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Climate Evolution and Building Typology in the Central African Republic: A Growing Concern

Emile Boris Kenza[1,2,3], Blaise Miguiri[4*], Ignatius Wirba[5], Thierry Serge Gbembongo[3], Saint-Cyr Lengaye[3], Noé Landry Privace Mbouana[1,3], Ruben Mouangue[5*]

[1] Industrial Engineering Depsartment, University of Bangui, Central African Republic

[2] Doctoral School of Science and Technology (EDST), University of Bangui, Central African Republic.

[3] Laboratory of Atoms, Matter, Energy and Radiation, Physics Department, University of Bangui, Central African Republic.

[4] Higher School of Transport, Logistics and Commerce, LASTIE, University of Ebolowa, Cameroon

[5] National Polytechnic School of Douala, University of Douala, Cameroon.

[*]Corresponding author: miguiriblaise@gmail.com and r_mouangue@yahoo.fr

Key words

Passive design, Building typology, Climate change, Bioclimatic architecture, Central African Republic.

Abstract

Sustainable construction in tropical regions must reconcile indoor comfort with reduced environmental impacts. Passive design strategies are increasingly promoted as effective means to lower energy demand and carbon emissions. This study analyzes the typology and characterization of residential buildings in Bangui, Central African Republic, to assess the extent to which local practices reflect the seven principles of passive design. Meteorological data covering two decades were collected using environmental sensors, while a large-scale survey was conducted (2,000 questionnaires distributed, 1,783 valid responses). Results revealed a warming trend, with temperature increases of 1.01 °C between 1991 and 1994 and 1.23 °C between 1991 and 2001. These changes have influenced construction practices, as nearly 60% of dwellings now rely on mechanical ventilation or air conditioning. Nonetheless, 55% of walls are built with local materials and 38% of buildings depend on natural ventilation. The study underscores the need to define optimal comfort thresholds and propose a locally adapted bioclimatic model.

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1. Introduction

Over the past decades, the building sector has been recognized as a major contributor to global energy consumption and greenhouse gas (GHG) emissions, accounting for approximately 36% of final energy use and 39% of global energy-related CO_2 emissions [1]. In tropical regions, characterized by intense solar radiation and elevated ambient temperatures, the demand for air conditioning continues to rise, exerting pressure on energy systems and further increasing carbon emissions. Passive design strategies—such as optimal building orientation, natural ventilation, shading, thermal mass optimization, insulation, airtightness, and the use of reflective materials—represent sustainable and cost-effective approaches to mitigating this demand by adapting the building envelope to local climatic conditions [2].

Standards and regulations frame these requirements to ensure indoor environments meet thermal comfort criteria. However, the pursuit of uniform and compliant indoor conditions throughout the year, irrespective of climate, site, or building characteristics, often leads to a proliferation of air conditioning systems. This results in high energy consumption, largely from finite and polluting fossil sources [3]. Audits conducted in air-conditioned buildings in tropical Africa confirm that air conditioning accounts for 40–80% of total electricity use, making buildings a priority target for energy-saving measures. Several studies in tropical climates have revealed a significant gap between experimentally determined optimal thermal comfort conditions and those prescribed by international standards [4]. These prescriptions are typically based on analytical models that overlook adaptive behaviors, which are particularly critical in such contexts.

The current energy landscape should therefore be viewed as an opportunity to promote ecological approaches and enhance energy efficiency, both in the design of new buildings and in the retrofitting of existing ones [5]. Sustainable construction is synonymous with healthier and more productive indoor environments. Achieving this requires careful control of the energy characteristics of construction materials as well as building orientation [6]. Numerical models and simulations can further support the analysis, understanding, and evaluation of building performance using local materials, with the aim of improving energy efficiency from the design stage through occupancy [7].

In efforts to adapt ASHRAE 55-81 and ISO 7730 standards to tropical conditions, researchers have conducted surveys of air-conditioned buildings in Douala and Yaoundé, Cameroon. Their findings revealed significant discrepancies between these universal standards and observed thermal comfort parameters in the studied areas [8]. Similarly, within the ECODOM project in the French overseas departments, experimental validation demonstrated the effectiveness of passive cooling measures. Combining optimized orientation, shading devices, and natural ventilation lowered indoor temperatures by 2–4 °C and reduced cooling-related energy consumption by up to 30% in new dwellings [9]. These findings confirm that passive strategies can be effectively implemented in hot and humid climates and provide a strong basis for best practices in sustainable building design.

