Again, humidity is just prescribed as a lower/higher limit in many of these documents.

The main results from Table 3 indicated that standards like EN 16798, BIS NBC, and NBR 16401–2, among others, have coupled humidity to thermal comfort in PMV/PPD models by providing upper and lower relative humidity thresholds, and thermal comfort zone can be formed from these values, as shown in Fig. 5. ASHRAE 55, on the other hand, couples humidity to thermal comfort via a

Table 2
Summary of humidity and thermal comfort coupling in different standards, guidelines, and codes.

No.	Document	Country/ Region	Scope	Humidity coupled?	How?
Standards					
1	EN 16798 (2019) a. PMV/PPD b. Adaptive	European Union	International	a. Yes b. No	a. For PMV/PPD model, a thermal comfort zone can be formed from the indoor operative temperature (T_{op}) (°C) and relative humidity (RH) (%) thresholds. b. For the adaptive model equation, indoor thermal comfort is influenced by outdoor air temperature (T_{out}) (°C), so no coupling.
2	ISO 7730 (2005)	International	International	No	For PMV/PPD model, there is a coupling of the T_{op} (°C) and RH (%) thresholds.
3	ASHRAE 55 (2020) a. PMV/PPD b. Adaptive	U.S.A and Canada	International	a. Yes b. No	a. For PMV/PPD model, a psychrometric chart couples T_{op} (°C) and RH (%). b. For the adaptive model equation, indoor thermal comfort is influenced by T_{out} (°C), so no coupling.
4	NBC Vol. 2 (2016) a. PMV/PPD b. Adaptive	India	National	a. Yes b. No	a. For PMV/PPD model, a thermal comfort zone can be formed from the T_{op} (°C) and RH (%) thresholds. b. For the adaptive model equation, indoor thermal comfort is influenced by T_{out} (°C), so no coupling.
5	PERENE (2009)	Réunion, France	Regional	No	No coupling between T_{op} (°C) and humidity.
6	SS 554 (2016)	Singapore	National	No	No coupling between T_{op} (°C) and humidity.
7	NBR 16401–2 (2008)	Brazil	National	Yes	A thermal comfort zone can be formed from the T_{op} (°C) and RH (%) thresholds.
8	SNI 6390 (2011)	Indonesia	National	Yes	A thermal comfort zone can be formed from the T_{op} (°C) and RH (%) thresholds.
9	MS 1525 (2014)	Malaysia	National	Yes	A thermal comfort zone can be formed from the indoor air temperature (T_a) (°C) and RH (%) thresholds.
10	GB/T 50,785 (2012)	China	National	Yes	A thermal comfort zone can be formed from the T_{op} (°C) and RH (%) thresholds.
Guidelines					
11	ASHRAE Handbook (2019)	U.S.A and Canada	International	No	No coupling between T_{op} (°C) and humidity.
12	CIBSE Guide A (2015)	UK	National	No	No coupling between T_{op} (°C) and humidity.
13	SafeWork NSW	NSW, Australia	Regional	Yes	A thermal comfort zone can be formed from the T_{op} (°C) and RH (%) thresholds.
14	OH&S (2018)	Australia	National	Yes	A thermal comfort zone can be formed from the T_{op} (°C) and RH (%) thresholds.
Codes					
15	LEHB (1970)	Japan	National	Yes	A thermal comfort zone can be formed from the T_{op} (°C) and RH (%) thresholds.

Table 3
Summary of recommended humidity requirements and control approaches in various standards, guidelines, and codes in terms of operation type, building type, and classification.

