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Article

Scoping Review of Thermal Comfort Research in Colombia

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Abstract: The analysis of thermal comfort in buildings, energy consumption, and occupant satisfaction is crucial to influencing the architectural design methodologies of the future. However, research in these fields in developing countries is sectorised. Most times, the standards to study and assess thermal comfort such as ASHRAE Standard 55, EN 15251, and ISO 7730 are insufficient and not appropriate for the geographical areas of application. This article presents a scoping review of published work in Colombia, as a representative case study, to highlight the state-of-the-art, research trends, gaps, and potential areas for further development. It examines the amount, origin, extent, and content of research and peer-reviewed documentation over the last decades. The findings allow new insights regarding the preferred models and the evaluation tools that have been used to date and that are recommended to use in the future. It also includes additional information regarding the most and least studied regions, cities, and climates in the country. This work could be of interest for the academic community and policymakers in the areas related to indoor and urban climate management and energy efficiency.

Keywords: thermal comfort; mechanical ventilation; comfort assessment; tropical developing countries; energy use; thermal comfort data collection

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1. Introduction

The 2018 census recorded 45.5 million people living in Colombia, being amongst the 30th most populated countries in the world, the 13th in the tropics and the 3rd in Latin America (after Brazil and Mexico) [1]. Of its population, 77.8% live in cities, 7.1% in small settlements, and 15.1% in rural areas [2]. Colombia's largest cities have very different climates (Figure 1). For example, its capital Bogotá is cold-climate type Cfb in the Köppen–Geiger classification, whereas Medellín is tropical monsoon type Am, Cali tropical warm-dry type As, and Barranquilla tropical wet-dry type Aw [3].

The Köppen–Geiger Climate Classification is the common system for comparison and generalisation in ITC research. However, this classification is described in past literature as unsuitable since it centres on vegetation and rainfall observations rather than on human-related aspects [5]. It also considers average rainfall rather than relative humidity, which is one of the main variables of indoor thermal comfort. Cities with the same classification often have different characteristics that influence thermal comfort. For example, Bogota shares the same classification with London, Amsterdam, and Berlin, but does not have extreme seasonal variations during the year. Instead, singularities in Colombia, such as altitude, play an important role. For example, in Bogotá, climatic conditions vary significantly during the day because of changes in atmospheric pressure related to altitude [6]. This is a central but overlooked variable in thermal comfort research, especially in the Andes Mountains, where most of the Colombian population is located. As altitude affects oxygen concentration in the body and the function of the vascular system, it can alter metabolic rates and, therefore, change the perception of thermal comfort.

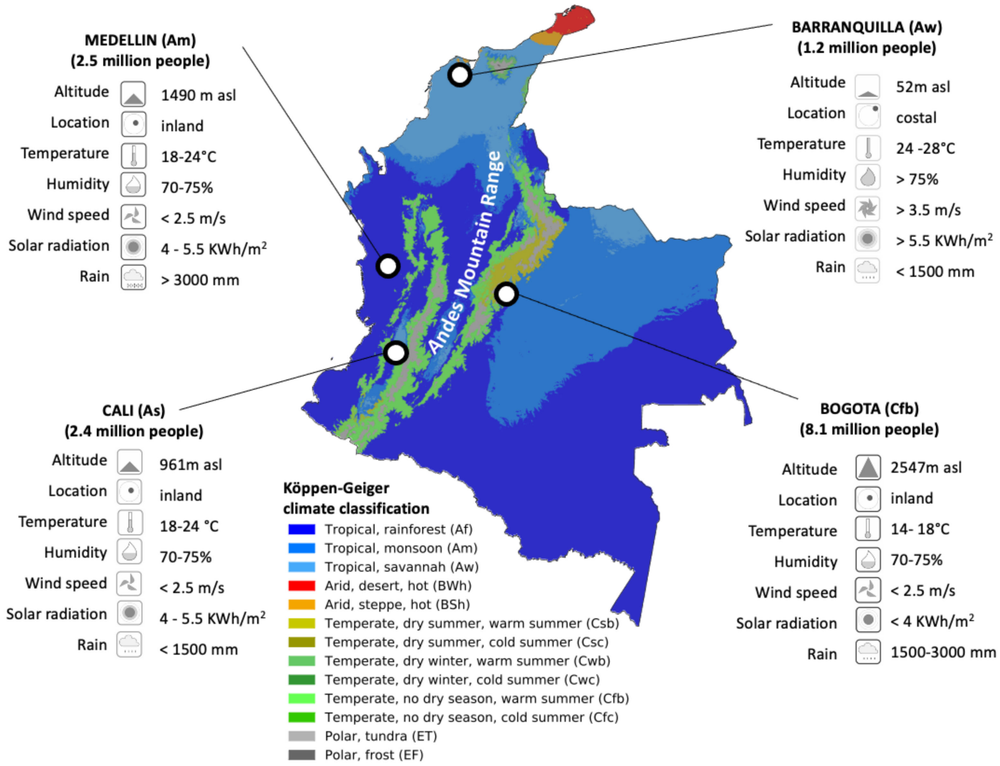

Figure 1. Map of climatic zones in Colombia (according to the Köppen–Geiger classification), adapted from [4].

Another aspect affecting indoor thermal comfort, but rarely accounted for in the generalised classifications, is the formation of urban microclimatic zones. This results from transformations, such as the increase of building density and paved surfaces and the reduction of vegetation, which contribute towards higher outdoor and radiant temperatures and further indoor cooling needs [7].

Between 2011 and 2016, the Air Conditioning (AC) demand in Colombia increased by 66%, ranking it as the 5th largest demand in Latin America, with approximately 200–250 thousand AC units sold per year [8]. The local standard regulating the use of HVAC systems is the Colombian Technical Standard for Thermal Environmental Conditions in Buildings (Norma Técnica Colombiana NTC 5316: Condiciones Ambientales Térmicas de Inmuebles para Personas) introduced in 2004 [9]. This standard is a literal translation (from English to Spanish) of the United States norm ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupation. Their application in the design of buildings is advised but not mandatory within sustainable architecture policies in Colombia. Normative is scarce, and policies are very recent compared to other countries, as shown in Figure 2.

Resolution 5926 of 2011 [10] was the first official policy to cover aspects related to eco-efficient buildings. Subsequently, in 2015, the Ministry of Housing introduced Resolution 0549 on sustainable construction, which focuses on mandatory reductions in water and energy consumption in new dwellings [11]. Although this resolution suggests actions such as natural ventilation, appropriate orientation, and sun protection, there are no compulsory or detailed guidelines to guarantee or test these parameters either in existing or in new constructions. Therefore, the minimum requirements for thermal comfort are difficult to measure or enforce.

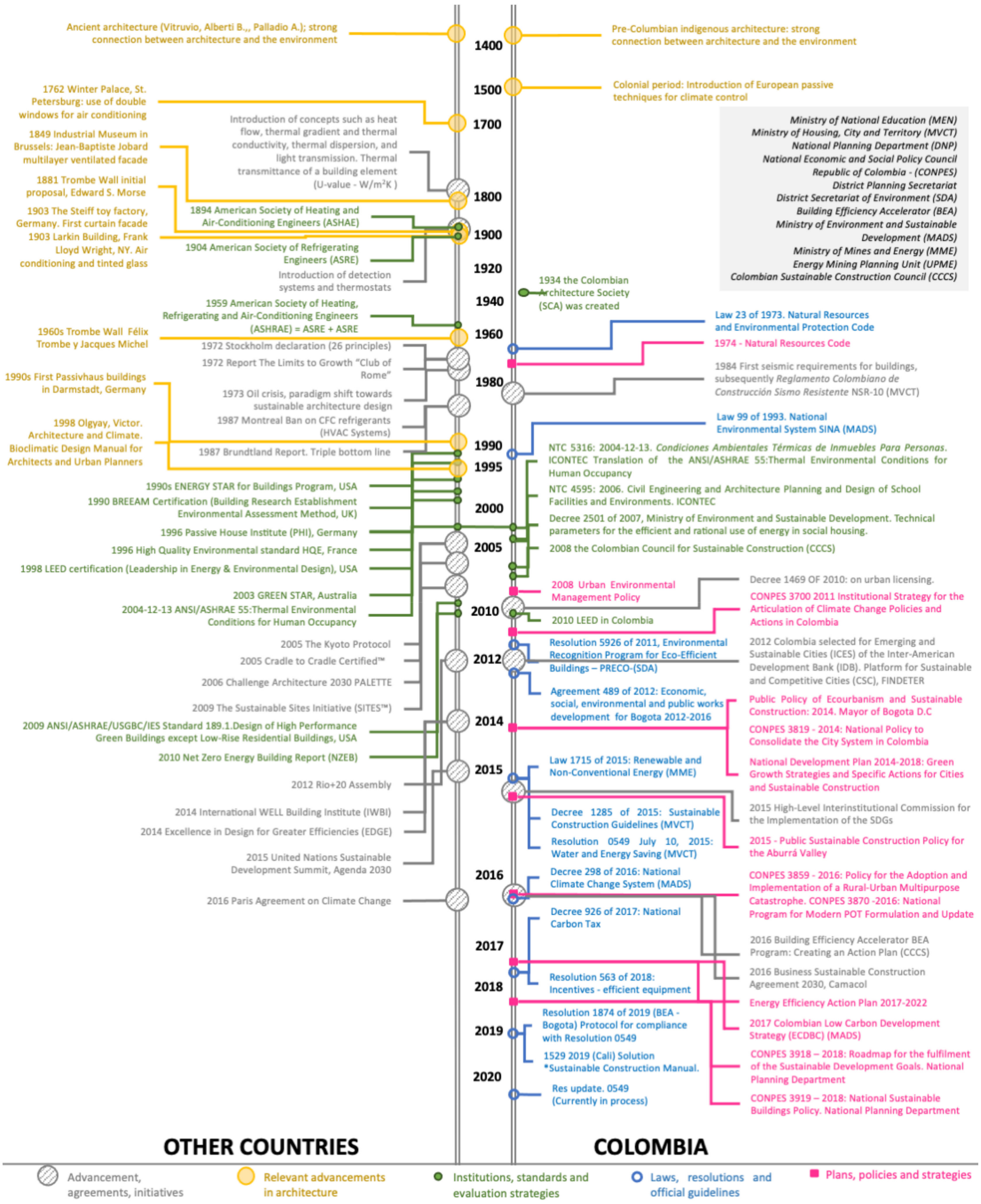

Figure 2. Timeline showing selected advancements, initiatives and policies related to thermal comfort. Comparison between Colombia and other countries.

