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Bioclimatic design recommendations for novel cluster analysis-based mapping for humid climates with altitudinal gradient variations

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ABSTRACT

Proper planning of urban environments in construction projects requires an accurate understanding of the prevailing climates in an area. However, the need for sufficient climate records in the Global South countries can make this characterization difficult. This study proposes using satellite information and cluster analysis to define the climatic behavior in Colombia, specifically in areas with intertropical climates with altitudinal gradient impact. The methodology used the statistical analysis of hourly temperature and relative humidity data for recent typical meteorological year (TMY) files. These data were obtained from the National Renewable Energy Laboratory (NREL). Subsequently, cluster analysis was applied to group regions with similar climatic characteristics. Standardization of the climatic variables ensured that all contributed equally to the research. The study results present an atlas with nine different climatic strategy zones, turning Colombia's climate into eight main clusters, each with specific characteristics and recommendations for the passive design of buildings. Identifying these zones made it possible to define the distribution of bioclimatic strategies in the different thermal floors of the region studied. This approach provides a framework for urban planners and city officials to develop climate-responsive building design guidelines adapted to the specific climatic conditions of each zone.

1. Introduction

1.1. Conceptualization

From the architecture and urban planning perspective, climate is fundamental in designing and constructing sustainable and efficient buildings [1]. In this context, some climate characterizations have been developed for different regions. The classifications presented by ASHRAE [2] and Köppen [3] are among the most famous methods to characterize climate in cities worldwide. For sustainable urban planning, there is a need to use recent weather data and develop corrected climate-responsive recommendations that consider the impact of climate change [4]. The development of climate change-sensitive recommendations allows for connecting the design guides and bioclimatic conditions for thermal comfort and energy-efficient building and city designs [5–7]. Bioclimatic architecture is becoming increasingly popular as an intelligent way to benefit from the climate and the environment to achieve the highest in-

Abbreviations: ASHRAE, American Society of Heating, Refrigerating, and Air-Conditioning Engineers; BBCC, Building Bio-Climatic Chart; GIS, Geographic Information System; NREL, National Renewable Energy Laboratory; NSRDB, National Solar Radiation Database; TMY, Typical Meteorological Year.

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door thermal comfort based on only passive systems [8]. Researching and defining the diversification of temperatures in a region is fundamental for the bioclimatic design of a building [5]. The climate contributes to the performance of buildings, promotes comfort and energy efficiency conditions in harmony with the natural environment, and faces the challenges posed by climate change in the long term [9]. Bioclimatic design professionals must evaluate the climatic characterization of the region rigorously to develop optimized-performance bioclimatic buildings.

The lack of adequate characterization of a region's climatic advantages and disadvantages represents one of the main challenges for bioclimatic designs [10]. The impact of climate on the performance of a building becomes especially relevant in geographic areas that present a wide range of climatic conditions [11]. The thermal exchange and the microclimate generated between the exterior and interior needs of a building impact the human's thermal comfort. This term refers to how the mind expresses thermal satisfaction with the surrounding environment [7]. The rupture of this thermal balance generates stress for the human that needs to be remedied. From this perspective, heating and cooling systems became popular a few decades ago to accomplish indoor energy balance and achieve adequate thermal comfort (no heat or cold). However, with the population increase, economic growth, and climate change, energy demand has become unsustainable, even in the short term [12]. Due to the above, one of the United Nations Sustainable Development Goals is to develop sustainable cities and communities in the fight against climate change by reducing energy consumption and resilient building designs [13].

Colombia, located in the equatorial zone, commonly exhibits hot and considerably humid climates due to its location. It is essential to highlight the presence of thermal floors in the country due to the influence of the altitudinal gradient provided by the Andes Mountain range. This climatic diversity is present in diverse urban settlements, resulting in a wide range of hot, humid, and cold climates [3]. Different climate conditions and microclimates presented in tropical regions commonly have yet to be deeply studied by principal classifications [14]. These climatic conditions have led to approximately 19 % of Colombia's energy consumption due only to residential buildings. In addition, Colombia's energy matrix is still majority based on fossil fuels [15]. Either way, the climatic zones defined for Colombia should be studied in more depth and consider more comprehensive ranges.

1.2. Background

Bioclimatic design, combining biology and climate, is an approach to building and landscape design using the local climate as a source of thermal comfort [16]. Fig. 1 shows how the environment, climate, and human beings are interconnected and are necessary to achieve thermal comfort and responsive bioclimatic design [17]. To gain this understanding, it is of utmost importance to achieve an adequate and accurate characterization of the behavior of these factors in each space and the design of the building. From this perspective, specific essential bioclimatic diagrams have been proposed to throw the time. Such charts facilitate the understanding between climate and passive design strategies and building construction, as well as energy efficiency systems, types of materials, and architectural solutions [18]. The first researcher who developed a chart representing the relationship between architecture and climate was Victor Olgyay. This author defined a graphical tool used to analyze thermal comfort: the properties of humid air, such as temperature and relative humidity. Also, the diagram allows evaluation of the state of moist air and calculation of the optimum climate properties to achieve thermal comfort in each environment. However, Olgyay's chart considers outdoor conditions, which only applies in regions with minimum fluctuations between outdoor and indoor conditions [19].

Then Givoni [20] introduced the psychrometric chart, used to produce a bioclimatic diagram that provides strategies to improve the indoor situation of the building based on the outdoor climatic conditions [21]. This Building Bio-Climatic Chart (BBCC) has been divided into different strategy zones for cooling or heating (depending on the study region) that provide a guideline for designers to achieve human comfort when no mechanical systems are provided. Initially, this chart considers weather characteristics such as relative humidity, dry bulb temperature, and air pressure [18]. However, throw the years, different researchers, including Givoni, have made some modifications or inclusions to the BBCC depending on the needs of the building. An example of that radiation was added as a limit for requiring shade in certain conditions. Fig. 2 presents the conventional Givoni's BBCC diagram [22] adapted from Manzano-Agugliaro [23]. It is used for different bioclimatic simulations where one can see the other boundaries. Also, Manzano-Agugliaro BBCC adaptation plot solar protection is an appropriate strategy for any space with a dry bulb temperature higher than 20 Celsius degree, no matter the humidity range or even if there is an optimum thermal comfort level.

Despite the functionality of BBCC, it is a complex tool to interpret due to its unconventional shape and difficulty finding climate information in its required form. For this reason, authors like Dekay and Brown [24] redrew the Givoni diagram based on the structure of the rectangular Olgyay diagram in a suitable form. Later, Roshan and Attia, in their research of Iran, included internal gains

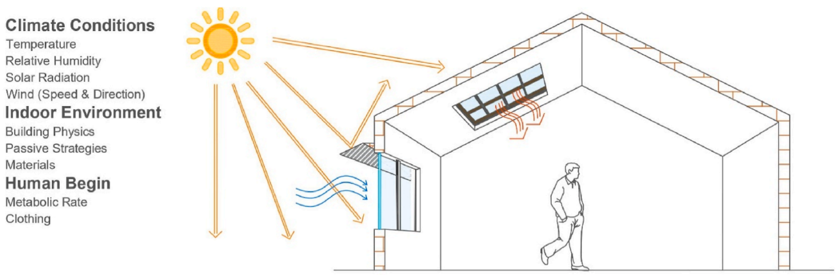

Fig. 1. Interactions between climate conditions, buildings, and humans being.

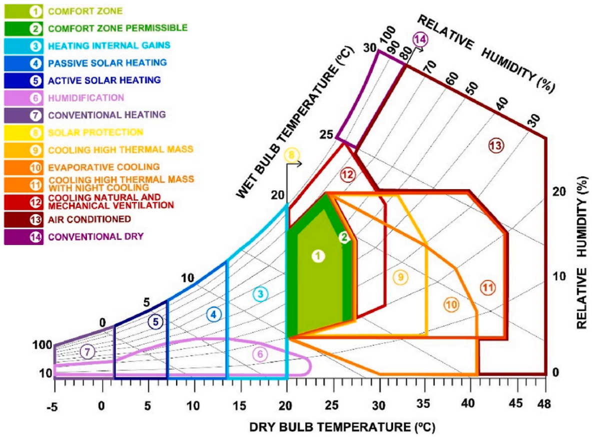

Fig. 2. BBCC Diagram from Manzano-Agugliaro [23] adapted from Givonni's [22].

strategies, conventional heating, and humidification zones initially presented in the Givoni diagram [7]. The chart designed by Roshan and Attia is adopted in this research due to including a no-industrial version and its straightforward interpretation. The diagram applied presents some adaptations to the boundaries between zones that will be defined later in the study.

1.3. Aim and contribution of this study

As mentioned before by previous research, bioclimatic design is fundamental for achieving adequate thermal comfort levels inside built environments and reducing energy consumption. In addition, studies show that the proper climatic characterization of a domain is a suitable tool for bioclimatic design and urban planning [25,26]. However, it has also been seen that this type of climate classification has been based on insufficient information, usually with a large spatial distance between meteorological stations and even with obsolete time series that still need to be adapted to current climate changes [4,27].