No.	Document	Operation type	Building			Classification	Control systems	
			Type	Category	RH% limits		Humidifiers	Dehumidifiers
Standards								
1	EN 16798 (2019)	All	Residential	Category I	30–50	Prescriptive	–	–
			Commercial	Category II	25–60			
				Category III	20–70			
				Absolute Humidity limited to 12 g/kg				
2	ISO 7730 (2005)	All	Offices, schools, etc.	–	60, summer 40, winter	Prescriptive	–	–
3	ASHRAE 55 (2020)	All	–	Absolute Humidity limited to 12 g/kg		Prescriptive	–	–
4	NBC Vol. 2 (2016)	All	Healthcare	Operation rooms	45–55	Performance	Mechanical atomizer	Desiccant
				Sterilizer	30–50		Point-of-use electric	Reheat coil
				Other	30–60		Ultrasonic	
			Data centers	–	25–60			
			Cold rooms	–	>90			
			Subway stations	–	55			
5	PERENE (2009)	Mechanically ventilated	Residential	Zone 3	–	Performance	–	Mechanical ventilation
		Naturally ventilated	Tertiary	Zone 4				
6	SS 554 (2016)	Air-conditioned	Offices, schools, etc.	–	<65, new <70, other	Prescriptive	–	–
7	NBR 16401–2 (2008)	Air-conditioned	–	–	35–65, summer 30–60, winter	Prescriptive	–	–
8	SNI 6390 (2011)	Air-conditioned	Offices	Offices	55–65	Prescriptive	–	–
				Lobbies	50–70			
9	MS 1525 (2014)	Air-conditioned	Commercial	–	50–70	Prescriptive	–	–
10	GB/T 50,785 (2012)	Air-conditioned	Civil buildings	–	40–80, winter 30–60, winter	Prescriptive	–	–
Guidelines								
11	ASHRAE Handbook (2019)	All	Offices	Offices, meeting, and common rooms	50–60, summer 20–30, winter	Performance	Self-contained portable Central atomizer	Desiccant DX refrigeration
				Cafeteria	50–60, summer 20–30, winter		Steam injection	Sprayed coil Air washers
			Stores	–	<50			
			Healthcare	Ancillary	40–50			
				Storage rooms	50			
12	CIBSE Guide A (2015)	Mechanically ventilated	Residential	–	40–60	Performance		–
		Mechanically ventilated	Commercial	–	40–70		Water spray Ultrasonic	
		Naturally ventilated	Residential Commercial	–	40–70		Steam injection	
13	SafeWork NSW	Air-conditioned	Offices	–	40–70	Performance	Evaporative coolers	Desk fans
		Naturally ventilated	Offices	–	>70, hot humid			Pedestal fans
		Both	Offices	–	40–80, extreme			Ceiling fans
14	OH&S (2018)	Air-conditioned	Offices	–	40–60, ideal	Prescriptive	–	–
				–	30–70, extreme			

(*continued on next page*)

Table 3 (*continued*)

No.	Document	Operation type	Building			Classification	Control systems	
			Type	Category	RH% limits		Humidifiers	Dehumidifiers
Code								
15	LEHB (1970)	All	>3000 m^2: Offices >8000 m^2: Schools	–	40–70	Prescriptive	–	–

psychrometric chart for operative temperature, relative humidity, humidity ratio, and wet bulb temperature. In the case of the adaptive model equations, the outdoor running mean temperature, calculated from the outdoor air temperature, influences indoor thermal comfort. Hence, there is no humidity to thermal comfort coupling in the adaptive model from EN 16798, ASHRAE 55, and BIS NBC, among others. However, standards like ISO 7730, and guidelines like CIBSE Guide A and ASHRAE Handbook do not provide any coupling. Furthermore, a thermal comfort zone graph can be formed from the psychrometric graphs provided in ASHRAE 55 [1,59]. In Fig. 5, the ASHRAE comfort zone is divided into comfortable and still comfortable with uncomfortably humid, warm, arid, and cold areas.

The investigation of humidity coupling in current thermal comfort standards indicated that humidity can be coupled with operative temperature for PMV/PPD models, so this paper explores the recommended humidity requirements in these best practices.