Besides the limitations of the current policy, there is also a scarcity of literature available on thermal comfort in Colombia, suggesting a generalised lack of research on this subject, compared to other regions in the world. This can be evidenced by quick bibliometric searches. For example, a Scopus search with the terms *thermal comfort* carried out on the 26th of March 2020 displayed 23,212 documents (13,992 articles and 7582 conference papers). The same search with the terms *thermal comfort Colombia* displayed only 29 documents (17 articles, ten conference papers, one conference review and one review). Of these documents, 14 were open access and 90% of this information was published after 2012 (30% after 2019).

There is no previous literature review that has comprehensively studied thermal comfort in Colombia, which is potentially a very significant gap considering the demographic characteristics, variety of climates and tendencies of AC use mentioned in this introduction. This article seeks to bridge this gap through a scoping review, which according to [12] is a suitable choice when the central aim is to identify knowledge gaps or scope for a body of available literature. This manuscript targets the volume, origin, emphasis, impact, findings, and gaps in thermal comfort research in Colombia with the following questions:

1. How much research and scientific documentation on thermal comfort in Colombia is available? (volume);
2. Where, when, and in which context has this information been produced? (origin);
3. What is the focus and influence of this documentation? (emphasis and impact);
4. What aspects of thermal comfort in tropical regions have been studied? (findings);
5. What areas require attention? (gaps in research).

2. Methods

The authors addressed the above questions based on a *search, appraisal, synthesis, and analysis* method (SALSA) [13] using primary and secondary information sources, including questionnaires and scholarly publications. The focus here was on identifying and mapping central characteristics and concepts in a sample of papers or studies related to thermal comfort in Colombia. Therefore, a scoping review was regarded as the better choice, over a traditional literature review or a systematic review [12]. Table 1 shows the efforts made to minimise bias in this case.

Table 1. Characteristics of traditional literature reviews, scoping reviews and systematic reviews compared to this review. Table based on [12].

Efforts to Minimise Bias Based on [12]	Traditional Literature Review	Systematic Review	Scoping Review	This Review
A priori review protocol	No	Yes	Yes (some)	Yes. A Prisma diagram of information flow used
PROSPERO registration of the review protocol	No	Yes	No	No
Explicit, transparent, peer reviewed search strategy	No	Yes	Yes	Yes. 4 different reviewers, who specialised in this subject, took part in the review process to reduce error and increase reliability.
Standardised data extraction forms	No	Yes	Yes	Yes. Mendeley reference manager and Excel pivot tables were used for recording, classifying, and coding all documents.
Mandatory Critical Appraisal (Risk of Bias Assessment)	No	Yes	No	No
Synthesis of findings from individual studies and the generation of 'summary' findings.	No	Yes	No	Yes. Data is extracted and presented in a structured way through

The review was carried out in two different phases (first search and second search). Figure 3 shows the flow of information through these phases, mapping out the type and number of records identified, included, and excluded and the criteria for exclusions.

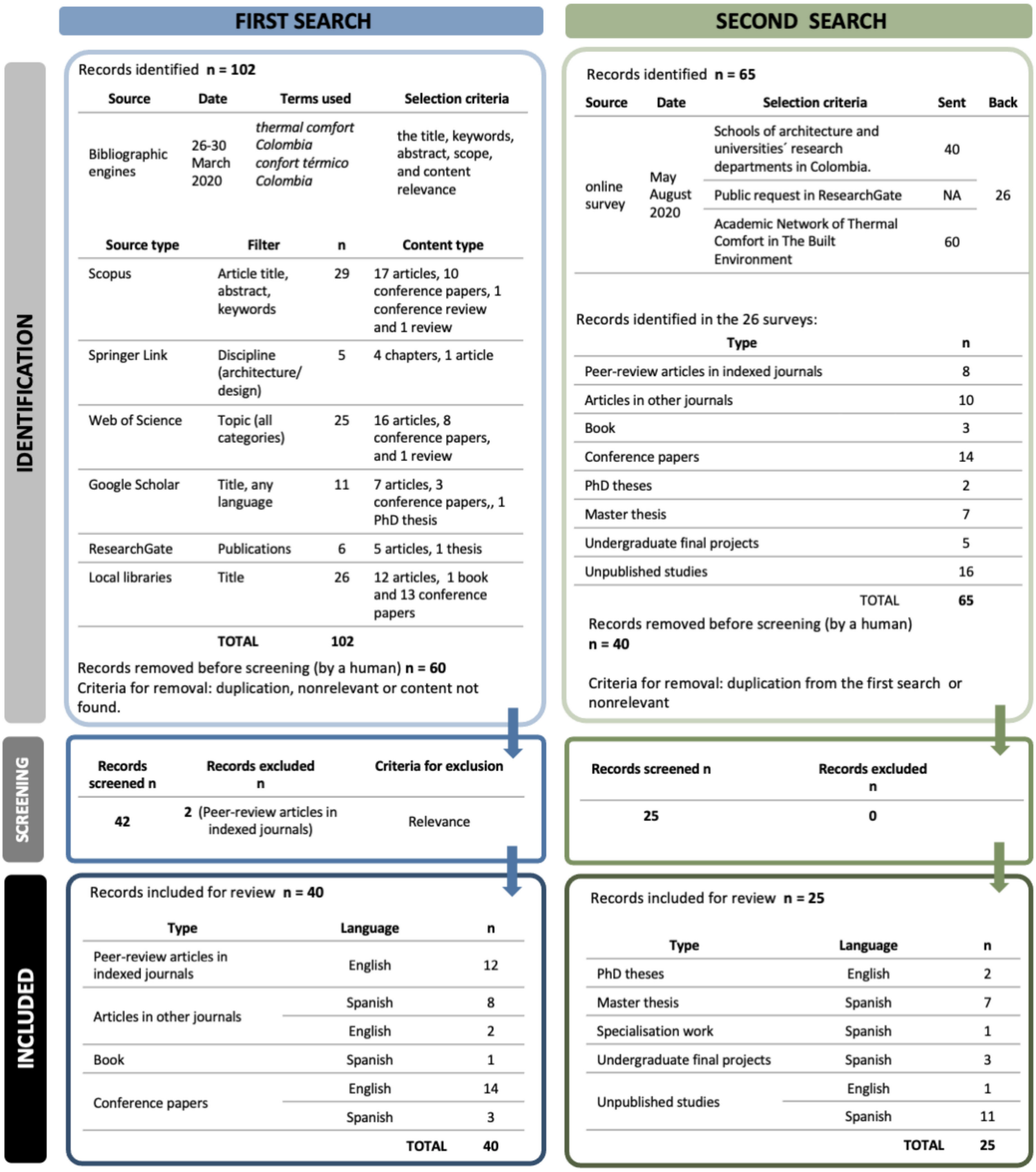

Figure 3. Diagram of information flow during the first and second searchers (adapted from a Prisma flow diagram [12]).

A total sample of 65 publications was selected for review during two main searches. They were narrowed down according to the title, keywords, abstract, scope, and content relevance. The first bibliographic search used Scopus, Springer Link, Web of Science, Google Scholar, ResearchGate, and local libraries (Universidad de Los Andes and Universidad Piloto de Colombia) following the structure for data collection in Table 2.

Table 2. Structure for data collection of the first search (bibliographic engines).

General Information	Title	**Study Features**	Research type
	Date		Case studies
	Main author		City/region studied
	Other authors or collaborators		Fieldwork's starting date
	Affiliation (University)		Fieldwork's Finish date
	Affiliation (Department)		Duration (months)
	Type		Building control
	Journal		Building Use
	Vol		Building Typology
	Publication (city)		Building height (Number storeys)
	Publication (country)		No. of Buildings
	# References		Research methodology
Impact	Field-Weighted Citation Impact		Analysis method
Citations (Search date March/2020)	# Citations in Scopus		Tools
	# Citations Google scholar		Equipment location (height)
Content	Abstract		Equipment location in the space
	Main findings/general conclusions		Sample size (number of people surveyed)
	Comfort ranges		Sample size (number of surveys)
	Future lines on research identified		Sample size (hours of environmental measurements)
	Comfort studied from other perspectives		Sample size (other)
	Relation with policy		% of the sample

The second search was carried out through an online survey sent to 40 schools of architecture and universities' research departments in Colombia. Additionally, a public question on ResearchGate was sent on the 10th of June 2020 with the title "Hi, is anyone here working on thermal comfort in Colombia?" The question was complemented with an explanation of the aim and scope of the study and the link to the online survey (all written in English). This was sent to all the contacts and followers of the authors ResearchGate pages (approximately 293 people from different countries). The link to the survey was also distributed during the first meeting of the Academic Network of Thermal Comfort in The Built Environment (Red Académica de Confort Térmico en el Espacio Construido) on the 17th of August 2020. This network is formed by over 60 professionals and researchers from 6 countries in Latin-American (Mexico, Colombia, Ecuador, Brazil, Argentina, Chile and Uruguay). A total of 26 answers to the survey were received. Table 3 shows the structure for data collection in the online survey.