This study applied a methodology based on satellite information. The methodology implemented one of the most used psychrometric diagrams worldwide for bioclimatic design (BBCC). Based on this diagram, a definition and spatial distribution of bioclimatic passive strategies in large extensions are achieved. This information allows the designer to make preliminary decisions about the project from a bioclimatic perspective of thermal comfort and energy efficiency. This research work reflects its contribution in the following points:

i. Introduce using updated TMY climate files based on high-resolution satellite information (4 km pixel).
ii. Perform a climate classification for a hot and humid region influenced by the altitudinal gradient based on the passive strategies presented in the BBCC diagram.
iii. Generate bioclimatic design recommendations for buildings located in different climate conditions.
iv. A new climate classification for architecture and bioclimatic design has been established for Colombia.

The methodology presented in this research seeks to facilitate the early design phases of buildings in a country with a hot and humid climate with thermal floors by generating a new climate classification. In this process, climate files updated to 2021 help eliminate spatial uncertainties that generally occur with weather stations. The methodology is based on a cluster analysis using different zones of passive strategies based on temperature and humidity for a Typical Meteorological Year (TMY).

The research is divided into four sections, starting with an introduction where a conceptualization of the problem is made. Also, it provides a statement on the importance of passive design strategies based on climate advantages to achieve thermal comfort and reduce energy consumption in buildings. The second section introduces and illustrates the methodological development carried out, presenting the generation of a new climatological atlas defined through hierarchical cluster analysis. This analysis was validated by different statistical methods to corroborate its adequate distribution. The third section discusses the results, clearly describing each new climatic zone and selecting a set of bioclimatic recommendations. Generally, this methodology can be replicated in any region with TMY information provided by the National Renewable Energy Laboratory (NREL) and knowledge of clustering analysis by statistical methods. Finally, a comparison is presented between different urban settlements in different climate zones and how the design behavior changes to account for each location.

2. Methodology

The research methodology is based on cluster analysis for a database of 69874 points spaced approximately every 4 km obtained from the data viewer from the National Renewable Energy Laboratory (NREL) covering the entire surface of Colombia [28]. The cluster analysis handled a hierarchical analysis based on the ward's method with Euclidian distance taken since other authors indicate a better fit in the clustering process [5–7]. The climate data includes, among others, temperature and relative humidity for a typical meteorological year (TMY); this analysis is already performed by NREL, which indicates that it uses a range of years between 2001 and 2021 [29]. This methodology includes the development of an atlas of 9 bioclimatic zone strategy maps. For the analysis, the different regions of Colombia were classified into eight main groups. Each was associated with the design recommendations proposed by various authors [7,10,12,23,25]. On the other hand, the cluster analysis allows a comparison between the climatic zones and the frequency of their presence in each of the main cities located in the clusters found. All the above will be described in depth in the methodological development.

2.1. Bioclimatic zone definitions and weather data

Following the methodology proposed by Roshan and Attia [7], comfort boundaries and climate zones were defined for the different groups of design strategies represented in the update of the BBCC made previously by them, which are based on the expected temperatures outside the building without considering mechanical systems in the analysis. It is essential to mention that these limits may vary depending on the type of building as well as the location of the building, so these models may only sometimes be applied equally in some countries [30]. Previous research mentions that people living in hot regions, especially in undeveloped countries such as Colombia, endure higher temperature or relative humidity levels due to lower expectations and a lack of natural air conditioning.

As previously mentioned, Colombia is considered an undeveloped country; therefore, regions were defined based only on the BBCC for no-industrial countries, as shown in Fig. 3. All the points extracted from NREL and compiled as a new temperature and relative humidity dataset or a TMY in Colombia updated to 2021" [31] covering the study region for the climate classification were considered. These climate data are based on the TMY concept, which performs a statistical analysis in which the monthly data of the year that is statistically closest to the average is selected from a time series, thus generating a fictitious year that considers only the most probable conditions that occur during the years on which they are based [32]. Also, this weather file is one of the most useful for model building energy performance [33]. NREL provides hourly climate data updated to TMY 2021, their current climate library [28]. It is important to note that many designers, both in practice and research, often use this type of climate archive to develop their activities [34–37]. The processing of the 69874 records included the evaluation of 8760 h (one year), where the frequency of recurrence of the different climatic zones was evaluated for each point assessed.

2.2. Climate zone characterization and spatial distribution

Different design zones were classified to create the bioclimatic atlas and diagrams. For this purpose, 16 climatic zones were defined, as shown previously in Fig. 3. Even so, the results showed that the use of any strategy located in a humidification region (CHH, ASHH, PSHH, IGHH, DIEC) or the use of only air conditioning (AC) is not strictly proper to achieve thermal comfort in the study region. Therefore, the final analysis was performed for nine identified zones.

Each of the zones that were considered will be explained. CH, ASH, PSH, and IG were defined for zones representing cold and cool climates. The first zone mentioned was strictly focused on conventional heating strategies. The second one represents the active solar heating zone without including another system, and the same happens with PSH and IG, referring to passive solar heating and internal gains, respectively. The next zone, CZ, refers to the comfort zone, which indicates the optimal conditions of thermal comfort, i.e., it relates to an area where it is not required to include active or passive systems to contribute to an excellent thermal sensation, at least outdoors of buildings. By the way, from 20 Celsius degrees and warmer, including CZ, all the strategies include solar protection, bearing in mind some preliminary research that considers it an adequate alternative to limit thermal gains inside the building

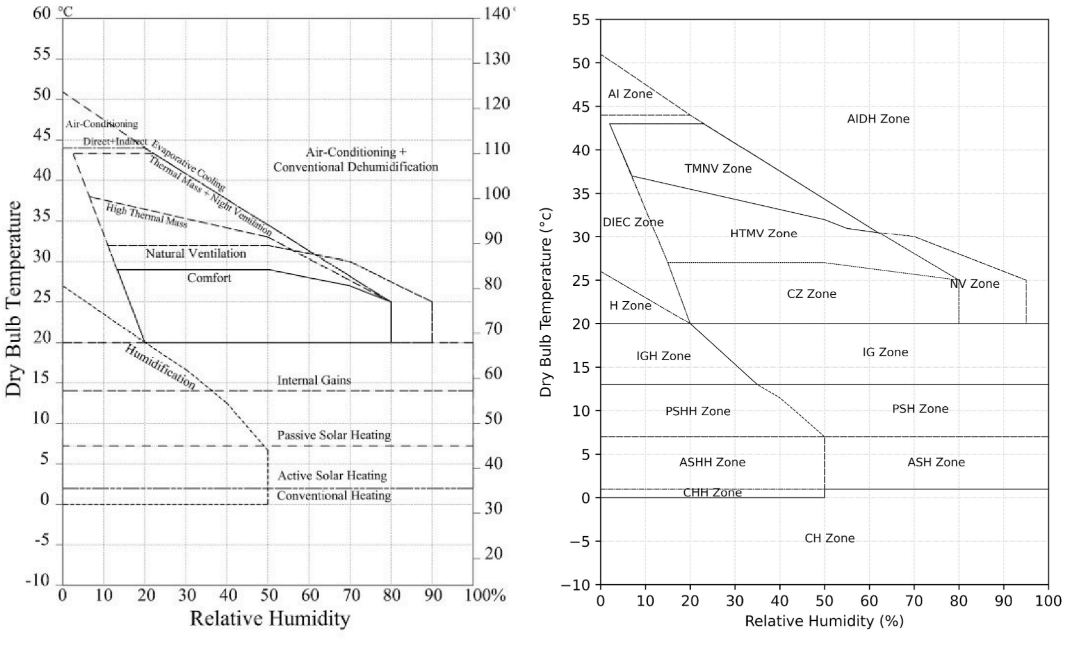

Fig. 3. BBCC adapted to hot no-industrial countries (left) [7]- Comfort bounders proposed for the present study (right).

[38–40]. NV represents passive design strategies based on natural ventilation. HTMV was defined as a combination of high thermal mass and natural ventilation as an effective group strategy. TMNV presents a variety of thermal mass and night ventilation for hot climates. Finally, ACDH was considered the region where the most effective strategy was a combination of air conditioning and traditional dehumidification.

2.3. Clustering analysis

Cluster analysis is considered an effective statistical tool to determine homogeneous relationships. Climate zoning allows data grouping based on the results of similarities in the evaluated meteorological parameters and the resulting thermal indicators. Unlike other statistical methods, cluster analysis is not based on theoretical distributions but explores the similarities and differences between data. The appropriate cluster analysis is also essential to define equative groups [41,42].

In climatological research, hierarchical clustering is a commonly used method because it is more suitable for exploratory analysis and determines climatic regions based on the mean of the grouped data [5–7,42]. Usually, this type of analysis is plotted on a diagram known as a dendrogram. The basis of this graph allows to join by roots the different groupings contained in different levels depending on the similarity between the data groups [43]. As previously mentioned, the values used to define the nine climatic zones were used for this cluster analysis based on the ward method and Euclidean distances. Then, the 69874 points were clustered by implementing a matrix of 9 x 69874 based on the frequency of occurrence of each bioclimatic zone, where the sum of all nine variables represents 100 % of the TMY hourly data.

Although previous work mentioned hierarchical clustering as the ideal method for clustering climate zones due to its complex methodology, it could be more computationally efficient [43]. Considering the last statement, the Partitional-Clustering K-means method was implemented to verify the optimal performance of the clustering process. In addition, two cut-off measures were implemented for selecting an adequate number of cluster groups: the silhouette index [44] and the elbow method [5]. The first one assigns each member of a cluster a value that indicates the degree of similarity between a member of a cluster and the other clusters. This value is between −1 and 1. If the value is close to 1, it means a correct clustering distribution. If it is at 0, it indicates no noticeable difference between the two clusters, and if the value takes negative values, it means an incorrect member assigned to a specific cluster [44].

