Title: Understanding the challenges of determining thermal comfort in vernacular dwellings: a meta-analysis

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Abstract

The thermal comfort assessment of vernacular dwellings, as well as their inherently linked thermal dynamic modelling process, present specific challenges which remain unaddressed in the literature. The overarching purpose of this review is to identify and analyse the main methods and challenges in thermal comfort evaluation and modelling of vernacular dwellings and recommend pathways for future improvement.

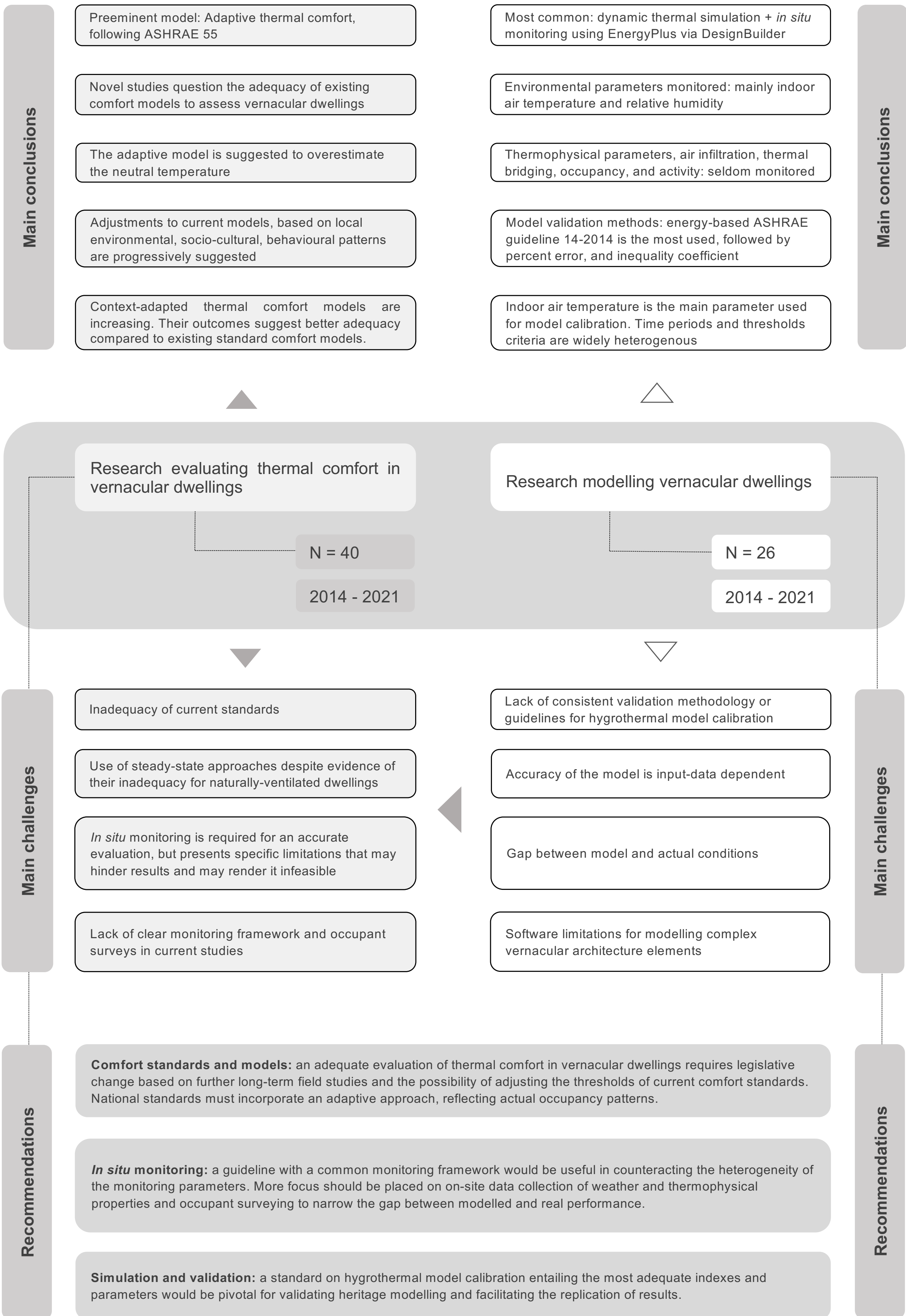
The main challenges found regarding thermal comfort evaluation intertwine with those of modelling vernacular dwellings. These are: i. the inadequacy of current standards; ii. the use of steady-state approaches despite evidence of their inadequacy; iii. the lack of a clear monitoring framework and insufficient occupant surveying; iv. increased uncertainty from imprecise or unfeasible *in situ* monitoring; v. inaccurate modelling, due to a lack of consistent methodology and guidelines for hygrothermal model calibration; imprecise input data and; inherent software limitations in modelling vernacular elements.