However, literature suggests that the seven principles of bioclimatic building design are rarely applied simultaneously in the same region [10]. Some studies document only partial adoption, often emphasizing ventilation and shading while neglecting thermal mass, airtightness, or insulation [11]. To address this limitation, researchers in Southeast Asia and the Pacific Islands have tested partial passive strategies, but their results indicate that incomplete adoption reduces the potential benefits [12]. These studies are further constrained by limited geographic scope, short monitoring periods, or insufficient integration of climatic data with the evolution of building typologies.

This study builds on existing knowledge by examining whether buildings in Bangui, Central African Republic, constructed according to local cultural and traditional practices, comply with all seven principles of passive design. Unlike previous works, this research incorporates meteorological data to assess the influence of climate change on building typology. Its originality lies in establishing a direct link between observed climatic changes (e.g., rising temperatures, intensified solar radiation) and construction practices, such as material choice, building orientation, and increasing reliance on air conditioning. These practices are then compared against passive design principles, which are often not fully implemented in a given locality. The objectives of this study are to enhance understanding of the typology of existing buildings in Bangui, identify dwelling types, predominant wall materials, main building orientations, and conditioning systems. This will enable the proposal of passive solutions to mitigate the effects of atmospheric disturbances on indoor environments and reduce discomfort hours in the study area. The overarching aim is to determine whether buildings in the Bangui region adhere to passive design principles. More specifically, it seeks to provide a typological classification of dwellings in Bangui, under the assumption that most housing consists of traditional structures that already integrate certain passive elements. This integrated approach offers an evidence-based framework for adapting building standards in the context of ongoing climate change.

2. Material and methods

2.1. Geographical location of Bangui

Bangui, the capital of the Central African Republic, is characterized by a tropical savanna climate. The city is located at approximately 4.36° North latitude and 18.56° East longitude.

2.2. Equipment

2.2.1. Meteorological Station

The meteorological station at the University of Bangui consists of an outdoor unit exposed to open air and an indoor unit housed in the LEC laboratory. It operates on the principle of instrumentation, defined as the set of methods and tools through which a system collects data from sensors, processes it, and provides usable information. Figure 1 illustrates the measurement station at the LEC laboratory, which supplied meteorological parameters for this study covering the period from 1991 to 2011.

(a) console recorder

(b) external sensors

Figure 1: Measuring station for meteorological parameters in the study area.

As with all data acquisition systems, the meteorological station is equipped with sufficient memory and incorporates solar probes (a pyranometer and a UV sensor) housed in a radiation shelter with continuous 24-hour active ventilation. The integrated pyranometer enables the calculation of potential evapotranspiration. Data transfer between the external sensors (ISS) and the console is achieved via radio frequency (868.0–868.6 MHz) with an effective range of up to 300 meters.

The console, which can be wall-mounted or placed on a table or shelf, features a large backlit LCD display. It provides real-time weather conditions, extreme values (maximum and minimum), and graphical representations of the measured variables. The transmitter receives signals from the sensors, converts them into corresponding data, and simultaneously powers the sensors. It also linearizes, pre-amplifies, calibrates, and displays the measured values.

The ISS is highly robust and mounted on a mast. A dual probe for outdoor temperature and humidity measurements is installed in a standardized radiation shelter with 24-hour active ventilation, ensuring high measurement accuracy. The integrated rain gauge is equipped with two tipping buckets for precipitation measurement and anti-bird spikes for protection. In addition, the anemometer-weathervane can be detached from the ISS and installed remotely using its 12-meter cable. Finally, the system includes a UV index sensor and an additional pyranometer for monitoring solar radiation and evapotranspiration.