On the other hand, the Within-Cluster Sum of Squares (WCSS) method, known commonly as the "elbow method," is based on measuring the internal variance of the clusters generated with different values of k (number of clusters). The clustering algorithm is run with different values of k, and the sum of squares of the distances from each data point to the centroid of its nearest cluster is calculated. The resulting graph shows a downward curve where the WCSS decreases as clusters increase. The end at which the curve shows a sharp change and resembles an "elbow" is where an optimal level of clustering is considered to have been reached [45]. From this process, the two methodologies show a better fit in 8 groups, as seen in Fig. 4. Correlating the climatic zones obtained and the climate and bioclimatic of Colombia, it can be said that certain climates have been generalized because the location of Colombia and its starry geography due to the Andes Mountains range gives way to more climates according to the Köppen classification. Despite this and considering that the climatic data from the TMY refer to a fictitious year, these zones have been defined as the predominant ones from a bioclimatic design perspective, such as the one being carried out. Finally, the clusters were compared and showed the cut offline that divided the dendrogram into the defined groups, as shown in Fig. 6.

3. Results and discussion

3.1. Bioclimatic zone strategies and their spatial distribution

As mentioned, all the analyses were based on the nine climatic zones in Table 1. It shows the strategies for the initial 16 zones to reduce to the final nine variables. It is essential to mention that this reduction occurs because the evaluation region is near the Ecuador line. In this context, areas located across the globe in this area are very humid zones and, therefore, are not present in climate seasons. Their temperatures remain relatively constant throughout the year with a reduced maximum temperature range. However, the influence of the altitudinal gradient proportionated by the Andes Mountain that crosses from the southwest to the country's center

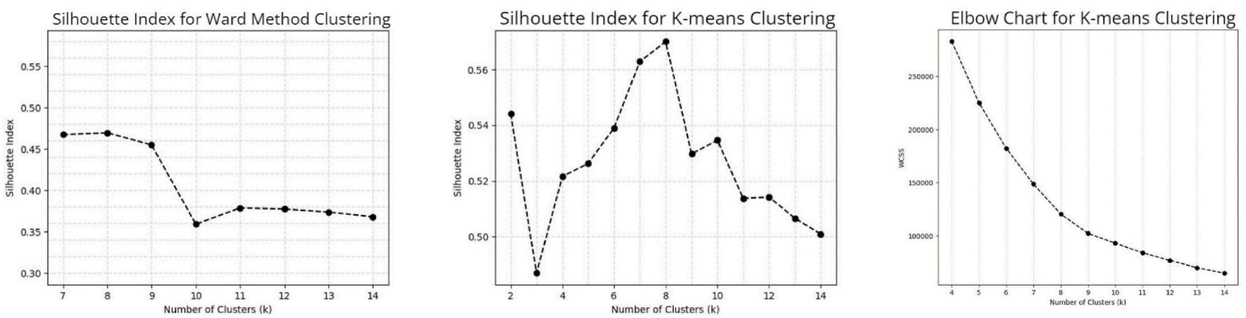

Fig. 4. Comparisons between silhouette index for Hierarchical Cluster (left) and Partitional Cluster (center) and Elbow method (right) for the appropriate number of clusters.

Table 1
Statistics for bioclimatic zone strategies mapping for Colombia.

Zones	BBCC Description	Max %	Considered clustering (Yes/No)	% weathers record that experienced the strategy (above 1 %)
CH	Conventional Heating	72.888	Yes	0.431
CHH	Conventional heating + Humidification	0.000	No	0.000
ASHH	Active Solar Heating + Humidification	0.000	No	0.000
PSHH	Passive Solar Heating + Humidification	0.000	No	0.000
IGH	Internal Gains + Humidification	0.000	No	0.000
H	Humidification	0.000	No	0.000
ASH	Active Solar Heating	75.377	Yes	3.378
PSH	Passive Solar Heating	84.121	Yes	9.315
IG	Internal Gains	92.283	Yes	21.443
CZ	Comfort Zone + Solar Protection	82.637	Yes	33.321
DIEC	Direct and Indirect Evaporative Cooling + Solar Protection	0.000	No	0.000
NV	Natural ventilation + Solar Protection	91.747	Yes	90.457
HTMN	High Thermal Mass + Natural Ventilation + Solar Protection	61.039	Yes	49.999
TMNV	Thermal Mass + Night Ventilation + Solar Protection	33.995	Yes	29.230
AC	Air conditioning + Solar Protection	0.000	No	0.000
AIDH	Air conditioning + dehumidification + Solar protection	96.221	Yes	80.788

impacts the thermal floors. Considering the last statement, climate zone strategies that include humidification would only be necessary if the temperature is high relative humidity in almost all the country's regions.

Figs. 5a to 5e show each defined bioclimatic zone's behavior. The spatial distribution shows the Andes Mountain influences on the bioclimatic zone definition. Three principal mountain chains can be observed, where the domain strategies are ASH, PSH, and IG. However, among the high mountains, it can be observed how the altitudinal gradient decreases strategies as HTMN and CZ are increasing because of the thermal floors where the increment of elevation is inversely proportional to the temperature value. Because of this topographic, it can further observe the generation of microclimates all over the country.

An example is "Santa Marta's Sierra Nevada," located north of Colombia, a mountain proximate to the Caribbean coast. It can be changed drastically by the bioclimatic need to achieve comfort in a relatively short distance because of the altitudinal gradient of the

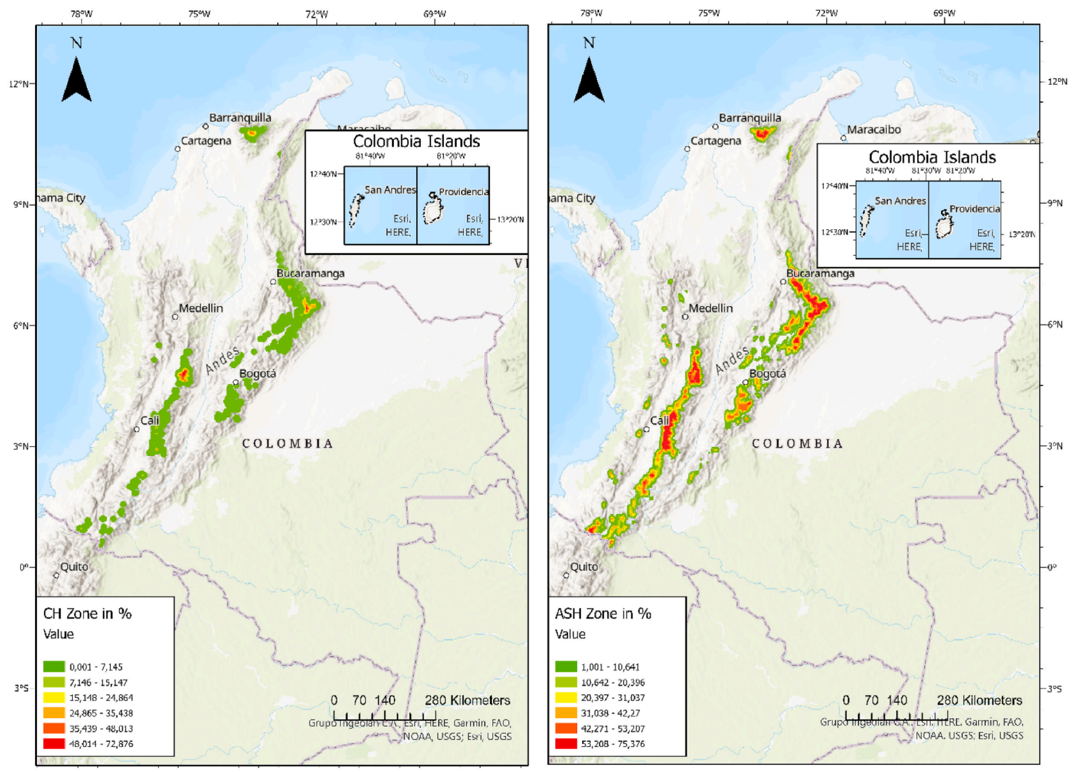

Fig. 5a. Spatial distribution of the nine bioclimatic zones based on BBCC for a humid climate with altitudinal gradient.