The main recommendations identified through this analysis include the improvement of current comfort standards and models based on further long-term field studies and the possibility of adjusting their thresholds, the development of a common monitoring framework and which parameters to focus on, and the creation of a standard on hygrothermal model calibration entailing the most adequate indexes and variables.

Keywords: Indoor thermal comfort, vernacular dwellings, adaptive comfort evaluation, model calibration.

[1]

Abbreviations: AMV: Actual Mean Vote; CV(RMSE): Coefficient of variation of the RMSE (%); MAE: Mean Absolute Error; MBE: Mean Bias Error; MCV: Mean Comfort Vote; NMBE: Normalised Mean Bias Error; PMV: Predicted Mean Vote; PPD: Predicted Percentage Dissatisfied; TS: Thermal sensation.



Graphical Abstract.

1. Introduction

The adaptive approach stands out as the model of choice for thermal comfort assessment in dwellings [1]. This is also found to be the case in traditional and vernacular dwellings, a free-running sub-category within residential buildings, where occupants regulate thermal conditions by resorting to adaptive strategies [2–5]. While recent research has started to address the evaluation of thermal comfort conditions in vernacular dwellings, existing studies mainly focus on assessing sustainability strategies [5,6] due to the challenges linked to their thermal comfort assessment. Further research on these challenges is needed to improve the accuracy of thermal comfort evaluations and, thus, heritage conservation measures for these dwellings.

This much-needed review aims to be a first stepping stone in helping address this gap, by identifying and analysing the main methods and challenges in thermal comfort assessment and modelling of vernacular dwellings and suggesting recommendations to overcome them. By doing so, this research significantly contributes to fostering correctly executed future work within this critical area and, hence, the adequate preservation strategies to be applied to cultural heritage worldwide.

2. Thermal comfort assessment in vernacular dwellings: analysis of research

This section provides an up-to-date overview of the most relevant research published in the past seven years on indoor thermal comfort evaluation in vernacular dwellings (Table 1). Regarding the inclusion criteria, apart from the publication date, studies reporting free-floating thermal indoor environmental performance but unaffiliated to any indoor comfort standard, were excluded from this overview. The main features of how thermal comfort is assessed in vernacular dwellings are listed in Table 1 under: case study location, climate classification, building materials, type of methods, monitoring standard, questionnaire standard, comfort model, and comfort evaluation standard.

2.1. Main features: case studies location, climate, and building materials

In recent years, Asian vernacular case studies have been the most assessed in regard to indoor thermal comfort [3,7,16–25,8,26,27,9–15] (60% of the analysed research), covering a wide variety of humid climate locations, which may be due to not only the prevalence of vernacular architecture at these locations but also the extensive availability of case studies that retain their residential functions. These are then followed at a considerable distance by Portuguese vernacular dwellings [2,5,28], in a Mediterranean hot-dry climate, generally built with local materials such as earth (adobe brick, rammed-earth), stone and wood, and dating back as far as the 17th century, and Iranian vernacular dwellings [29–31], mixing earth, brick, and limestone, in a hot-dry and hot-humid tropical climate.

2.2. Main methods

2.2.1. Quantitative, qualitative, and mixed-methods

Different methodological approaches, quantitative (i.e. *in situ* monitoring, simulation model, and laboratory measurements) and qualitative (i.e. questionnaire-based survey), were found to be implemented in the thermal comfort evaluation of vernacular dwellings. In particular, the combination of *in situ* short-term monitoring and questionnaire-based occupant surveys stood out as a popular method. For the purpose of this analysis, monitoring periods under three months were considered short-term, while those exceeding a three-month period in total referred to as long-term monitoring. Most recently, studies coupled *in situ* monitoring with dynamic simulation for thermal comfort assessment, mostly using EnergyPlus via the DesignBuilder interface [15,26,30,32–35]. Further details are presented in the modelling analysis in the next section (3. Modelling vernacular dwellings: analysis of research).

2.2.2. Monitoring and occupant survey standards

ASHRAE Standard 55, ISO 7726, and ISO 7730 are the most frequently used standards for monitoring-based studies, while the occupant surveys are largely based on Appendix E of ASHRAE standard 55, Thermal Environment Survey, and ASHRAE's Thermal sensation (TS) scale.

2.2.3. Comfort model and evaluation standards

The adaptive thermal comfort model accounts for the overwhelming majority of vernacular thermal comfort assessments, by itself [2,3,18,19,21–24,26–28,31,5,34–39,7–9,11,13,16,17] or alongside the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) indexes of Fanger's model for comparison purposes [15,25,32,40–43]. The PMV and PPD indexes alone [20,29,30] and the Olgyay and Givoni models [33,44] are scarcely used. Additionally, the former is considered inadequate to predict thermal comfort in naturally-ventilated dwellings, such as vernacular ones, as results deviate from real indoor conditions [10,15].