Table 3. Structure for data collection of the second search (researchers' survey).

	Number	Question	Answer Options
General Information	G1	Name of the researcher	
	G2	Institution	
	G3	Email	
	G4	Use of personal data authorisation	Yes
			No
	G5	Research project title	
	G6	Date	
Objectives and Methodology	O1	Project's main objective	To study aspects of thermal comfort in urban spaces
			To study aspects of indoor thermal comfort
			To analyse post-occupancy thermal comfort evaluation methods
			To analyse thermal comfort evaluation methods at the design stage
			To analyse regulations on thermal comfort
			Other
	O2	Project's methodology	Theoretical (e.g., literature review, databases, secondary information)
			Practical (e.g., fieldwork, on-site measurements, interviews)
			Theoretical—practical
			Other
	O3	Use of cases studies	Yes
			No
	O4	Number of cases	
	O5	Building typology (case studies)	
	O6	Location (case studies)	
	O7	Data collection methods	Measurement of environmental conditions on-site (e.g., temperature, relative humidity, airspeed)
			Occupant surveys
			Simulations with specialised software
			Existing databases
			Other
Analysis Strategies	A1	Methods or standards used to analyse the information	PMV and PPD model (ASHRAE Standard 55)
			Adaptive model (ASHRAE Standard 55)
			Adaptive model (EN Standard 15251)
			Griffiths' method
			Other

Table 3. *Cont.*

	Number	Question	Answer Options
	A2	The national policy used or consulted	NTC 5316. Environmental Thermal Conditions of Buildings for People (2004)
			NTC 4595. Planning and Design of School Facilities and Environments (2015)
			NTC 6199. Planning and Design of Environments for Early Education in the Framework of Comprehensive Care (2016)
			Resolution 0549 of 2015—Ministry of Housing
			None
			Other
	A3	Comfort levels achieved by the analysed spaces	All or most of the spaces were within the comfort ranges with the analysis models used
			None or very few spaces were within the comfort ranges with the analysis models used
			The results were very varied, depending on the method used
			Other
	A4	Causes of comfort deficiencies when they were found	Design issues
			Construction materials issues
			Building orientation issues
			Lack of adaptive opportunities for occupants
			Lack of mechanical conditioning or air conditioning
			Lack of thermal comfort policies or standards
			Other
	A5	Impact of comfort deficiencies when they were found	Occupants' physical health
			Occupants' mental health
			Occupants' productivity
			The need for mechanical conditioning
			The increase in energy consumption
			Building maintenance issues
			Other
Results	R1	General results or conclusions of the research project	
Publications	P1	Was the research published?	Yes
			No
	P2	Publication details	Author
			Date
			Title
			Source
			DOI or link

3. Results

Out of the 40 publications selected during the first search, there were 12 peer-review articles in indexed journals, 10 articles in other journals, one book and 17 conference papers (Table 4). Data regarding general information, impact, citations, content, and study features were collected and analysed. The individual impact of all publications was examined and ranked with the Field-Weighted Citation Impact (FWCI) and the number of citations recorded in Scopus. The FWCI measures the ratio of total citations received versus the expected based on the average of the subject field. Numbers above 1 mean that the output is more cited than expected according to the global average.

Table 4. Sample of selected publications including year, city or region studied, FWCI, and citations. (first search).

Publication	Year	C. Scopus	FWCI	City/Region Studied	Reference
Article in Indexed Journal					
Outdoor thermal comfort in a hot and humid climate of Colombia: A field study in Barranquilla	2014	59	3.75	Barranquilla	[14]
A field study of indoor thermal comfort in the subtropical highland climate of Bogota, Colombia	2015	17	2.36	Bogotá	[15]
The environmental design of working spaces in equatorial highlands zones: The case of Bogotá, buildings	2015	3	0	Bogotá	[16]
Review of energy-efficient features in vernacular architecture for improving indoor thermal comfort conditions	2016	32	0.61	Tropics	[17]
Thermal comfort and satisfaction in the context of social housing: Case study in Bogotá, Colombia	2019	1	0.43	Mosquera	[18]
Thermal comfort assessment in naturally ventilated offices located in a cold tropical climate, Bogotá	2019	4	2.81	Bogotá	[19]
Suitability of Passivhaus design for housing projects in Colombia	2019	0	0	Bogotá, Barranquilla	[20]
The importance of standardised data-collection methods in the improvement of thermal comfort assessment models for developing countries in the tropics	2019	1	0.66	Bogotá	[21]
Urban form and population density: Influences on Urban Heat Island intensities in Bogotá, Colombia	2019	0	0	Bogotá	[22]
A post-occupancy strategy to improve thermal comfort in social housing in a tropical highland climate: A case study in Bogotá, Colombia	2019	0	0	Mosquera	[23]
Classroom-comfort-data: A method to collect comprehensive information on thermal comfort in school classrooms	2019	2	0.64	Bogotá	[24]
Indoor thermal comfort review: The tropics as the next frontier	2019	4	1.89	Tropics	[25]
Article Other Journals					
Simulaciones ambientales aplicadas a la selección de materiales para el diseño de alojamientos temporales en climas tropicales	2014	0	0	Girardot, Bogotá	[26]
Calidad de vida en la vivienda social de San Andrés, Colombia, mediante la gestión bioclimática de flujos de aire	2015	0	0	San Andrés	[27]
Ventajas del uso de fachada ventilada en Girardot (Colombia). Un complemento tecnológico a fachadas modulares industrializadas	2015	0	0	Girardot	[28]
Evaluación de las condiciones térmicas ambientales del área de producción en una panadería en Cereté (Córdoba)	2016	0	0	Cereté	[29]
Ventilación pasiva y confort térmico en vivienda de interés social en clima ecuatorial	2017	0	0	Cali	[30]

Table 4. *Cont.*

Publication	Year	C. Scopus	FWCI	City/Region Studied	Reference
Confort térmico en viviendas de Medellín	2019	0	0	Medellín	[31]
Thermal comfort in buildings for wet processing of coffee	2019	0	0	Medellín	[32]
Evaluación del mejoramiento del confort térmico con la incorporación de materiales sostenibles en viviendas en autoconstrucción en Bosa, Bogotá, Colombia	2019	0	0	Bogotá	[33]
Indoor thermal comfort in the tropics	2019	0	0	Tropics	[34]
Climatización sostenible para vivienda de interés social, en zonas cálidas de Colombia	2019	0	0	Girardot	[35]
Book					
Comodidad ambiental en las aulas escolares: incidencia en la salud docente y en el rendimiento cognitivo de los estudiantes en colegios públicos de Bogotá, Medellín y Cali	2018	0	0	Bogotá, Medellín, Cali	[36]
Conference Paper					
Passive cooling for complex buildings in a humid tropical area-Study case Colombia	2006	1	0	Villavicencio	[37]
Evaluation of the relationship between natural ventilation and the grouping of five-year-old children in a kindergarten classroom of Medellin	2012	1	0	Medellín	[38]
Design guidelines for residential envelope openings in the equatorial tropics: Studies in suburban housing in the Cauca Valley of Colombia	2012	1	0	Cali	[39]
Problemas de confort térmico en edificios de oficinas. Caso estudio: Torre Colpatria en la ciudad de Bogotá	2012	0	0	Bogotá	[40]
Conductive cooling using underground buried pipes low energy cooling systems for providing comfort to workers in an industrial building	2012	1	0	Armenia	[41]
Urban energy simulation of a social housing neighbourhood in Bogota, Colombia	2013	0	0	Bogotá	[42]
Natural ventilation and ground cooling to improve thermal comfort conditions of workers in an industrial building: passive cooling techniques applied in an industrial building	2013	0	0	Cali	[43]
Contemporary use of earthen techniques in Colombia: Thermal performance of domestic and non-domestic building typologies.	2013	0	0	Bogotá	[44]
Climate and context adaptive building skins for tropical climates: A review centred on the context of Colombia	2014	0	0	Bogotá, Medellín, Cali	[3]
Testing a method to assess the thermal sensation and preference of children in kindergartens	2014	0	0	Medellín	[45]
Eficiencia energética y sostenibilidad en la Vivienda de Interés Social en Colombia	2015	0	0	Cali	[46]
Study of heat island phenomenon in Andean Colombian tropical city, case of study: Manizales-Caldas Colombia	2015	0	0	Manizales	[47]
Forecast about energy behavior and the indoor quality of a tower of social dwellings in Bucaramanga (Colombia)	2016	0	0	Bucaramanga	[48]
Characterization of environmental and energy performance of an average social dwelling in a tropical region of Colombia	2016	0	0	Bucaramanga	[49]

Table 4. *Cont.*

Publication	Year	C. Scopus	FWCI	City/Region Studied	Reference
Population density and urban heat island in Bogotá, Colombia	2018	0	0	Bogotá	[22]
Evaluación del confort térmico en una institución educativa en la ciudad de Barranquilla	2018	0	0	Barranquilla	[50]
The development of data-collection methods for thermal comfort assessment in tropical countries	2019	0	0	Bogotá	[51]

Out of the 25 documents selected during the second search, there were two PhD theses, seven Master thesis, one specialisation work, three undergraduate final projects, and 12 unpublished studies (Table 5).

Table 5. Studies collected during the second search.