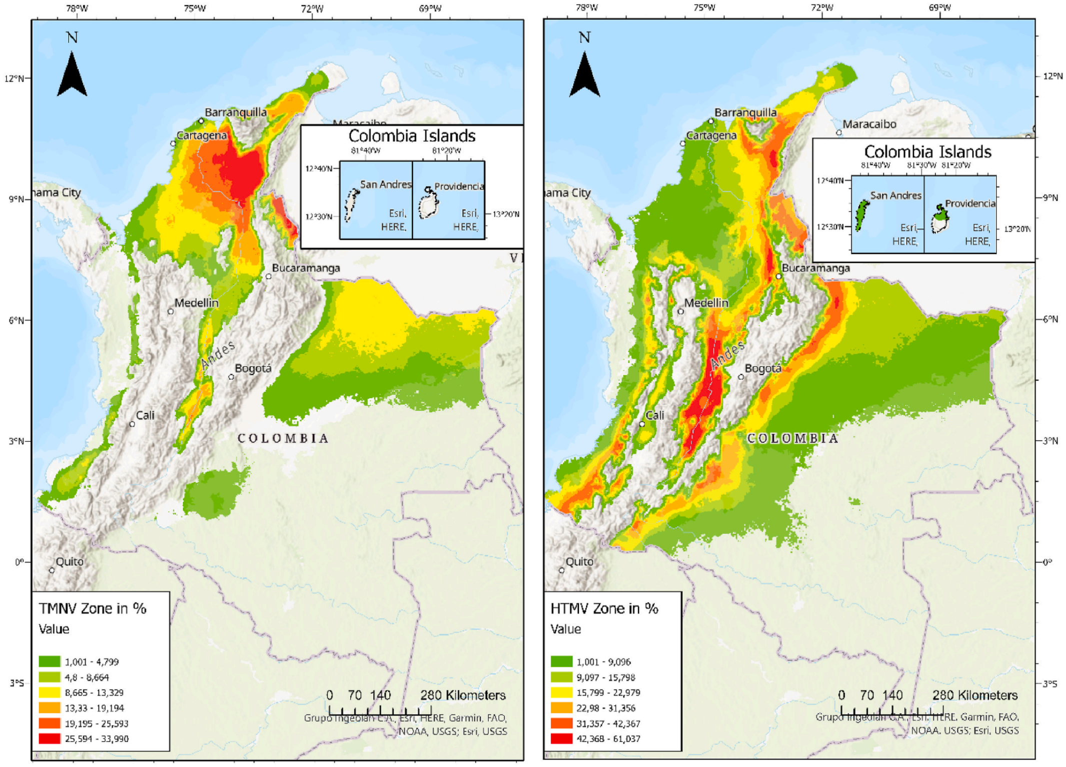

Fig. 5b. Spatial distribution of the nine bioclimatic zones based on BBCC for a humid climate with altitudinal gradient.

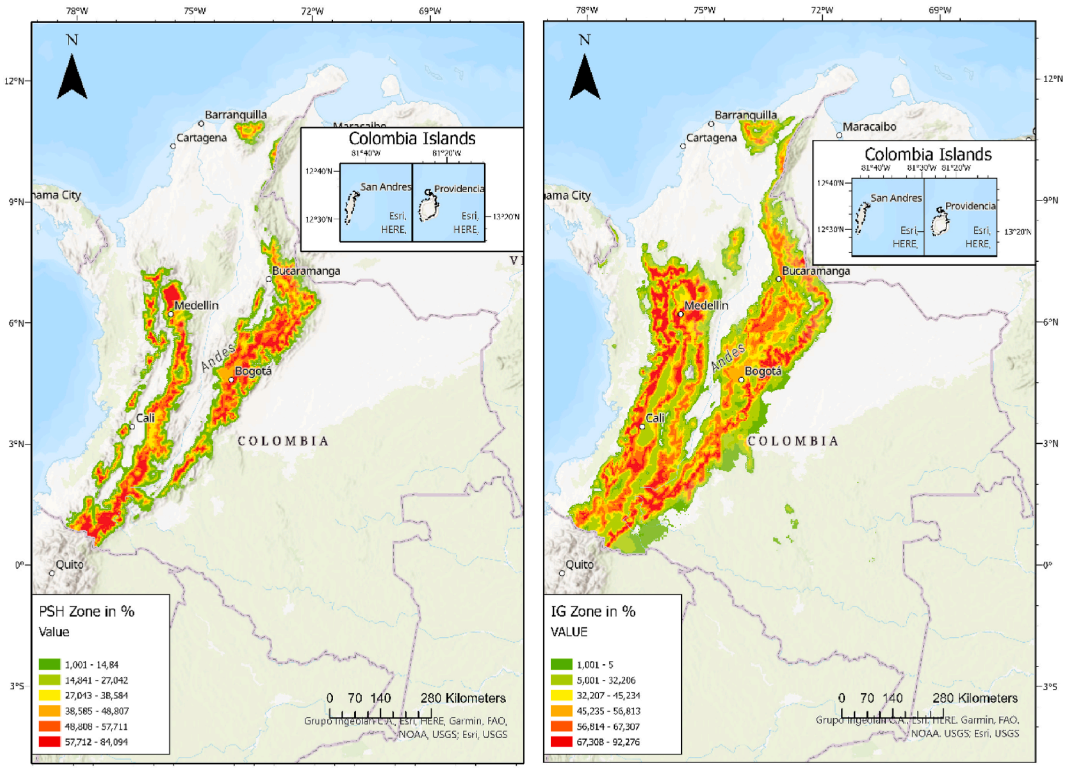

Fig. 5c. Spatial distribution of the nine bioclimatic zones based on BBCC for a humid climate with altitudinal gradient.

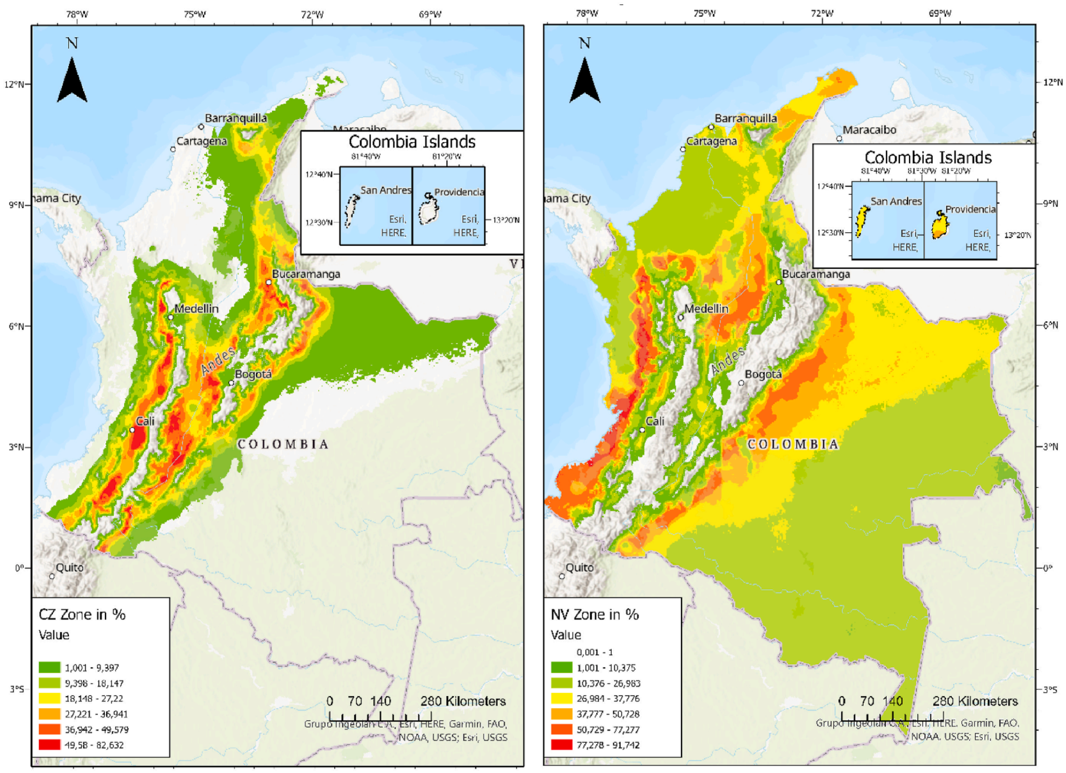

Fig. 5d. Spatial distribution of the nine bioclimatic zones based on BBCC for a humid climate with altitudinal gradient.

mountain and the heat and moisture of the near coastal climate. On the other hand, the more significant portion of the country not influenced by the mountain climate shows at different levels the need for bioclimatic strategies for hot and humid environments such as NV, TMNV, and AIDH. The variety of the status of each zone strategy is linked to other variables, like solar radiation, rainfall, and vegetation, that are not directly contemplated in this research.

3.2. Bioclimatic design strategies recommendations for Colombia's clustering

As mentioned before and shown in Fig. 4 and from the dendrogram seen in Fig. 6, the appropriate number of clusters for Colombia is eight geographical clusters. This section will describe each cluster's geographic and climatologic characteristics, given some bioclimatic design strategy recommendations according to the previous classification and previous works. In Table 2, the bioclimatic zones' frequency for every defined region can be seen. Each cluster was given a name taken in counting the past mentioned characteristics.