The preeminent thermal comfort assessment standard is ASHRAE 55, both as a stand-alone [3,8,31,33–35,37–40,10,12,16–19,21,26], and in combination with EN 15251 [2,5,7,9] and national building codes [11,14,25,44]. No studies adopting the updated EN 16798 were found.

2.3. Questioning current comfort models

Vernacular dwellings are often considered beyond the scope of 'modern' thermal comfort models, which are considered to inadequately represent their specific conditions. Novel studies shedding light on whether existing comfort models are adequate to evaluate thermal comfort in these buildings are emerging. In fact, nearly all research questioned the adequacy of existing comfort standards and local building and energy codes in assessing thermal comfort in vernacular dwellings. Furthermore, while most studies adopting an adaptive comfort model consider it suitable for evaluating vernacular thermal comfort conditions, a handful of studies point to its deviation from experimental values and overestimation of the neutral temperature (i.e. as an estimation of comfort temperature) due to not considering behavioural, psychological, and physiological adaptation parameters. Adjustments to the existing comfort models are subsequently suggested by setting forth modified equations to predict thermal comfort based on local environmental parameters, socio-cultural setting, behavioural action, activities and clothing pattern, which specifically characterise vernacular dwellings [2,12,13,19,22,28]. As a result, context-adapted thermal comfort models are becoming increasingly available, and their published outcomes suggest overall better results compared to existing standard comfort models.

Table 1
Overview of recent studies focusing on thermal comfort assessment in vernacular dwellings, in chronological order.

	Reference	Case study location	Climate classification	Building materials	Methods		Monitoring Standard	Questionnaire Standard	Comfort model	Comfort evaluation standard
					Quantitative	Qualitative				
[40]	Adunola, 2014	Nigeria, Ibadan	Tropical climate	Laterite, clay brick, sandcrete blocks	Short-term monitoring [2]	Question. survey	-	ASHRAE 55 and TS scale	Adaptive; MCV	ASHRAE Standard 55
[7]	Du et al., 2014	China, Chongqing	Hot summer and cold winter Climate	Wood structure, stone and brick walls, grey tiled roof	Short-term monitoring	-	-	-	Adaptive	ASHRAE Standard 55; EN15251
[8]	Kubota et al., 2014	Malaysia, Malacca	Hot-humid climate	Timber frame and brick/concrete with lime plaster masonry walls	Short-term monitoring	-	-	-	Adaptive	ASHRAE Standard 55
[41]	Nematchoua et al., 2014	Cameroon, Nkongsam-ba; Douala; Bafang	Equatorial climate	Clay bricks, wood or planks, breeze blocks	Long-term monitoring	Questionnaire survey	ASHRAE Standard 55 ISO 7730	ISO 7730; ISO 10551	Adaptive PMV; PPD	ISO 7730; ISO 10551
[9]	Djamila et al., 2015	Malaysia, Kota Kinabalu	Equatorial humid climate	Wood	-	Questionnaire survey	-	ASHRAE Standard 55, ASHRAE TS scale	Adaptive; Griffiths method	ASHRAE Standard 55; EN15251
[2]	Fernandes et al., 2015	Portugal, Tabuaço; Moura	Mediterranean climate, sub--type with rainy winters and hot and dry summers	Granite walls, timber ceiling and balcony Lime-washed rammed-earth walls, clay floor tile, timber roof with ceramic tiles	Short-term monitoring	Questionnaire survey	ISO 7726; ISO 7730; ASHRAE Standard 55-2010	ASHRAE Standard 55-2010; ASHRAE TS scale	Adaptive	EN15251; Adaptation of ASHRAE Standard 55-2010
[28]	Fernandes et al., 2015b	Portugal, Évora	Mediterranean temperate with hot and dry summer	Rammed-earth/Massive brick masonry	Short-term monitoring	-	-	-	Adaptive	Adaptation of ASHRAE Standard 55-2010
[10]	Hermawan et al., 2015	Indonesia, Java	Humid tropical climate	Timber-frame walls	Short-term monitoring	Questionnaire survey	-	ASHRAE Standard 55-2004; ASHRAE TS scale	AMV/PMV	ASHRAE Standard 55-2004
[11]	Sarkar et al., 2015	India, Mandi	Sub-tropical climate with warm summers and cold winters	Thick adobe and stone wall with mud plaster	Short-term monitoring	Questionnaire survey	ASHRAE Standard 55-2004	ASHRAE Standard 55-2004; ASHRAE TS scale	Adaptive	ASHRAE 55; Indian Building Code 2005; Tropical summer Index
[12]	Singh et al., 2015	India, Tezpur; Imphal; Cherrapunjee	Warm and humid; cool and humid; cold and cloudy zones	Lightweight walls, porous structure	Long-term monitoring	Questionnaire survey	-	ASHRAE Standard 55-2013; ASHRAE TS scale	Adaptive (Humphreys)	ASHRAE Standard 55-2013
[32]	Stefanizzi et al., 2015	Italy, Brindisi	Mild and temperate climate	Limestone and sand containing clay	Long-term monitoring Simulation model - DesignBuilder	-	-	-	Adaptive, PMV	EN15251, ISO 7730
[13]	Toe & Kubota, 2015	Malaysia, Pontian; Malacca	Hot-humid climate	Zinc roof, timber structure, wooden walls and flooring; Lime-plastered brick walls	Short-term monitoring	-	-	-	Adaptive (equa-tion by authors)	Adaptive equation based on RP-884