4.3. How do these standards, guidelines, and codes recommend humidity requirements?

Table 3 analyzes the existing standards, guidelines, and codes based on.

1. Operation type: Indicates if the analyzed document is for naturally ventilated and/or mechanically ventilated operation.
2. Building type: Analyzes if the standard is for residential and/or commercial buildings, including categories and relative humidity thresholds.
3. Classification: The standards, guidelines, and codes are classified as prescriptive if it only provides humidity thresholds and as performance, if a humidity control technology is included.
4. Control approaches: The humidity control systems like humidifiers and dehumidifiers recommended in the documents are also included in Table 3.

The main results from Table 3 indicated that standards like EN 16798, ISO 7730, CIBSE Guide A, etc., recommended relative humidity in percentage values. However, ASHRAE 55 recommended absolute humidity in g/kg. These standards also recommended humidity limits for mechanically ventilated, naturally ventilated, and air-conditioned buildings. Standards like EN16798, among others also recommend humidity limits for all building operation types.

The building type would be classified as residential and commercial as EN 16798 or as offices, schools, and stores as in ISO 7730. Building categories also varied from one standard to another. EN 16798 categorized the buildings from I to III based on new and existing buildings, whereas ASHRAE Handbook for HVAC applications categorized the building rooms as office rooms, conference rooms, cafeterias, etc. The analysis is listed in Table 3.

In addition, prescriptive standards that recommended directives include EN 16798, ISO 7730, etc., and guidelines like OH&S. Performance guidelines that recommended control systems in addition to directives include the ASHRAE handbook, CIBSE Guide A, etc. Standards like BIS NBC and guidelines like SafeWork NSW recommended both humidifiers and dehumidifiers, whereas guidelines

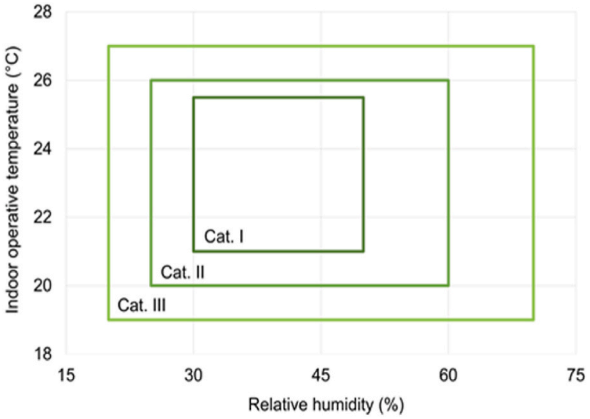

Fig. 5. Thermal comfort zone between relative humidity and indoor operative temperature for spatial assessments from 16,798 PMV/PPD model for categories I to III - office buildings.

Table 4
Summary of physiological and psychological models for personalized thermal comfort assessment.