Cluster 1 - Moderate Transition Subtropical (Monsoon Climate). This designation reflects the nature of this zone as a transition between tropical equatorial climate zones, generally with warm and high moisture. The predominance of traditional air conditioning and dehumidification use during 51.29 % of the year indicates the need to consider temperature and humidity control strategies in architectural designs. However, the relatively low percentage of 2.19 % for implementing thermal mass strategies combined with night ventilation suggests more favorable options in this zone. The possibility of using high thermal mass and natural ventilation strategies 5.6 % of the time indicates that there are opportunities to take advantage of the thermal inertia of materials and natural ventilation at certain times. In addition, 40.69 % of the time, natural ventilation as an independent strategy may be most appropriate, highlighting the importance of considering air circulation and breeze capture to improve thermal comfort. The very low percentages of 0.52 % for direct thermal comfort and 0.15 % for internal gain strategies (Table 2) indicate that these are both the most frequent and the most recommended in this area. The most important recommendations given for this zone include:

- Thermal insulation: Since the area frequently needs traditional air conditioning and dehumidification, it is essential to ensure good thermal insulation in the building's envelopes. Thermal insulation will help reduce unwanted heat losses or heart gains, improving energy efficiency [46].
- Controlled ventilation: Designing buildings with controlled ventilation systems that allow fresh air to enter when favorable weather conditions ensure an adequate exchange of indoor and outdoor air.
- Solar control: Given that the percentage of air-conditioning time is very high, it is vital to implement solar control strategies. Elements such as eaves, brise-soleils, louvers, or vegetation to avoid overheating in interior spaces and reduce the cooling load can be effective [47].

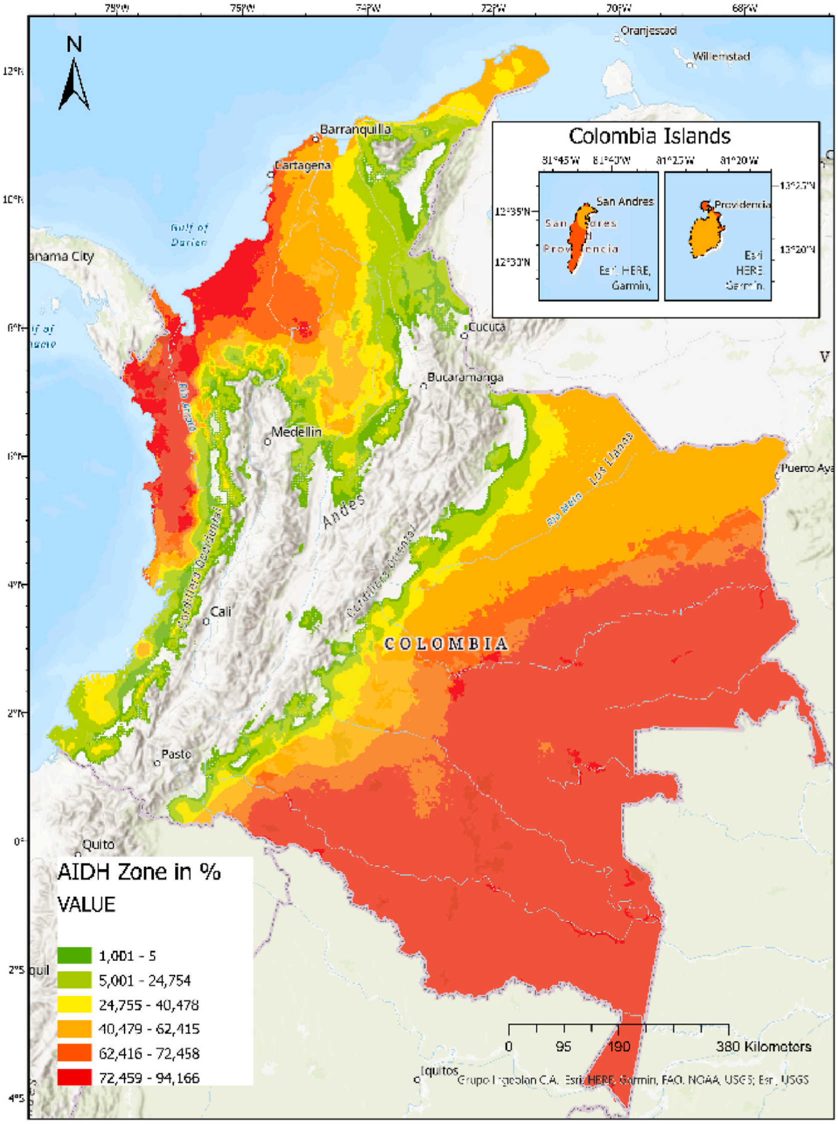

Fig. 5e. Spatial distribution of the nine bioclimatic zones based on BBCC for a humid climate with altitudinal gradient.

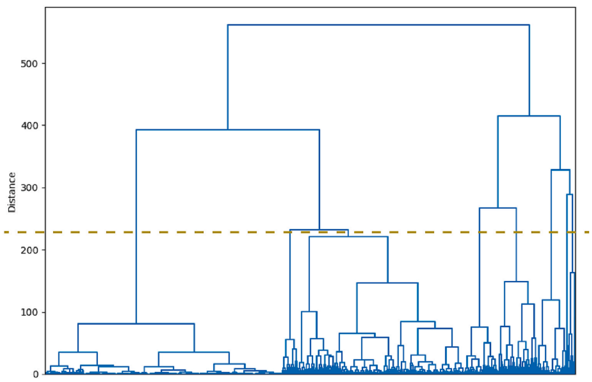

Fig. 6. Cut off eight groups shown on the Ward Method Dendrogram.

Table 2
Average characteristics for each specific cluster.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8
% of points in the same cluster	16.06	8.72	7.63	4.57	5.1	12.31	1.89	43.71
Bioclimatic Zone Strategy in %								
CH	0.00	0.00	0.00	0.00	0.00	0.00	3.13	0.00
ASH	0.00	0.00	0.00	0.00	0.00	0.00	44.72	0.00
PSH	0.00	0.00	2.13	0.00	50.63	0.00	45.44	0.00
IG	0.15	4.54	62.86	9.45	45.90	0.00	8.48	0.08
CZ	0.52	8.33	25.27	36.38	3.02	2.28	0.05	0.08
NV	40.69	48.32	6.67	20.51	0.04	28.69	0.00	17.89
HTMN	5.60	23.78	2.01	30.21	0.00	12.35	0.00	0.57
TMNV	2.19	1.95	0.00	4.00	0.00	14.17	0.00	0.23
AIDH	51.29	13.91	2.33	0.59	0.00	43.03	0.00	81.38

- Passive design: Explore passive bioclimatic design strategies, such as the proper orientation of buildings to take advantage of solar radiation and natural air currents. Consider the configuration of interior courtyards or atriums that can facilitate ventilation and natural light [48].

Energy efficiency: Since the high need for hot conventional systems is required, it must be promoted energy efficiency in lighting, ventilation, and air conditioning systems. Use high-efficiency equipment and control systems that adjust to actual demand, minimizing energy consumption [48].

Cluster 2 - Low transition Subtropical Climate. This designation reflects similar characteristics from the previous zone. However, this transition zone presents lower temperatures and humidity values where natural ventilation is fundamental. The most significant percentage of the time, 48.32 %, indicates that natural ventilation is this zone's most appropriate climatic strategy. The favorable conditions for air circulation and the entrance of breezes allow for maintaining thermal comfort conditions without the need for mechanical cooling systems. The percentage of 13.91 % for the need for air conditioning and traditional dehumidification indicates that, to a lesser extent, there are still times when mechanical cooling systems are required. The 23.78 % of the time when high thermal mass and natural ventilation strategies can be implemented indicates the importance of considering the thermal capacity of materials in the design of buildings in the plains. The percentages of 8.33 % for direct thermal comfort and 4.54 % for using internal gains strategies underline the possibility of taking a minimum advantage of internal heat sources and solar radiation to improve thermal comfort in this zone. For this cluster, the given recommendations are:

- Orientation: Design buildings that allow maximum use of air currents and natural ventilation, considering the predominant wind direction in the area [49].
- Cross ventilation: Design spaces to achieve adequate cross ventilation, allowing fresh air to enter from different directions and improving indoor and outdoor air exchange.
- Thermal insulation: Ensure good thermal insulation of building envelopes to minimize heat gains during hot seasons [50].
- Solar control: implementing effective solar control strategies, such as eaves, brise-soleils, and louvers, to prevent overheating in interior spaces during periods of high solar radiation.
- High thermal mass materials: The use of high thermal capacity materials in building construction to take advantage of thermal inertia and maintain a more stable indoor temperature.
- Strategic vegetation: When trees and vegetation are available around buildings to provide shade and help regulate temperature, especially in sun-exposed areas.

Cluster 3 - Mid-Altitude Mountain Cool Climate. This designation reflects the nature of this zone as a climatic zone in which a high percentage of time is experienced in thermal comfort conditions (25.27 %). The geographic location for this cluster shows a relation at elevations between 1000 and 2000 m.a.s.l adds dimension to the zone's climate, as the average altitude can influence thermal conditions and other climatic factors. The most significant percentage of the time, 62.86 %, indicates that internal gain strategies can be used to maintain indoor thermal comfort. These strategies may include internal heat sources, such as electronic equipment, lighting, or human activities, contributing to space heating. The percentage of 2.33 % for the need for traditional air conditioning and dehumidification indicates that, although to a lesser extent, there are still times when mechanical cooling systems are required, but can be replaced by other more efficient strategies. 6.67 % of the time, natural ventilation could be the most appropriate strategy for promoting fresh air intake and circulation to maintain comfortable building conditions. The percentage of 2.01 % for using high thermal mass strategies and natural ventilation indicates the possibility of taking advantage of the thermal capacity of materials combined with ventilation to maintain stable thermal conditions. The 2.13 % percentage of the time when passive solar heating strategies are included indicates that solar resources can be harnessed to heat spaces passively. Specific strategies and recommendations mentioned:

- Solar orientation: Design spaces to take advantage of direct solar radiation during periods when internal gain strategies can be applied. This orientation will depend on the specific building location and urban composition.