[2] For the purposes of this overview, monitoring periods inferior to 3 months are referred to as short-term monitoring, while those that exceed a 3-months period as a whole are referred to as long-term monitoring, based on [66].

[31]	Foruzanmehr et al., 2016	Iran, Yazd	Hot-dry climate	Mud brick walls	Short-term monitoring	Questionnaire survey	-	ASHRAE Standard 55-2004; ASHRAE TS scale	Adaptive	ASHRAE Standard 55-2004
[14]	Huang et al., 2016	China, Lhasa	Snow climate (dry winters and cold summers); polar tundra	Adobe clay, granite slab, lime sand render Roof w/ tree branches, gravel, and clay	Short-term monitoring	Questionnaire survey	-	ASHRAE Standard 55 ASHRAE TS scale	Adaptive; PPD	ASHRAE Standard 55; GB/T50785; ISO 7730
[37]	Rubio-Bellido et al., 2016	Spain, Cádiz	Hot-summer Mediterranean climate	Porous stone, sedimentary rock	Long-term monitoring Simulation model – DianaX	-	-	-	Adaptive	ASHRAE Standard 55
[15]	Shastry et al., 2016	India, Suggenahalli	Warm-humid climate	Stones and boulders for walls, mud floors	Long-term monitoring Simulation model – DesignBuilder	Questionnaire survey	-	ASHRAE Standard 55-2004 (modified version)	Humphreys Adapt; PMV/PPD	EN15251; ISO 7730
[16]	Yan et al., 2016	China, Turfan	Hot-arid climate	Soil or brick-soil walls, wooden flat roof covered with soil	Short-term monitoring	Questionnaire survey	ISO7726 (2001)	ASHRAE Standard 55-2010; ASHRAE TS scale	Adaptive	ASHRAE Standard 55-2010
[17]	Gupta et al., 2017	India, Jharkhand	Composite climate with hot dry summers and cold winters	Mud mixed with cow dung, straw, gravel, And clay-tiled roofs	Short-term monitoring Simulation model - Ecotect	-	-	-	Adaptive; discomfort hours	ASHRAE Standard 55
[18]	Huang et al., 2017	China, Zhaji	Humid climate	Clay bricks and timber wood	Long-term monitoring	-	-	-	Adaptive	ASHRAE 55-2013
[19]	Kubota et al., 2017	Malaysia, Malacca	Hot-humid climate	Timber frame and concrete column and brick with lime plaster masonry walls	Short-term monitoring	-	-	-	Adaptive (equa-tion by authors)	ASHRAE Standard 55
[20]	Liu et al., 2018	China, Hunan	Humid subtropical climate	Fir wood	Short-term monitoring Simulation model – DeST-h	-	-	-	PMV, PPD	ISO7730
[33]	Mallea et al., 2018	Spain, Basque Country	Temperate-humid climate	Heavy stonewalls (sandstone, limestone), lime mortar coating	Simulation model - DesignBuilder	-	-	-	Adaptive; Olygay and Givoni	ASHRAE Standard 55-2013
[34]	Rajapaksha, 2018	Italy, Pompeii	Hot-summer Mediterranean climate	Volcanic rock and sand	Short-term monitoring Simulation model - DesignBuilder	-	-	-	Adaptive; De Dear & Brager	ASHRAE Standard 55
[29]	Shaeri et al., 2018	Iran, Bushehr	Tropical, hot-humid climate	Coral reef limestone, mortar of clay and lime, mangrove wood	Short-term monitoring	-	-	-	PMV, PPD	ISO7730
[30]	Shaeri et al., 2018b	Iran, Shiraz	Tropical, hot-dry climate	Brick and adobe walls	Short-term monitoring Simulation model - DesignBuilder	-	-	-	PMV, PPD	ISO7730
[35]	Thravalou et al., 2018	Cyprus, Pera Orinis	Hot summers, mild winters	Masonry walls of adobe bricks laid on a stone base, gypsum slab floor and timber, reeds, earth and ceramic tiles roof	Long-term monitoring Simulation model - DesignBuilder Measurements in laboratory	-	-	-	Adaptive	ASHRAE Standard 55-2013