No.	Models	Principle	Humidity coupled?	How?
Physiological models				
1	Two-node model with transient response [65]	This model combined the modified version of the two-node model [22] with the transient clothing model [66]. The two-node model determined the regulatory sweat rate, which is thought to be uniform throughout the entire body. For each segment, skin temperature and vapor pressure were calculated. The clothing model determined the sensible and latent heat loss to the environment from each segment and clothing surface.	Yes	Evaporative heat loss from each segment and clothing surface is calculated.
2	Multi-node thermal model [67,68]	In the Stolwijk model, the body was essentially divided into six segments, with each segment being further subdivided into four layers in a radial direction. This model has a higher precision and flexibility compared to the earlier models since physiological phenomena for each section can be controlled. Despite being limited to constant environmental conditions, the majority of multi-segment, multi-node bioheat models today were based on this model.	Yes	Evaporative heat loss from the skin is accounted for in this model.
3	Multi-node thermal model, 65-node [69]	This model used the Stolwijk model as a base with 16 body sections on the model, each consisting of core, muscle, fat, and skin subsections. Thermal manikin experiments were used to derive the convective and radiative heat transfer coefficients. Under the conditions of thermal neutrality, this model can predict the skin temperature distribution reasonably well. Under transient conditions, the evaporative heat loss trends and mean skin temperature trends matched those in the Stolwijk experiment.	Yes	Evaporative heat loss from the skin is accounted for in this model.
4	Multi-node thermal model w/arbitrary number of segments [70]	Based on the Stolwijk model, the Berkeley model offered enhancements like unlimited body segments. Various physiological processes like sweating, vasodilation, and metabolic heat production were explicitly considered in this model. The model treated convection, conduction to surfaces in contact with the body, and radiation between the body and the environment independently. The model can predict how the human body reacted to transient, non-uniform thermal environments.	Yes	Evaporative heat loss from the skin is accounted for in this model.
Psychological models				
5	Local SET[b]: Uniform and non-uniform [71,72]	A two-node prediction method substituted the subjective evaluations and predicted the distribution of heat flux through the skin surface, skin temperature, and skin wettedness. The target precision for the skin temperature was less than 1 °C. Therefore, first-order approximation nearly achieved the desired performance. However, a sizable amount of additional research will be necessary to develop a general, inclusive, and universal prediction method.	Yes	The model is based on the heat balance equation and accounts for evaporative heat transfer.
6	New thermal comfort zones based on t_{eq}: Steady-state and non-uniform [73,74]	This method aimed at combining different climate evaluation methods like human subjective ratings, manikin measurements, and computer modeling. The model used equivalent temperature, which included non-evaporative heat loss from the body. The model used clothing independent zones to convert comfort sensations into physical quantities. This is not always true since the clothing insulation influenced the heat loss and this requires further investigation and development.	No	The model doesn't include a thermoregulation model and evaporative heat loss from the skin is not reliable.
7	Dynamic thermal sensation model [75,76]	Developed based on experiments assessing thermal sensation using the ASHRAE seven point scale. A transient thermal sensation model was proposed based on the regression analysis of the experimental data and IESD-Fiala physiological model results.	Yes	The latent heat and mass transfer through processes like respiration, sweating, etc., are accounted for in this model.

(continued on next page)

Table 4 (*continued*)

No.	Models	Principle	Humidity coupled?	How?
8	UC Berkeley thermal comfort model [78,79]	The dynamic component of thermal sensation was comprised using a positive and negative changing rate of the mean skin temperature. This model incorporated static and dynamic inputs, similar to Wang's thermal sensation model [77]. One of the main constraints of this model was that it does not account for the effects of non-uniform environments. This model considered the intra-personal variations in sensation and comfort, both between the perceived whole-body sensation and among the local body parts. The UC Berkeley thermal comfort model assessed comfort and sensation response patterns for transient and stable conditions for both uniform and non-uniform thermal environments.	Yes	The model accounts for skin temperature during heating and cooling cycles.

like CIBSE Guide A proposed only humidifiers and standards like PERENE Réunion recommended only dehumidifiers.

4.4. How do existing indoor physiological and psychological thermal comfort models for personalized assessment account for humidity?

In Table 4, various physiological and psychological thermal comfort models were analyzed. In this table.

1. The main principle behind these models was studied.
2. It was also considered if the humidity was coupled in these models.
3. The Table also includes how humidity was coupled to these models.

The main results from Table 4 indicated that when the air temperature is in the comfortable range, humidity has a minimal impact on thermal perception according to Ref. [60]. The evaporative heat loss from human skin was found in earlier studies to be influenced by relative humidity in warm conditions, which would also affect thermal perception [61,62]. It is important to understand how relative humidity affected human thermal perception in both steady-state [63,64] and transient conditions [65,66]. Different physiological and psychological thermal comfort models are listed in Table 4.