Study	Year	City/Region Studied	Institution	Reference
PhD Thesis Other Countries				
The influence of courtyards: thermal comfort in Bogota—Colombia	2017	Bogotá	Illinois Institute of Technology	[52]
Optimización del confort térmico en clima ecuatorial con tecnologías pasivas en fachadas: el caso de las viviendas de interés social de Cali	2018	Cali	Universidad Nacional de La Plata	[53]
Master's Thesis in Colombia				
La evaluación bioclimática en vivienda VIS: un avance hacia la calidad de la vivienda social en Colombia: caso de estudio Bogotá, Colombia	2017	Mosquera	Universidad de Los Andes	[54]
Fachada vegetal en edificaciones tropicales: La doble piel vegetal como filtro térmico y lumínico en edificaciones tropicales de altura	2018	Medellín	Universidad de San Buenaventura Colombia	[55]
Evaluación del confort térmico en la universidad de la costa en la ciudad de Barranquilla	2018	Barranquilla	Universidad de La Costa	[56]
Integración de patios en altura a viviendas masivas de la ciudad de Montería para la optimización del desempeño térmico y lumínico	2019	Montería	Universidad de San Buenaventura	[57]
Confort térmico y calidad del aire, una evaluación cuantitativa post ocupación desde la arquitectura: casos de estudio, tres edificios de oficinas con ventilación natural en Bogotá.	2019	Bogotá	Universidad Piloto de Colombia	[58]
Análisis del comportamiento térmico de las Envolventes de las viviendas Vis en la ciudad de Tunja desde el enfoque de las tecnologías limpias	2019	Tunja	Universidad Católica de Colombia	[59]
Propuesta de intervención de la envolvente de edificaciones existentes: caso de estudio bloque de aulas de una institución educativa	2019	Envigado	Universidad de San Buenaventura	[60]
Specialisation Work in Another Country				
Diagnóstico del funcionamiento bioclimático del Museo de Arquitectura de la Universidad Nacional de Colombia, sede Bogotá, diseñado por el arquitecto Leopoldo Rother	2016	Bogotá	Universidad Nacional de La Plata	[61]

Table 5. *Cont.*

Study	Year	City/Region Studied	Institution	Reference
Undergraduate Work in Colombia				
El doble acristalamiento como alternativa tecnológica para el mejoramiento en el confort térmico de la vivienda de la Sabana de Bogotá	2017	Chía	Universidad Piloto de Colombia	[62]
Evaluación de la percepción de confort térmico que tienen los estudiantes en el bloque 10 de la Universidad de la Costa	2019	Barranquilla	Universidad de La Costa	[63]
Propuesta de criterios bioclimáticos para el diseño urbano en ciudades con climas tropicales. Caso de estudio: Barranquilla, Colombia	2019	Barranquilla	Universidad de La Costa	[64]
Unpublished Studies				
Estrategias bioclimáticas en edificaciones institucionales de alta montaña—Cerro Azul, Calarcá—Quindío	2014	Calarcá	Universidad La Gran Colombia	NA
Diseño de espacios escolares confortables para básica primaria en el departamento del Quindío	2016	Filandia Montenegro Salento	Universidad La Gran Colombia	NA
Confort térmico y calidad del aire en oficinas	2018	Bogotá	Universidad Piloto de Colombia	NA
Sistema liviano alternativo de construcción para vivienda a partir de módulos a base de materiales reciclados y método de fabricación del mismo (Patente SIC 2018)	2018	Armenia	Universidad La Gran Colombia	NA
Confort térmico, cargas internas y condiciones de ocupación: una aproximación metodológica para la cuantificación del confort en el ambiente térmico	2019	Bucaramanga	Universidad Santo Tomás, Colombia	NA
Estrategias para la rehabilitación energética de la envolvente del edificio Fray Angélico para la mejora del confort térmico y reducción del gasto en consumo de energía—fase 1 y fase 2	2019	Floridablanca	Universidad Santo Tomás, Colombia	NA
Estrategias bioclimáticas para mejorar el confort térmico en viviendas medianeras en el centro de la ciudad de Quibdó	2020	Quibdó	Universidad de San Buenaventura, Colombia	NA
Confort térmico y calidad del aire durante obras de rehabilitación en edificios de viviendas	2020	Bogotá	Universidad Piloto de Colombia	NA
Análisis del efecto isla calor y ciclo de vida de los materiales del espacio público en Bucaramanga para la formulación de un manual de lineamientos de diseño sostenible.	2020	Bucaramanga	Universidad Santo Tomás, Colombia	NA
Thermal behaviours based on air temperature observations in different local climate zones in Bogotá, Colombia	2020	Bogotá	Universidade Federal de São Carlos, Brazil	NA
Preferencias ambientales en el espacio urbano según factores sociodemográficos y de uso	2020	Medellín	Universidad de San Buenventura, Colombia	NA
La envolvente profunda, como estrategia bioclimática pasiva para el logro del confort térmico en el clima ecuatorial (PhD Thesis in progress)	2020	Cali	Pontificia Universidad Javeriana, Colombia	NA

The total sample of 65 documents was examined regarding the volume, origin, impact, focus, and content of past and current research projects and documentation on thermal comfort in Colombia. The analysis stage identified general tendencies, emphasis, findings, and prospects in this area.

3.1. Volume Emphasis and Impact of the Information

The 65 studies in the sample were classified according to the type of publication and methodology used (Figure 4A,B). The results show that most studies focused on practical issues employing fieldwork (51%), followed by urban measurements (15%), dynamic simulations (14%), and experimental prototypes (9%). The remaining studies focused on theoretical aspects such as literature and methods. Although the statistics showed a marked tendency on the use of practical over theoretical methodologies, a t-test comparing the two found no significant difference between them (p = 0.18).

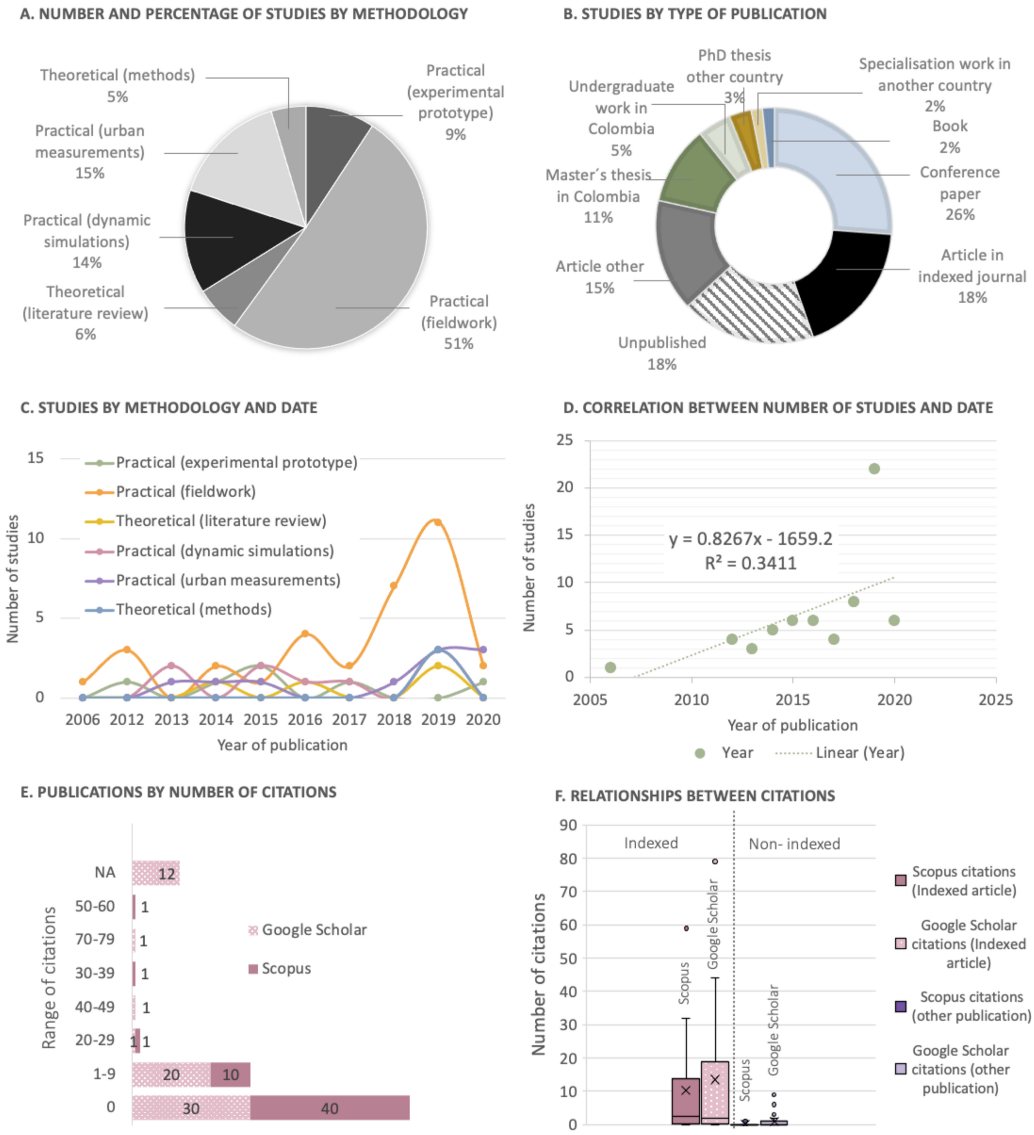

Figure 4. Volume emphasis and impact of the information. (**A**) Number and percentage of studies by methodology. (**B**) Studies by type of publication. (**C**) Studies by methodology and date. (**D**) Correlation between the number of studies and the date. (**E**) Publications by number of citations. (**F**) Relationships between citations.

Figure 4C illustrates how studies increased between 2017 and 2019, especially those focusing on fieldwork. A moderate linear correlation with positive direction was found in the data, suggesting that the number of publications grew as time passed (Figure 4D).