[3]	Xu et al., 2018	China, Nanjing	Subtropical monsoon climate, humid	Black brick, stone and timber wood	Short-term monitoring	Questionnaire survey	ISO7726; ASHRAE Standard 55-2004	ASHRAE Standard 55-2004 and TS scale	Adaptive	ASHRAE Standard 55-2004
[21]	Zhang et al., 2018	China, Guangdong	Hot-humid climat	Bricks and stone walls, wood and tile roof	Short-term monitoring	Question. survey	ISO7726; ASHRAE 55	ISO15001; GB/T 18977	Adaptive	ASHRAE 55-2004
[44]	Bencheikh & Bederina, 2019	Algeria, Laghouat	Tropical and subtropical desert climate	Adobe brick	Short-term monitoring Simulation model - EnergyPlus	-	ASHRAE Standard 55	-	Adaptive Givoni's model	ASHRAE Standard 55 French reg. RT2012
[5]	Fernandes et al., 2019	Portugal, Alentejo	Mediterranean climate, sub--type, hot and dry summer	Rammed-earth	Short and long-term monitoring	Questionnaire survey	ISO7726; ISO7730 ASHRAE Standard 55	ASHRAE Standard 55-2004; ASHRAE TS scale	Adaptive	EN15251; ASHRAE Standard 55-2004
[22]	Zhu et al., 2019	China, Kham	Snow climate (dry winters and cold summers); polar tundra	High-glutinosity clay, granite slabs, sandstone and dried wood	Short-term monitoring	-	-	-	Adaptive; Humphreys	Equation from [45]
[38]	Rincón et al., 2019	Burkina Faso (BF); Spain, Lleida	Hot semi-arid climate	Adobe brick, interior clay coating, exterior lime coating	Simulation – EnergyPlus + Open-Studio; experimental measurement	-	-	-	Adaptive	ASHRAE 55; Discomfort degree days/hours
[23]	Tsovoodavaa et al., 2019	Mongolia, (various)	Continental subartic; cold semi-arid; desert climate	Wood and felt	Simulation model – IDA ICE	-	-	-	Adaptive	EN 15251
[42]	Ibrahim et al., 2020	Northern Syria	Mediterranean climate	Earth	Simulation model – IDA ICE	-	-	-	Adaptive; PMV	EN 15251; ISO 7730
[24]	Yang et al., 2020	China, Turpan	Snow climate (dry winters and cold summers); polar tundra	High-glutinosity clay, granite slabs, sandstone and dried wood	Short-term monitoring; Simulation model – Sketchup + EnergyPlus	-	-	-	Adaptive	GB/T50785-2012 (Chinese Standard)
[25]	Zhao et al., 2020	China, Gongyi	Humid subtropical climate	Adobe	Short-term monitoring	Questionnaire survey	ISO7726	ASHRAE Standard 55; ASHRAE TS scale	Adaptive; PPD	ASHRAE Standard 55; GB/T50785; ISO 7730
[26]	Henna et al., 2021	India, various	Warm-humid, temperate and cold climate	Rubble wall with mud plaster, mud wall w/ clay plaster, stone and timber wall	Short-term monitoring Simulation model - DesignBuilder	-	-	-	Adaptive;	ASHRAE 55; Heating/ Cooling Degree days
[24]	Rijal, 2021	Nepal, Lo Manthang	Cold semi-arid climate	Thick brick walls, earthen floors, and mud roof	Short-term monitoring	Questionnaire survey	-	ISSO 10551	Adaptive; Griffith's method	-
[43]	Sun et al, 2021	China, Hainan island, Haikou	Humid subtropical climate	Volcanic rock, dried wood, and clay tile	Short-term monitoring	Questionnaire survey	China National Stan-dard; ISO 7726	-	Adaptive; PMV-PPD	ISO 7730
[39]	Widera et al, 2021	Togo, BF, Ivory Coast Nigeria, Ghana, Benin	Tropical savanna climate	Timber, bamboo, grass, palm leaves	Short-term monitoring Simulation model	Questionnaire survey	-	ASHRAE Standard 55; ASHRAE TS scale	Adaptive	ASHRAE Standard 55

Questionnaire standard: ASHRAE TS scale: ASHRAE Thermal sensation scale.
Comfort model: MCV: Mean Comfort Vote; PMV: Predicted Mean Vote; PPD: Predicted percentage dissatisfied; AMV: Actual Mean Vote.