The personalized models examined here addressed the human responses to both non-uniform and transient conditions with a thermoregulation model, but they are restricted to specific environments. The UC Berkeley thermal comfort model focuses on the cooling effects in warm environments, whereas the Fiala model seems to primarily address the transient conditions. Hence, further research and development are required for the existing physiological and psychological comfort models that consider asymmetrical environments.

In addition, high humidity levels in warm environments can make people feel uncomfortable if they have too much moisture on their skin. In addition, higher humidity tempers local discomfort from overcooling parts of the skin due to evaporation at cooler temperatures. However, this effect is highly dependent on the local sensations of the skin rather than the whole body itself. Numerous models have been developed to predict thermal comfort conditions, as listed in Table 4. A detailed numerical investigation of these models was done in Ref. [12]. Both physiological and psychological models developed for personalized thermal comfort assessment do not include the humidity signal directly. However, these models do consider parameters like evaporative heat transfer, thereby accounting for the effects of humidity indirectly.

4.5. How does existing indoor thermal comfort incorporate humidity - a point-in-time or time-integrated approach?

In Table 5, the following parameters were studied.

1. Humidity indices: Here, different indices that consider humidity in an indoor environment were studied.
2. Equation: This includes how these indices can be mathematically computed.
3. Index type: This indicated if the indices only consisted of measurable environmental parameters or if they included personal parameters like metabolic rates. Spatial indices are measurable, whereas personal indices include measurable and personal parameters.
4. Humidity coupling: This identified whether the humidity indices are coupled with other parameters like air temperature, or if they are uncoupled.
5. Time temporality: Point-in-time indices evaluate the parameters at a single point or an instantaneous moment, whereas time-integrated indices evaluate the parameter over a while and predict the underlying phenomena, synthetically.

The main results from Table 5 indicated that the indoor thermal comfort indices from no. 1 to 7 can be used by building designers and engineers for spatial thermal comfort assessment during the early-stage building design, whereas the comfort indices from no. 8 to 11 can be used for a personalized post-occupancy thermal comfort assessment including the personal factors, which influence the occupant's comfort. In addition, the analysis of existing indices found that these indices use a point-in-time approach.

Table 5
Summary of indoor thermal comfort indices in terms of type, humidity coupling, and time temporality.