- Thermal storage materials: Use materials with high thermal storage capacity, such as concrete, brick, or stone, in structural elements such as walls and floors. These materials can gradually absorb and release heat, helping maintain a more constant indoor temperature [50].
- Space distribution: The design might contemplate spaces to facilitate the circulation of internally generated heat. This involves considering the location of heat sources, such as appliances and electronic equipment, so that they can contribute efficiently to space heating.
- Insulation: The design may ensure that building envelopes are well insulated to reduce heat losses and maximize internal gains.
- Internal heat management: It would implement internal heat control systems, such as cross ventilation and efficient cooling systems, to prevent overheating when internal gains generate excessive temperatures.

Cluster 4 - Foothill and Warm Climate. This designation highlights the highest average for thermal comfort zones; however, seen in their geographic locations, it can be denominated as warm transition zones between cold climates and more hot climates. Although, as a transition area, natural ventilation and a combination of thermal mass strategies are essential, considering the average altitude at which it is located. As mentioned, the most significant percentage, 36.38 % of the time, indicates that it is in thermal comfort conditions, a relevant factor in the bioclimatic design of buildings in this zone. The percentage of 30.21 % for natural ventilation combined with high thermal mass strategies underlines the importance of taking advantage of the thermal inertia of materials in combination with ventilation to maintain stable thermal conditions. The percentage of 20.51 % for the use of natural ventilation indicates that there is considerable time in which this strategy may be the most appropriate to ensure thermal comfort. The percentages of 9.45 % for the use of internal gains strategies and 2.13 % for passive solar heating indicate the possibility of taking advantage of internal heat sources and solar resources to improve thermal comfort in this area. Finally, specific strategy recommendations are mentioned below:

- Thermal insulation: The design may contemplate efficient insulation in the building envelopes; as a transition zone, verifying which materials suit the climate and local conditions is essential.
- Natural ventilation: Design spaces in such a way that they can facilitate cross ventilation, allowing the entry of breezes from different directions. In areas with high building density, strategies such as chimney effect ventilation should be more appropriate, and a wind speed analysis should be performed to make the most appropriate decision [51].
- Solar control: It is essential to implement solar control strategies, such as eaves, brise-soleils, or blinds, to maintain indoor comfort and to regulate the entry of direct solar radiation and avoid overheating in the interior spaces and consider the angle of the sun in each region of Colombia to optimize this strategy.
- Open space design: Creating open spaces and transition areas that allow airflow and facilitate natural ventilation inside buildings. May consider the integration of internal courtyards, gardens, or ventilated corridors to improve air circulation.

Cluster 5 - High-Altitude Mountain Cold Climate. This designation fits regions between 2000 and 3000 m.a.s.l. with a cold climate and high humidity. The analysis highlights the importance of passive solar heating and internal gain strategies in the zone, considering its location at higher altitudes. The most significant percentage, 50.63 % of the time, indicates that passive solar heating is the most efficient strategy to take advantage of solar resources and maintain adequate thermal conditions in the zone. The percentage of 45.9 % for the use of internal gain strategies highlights the importance of taking advantage of internal heat sources to reduce the need for additional heating systems. The percentage of the low value of 3.0 % for thermal comfort indicates that even though there are periods when climatic conditions are optimal, bioclimatic strategies must be applied to achieve adequate thermal conditions. Some bioclimatic design recommendations include:

- Solar orientation: The design of buildings should seek to take maximum advantage of direct solar radiation, orienting the areas of most significant use towards the south to receive sunlight and maximize passive solar gains.
- Thermal insulation: Ensure excellent insulation in building envelopes, especially in roofs, walls, and floors, to minimize heat loss during winter and maximize internal gains [50].
- Strategic windows: Place windows on the south and east facades to allow direct sunlight to enter during the winter and maximize passive solar heating. Be sure to use Low-E glass to reduce heat loss.
- High thermal capacity materials: Use materials with high thermal capacity, such as bricks or concrete, in building structures to take advantage of thermal inertia, store heat during the day, and release it slowly at night.
- Internal solar radiation control: Implement internal solar control strategies, such as curtains or blinds, to regulate the entry of direct solar radiation and prevent overheating at times when internal gains are not required.
- Efficient management of internal gains: Design spaces to maximize internal heat generation during the day, such as strategic placement of heat sources, electronic equipment, and heating activities.

Cluster 6 - Low Warm and extremely Humid Plains Climate. This denomination reflects the prevailing need for air conditioning and traditional dehumidification due to the high temperatures and relative humidity. It is characteristic of regions located near the Equatorial Line and that have low elevation from the sea. Moreover, these zones used to have a hot season and rainfall season. Emphasis is placed on using thermal mass strategies combined with night and high thermal mass with natural ventilation in specific periods. The percentages of use of each climatic strategy indicate the relevance of traditional air conditioning and dehumidification during approximately 43.03 % of the year. In turn, natural ventilation and high thermal mass strategies with night or natural ventilation are adequate for a significant part of the time, respectively, 12.35 % and 28.69 %. Although low (2.28 % of the time), the percentage of thermal comfort shows the moments in which the climatic conditions allow comfort without additional strategies. The topography of plains or low elevations is considered a predominant factor in the climatic characteristics of the area. Some specific bioclimatic recommendations for these zones are:

- Thermal insulation: For warm and hot climates, it is important to ensure good insulation in building envelopes, especially in roofs and walls, to minimize heat gain across the year.
- Cross ventilation: The design must include spaces to facilitate cross ventilation, using the breezes and air currents to cool the rooms during moderate temperatures.
- Solar control: The Implement of external solar control strategies, such as eaves, shading, or sun protection devices, to reduce direct solar radiation and overheating in interior spaces.
- Energy Efficiency: Use energy-efficient lighting, air-conditioning, and appliance systems to reduce energy consumption and minimize the heat load on buildings; mechanical ventilation should be a good alternative for air-conditioning.
- High Thermal Mass Materials: Designs incorporating materials with high thermal storage capacity, such as concrete or brick, into building structures to help stabilize indoor temperatures and reduce air conditioning.
- Open Space Design: Create open spaces and transition areas that allow air circulation and encourage natural ventilation, providing thermal comfort and reducing the need for additional cooling systems.
- Taking advantage of natural shadows: Use the appropriate vegetation and shading elements to reduce direct solar radiation in outdoor areas and minimize the heating of spaces.

Cluster 7 - Humid Paramo Mountain (extremely cold climate). Geographically, this cluster refers to previous groups to zones in the Andes Mountains that cross Colombia's territory. In this case, this zone represents elevations over 3000 m.a.s.l. This designation highlights the importance of solar heating strategies, both active and passive, in the area due to the predominant need for heating and the specific climatic conditions at high altitudes. The percentages of use of each climatic strategy indicate that conventional heating may be necessary for approximately 3.13 % of the year, especially in some areas where it can reach higher values up to 70 % of the time. The percentages of active solar heating (44.72 % of the time) and passive solar heating (45.44 % of the time) show that these strategies are the most efficient and adequate to maintain thermal comfort conditions in the area. However, conventional heating from efficient systems must be taken into account. The percentage of time in which internal gain strategies are sufficient (8.48 %) indicates the possibility of taking advantage of internal heat sources to complement heating strategies. Some specific bioclimatic recommendations for these zones are:

- Active solar heating: Implement active solar heating systems, such as solar thermal panels, to take advantage of solar radiation and generate heat. These systems can be used to heat water or air, providing heating to interior spaces [52].
- Taking advantage of direct solar radiation: Design buildings with windows strategically located to take advantage of direct solar radiation during the day. This will help warm the interior spaces and reduce the need for additional heating.
- Passive solar heating: Design spaces to benefit from passive solar heating. Be sure to take advantage of the orientation and geometry of the building to capture solar heat during the day and store it in materials with high thermal capacity, such as adobe or concrete walls [9].
- Thermal insulation: Ensure good insulation in the building envelope to minimize heat loss. Use high-quality materials and consider the proper thickness to maximize insulation performance.
- Thermal storage systems: Consider increasing the thermal mass of the building to take advantage of the excess heat generated during the day and release it at night or the most significant demand.

Cluster 8 - Tropical super humid Climate. Geographically, this cluster refers to previous groups to zones in the Amazon jungle and Pacific Jungle, characterized by hot temperatures, a mean temperature above 26 Celsius degrees with constant rainfall over the year. In addition, most of these regions are considered a biodiversity reserve, so there is a small population density. The results highlight the importance of dehumidification strategies combined with air-conditioned systems (HVAC). The percentages of use of each climatic strategy indicate that this combination is used approximately 81 % of the year.

On the other hand, Natural ventilation can be used 17.89 % of the time. However, due to the vegetation density of very tall trees, natural ventilation could be more efficient most of the time. The general recommendations for these regions should include adequate solar protection, like wide eaves, awnings, and shading devices, to reduce direct solar radiation on exterior surfaces. Finally, in most cases, HVAC systems will be needed. However, they should use only energy-efficient technologies since the area's energy source would be limited [52,53].