However, a considerable number of studies are still not published (18%), and only a limited number are available from recognized quality outlets such as indexed journals (18%) or books (2%) (Figure 4B). Citations are scarce with 40 publications registering no citations in Scopus (62%) and 30 publications with no citations in Google Scholar (46%) (Figure 4E). The box plots of Figure 4F show alignment between the medians in the number of citations in Scopus and Google Scholar, and interquartile ranges are reasonably similar within each type of publication (indexed and non-indexed). A paired *t*-test shows a correspondence between the data from Scopus and Google Scholar (p = 0.12), which shows consistency in both reference tools to record citations. All sets of data appear to be positively skewed (towards the cero line) with noticeable outliers, indicating a general tendency for low citations. Marked differences between the indexed and non-indexed publications are observed with p-values between 0.08 and 0.1.

3.2. Origin and Location of the Studies

The studies in the sample originate from 33 institutions, of which 18 are in Colombia and the rest in 9 other countries (Figure 5A). The studies from Colombian institutions correspond to 67% of the sample. However, only 2 of these institutions have published results in Scopus indexed journals, compared to 10 institutions from abroad. The preferred type of publication by Colombian authors working on thermal comfort is conference papers, followed by articles in local journals. A significant number of studies are not yet published, and most authors that have published have only a single record within this area of research. Out of 118 authors, 16 have two or more publications (Figure 5B). The above results show limited exposure of Colombian authors and institutions within peer-reviewed international outlets.

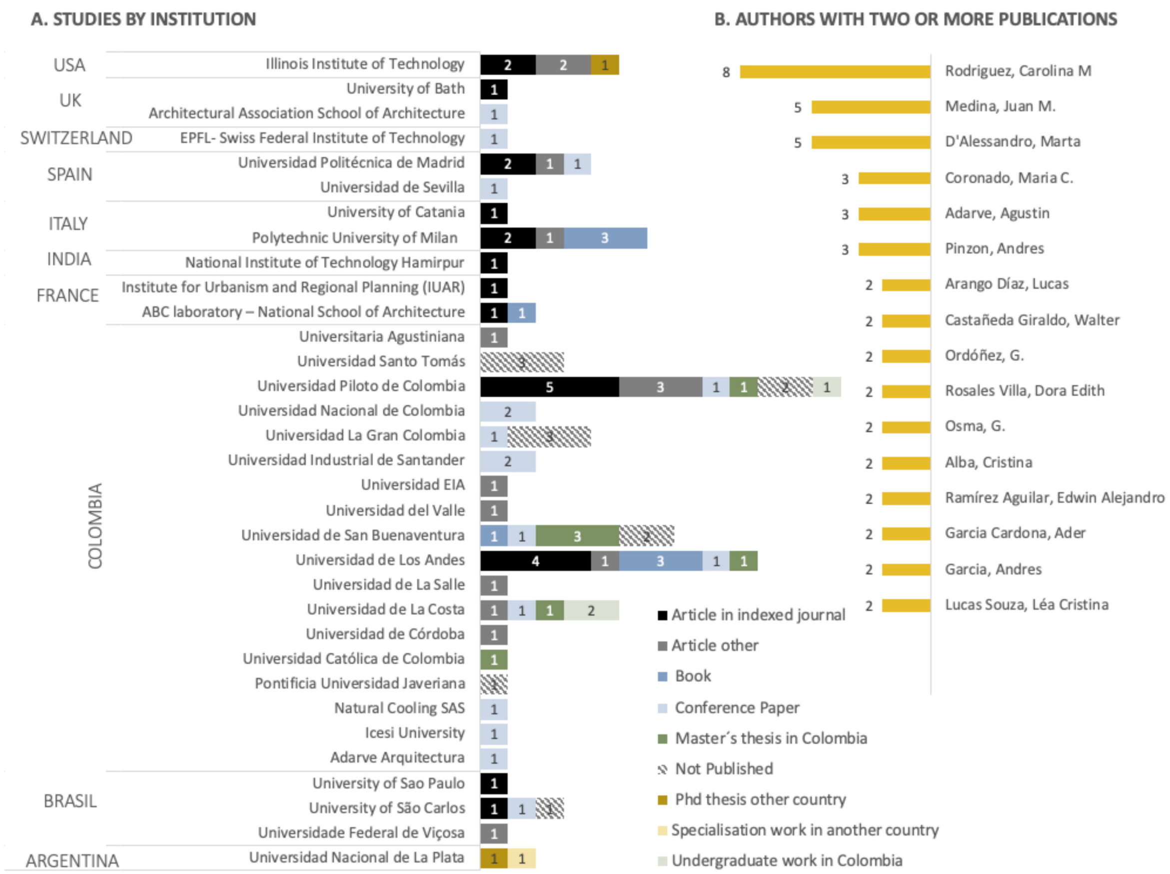

Figure 5. Analysis of the studies' sample by institutions and authors.

3.3. Climates and Regions Covered

A total of 22 cities in 12 different regions (known as departamentos in Spanish) were studied within the sampled documents. These cities were featured 70 times, as some studies analysed various cities in parallel. Cundinamarca was the most featured region with 29 counts and Bogotá the most featured city with 22 counts (Figure 6A,C). Other regions such as Antioquia, Valle del Cauca, and Atlántico are far behind with 9, 8, and 6 counts, respectively. Their principal cities (Medellín and Cali) were both featured 8 times, while Barranquilla appeared on 6 counts. As shown in Figure 6B, the most studied climate corresponds to Cfb (41%), followed by Aw and Am (18% each).

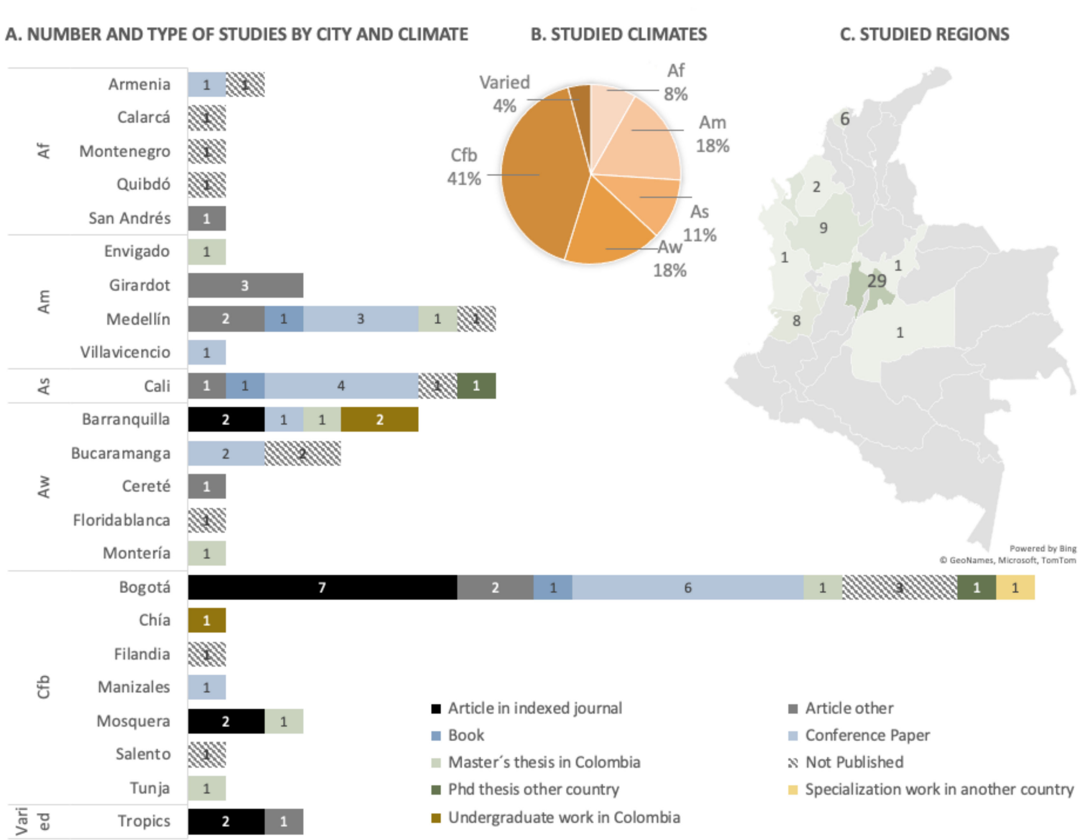

Figure 6. Climates and regions covered. (**A**) Number and type of studies by city and climate. (**B**) Studied climates. (**C**) Studied regions.

3.4. Types of Buildings Studied

Residential buildings are the most commonly studied in the sample, with 18% of the counts registering apartments, 17% single-family detached houses, and 4% housing complexes (Figure 7A). Schools are the next most studied building use (20%) followed by offices (13%) and urban space (11%). Counts for other uses where thermal comfort is vital, such as hospitals or care homes were not found. Single blocks or buildings were the most recorded configuration and buildings with natural ventilation across all uses (Figures 6C and 7B). Mechanical ventilation accounted for 17% of the studied buildings, whereas mix mode ventilation appeared in 11% of the samples.