2.2.2. Typical buildings in the study area

This section presents representative examples of dwellings in the Bangui region, the designated study area. The majority of these buildings are constructed in a largely unplanned manner, often without adherence to established construction standards. Figure 2, derived from CNES–Astrium imagery (2017), corresponds to the survey period and illustrates typical settlement patterns in the locality.

Figure 2: Some housing patterns in the Bangui Region [**13**].

2.3. Methods

2.3.1. Passive Strategy Method

The methodological framework is based on the principles of energy-efficient building design specifically adapted to tropical environments [14]. These principles include:

- The orientation of buildings to mitigate excessive solar radiation;
- The promotion of natural ventilation within indoor spaces;
- The maximization of indirect natural lighting rather than direct exposure;
- The reduction of heat transfer through roofs by facilitating natural ventilation between roof and ceiling, and by decreasing roof surface temperature;
- The use of energy-efficient construction materials;
- The minimization of heat transmission through external walls, primarily via insulation;

- The incorporation of exterior and transitional spaces such as balconies, terraces, atriums, and corridors to improve thermal comfort.

2.3.2. Data Collection Method

To ensure both the reliability of results and the representativeness of the dataset, a proportional stratified random sampling method was applied in the selection of buildings. The overall population was stratified according to building typologies—namely individual, semi-collective, collective, and marginal housing—while also considering their distribution across the two major zones of Bangui (Bangui River and Bangui Kaga), which are further subdivided into ten administrative districts.

The study draws upon data collected through a survey conducted between 2017 and 2019 in the tropical savanna zone of Central Africa. This temporal window was selected in order to capture construction practices over a sufficiently representative period, particularly with regard to the integration of passive design principles.

The survey investigated building typologies, construction characteristics, and conditioning systems within the Bangui region. It encompassed individual houses, semi-collective dwellings, collective housing, and marginal structures, which constitute the most prevalent forms of construction in the area. The primary objective was to identify the most representative building type for detailed characterization. This characterization focused on external wall, roof, and insulation materials, façade orientation, and lighting conditions. In addition, conditioning practices were documented, with particular attention to the use of air conditioning and natural ventilation systems.

3. Results and Discussion

3.1. Evolution of Outdoor Climatic Parameters

The analysis of meteorological data reveals clear evidence of climatic change in the Bangui region over the study period. Figure 3 illustrates the variation in annual temperatures for the years 1991, 1994, and 1997. A temperature increase of 1.01 °C was observed between 1991 and 1994, followed by a smaller increment of 0.08 °C between 1994 and 1997. Although the second variation appears less pronounced, the cumulative trend underscores a progressive warming of the local climate.

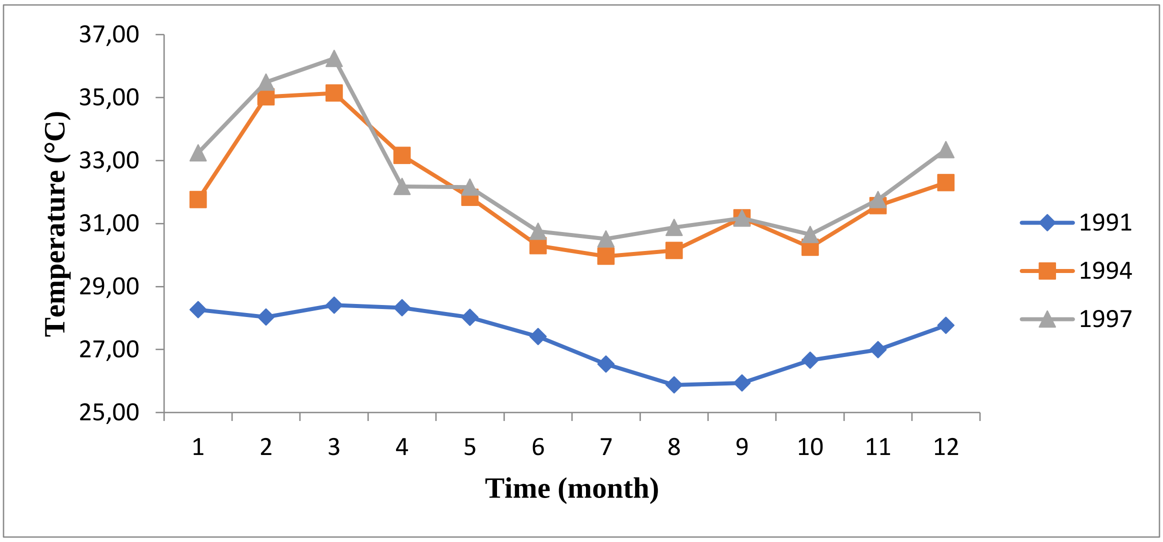

Figure 3: Temperature variation at the study site for the years 1991, 1994 and 1997.