3. Modelling vernacular dwellings: analysis of research

The simulation of vernacular dwellings is a developing research field that allows, *inter alia*, to obtain long-term performance predictions for a validated model, perform sensitivity and parametric analyses for improving overall performance and comfort, and examine climate change resilience and its impact on thermal comfort. In the past years, it has mainly been applied to assess thermal performance and bioclimatic strategies [22,26,53–55,39,46–52], thermal comfort [15,17,38,42,20,23,25,29,32–35], energy consumption [23,55], illuminance [56], and computational fluid dynamics [57]. This section highlights the key findings stemming from the analysis of the most relevant recently published research on the simulation of vernacular dwellings for thermal performance and comfort analysis, amounting to 26 publications.

3.1. Main methods

The most commonly used methodology combines dynamic thermal simulation with *in situ* monitoring (65 %), albeit with extremely variable ranges, i.e. from 28 hours to 10 months of monitoring. Less than 30 % rely on simulation alone, with input data being based on typical values from national building codes or software defaults assumptions. Fewer than 8 % of studies utilised methodological triangulation that integrated monitoring, occupant surveying, and simulation. EnergyPlus via the DesignBuilder interface is by far the most employed (nearly 50 % of studies), followed by Sketchup (12 %) and OpenStudio (< 4 %). A few other software tools were used, such as Ecotect (12 %) and IDA ICE (< 1 %).

3.2. Main parameters

3.2.1. Environmental parameters

More than 50 % of studies focus on earthen architecture, followed by wood or bamboo research (27 %), with stone-built dwellings being the focus of the least research (< 20 %). The indoor environmental parameters monitored *in situ* mostly entail air temperature (80 %) and relative humidity (65 %), followed by air velocity (27 %) and surface temperature (23 %). Mean radiant temperature and CO_2 levels are rarely monitored (4 %). Outdoor on-site weather stations or environmental parameters are considered in just under half of the studies, often encompassing air temperature, relative humidity, wind velocity, and solar irradiance.

The choice of weather data has a considerable impact on the accuracy of the simulation model. The overwhelming majority of studies used a typical template from the nearest reference weather station with historical meteorological national data sets (70 %), while 12 % of studies installed outdoor weather stations on site and generated modified weather files accordingly.

3.2.2. Thermophysical parameters

These are contemplated in *in situ* monitoring to a lesser extent than environmental parameters. Most studies therefore used typical values established in building codes, through theoretical calculations, or taking the software default data at face value, which may impact the accuracy of the model. *In situ* measurement of these parameters only occurred in 4 % of studies, covering thermal conductivity, specific heat capacity, and density.

3.2.3. Other parameters

Other parameters affecting the indoor thermal comfort of dwellings such as airtightness or air change rates, thermal bridging, and occupancy and activity are seldom mentioned in the studies. Typical and software default values, and sensitivity analysis were used to input air change data and thermal bridging into the models, yet, a qualitative scale from “very poor” to “good” was more often than not adopted to portray airtightness. No blower door tests were conducted in the analysed studies. Due to the heterogeneity of climates and materials in the analysed dwellings, a vast range of values for air change were reported, from 0.13 ach [20] to 15-35 ach [47]. Occupancy, activity, and clothing data are crucial for interpreting thermal monitoring results and assess thermal comfort. Yet, these are disclosed in less than 60 % of vernacular studies, and for most part based on typical values and assumptions linked to the national average of family members and literature-derived data. Under 20% of studies based their data on direct observation. Dwellings were also found to occasionally be modelled as inhabited, bypassing the impact of occupancy on thermal behaviour altogether.

3.3. Model validation

Validation and calibration are crucial for decreasing uncertainty and enhancing the accuracy of simulation. ASHRAE Guideline 14-2014 [58] is currently the most followed protocol, which suggests two main statistical indicators for model validation according to hourly or monthly data: the Coefficient of Variation of the Root-Mean-Square Error ((CV)RMSE) and the Mean Bias Error (MBE). Alternatively, the FEMP [59] and IPMVP [60] criteria for validation of building simulation models may be adopted. All three guidelines take an energy-based approach to the validation process. Hence, thermal comfort studies in vernacular dwellings have adapted the criteria devised for predicted energy consumption by using the environmental parameters monitored in place of the energy data, with no clear framework, leading to a heterogeneity of indexes, control parameters, validation periods and thresholds, which hampers the comparative analysis and replicability of findings in this field.

3.3.1. Validation method

More than half of studies resort to ad hoc comparisons between simulated and monitored data with no fixed criteria or do not conduct or outline the statistical validation of their model. ASHRAE 14 indexes (15.2 %), percent error (15 %) and the inequality coefficient (12 %) were found to be the most used validation techniques. Regarding the former, these are applied anew without criteria, with some studies using both NMBE (Normalised mean bias error) and CV(RMSE) and others using MBE and CV(RMSE) or CV(RMSE) alone.