No.	Indices	Equation	Index Type	Humidity coupling	Time temporality
1	Relative humidity [80]	$RH = \frac{P_W}{P_{WS}} \bullet 100\%$ where P_W is the water vapor pressure in (Pa). P_{WS} is the saturation water vapor pressure (Pa).	Spatial	Uncoupled	Point-in-time
2	Absolute humidity [81]	$AH = \frac{M_{H_2O} \bullet P_W}{R \bullet T_K}$ Where M_{H_2O} is the molecular mass of water (g/mol). P_W is the water vapor pressure in (Pa). R is the universal gas constant 8.3145 J K^{-1} mol^{-1}. T_K is the temperature (K).	Spatial	Uncoupled	Point-in-time
3	Specific humidity [82]	$q = \frac{r_v}{1 + r_v}$ where q is the specific humidity. r_v is the mixing ratio. $r_v = \frac{0.622e}{p - e}$ where e is the water vapor pressure (Pa). p is the pressure (Pa).	Spatial	Uncoupled	Point-in-time
4	Enthalpy [83]	$h = (1.007 \bullet T - 0.026) + (2502 - 0.538 \bullet T) \bullet \frac{0.622}{\left(\frac{P_a}{\left(\frac{RH}{100}\right) \bullet 10^{\left(\frac{0.7859 + 0.03477 \bullet T}{1 + 0.00412 * T} + 2\right)}}\right) - 0.378}$ where T is the temperature from 0 to 40 °C. RH is the relative humidity (%). P_a is the atmospheric pressure (Pa).	Spatial	Coupled	Point-in-time
5	New Effective Temperature [84]	$ET^* = 37 - (37 - T_a) \bullet [0.68 - 0.0014 \bullet RH + (1.76 + 1.4 \bullet {V_a}^{0.75})^{-1}]^{-1}$ where T_a is the air temperature (°C). RH is the relative humidity (%). V_a is the air velocity (m/s).	Spatial	Coupled	Point-in-time
6	Effective Temperature [85]	$ET = T_a - \left(0.4 \bullet (T_a - 10) \bullet \left(1 - \frac{RH}{100}\right)\right)$ where T_a is the air temperature (°C). RH is the relative humidity (%).	Spatial	Coupled	Point-in-time
7	Humidex [86,87]	$Humidex = T_a + \frac{5}{9}(e - 10)$ $e = 6.112 \times 10^{\left(\frac{7.5T_a}{237.7 + T_a}\right)} \times \frac{RH}{100}$ where T_a is the air temperature (°C). RH is the relative humidity (%).	Spatial	Coupled	Point-in-time
8	Wet Bulb Globe Temperature [88]	$WBGT = (0.7 \bullet T_{WB}) + (0.3 \bullet T_g)$ where T_{WB} is the wet-bulb temperature (°C). T_g is the globe temperature (%).	Personal	Coupled	Point-in-time
9	Standard Effective Temperature [1,89]	For thermal equilibrium between 23 and 41 °C, SET is linearly related to the average body temperature (T_b): $SET = 34.95 \bullet T_b - 1247.60$ below 23 °C: $SET = 23 - 6.13 \bullet (36.4 - T_b)^{0.70}$ Above 41 °C: $SET = 41 + 5.58 \bullet (T_b - 36.9)^{0.87}$ The measurement procedure determines the mean radiant temperature (T_{mrt}), then air velocity (v), evaluates metabolic rate (M), and clothing (clo), then predicts the average body temperature (T_b) by using the two-node model.	Personal	Coupled	Point-in-time
10	Predicted Mean Vote [4]	$PMV = \left(0.352e^{-0.42\left(\frac{M}{A_{Du}}\right)} + 0.032\right)\left[\frac{M}{A_{Du}}(1 - \eta) - 0.3\left[43 - 0.061\frac{M}{A_{Du}}(1 - \eta) - p_a\right] - 0.42\left[\frac{M}{A_{Du}}(1 - \eta) - 50\right] - 0.023\frac{M}{A_{Du}}(44 - p_a) - 0.0014\frac{M}{A_{Du}}(34 - T_a) - 3.4 \cdot 10^{-8} f_{cl}\left[(T_{cl} + 273)^4 - (T_{mrt} + 273)^4 - f_{cl} \cdot h_{cl}(T_{cl} - T_a)\right]\right]$ where M is the metabolic rate (met). A_{Du} is the surface area of the human body (m^2). η is the mechanic efficiency. p_a is the ambient vapor pressure (Pa). T_a is the ambient air temperature (°C). f_{cl} is the clothing insulation factor (clo).	Personal	Coupled	Point-in-time

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Table 5 (*continued*)

No.	Indices	Equation	Index Type	Humidity coupling	Time temporality
		T_{cl} is the surface temperature of clothing (°C). T_{mrt} is the mean radiant temperature (°C). h_{cl} is the convective heat transfer coefficient (W/m^2.°C).			
11	Predicted Percentage of Dissatisfied [4]	$PPD = 100 - \left(95 \times e^{-\left(0.03353 \times PMV^4 + 0.2179 \times PMV^2\right)}\right)$	Personal	Coupled	Point-in-time

5. Discussion

This section presents the study's main findings, limitations, and makes suggestions to building designers, engineers, and scientists for future practice and future work involving spatial and personalized thermal comfort assessments.

5.1. *Main findings*

The main findings of this study were.