To further substantiate this trend, Figure 4 presents the ten-year mean annual temperature for 1991, 2001, and 2011. March consistently emerges as the warmest month, with mean values increasing from 27.67 °C in 1991 to 28.9 °C in both 2001 and 2011. The decade-long difference of 1.23 °C exceeds the three-year variation noted earlier, thereby confirming a sustained warming trend. This aligns with global climate change patterns and highlights the growing need to reassess local construction practices.

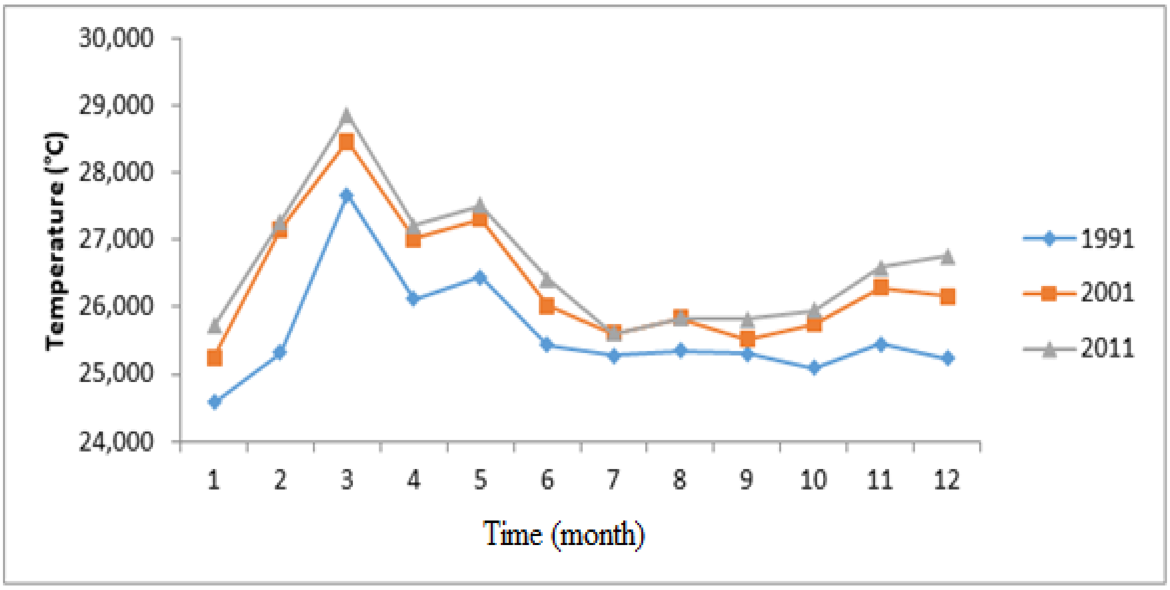

Figure 4: Trend in ten-year mean annual temperature (1991, 2001 and 2011) and determination of the warmest month.

Further evidence is provided by Figure 5, which reports the maximum temperatures recorded during the hottest days of the hottest months across the three selected years. Peak values reached 39.3 °C in 1991, 43.0 °C in 2001, and 43.0 °C again in 2011, typically occurring between late morning and early afternoon. The escalation of peak temperatures indicates an intensification of heat extremes, which directly impacts indoor comfort conditions and increases reliance on active cooling systems.