3.3.2. Validation parameters, period, and thresholds

The validating parameter adopted in the studies was indoor air temperature alone (60%) or alongside relative humidity (15 %). Given the lack of a framework for hygrothermal model validation, the period and thresholds criteria were found to be widely heterogeneous, with reportedly ‘validated’ numerical models based on as little as two days up until 10 months. Those implementing the ASHRAE statistical indexes follow the suggested 10 % for MBE and 30 % CV(RMSE) thresholds, while no common ground could be identified for the remaining studies, with validating ranges from 0.13 to 0.19 for the inequality coefficient, 1.7 % to 11.6 % for the percent error, and from 0.2 ºC to 1.1 ºC of indoor temperature difference. The authors draw attention to what may be a nomenclature error between the MBE and the NMBE, which may exacerbate the disparity and lack of clarity between studies. Studies were found to use the NMBE and MBE indexes interchangeably, both expressed in percentage unit, and hence, applying the 10 % threshold suggested in ASHRAE 14-2014 for both MBE and NMBE. However, previous research [61,62] pointed to the fact that MBE is actually data-dependent and it is NMBE which is expressed as a percentage unit, highlighting the need of correction and standardisation of this nomenclature to prevent further errors.

4. Discussion and concluding remarks

4.1. Summary of main challenges

The lack of a clear framework was identified for both the monitoring and simulation stages that lead up to the assessment of thermal comfort in vernacular dwellings. These are inherently linked and present specific issues that generate inaccurate models, lead to unsound conclusions and the thus inappropriately inform conservation strategies for vernacular dwellings. In summary, the main challenges for evaluating thermal comfort in vernacular dwellings are three-fold:

- ***Thermal comfort standards are not adapted to vernacular dwellings, which would require legislative change based on further long-term field studies***: While steady-state approaches to thermal comfort are still being adopted in current vernacular studies despite evidence of their inadequacy for naturally-ventilated dwellings, existing adaptive comfort models have been shown to lead to the overestimation of the neutral temperature when compared to context-based ones.
- ***Lack of common methodology for in situ monitoring and modelling validation:*** There is no consensus regarding the monitoring and model validation method, parameters, period, and thresholds. Additionally, input data in published research is insufficiently detailed which undermines the reproducibility of results [63], increases uncertainty, and impacts trust in research within this area.
- ***Additional methodological and validation issues in simulation:*** the simulation process of vernacular dwellings presents additional obstacles which impact thermal assessment.

4.2. Specific challenges

This section presents an in-depth discussion on the particular challenges found to be associated with monitoring and simulation for assessing thermal comfort in vernacular dwellings.

4.2.1. Lack of consistent methodology or framework

4.2.1.1. Monitoring

The evaluation of thermal comfort in vernacular dwellings ideally requires an *in situ* physical survey, even when it is simulation-based. This may pose challenges such as accessibility issues, occupants' willingness, and equipment availability. Said challenges may lead to a limited number of case studies, but also short-term monitoring stages, which could be insufficient for the assessment. Uncertainty may arise from the experimental phase, as the monitoring devices should comply with monitoring standards such as ISO 7726, ISO 7730, and ASHRAE 55, which was unclear for most studies. Despite the definition of parameters that should be measured for evaluating thermal comfort in naturally-conditioned spaces, i.e. indoor air temperature, mean radiant temperature, and outdoor air temperature [64], existing research on vernacular dwellings is characterised by the heterogeneity of the parameters included.

4.2.1.2. Modelling

The accuracy of simulation models is input-data dependent. Yet, a major limitation detected is the impossibility of monitoring-based validation in studies that rely on simulation alone. Building research on unverified models to assess thermal comfort could easily introduce reliability issues and widen the gap with real conditions. Moreover, the lack of existing guidelines for the calibration of hygrothermal models leaves room for a raft of ad-hoc validation processes, generally employing arbitrary criteria and thresholds, on top of the application of statistical validation techniques with different robustness and adequacy. For instance, the most used parameter for model validation found, i.e. stand-alone air temperature, may lead to an incomplete validation and render moisture prediction studies infeasible, while the use of relative humidity can generate calibration inaccuracies as it depends on air temperature and water vapour pressure. According to a review of hygrothermal model validation for historical and cultural heritage buildings [61], the adoption of indoor air temperature as a validating parameter would require its combination with a humidity parameter, such as humidity ratio or specific humidity. On the other hand, the most used statistical indicators for model validation in vernacular dwellings present some drawbacks. The MBE and NMBE are affected by the error cancellation effect and the results linked with NMBE and CV(RMSE) are dependent on the dataset scale due to the normalisation process, leading to possible misinterpretation, and hence requiring more reliable auxiliary metrics [61]. For more detailed studies on simulation errors, the interested reader may refer to [61,62,65].