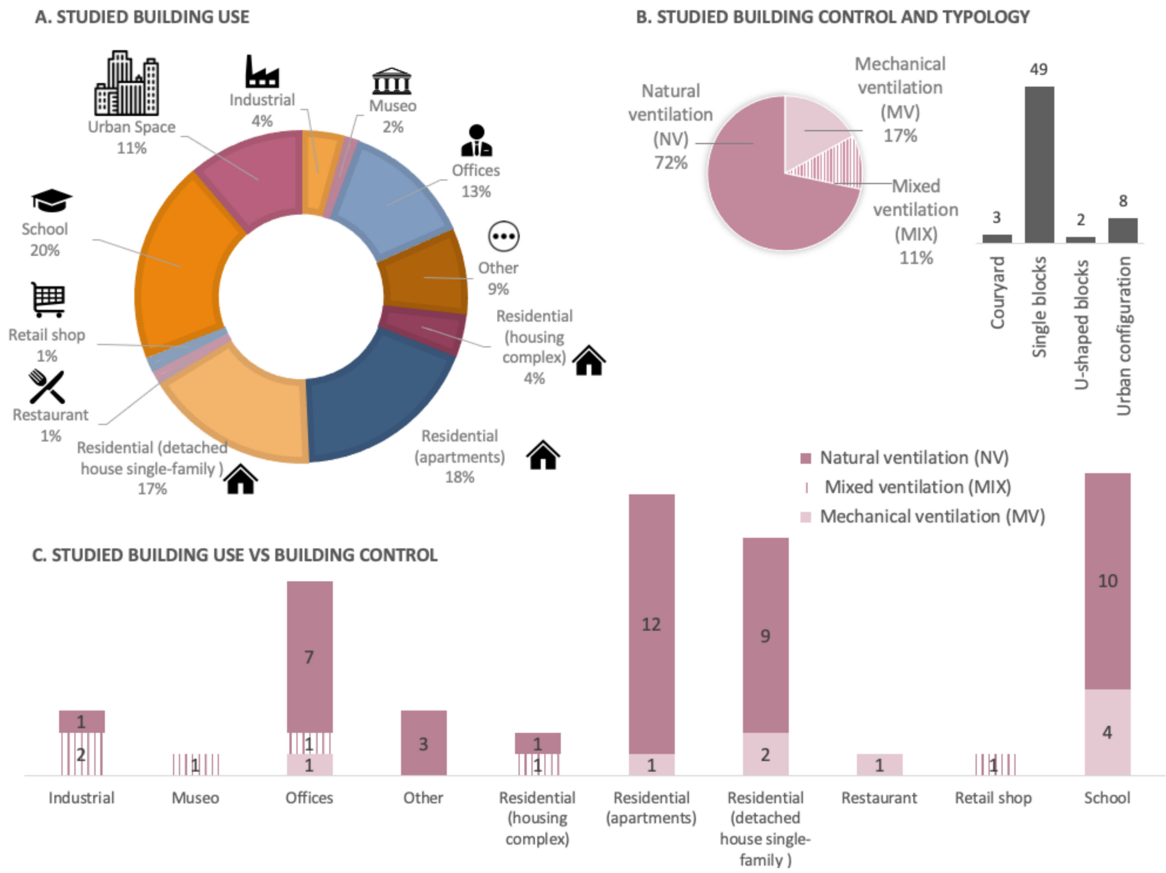

Figure 7. Types of buildings studied. (**A**) Studied building use. (**B**) Studied building control and typology. (**C**) Studied building use vs. building control.

3.5. Data Collection Tools and Assessment Models for Fieldwork

Out of the 65 studies, 50 included data collected during fieldwork. The most frequent tools to gather environmental records (temperature and RH) were data loggers, especially within residential apartments (Figures 7C and 8A). Other tools, such as hot-wire anemometers, were used to monitor airspeed, and outdoor weather stations, to record external conditions. Surveys were the preferred tool to collect information from the buildings' occupants, particularly in schools, where 2792 people were sampled (Figures 7B and 8A). The Adaptive method was the most regularly applied for data analysis, followed closely by the PMV model, both from the ASHRAE Standard 55 (Figure 8D).

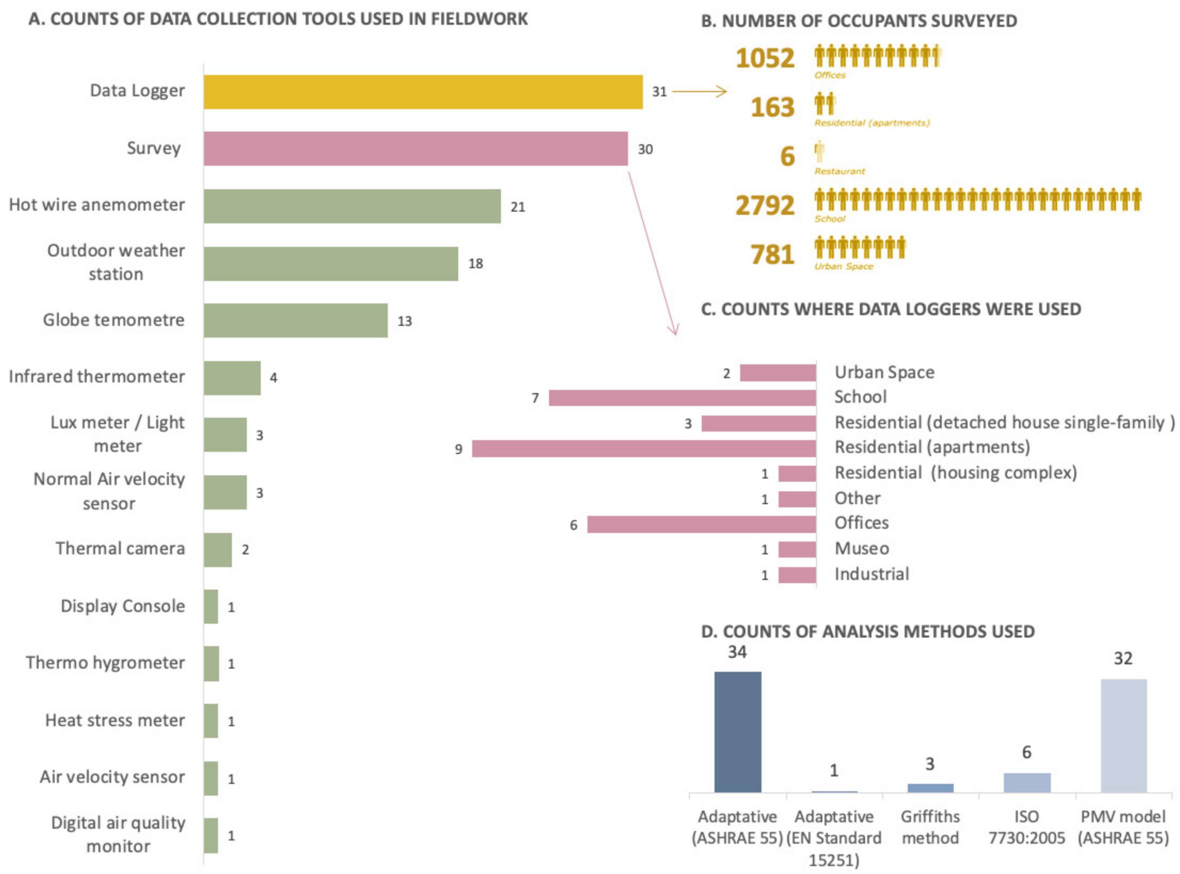

Figure 8. Data collection tools and assessment models. (**A**) Counts of data collection tools used in fieldwork. (**B**) Number of occupants surveyed. (**C**) Counts where data loggers were used. (**D**) Counts of analysis methods used.

3.6. Main Findings from the Published Documents

During the review of the selected documentation, recurrent themes were identified concerning limitations of the assessment models. Various studies emphasised on the inadequacy of mainstream evaluation standards applied in Colombia and the need to confirm these models with further post-occupancy studies and standardised fieldwork data [21,51]. For example, a study in three office buildings in Bogotá compared different assessment models to assess three ventilation scenarios (natural ventilation, mechanical ventilation, and mixed mode), via occupant surveys and simultaneous environmental measures [15]. The results indicated that both the PMV model and adaptive models (in ASHRAE 55 and EN 15251) could predict mean thermal perception in mechanically ventilated offices. However, they were unsuccessful at estimating occupants' thermal sensations and perception of discomfort in naturally ventilated or in mix-mode offices. In these scenarios, the results from the theoretical models were significantly distant from the physical data and comfort votes gathered on site. It was also argued that the lack of personal control over the windows invalidated the model predictions.

A similar study in eight office buildings in Bogota, which repeatedly surveyed 72 occupants for three months, also found no relationship between the thermal perception analysis obtained with the actual user votes and the analysis with the PMV model [19]. Here, the ASHRAE Standard 55 adaptive model and the Griffiths' method were more compatible with the votes. For a thermal acceptance of 96.58% with the latter method, the comfort operative temperature was 23.47 °C. However, relative humidity, which is not integrated into these methods, was regarded as the most important factor influencing perception.

Some studies showed that the standards have limited suitability in environments such as educational buildings, as they were developed based mainly on adult subjects working in offices. Therefore, alternative methods such as the one proposed in [24,65] are needed for comprehensive data gathering within different contexts.

The literature review found thermal comfort deficiencies in most of the studied buildings. Some research exposed substantial deficits in social housing projects. This includes a study comprising 44 social housing apartments in the outskirts of Bogota which revealed, through structured surveys, very high percentages of occupant dissatisfaction (between 60–80%) [18]. Indoor temperature measurements presented fluctuations of up to 4 °C between maximum and minimum values throughout the day, which related directly to outdoor fluctuations of up to 11 °C. The study exposed considerable thermal losses through the overall building's envelope, resulting in all units being outside the thermal comfort zones recommended by both the static and the adaptive models. A retrofit intervention within one of the studied apartments, to improve the facade thermal mass and the windows performance, achieved considerable improvements increasing indoor temperatures by 2 °C with a simple and cost-efficient solution [23].

A similar study in Medellin also warned about the vulnerability to extreme temperature fluctuations in common housing constructions, because of the low thermal inertia of the materials [31]. Buildings with opaque concrete elements performed the best regarding thermal comfort. In contrast, buildings using light materials (e.g., wood and zinc sheets) or the traditional combination of brick walls and tongue-and-groove roofs (common in low-income neighbourhoods) were outside the PMV and PPD comfort ranges.

Likewise, a study in Cali argued, through the analysis of environmental measurements, that the typical social housing designs were uninhabitable for most of the day [30]. The study proposed a solar chimney to encourage airflow and remove thermal loading to acceptable levels in the PMV model. The estimated cost of the intervention was 137 USD, which was slightly more than the cost of a mechanical fan but half the price of an air conditioning system.