3.3. Bioclimatic strategies in urban environments

In the following section, some clarifications will be made on grouping the clusters with urban settlements. Following the description of the climatic characteristics of each cluster and as visualized in the dendrogram in Fig. 6 and Table 2, the country is divided into mountain climates (Clusters 3,4,5,7) and hot and humid climates (Clusters 1,2,6,8). The hot and humid climate prevails with a presence of 80.8 % of the evaluated territory. This indicates that the mountain clusters are considerably smaller; however, they have relevance because historically, the largest urban settlements (except for coastal cities) have been in these climatic zones due to different demographic, social, political, and economic factors [54]. On the other hand, Clusters 1 and 8 are smaller and larger, respectively. These Clusters are in regions with lower population density due to the abovementioned factors and climatic conditions.

Weather records for different urban settlements in the clusters were made, as shown in Table 3 and Fig. 7. The variation between the individual results of each urban location compared to the average values defined for each cluster is remarkable. This difference is likely because many settlements in Colombia are located between the boundaries of the different clusters, which gives way to varia-

Table 3
Strategies zone characteristics for urban settlements located in different clusters.

Bioclimatic Zone Strategy in %	C. 1	C. 2	C. 3	C. 4	C. 5	C. 6	C. 7	C. 8
Urban Assessments	Barrancabermeja	Villavicencio	Medellin	Bucaramanga	Bogotá D.C.	Sabana de Torres	Vetas	Leticia
CH	0,00	0,00	0,00	0,00	0,00	0,00	2,91	0,00
ASH	0,00	0,00	0,00	0,00	0,07	0,00	63,07	0,00
PSH	0,00	0,00	0,00	0,00	41,45	0,00	33,66	0,00
IG	0,00	0,66	66,48	15,18	55,25	0,00	1,64	0,05
CZ	0,25	9,93	28,89	40,78	4,98	1,15	0,00	0,05
NV	43,16	57,31	5,56	23,97	0,00	38,05	0,00	15,46
HTMN	6,47	0,17	0,00	0,01	0,00	14,11	0,00	0,00
TMNV	8,56	32,37	0,03	21,82	0,00	11,53	0,00	0,34
AIDH	42,04	0,00	0,02	0,00	0,00	35,62	0,00	84,27

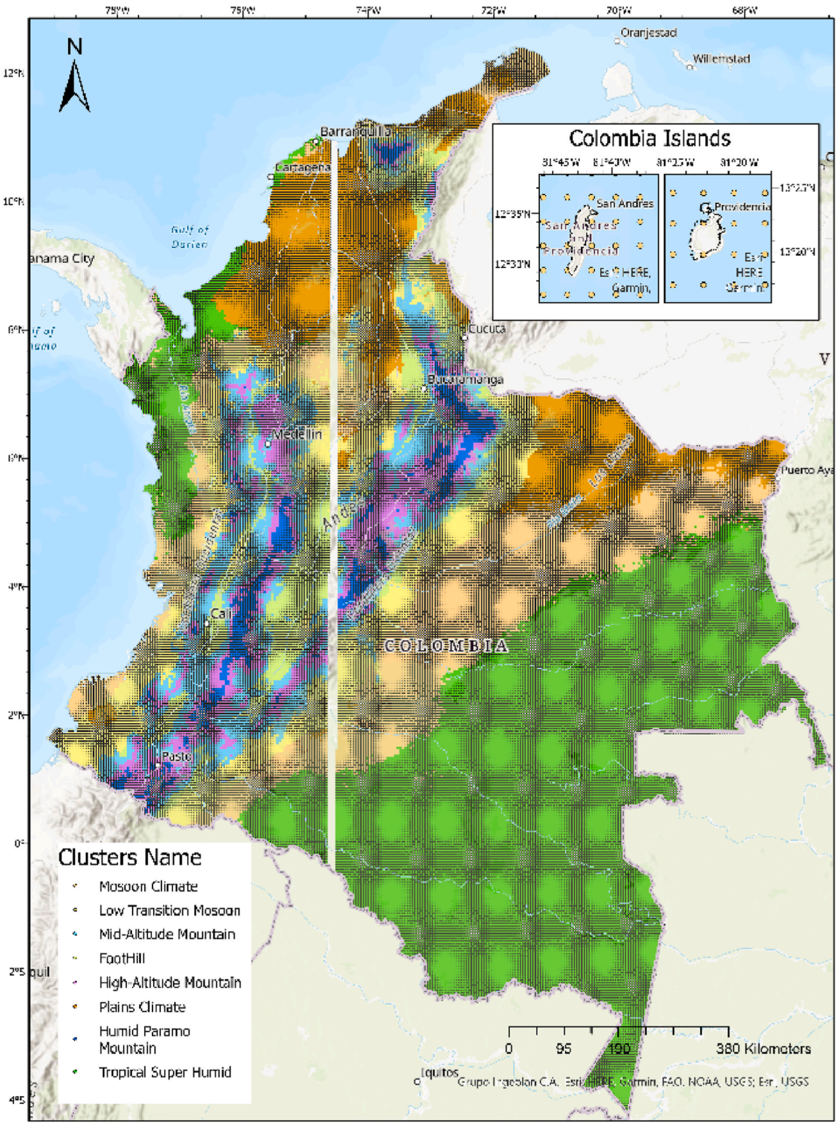

Fig. 7. Bioclimatic cluster zones for Colombia.

tions between the average values due to the formation of microclimates. Eight Colombian municipalities were selected to analyze urban settlements that fit each of the clusters found. However, it is essential to note that not all cities were considered in this visualization because some share the same clusters. For this purpose, the evaluation of the BBCC diagram for the main towns and the locations in Table 3 can be found in Supplementary Material 1.

It is essential to mention that Leticia, the capital of the Amazonas province, is the main urban settlement in the country's south, where Cluster 8 predominates. However, the population density is considerably lower than in other country areas due to vegetation, economy, and climate characteristics. Thus, although 43.8 % of the points fit into Cluster 8, it is one of the most uninhabited areas in the study region. This is coherent, considering that it is a highly humid hot zone where Leticia must use air conditioning and traditional dehumidification systems approximately 84 % of the year. Using efficient active systems is indispensable for this area to achieve thermal comfort because the region's energy matrix is not the most stable. Moreover, Cluster 8 needs air-conditioning and Dehumidification systems. Clusters 1 and 6, represented by Barranbermeja city and Sabana de Torres town, respectively, need this strategy due to their low altitude and hot climate.

Urban settlements like Villavicencio located in Cluster 2, while sharing similarities with the previous clusters, differ in that using high thermal mass strategies combined with natural ventilation tends to be more effective than in the earlier groups. It is, therefore, evident that strategies are linked to a combination of cross ventilation and the use of materials with a high mass capacity to absorb heat, thus preventing the heat from the outside from penetrating to the inside. In contrast, natural or mechanical ventilation systems will allow air renewal inside the building [23].

For their part in Clusters 3, 4, 5, and 7, they are represented by the cities of Medellin, Bucaramanga, Bogota, and Vetas, respectively. These climates are gradually affected by the elevation of the land formed by thermal floors. The foothill climates, or low-altitude plateaus such as Bucaramanga, are the climates with the highest level of comfort during the year. However, to maintain these levels of optimal thermal sensation, it is necessary to implement materials with heat absorption and natural ventilation systems and night ventilation, such as the implementation of cross ventilation or thermosiphons. Of course, it is crucial that the latter be linked to the wind rose of the sector for an adequate functioning of the strategy. Cluster 3, represented by main cities such as Medellin and Cali, represents cool climates with considerable thermal comfort values. However, due to their geographical and altitudinal conditions, it is common for nights to be fresher, making it necessary for most of the year's internal gains to take advantage of the different systems that produce heat inside the home. Although a small portion of the year requires natural ventilation, it would be adequate to use it to renew the air inside the house. However, it would be appropriate that the surfaces that use this strategy have reduced dimensions, avoiding the excessive generation of ventilation that leads to a loss of heat inside.

For urban settlements located in Cluster 5, where the capital of the country with the highest population density is found, the design recommendations focus on passive solar heating zones and internal gains that occupy more than 95 % of the average frequency for this cluster, being evident the need to use thermal insulation in the building envelope. This should be complemented by passive solar systems such as glazed galleries, greenhouses adjacent to the building envelope, or Trombe walls to ensure internal gains due to solar radiation [18,23].

3.4. *Compiling the findings*

In this section and based on the results of this study, a list of each municipality in Colombia is presented in Supplementary Material 2, regardless of its population density. This database will provide information on the location of the different bioclimatic clusters, allowing the identification of the most appropriate bioclimatic design strategies for the region where construction is sought.

The results showed that the areas with the highest frequency of sensation of comfort are located at the foothill of the Andes Mountains, where some of the main population settlements can be found; cities such as Bucaramanga achieve values of up to 40.78 % of comfort of annual form. The previous statement can be seen in Figs. 5d (left), showing that for most of the year hours, thermal comfort can be identified in the foothill of the Andes Mountains between altitudes of 1000–1500 m.a.s.l. In the same way, in the vicinity of the Sierra Nevada de Santa Marta, one can find average comfort values where between 18 and 27 % of the year, there are favorable conditions for this type of well-being. On the other hand, in the plains bordering the mountainous system, relatively low comfort values between 1 and 9 % can still be found. Examples that support the above are the northeast and east of the country, where they get a few hours of comfort annually despite being characterized by hot and humid climates.