1. Surprisingly, there is no convincing formulation up to date on the effect of humidity on indoor thermal comfort, except in Ref. [8] for spatial assessment. A prior study that developed an adaptive model for the hot-humid regions of southeast Asia discovered a comfort equation for naturally ventilated buildings that were similar to the ASHRAE adaptive model [11].
2. Many standards, like EN 16798, ISO 7730, BIS NBC, etc., prescribes an upper and lower threshold value for relative humidity, whereas standards like ASHRAE 55 do not provide any thresholds for relative humidity. Humidity coupling to thermal comfort models is more evident in PMV/PPD models, whereas the humidity signal is absent in adaptive model equations.
3. The existing indoor comfort indices with humidity use a point-in-time approach where the measured parameter is evaluated at a single point in time or an instantaneous moment. There is a need to develop indices that can measure the thermal comfort parameters over a while and predict the underlying phenomena like overheating.
4. There is a need for the development of an indoor hygrothermal discomfort indicator, which assesses comfort in terms of both operative temperature and relative humidity. The IOD index proposed by Ref. [90] considers the characteristics of this suggested indicator like time-integration and multizonal analysis. However, this index is based on operative temperature and ignores relative humidity. Another disadvantage of the existing IOD index is that there are no recommended threshold values for limiting short-term and long-term overheating [91,92].
5. Humidity has a complicated impact on thermal comfort. This is since evaporative heat loss from the skin is how humidity primarily affects thermal comfort. Along with humidity, and vapor pressure difference, evaporative heat loss is also influenced by air velocity, skin wettedness, etc. [22,23]. To understand how humidity affects thermal comfort, future work should perform spatial assessments along with personalized assessments that take the human factor into account through quantitative field measurements and qualitative surveys.
6. If people are already in a thermal steady state below the sweating threshold, high humidity is not perceptible, right up to 100%. Here, high humidity might feel sultry because the occupants who are initially in heat balance cannot significantly elevate their activity level without breaking a sweat. This in turn will increase their skin wettedness due to the lost evaporative potential caused by the humid environment. Therefore, transient process like the metabolic rate that changes in warm temperatures and humidities also affects comfort perception.
7. The air movement rate across the skin enhances the convective heat and moisture loss for a given skin-to-air temperature difference and allows acceptable comfort at higher humidities for a given sweat rate. This will allow higher acceptable humidities for a given sweat rate [22,23]. In addition, higher humidities can also temper local discomfort caused by overcooling parts of the skin due to evaporation at cooler temperatures.
8. The study findings indicated that thermal comfort is not influenced just by temperature. At very low humidity levels, the occupants could feel warm and still feel comfortable or slightly uncomfortable. However, at very higher humidity levels, they would feel very uncomfortable. This level of comfort or discomfort will influence their actions, such as turning on the fan or air conditioner, etc. Therefore, humidity should be considered while addressing thermal comfort and overheating issues.

5.2. *Limitations*

As far as the limitations of this study are concerned.

1. The concept of incorporating humidity in thermal comfort assessments is still relatively rare except for a few studies that address it [8–10].
2. Although the current paper recommended a humidity-based adaptive thermal comfort model from Ref. [8] and a hygrothermal discomfort indicator, neither is capable of a practical formulation that practitioners can use at this time for a wide range of climatic zones and different building types and categories.
3. Therefore, the paper was a strictly qualitative and review-based study, and new thermal comfort assessments and models must be validated by comprehensive experimental field studies with quantitative measurements [92] and qualitative surveys.

5.3. Suggestions for practice and future work

The suggestions for future practice and future work are.