4.2.2. Gap between modelling and actual conditions

4.2.2.1. Modelling material data

Local and traditional material configurations are not available in standard software libraries. To obtain a reliable model, it is instrumental that the thermophysical properties of the dwellings be tailored to the *in situ* measurements, as typical and default values are likely to impact model accuracy. Yet, as observed in this analysis of research, said measurements are rarely implemented in vernacular studies. The same applies to airtightness, occupancy, activity, and clothing input data.

4.2.2.2. Weather data

The fact that most studies used a typical template from reference weather stations with historical data sets contributes to widening the gap between simulation and actual indoor behaviour. The inaccuracies introduced by this approach are reported among the analysed studies [15].

4.2.2.3. Occupancy, activity, and adaptive behaviour

The uniqueness of the occupancy and adaptive behaviour patterns in vernacular dwellings have a significant impact on thermal comfort. Non-typical behaviour can be difficult to predict with precision and inherently introduce a degree of uncertainty but could be offset by the correlation of long-term monitoring with occupant surveying. However, this approach was non-existent in literature, which used typical occupancy and activity templates or modelled dwellings as unoccupied, adding to model inaccuracy and bypassing the occupants' active role in the bioclimatic performance of the dwellings. Similarly, the occupants' thermal perception, a fundamental part of thermal comfort assessment, is seldom considered in vernacular dwellings' simulation studies.

4.2.3. Software limitations

Simulation software are developed with standardised contemporary buildings in mind, and thus present limitations for modelling the complex nature of vernacular dwellings. Parameterised model libraries do not accurately represent vernacular elements and may lack the flexibility to adequately simulate them. The creation of new bespoke elements can be time-consuming and requires proper monitored-based input data, which is not always undertaken, but is essential to the accuracy of simulation results. The lack of a current guideline for modelling heritage dwellings translates into a proliferation of heterogeneous approaches, potentially undermining the reliability of simulation results.

4.3. Recommendations

4.3.1. Comfort standards and models

- Current comfort standards must predict the possibility of adjusting their thresholds according to the metabolic activity and clothing of an elderly population, and include night-time adjustments.

- Evidence supports that context-based models tailored to local thermal and cultural conditions are the future of thermal comfort assessment in vernacular dwellings. Extensive field studies and in-depth long-term continuous *in situ* monitoring coupled with occupant surveying are necessary to compile robust databases that allow the consideration of common patterns and adaptive behaviours to develop adequate thermal equations.
- National standards must incorporate an adaptive approach reflecting the actual occupancy patterns, energy use, and adaptive behaviours of occupants in dwellings, and hence narrow the gap between legislative fixed thresholds and the broader tolerance thresholds found in occupants of vernacular dwellings.

4.3.2. Simulation model validation

The dynamic thermal simulation of vernacular dwellings has tremendous potential, on the proviso that a common framework is created and adopted. A vernacular architecture database focused on thermal comfort could serve the dual purposes of enabling conservation and knowledge sharing at a global level and developing a model that improves thermal comfort in modern dwellings. To that end, scientific consensus would be necessary on key parameters, regarding modelling and validation:

- The nomenclature errors detected in the analysis regarding the statistical indexes used for validating simulation models need correction and standardisation to prevent further calibration errors and disparity.
- To overcome the drawbacks of the most commonly used indexes, the MAE (Mean Absolute Error) together with RMSE could be applied for validating vernacular case studies [61]. The inequality coefficient is also proposed as adequate under a threshold of 0.25.
- A standard on hygrothermal model calibration entailing the most appropriate indexes and parameters, would be pivotal for validating vernacular heritage modelling and facilitating the replication of results. A validating humidity parameter, such as humidity ratio or specific humidity, should be implemented along with the usual air temperature. Additional ones, such as surface temperature and thermal transmittance of the envelope, could provide further robustness.
- Updating software libraries with context-specific materials based on field studies of vernacular and traditional dwellings would be key to increase precision, create common ground, and foster more

research on this topic. Open-source databases could facilitate the code sharing of library objects.

- More focus should be placed on on-site data collection of weather, thermophysical properties, occupancy, activity, and clothing to narrow the gap between modelled and real performance.
- Recent simulation-based thermal comfort studies were found to use outdated standards available in the software, e.g. EN 15251 versus EN 16798. Cutting edge research requires flexible up-to-date resources. A common open access database that would feed thermal comfort simulation software with context-based models for different climatic regions, would lead to a more robust evaluation of current thermal comfort conditions in vernacular dwellings.

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