The results show that the strategy with the most extensive presence in the study region is the area of natural ventilation. This area is shown as an ideal alternative for hot and humid climates present in approximately 80 % of the country and in low and medium mountain locations where, for example, cities such as Medellín and Bucaramanga can take advantage of it 5.56 and 23.97 % of the time, respectively. On the other hand, the highest values of natural ventilation are in the south of the Colombian Pacific, where ranges of use between 50 % and 77 % of the time are displayed.

For its part, as can be seen in Figs. 5b and the average values of Tables 2 and 3, the thermal mass and natural ventilation strategies are in areas with low elevations. Its highest values occur in the country's north, consistent with the high temperatures during the day in these areas [55]. However, compared to other strategies, its maximum values are low, reaching a maximum weight of annual presence. 32 %. On the other hand, the areas with high thermal mass materials and natural ventilation spatially cover most of the territory with different values ranging from 1 % to a high 61 % located between the central mountain ranges. And the eastern part of the country. However, in highly humid areas and high mountain climates, they are not included in these zones as expected.

On the other hand, it is evident that the results of Cluster 8 show the need to use strategies of active air conditioning and dehumidification systems due to the extreme humidity presented by its spatial location near the equator line, including the dense jungle that occurs in these regions of the country. In the same way, in areas with plains and islands belonging to Colombia, between 40 % and 72 % of the time, these systems are needed due to the average temperatures and humidity that occur in these regions where previous investigations suggest the application of these systems. Thus defining Colombia as a humid and warm country. However, as previously indicated, the mountain chains play an essential role in the climatic diversification of the country; the influence of the altitudinal gradient of mountain systems generates a critical need for the implementation of internal gains in practically all mountain climate clusters defined in the study, having a gradual increment as elevation of the region increase. After 2000 m above sea level, using passive solar heating systems with average ranges of 50.63 % becomes essential. Finally, in the coldest areas of the country, humid climates characterized by geographical position are preserved, but with low temperatures due to high mountain climates where passive systems are insufficient, and the application of active solar systems becomes a necessity. Based on the characterization performed for all clusters, a list of passive strategies applied to building design is presented in Table 4. Thus, it is possible to synthesize the findings through the following points: The atlas, whose representations are found in Figs. 5a to 5e, can identify thermal comfort zones throughout the country. In addition, it allows for identifying the areas that demand heating, cooling, or hybrid air conditioning strategies based on the percentage of influence of each one.

On the other hand, the atlas represented in Fig. 7 shows a new classification and delimitation of the different climatic groups based on a rigorous statistical analysis. These results, complemented by the specific group strategies presented in Table 4, will allow designers, urban planners, and other interested professionals to locate their construction projects. In addition, they will give them a set of guidelines and recommendations that will contribute to the conception of efficient bioclimatic designs during the initial stages of civil works.

3.5. Novel bioclimatic dataset: strongs and limitations

This article manages to identify different bioclimatic patterns for Colombia from a database that starts from satellite information, with updated data to date, including temperature and relative humidity. This document presents significant contributions not previously evaluated, especially in the study region. As a first point, using a satellite database containing spatial information for each area eliminates the limitation of using meteorological stations that often have limited records, and their distribution in a region generates considerable uncertainty. The second contribution is linked to the generation of maps that present spatial distribution as a guide for bioclimatic designs based on BBCC diagrams based on TMY data, commonly used in this kind of simulation. The third contribution addresses the list of design strategies for each municipality in Colombia that will allow progress in developing more sustainable cities and more efficient buildings. The climatic maps were created using interpolation methods that will extend the spatial distribution of each zone. These represent the frequency of time when is useful those strategies all over the country. The cluster analysis was validated for different methods to corroborate its veracity, where different microclimates were found because Andes Mountain was produced in an equatorial region such as Colombia. The effects of the altitudinal gradient in the formation of thermal floors were identified and were essential to the cluster characteristics definition.

Table 4
List of applicable passive strategies for each cluster.

Principal Strategy	Material/Specific Strategy	Contribution	C.1	C.2	C.3	C.4	C.5	C.6	C.7	C.8
Thermal Insulation	Rockwool material	Thermal transmittance reduction			x		x		x	
	Fiberglass material	Thermal transmittance reduction			x		x		x	
	Expanded Polystyrene (EPS)	Thermal transmittance reduction	x	x	x	x				x
	Polyurethane Foam	Thermal transmittance reduction	x	x	x	x				x
Controlled Ventilation	Cross Ventilation	Promote air flow by placing openings on opposite sides	x	x		x		x		x
	Skylights	Allow rising warm air to escape and ventilate with fresh air	x	x		x		x		
	Double-skin facades	Intermediate space between facades allows air to naturally filter	x	x		x		x		x
	Ventilated façades with solid surfaces	Allow solar protection and promote airflow	x	x		x		x		
	Natural induced ventilation	Promote the entrance or cold air flow to displace the warm air	x	x		x		x		
	Facades orientation	Allow maximum use of air currents considering the predominant wind direction	x	x		x		x		
	Night Ventilation	Provide air flow during night hours to remove excess heat accumulated during the day.						x		
Solar Protection	Solar shapes/Louvers	Provide shade and reduce direct solar radiation	x	x	x	x				x
	Eaves	Block excessive heat on glass surfaces	x	x	x	x	x			x
	Green facades	Provide shape and cool environment indoor.		x	x	x				x
	Double envelope design	Create a thermal buffer that traps solar heat	x	x	x	x				x
High Thermal Mass Materials	Conventional Construction Materials (concrete, masonry, stone)	Allow to absorb and liberate slowly the heat		x	x	x		x		
	Earth walls (adobe, rammed earth, CEB)	Allow to absorb and liberate slowly the heat		x		x		x		x
Solar Orientation	Strategic solar orientation	Provide direct solar radiation			x		x		x	x
Internal Gains Strategies	High-performance glazing	minimize heat loss in cold climates and reduce heat gains in hot climates	x	x	x	x	x	x	x	x
	Trombe walls	Allow the capture and release of solar heat during the night			x		x		x	
Passive Solar Strategies	Solar Corridors	corridors that act as solar conductors, allowing solar heat					x		x	
	Solar Greenhouses	Capture solar heat and transfer it indoors.					x		x	
	Solar Atriums	glazed surfaces that act as solar collectors					x		x	

On the other hand, despite the use of TMY data, which includes other weather variables, only hourly temperature and relative humidity data were considered due to the methodology and the BBCC chart used. However, other variables could affect the energy demand and building performance, such as building use, sky cover, solar radiation, occupant density, and clothing. Although this cluster characterization is a rewarding tool for understanding outdoor climate conditions, more is needed to represent building performance [7]. With the last statement, it is essential to indicate that the cluster analysis and the passive strategies evaluation must be used in early design stages where it is crucial to identify the climate conditions to generate the is of the base for the design. In addition, based on the created dataset [31] would be possible for the designers to extract that TMY data that will allow to performance of the building simulations in the following stages of the design process.

4. Conclusions

Climate has a considerable impact on the energy consumption of a building, especially in countries with hot and humid climates. Defining an appropriate climate zone can be a valuable tool for bioclimatic design in the early stages of the project. For its part, using TMY from satellite databases can be a helpful alternative, especially in regions with insufficient data or outdated information that does not reflect climate change's current challenges.

A cluster analysis for 69874 climate records spaced approximately every 4.4 km was carried out in Colombia. This analysis defined nine viable bioclimatic strategy zones in the study region based on the Givoni psychrometric diagram redrawn by Roshan and Attia. The climatic information on which the research is based on a typical meteorological year updated to 2021 by the National Renewable Energy Laboratory, from which spatial details covering the entire study region were obtained. Among the most important findings is that Colombia, due to its location near the equator, is prone to hot and humid climates covering most of the territory. However, due to the influence of the mountain chains of the Andes that cross the country, new climates are generated that change depending on the altitudinal gradient and are commonly known as thermal floors. The generation of these microclimates in the mountains and surrounding areas generates the ranges of the effectiveness of cooling strategies gradually changing to heating strategies. However, the country maintains a greater need for an air-conditioning system for hot and humid climates, where, depending on the region, some will be more effective than others.

The study's results allow the zoning of the most suitable bioclimatic strategies for the region and show a new climatic classification for Colombia. With the results obtained in Figs. 5 and 7, Tables 2–4, and supplementary materials 1 and 2, it can be inferred that the most significant urban settlements have historically been in fresh and more comfortable climates in the foothills of the Andes Mountains. Although there are no known precedents of this type of study in the area, climatic classifications such as those previously carried out by the country's meteorological service show that the results are consistent with the temperatures and humidity recorded by these institutional sources. Based on the present study, new investigations can be developed where the bioclimatic strategies proposed for each climatic sector are applied, reflecting the behavior of the buildings inside with the external climatic conditions evaluated in this study.

CRediT authorship contribution statement

Cristian Mejía-Parada: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization. **Viviana Mora-Ruiz:** Data curation, Investigation, Writing – original draft, Writing – review & editing. **Shady Attia:** Conceptualization, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

I hereby certify that this paper consists of original, unpublished work not under consideration for publication elsewhere.

We wish to confirm that there are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that all have approved the order of authors listed in the manuscript of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, concerning intellectual property. In so doing, we confirm that we have followed the regulations of our institutions concerning intellectual property.

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2023.108262.

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