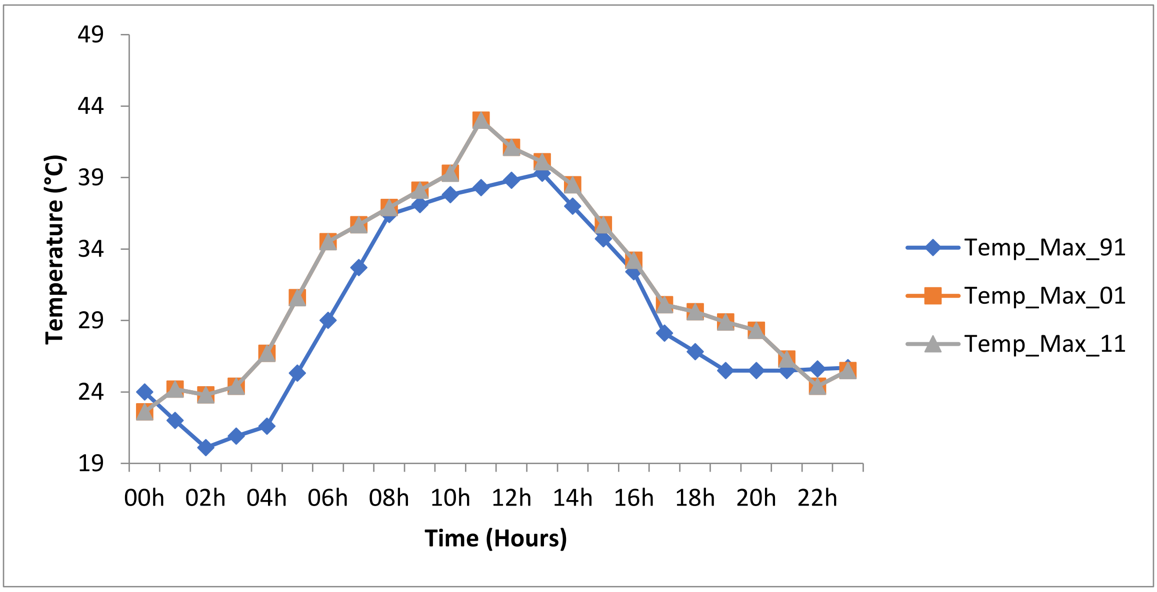

Figure 5: Highest temperatures on the hottest days.

Relative humidity trends are displayed in Figure 6. Average monthly values range between 48% and 87.6%, with consistently high levels during the rainy season (May to October). Over time, a negative correlation is observed between rising temperatures and relative humidity, suggesting that climate change not only intensifies heat stress but also alters the hydrometeorological balance of the region. These results are consistent with previous studies reporting declining relative humidity as a direct consequence of temperature rise **[9].**

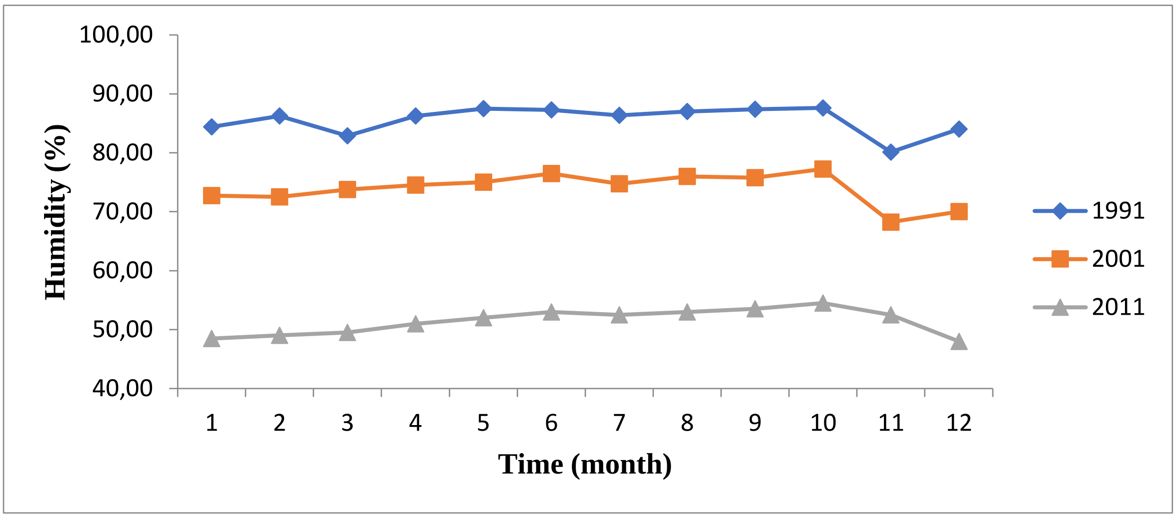

Figure 5: Ten-year monthly average relative humidity at the study site.