Various studies looked at the general potential of material choices and passive design strategies to improve indoor comfort conditions in contemporary buildings [3] and vernacular architecture [17]. A study in Girardot argued that local materials such as *guadua* (bamboo), vegetable fibres, and synthetic fibres could be successfully combined with insulation and ventilation strategies to improve thermal comfort [26]. While a study in Bogotá proposed a roof structure using recycled Tetra Pak boards and hay for insulation to increase indoor temperatures up to 6 °C [33].

Cooling strategies such as stack ventilation, ventilated facades, and shading devices to avoid solar gains were frequently found in the literature [37]. For example, a qualitative airflow study, in a typical school classroom in Medellin, illustrated how air movement changes according to variations in the occupants´ position within the space via scale models and three tracer elements (expanded polystyrene, quartz sand, and smoke) [38]. Table 6 describes other general passive design strategies and recommendations for the main Colombian climates found in [3].

Table 6. Passive design strategies for the main Colombian climates (based on [3]).

Climate		Cold Climate	Temperate Climate	Hot-Humid Climate	Hot-Dry Climate
Representative City		**Bogotá**	**Medellín**	**Barranquilla**	**Cali**
Prevalent Comfort Indicator		**Insulation**	**Shade**	**Airflow**	**Sun protection**
Recommendations	**Air flow**	Minimisation of openings to control heat loos and drafts.	Use of lattice screens for controlled air flow.	Large openings and controllable windows with various layers.	Courtyards to trap cool night air and release hot air during the day.
	Facades	Increase facade's surface area to maximize sun absorption.	Roof overhangs for sun protection of the facades and to create buffer zones.	Vertical shading elements on the facade to protect from direct and diffuse solar radiation.	Buffer zones (e.g., long balconies or covered terraces) around the building.
	Roofs	Roof insulation.	Double roofs.	Ventilated double roofs.	High and ventilated double roofs.
	Walls	Use of high thermal mass to reduce indoor-outdoor variations.	Use of medium thermal mass for insulation.	Light wall construction to avoid heat storage, built with materials that dry quickly.	Ventilated walls with operable layers.
	Others	Use of passive solar heating when possible or efficient fireplaces and kitchen stoves to heat air flow.		Use of vegetation to moderate solar impact. Buildings elevated above ground.	Adiabatic or evaporative cooling through water fountains of features.

Using dynamic simulations with IESVE software, another study explored the implementation of typical Passivhaus principles (e.g., envelope super-insulation, airtightness, and mechanical ventilation systems with heat recovery) in detached houses and apartment blocks in Bogota and Barranquilla [20]. It found that under the business-as-usual construction scenario slightly cold indoor conditions were perceived in Bogotá ($-0.8 \leq$ PMV ≤ 0.15), whereas pronounced overheating ($1.45 \leq$ PMV ≤ 1.95) was predicted in Barranquilla. Trough passive measures, PMVs were significantly improved, and compliance with the Passivhaus Standard (regarding heating energy demand and primary energy consumption) was achieved for all case studies in Bogota. However, these measures did not meet the standard prescriptions for cooling energy demand and consumption in Barranquilla.

Few documents in the sample discussed occupants' adaptive strategies or social and phycological aspects of thermal comfort. However, one study which surveyed 147 occupants from four different naturally ventilated office buildings in Bogotá found that adaptive design strategies significantly improved thermal comfort perception [16]. These strategies included variations in occupancy density, a schedule for coupling and decoupling of indoor spaces with the outdoors and placing workstations close to a window.

Another study on outdoor thermal comfort carried out in six different areas in Barranquilla, which employed 781 thermal sensation surveys and simultaneously measured climatic conditions, found high tolerance to elevated temperature and relative humidity [14]. The average mean air temperature associated with neutral thermal sensations was 27.9 °C. However, different microclimate conditions were perceived between the richest and the poorest neighbourhoods, due to lack of shade and vegetation. The authors argued that this encourages inequalities in terms of climate conditions and thermal comfort, while impacts expectation and memory, thus influencing thermal perception.

In the subject of outdoor thermal comfort also, a study on Urban Heat Islands in Bogota collected monthly air temperature data from nine different urban meteorological stations for one year [22]. The results showed that urban density above 14,500 inhabitants/km^2 may cause air temperature differences higher than 1 °C, greater obstruction of the Sky View Factor (SVF < 0.45) and a larger decrease in green areas and vegetation cover (Pervious Surface Fraction PSF% < 30).

3.7. Main Findings from the Researchers' Surveys

The survey answered by 26 researchers requested general information about their research objectives and methodology, analysis strategies, results, and publications. The results show that most researchers (54%) combined theoretical and practical methodologies in their work (Figure 9A). Furthermore, 23% focused on fieldwork (primary research), whereas 19% centred on secondary research. The main objective of most of the studies was linked to aspects of indoor thermal comfort (67% of the counts), followed by thermal comfort in urban spaces (16% of the counts) (Figure 9B). However, the study of evaluation methods was less frequent. Other objectives mentioned included to test the correlation between comfort and learning or to study energy efficiency in constructed buildings.

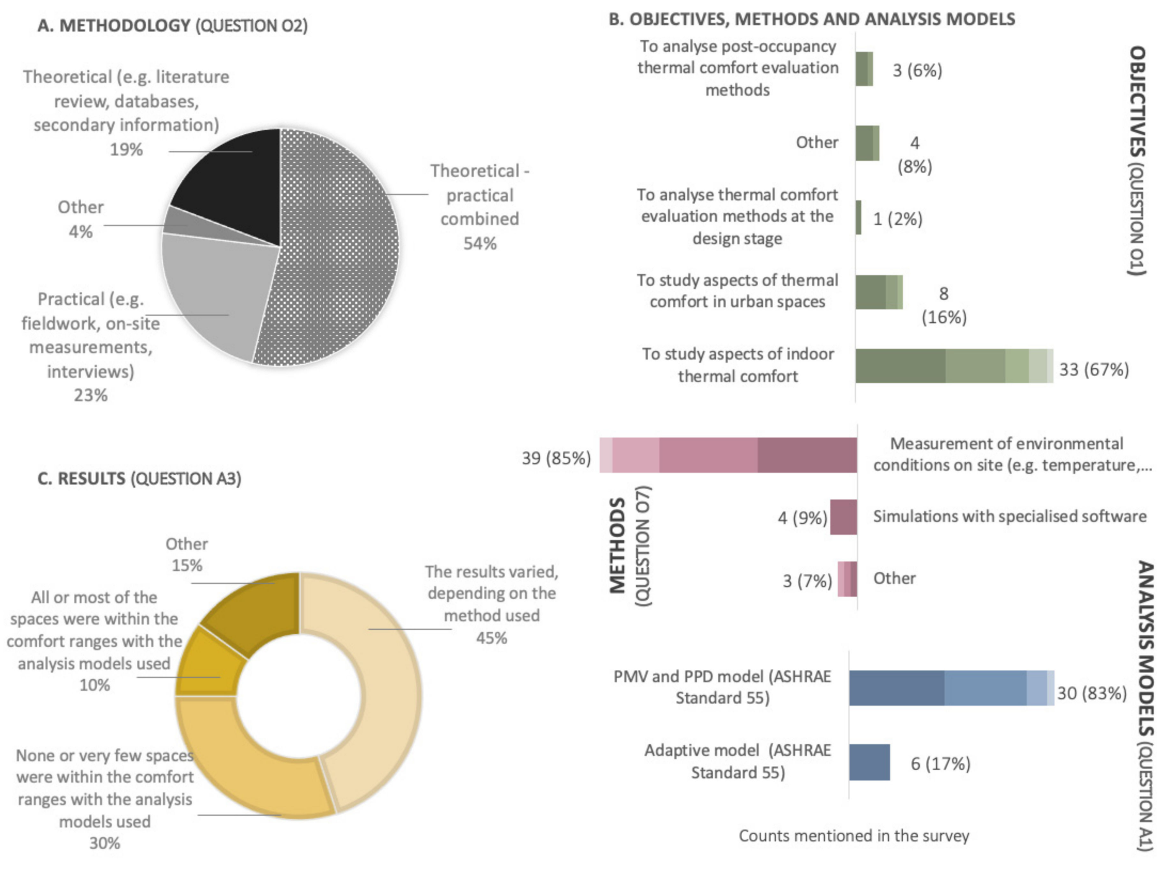

Figure 9. Findings from the researchers' surveys. (**A**) Methodology. (**B**) Objectives, tools, and analysis models. (**C**) Results.

Researchers used equipment to measure on-site environmental conditions (e.g., temperature, RH and airspeed) 10 times more than simulations with specialised software. They were also five times more likely to use the PMV and PPD model than the adaptive model (Figure 9B).

According to 45% of the respondents, the results from their thermal comfort assessments varied, depending on the method choice (Figure 9C). Thirty per cent agreed that none or very few of the spaces studied were within the comfort ranges, whereas only 10% stated the opposite (most spaces were within the comfort zone). Others mentioned that their results were not conclusive or depended on particular building layouts and thermal insulation levels.

Regarding policy, the most consulted document during the research projects was the Norma Técnica Colombiana NTC 5316: Condiciones Ambientales Térmicas de Inmuebles para Personas 2004 (Spanish version of the ASHRAE Standard 55-2004), as it was mentioned in 16 counts (46%) (Figure 10A). Meanwhile, Resolution 0549 of 2015 form the Ministry of Housing was the least consulted policy, even when it is the principal Colombia policy to establish parameters and guidelines for sustainable construction and water and energy saving in buildings.