1. Future developments should include the incorporation of the humidity signal into the building design to ensure comfort and health, even though humidity can be mitigated by a variety of adaptive activities like fans, opening windows, and clothing, among others [10,93]. These developments should consider early-stage spatial assessment and post-occupancy personalized assessments.
2. The humidity sensitive adaptive thermal comfort model in Ref. [8] depicts the effects of outdoor relative humidity on indoor comfort temperature for spatial thermal comfort assessment. A more significant question for future work could be the effects of outdoor temperature and humidity on the indoor acceptable humidity level.
3. Future work should implement comprehensive experimental field studies that assess the effects of humidity on the subjective perception of the occupants. These models should be discussed and validated based on ASHRAE global database II, which is a more current database compared to the original database used to develop the model [8]. These studies should focus on developing an adaptive comfort limit for indoor humidity based on outdoor temperature and humidity for spatial assessment.
4. The difference of up to 4 °C in comfort temperature between the high and low humid environments [8] will affect the building energy consumption. Maintaining the humidity levels of indoor environments through energy-efficient humidity control approaches like ventilation dehumidification will impact the overall building energy efficiency by decreasing the cooling load.
5. Future studies should focus on the effect of transient processes like metabolic activities on thermal comfort perception in addition to relative humidity. These studies should develop an empirical model, which can effectively account for these effects. Physiological and psychological reactions complicate human thermal sensation and comfort in asymmetrical environments. This subject has been the focus of research for decades. However, a complete thermal comfort model should include physical, physiological, and psychological factors.
6. The effects of higher humidity levels are more on local skin sensations rather than the whole body skin sensation itself. Hence, it is important to design higher humidity thresholds from the heat balance model for localized parts of the body. This model should also include local sensation and comfort for both dynamic and steady-state environments.
7. Building experts commonly agree that there is a growing risk of overheating in buildings due to the impact of climate change [94] and thus it is important to develop new indicators and comfort models that could predict and monitor the extent of discomfort.
8. The existing standards should include these new indicators in the future, as well as sustainability assessment methods, such as Building Research Establishment Environmental Assessment Method (BREEAM), and Leadership in Energy and Environmental Design (LEED), among others. Software like DesignBuilder which is used to design building models should also implement these indicators for early-stage building design.
9. Future studies should include the assessment of the effects of humidity on occupant health like sensory irritation as analyzed in various studies [95–97]. Incorporating humidity into thermal comfort assessment models could pave a path toward a common indicator integrating thermal comfort and occupant health.
10. Despite all the research into thermal comfort, there are still concerns about using it as a framework for evaluating issues such as morbidity and mortality, during extreme events like heatwaves [98].
11. Furthermore, existing models lack true understanding when it comes to the most vulnerable population like the elderly [99]. As a result, additional research into thermal comfort and its impact on morbidity and mortality rates is needed to solidify our understanding.
12. It will be useful to have a hygrothermal indicator to compare the effects of thermal comfort on occupant health while considering various physiological and psychological parameters in line with existing regulatory documents like national building codes.

6. Conclusion

The main concepts and criteria of this paper were based on qualitative research methodology. Future research should build on the paper's findings to develop a more humidity inclusive thermal comfort framework for spatial and personalized assessments that includes consistent comfort models, quantifiable discomfort indicators, and performance threshold limits for control approaches validated by comprehensive experimental field studies and surveys. The paper also supports and guides the building professionals' and designers' decision-making in assessing indoor discomfort while accounting for humidity. This paper reiterated the importance of considering humidity as a thermal comfort parameter, as its direct effect is ruled out in existing adaptive thermal comfort models for spatial assessment. The current paper also recommended personalized assessments during post-occupancy periods. Future research should be expanded to identify benchmarks and case studies with reference values and threshold ranges, as well as tools and reporting mechanisms for hygrothermal discomfort in buildings. Finally, we recommend that the humidity inclusive thermal comfort framework should evolve in terms of research and practice while contributing to a better understanding of hygrothermal discomfort, energy efficiency, and occupant health.

CRediT author statement

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Methodology, Validation, Writing – Reviewing and Editing, Visualization. Mirjana Velickovic: Conceptualization, Validation, Writing – Reviewing and Editing, Project administration, Funding acquisition, Shady Attia: Conceptualization, Methodology, Supervision, Validation, Writing – Reviewing and Editing, Resources, Visualization, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

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

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