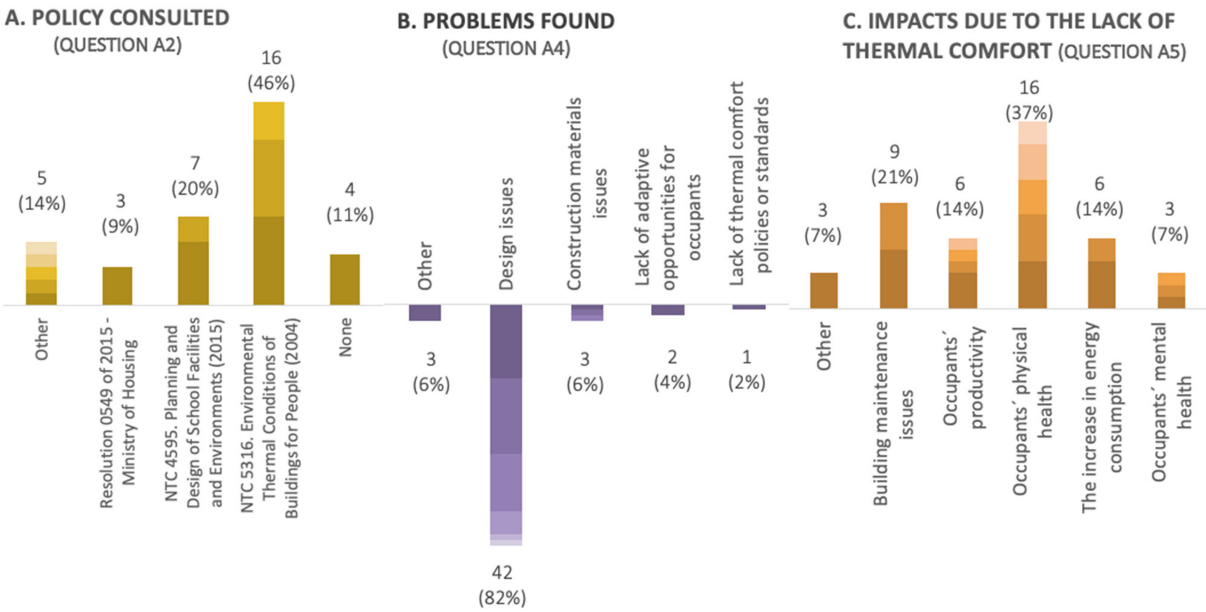

Figure 10. Findings from the researchers' surveys. (**A**) Policy consulted. (**B**) Problems found. (**C**) Impact due to lack of thermal comfort.

Additionally, the results show that design issues were the most common cause for the deficiencies in thermal comfort found during the studies, as mentioned by researchers in 42 counts (82%) (Figure 10B). The main effects because of the lack of thermal comfort were related to the building's occupants, as mentioned 58% of the time in 25 counts (37% for occupants' physical health, 14% for occupants´ productivity, and 7% occupants' mental health) (Figure 10C). Likewise, 35% of the counts were linked to impacts on the building (21% for building maintenance issues and 14% for the increase in energy consumption).

4. Discussion and Conclusions

The present review provides evidence that thermal comfort research in Colombia is very recent (mainly from 2017 to 2019) and still has limited scientific impact regarding availability within index journals and influence on national regulations. The citations of the reviewed documents are scarce, and only 10% of the authors have two or more publications, showing little continuity in the studied field. It is argued that the limited number of citations is not only due to the recent date of the publications but also to the lack of exposure. For example, References [15,17], published in 2015 and 2016, respectively, have a significant number of citations compared to similar documents published years before. Additionally, the FWCI for most of the publications available in Scopus is below 1, meaning that the outputs are cited less than expected according to the global average.

The point of reference for the evaluation tools and methods is the ASHRAE 55 Standard (usually the PPD and PMV values), even when there is ample evidence of its inadequacy for the study of thermal comfort in tropical climates or buildings with natural ventilation. However, the ASHRAE 55 Standard still offers more precise guidelines to assess thermal conditions, compared to the existing local policy. For example, the national technical guide that supplements Resolution 549 of 2015 only states that "as a rule of thumb, comfort lays between 21 °C and 25 °C, and relative humidity between 20% and 75%" [11]. It is unclear which thermal comfort model is guiding this assumption, as comfort zones change depending on the model used, which leaves this selection open for interpretation. The document only briefly references the PMV and PPD model, which is considered unsuitable for NV buildings (the largest portion of the country's building stock). Relative humidity levels above 60% are usually discouraged, as they can damage materials and promote mould and bacteria growth [66]. Other technical standards such as the NTC 4595 for schools mainly present a series of design features to achieve comfort, failing to include a metric or model to assess comfort conditions [67]. As a result, no technical documentation is required regarding sustainable construction regulation or any comfort standard for the approval of new building designs. To date, the only compulsory information for construction permits is to state the type of climate where the project will be built and a self-declaration of compliance with sustainable design attached [68]. This leaves a regulatory void in which most projects self-declare compliant even if they do not have the technical studies required for it.

The authors argue that standards such as the ASHRAE Standard 55 currently include very little data from fieldwork in South American countries because of their lack of availability or exposure in international outlets. Additionally, these standards have been adopted in Colombia partly because of the lack of knowledge on local thermal comfort studies, which describe their limitations. This could be happening in other countries that use these assessment models for similar geographical and climatic conditions or that have limitations regarding public policies and research access and investment. The different versions of adaptive models that have emerged in recent years from countries such as Brazil, Mexico, and India indicate that this is the case. Therefore, the results from this literature review can be interpreted or extrapolated to comparable contexts.

Current research trends centre on practical studies (often including fieldwork), rather than theoretical studies or computer simulations. This is very positive, considering the need for these kinds of enquiries within the formulation and adjustment of evaluation methods. However, the focus is still on very few building types and climates, leaving substantial research gaps in other areas. No alternatives to the Köppen–Geiger classification were mentioned in the documents reviewed, and none of them underlined altitude as a significant variable affecting thermal comfort, which leaves these areas or research still unexplored. Researchers have directed their work according to the availability of recourses or accessibility to study subjects. Therefore, the existing documentation is scattered and circumstantial, as there is no general coordination or research strategy in the country for the study of thermal comfort. This is alarming, bearing in mind that thermal comfort in the built environment is one of the most defining parameters influencing energy use, environmental quality, CO_2 emissions and occupant's physical and mental health and productivity. As temperature and humidity continue to increase worldwide, Colombia is among the most vulnerable regions to heat stress in the near future [69].

The information reviewed evidenced widespread agreement within the scientific community on the generalised feeling of discomfort in the studied buildings across Colombia. The lack of regulations and control appears to influence the quality of the current constructions, being inadequate design the most common cause for the existing thermal comfort deficiencies. Therefore, the authors advocate for the urgent need of detailed regional and national norms on design policies associated with thermal comfort and energy consumption in buildings. Advancements in thermal comfort design in Colombia would require greater efforts to develop or recommend the most applicable standards for the country.

Basic principles, such as reducing or eliminating cooling and heating needs in tempered climates, ought to be informed by and enforced with regulation. This is even more critical for warm climates in the light of increasing air conditioning demands.

This manuscript provides a broad overview of the state-of-the-art of thermal comfort research in the country. However, a systematic body of knowledge is necessary covering the particularities of cities with different climates, altitudes, construction systems, and cultural adaptations to determine a set of comfort conditions applicable to specific building types. Such an effort would allow the regulatory bodies to enact comfort requirements and accurately control their implementation. These regulations must consider the results of the studies performed in actual buildings in Colombia, avoiding the adoption of foreign standards originally developed for other contexts. Priority should be given to implementing passive design strategies over mechanical acclimatisation, because of their impact on energy consumption and association with the speared of infectious diseases.

During this review, the authors identified further limitations regarding education, policies, and practice that may hinder the development of thermal comfort research in Colombia. Table 7 proposes some opportunities to overcome these limitations.

Table 7. Limitations and opportunities linked to the development of thermal comfort research in Colombia.

Limitations	Opportunities
Existing policies are vague, mainly qualitative, and most times contradict each other.	To introduce minimum and measurable sustainable design requirements. To define common objectives between different policies.
The adopted foreign standards and certifications were created for contexts different to Colombia.	To design national certification programs appropriate to the particular conditions of the country.
There is a disjunction between policymakers, evaluators, and control authorities.	To specify evaluation processes and control bodies at the government level.
Research is not economically rewarded within the practice of architecture and in the academic context, the investment return is very low.	To encourage research careers, not only by promoting doctoral studies but also by generating better-paid career development opportunities.
Research and Development (R&D) expenditure as a percentage of the national GDP is only 0.24% compared to 1.16% in Brazil or the average 0.62% for Latin America and the Caribbean. This affects the lack of available information and publications in index journals (which are mainly in English and difficult to access for many academics). Therefore, there are only 2664 papers in SCOPUS per 100 thousand inhabitants compared to 8009 in Chile or 20,946 in the USA [70].	To increase R&D investment at national level and support and encourage academics by promoting publications in indexed journals.
Purely academic research tends to be disconnected from reality. Purely practical research lacks a theoretical basis or limited dissemination for commercial reasons.	To involve professionals from different disciplines and private companies in the generation of new knowledge on sustainable architecture with incentives for all parties.
Thermal comfort as a subject is rarely taught in undergraduate programmes. In the courses that include it, there are gaps between the theory and its application in practice.	To allow for the progression between education and practice, with paid research and practice positions for students.
Students have few opportunities to practise in a real context during their studies. Students could be better prepared for the challenges that professionals face where a variety of skills is needed.	To strengthen the professional practice program, making it mandatory within public and private institutions.
Graduate evaluation systems are inconsistent with the dynamics they will encounter in practice.	To adjust evaluation systems considering the dynamics of real contexts.

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