Wind speed variation is presented in Figure 7. Results show that March to June are the windiest months, with average speeds increasing between 1991, 2001, and 2011. This increase is linked to changes in thermal gradients and atmospheric circulation associated with rising temperatures. Meanwhile, wind direction analysis in 2011 (Figure 8) reveals predominant flows along the north–south axis, likely reflecting the combined influence of the Harmattan and the Monsoon. Such patterns are critical when considering natural ventilation strategies for passive cooling.

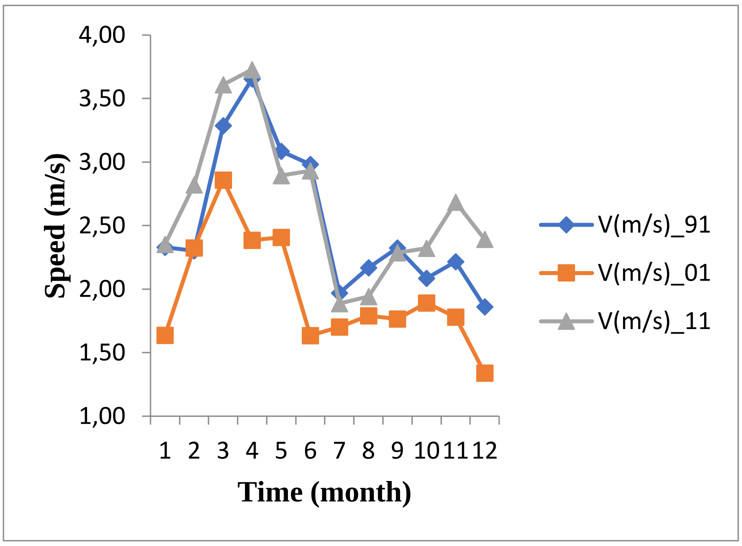

Figure 7: Ten-year average wind speed variation graph.

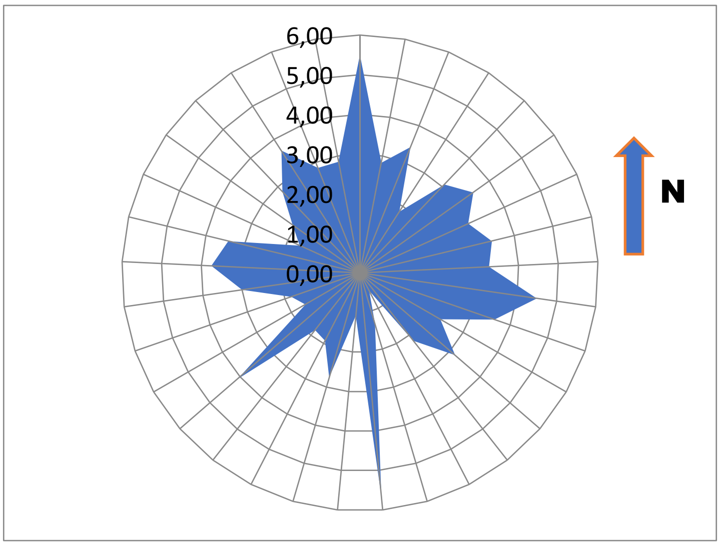

Figure 6: Graph of 2011 annual average wind direction

Finally, Figure 9 presents the evolution of solar irradiance. February and March appear consistently as the sunniest months, with a secondary peak in July. The highest annual irradiance levels were recorded in 2001 and 2011, confirming the intensification of solar exposure over time. This has direct implications for building envelope design, shading requirements, and the sizing of potential photovoltaic systems.

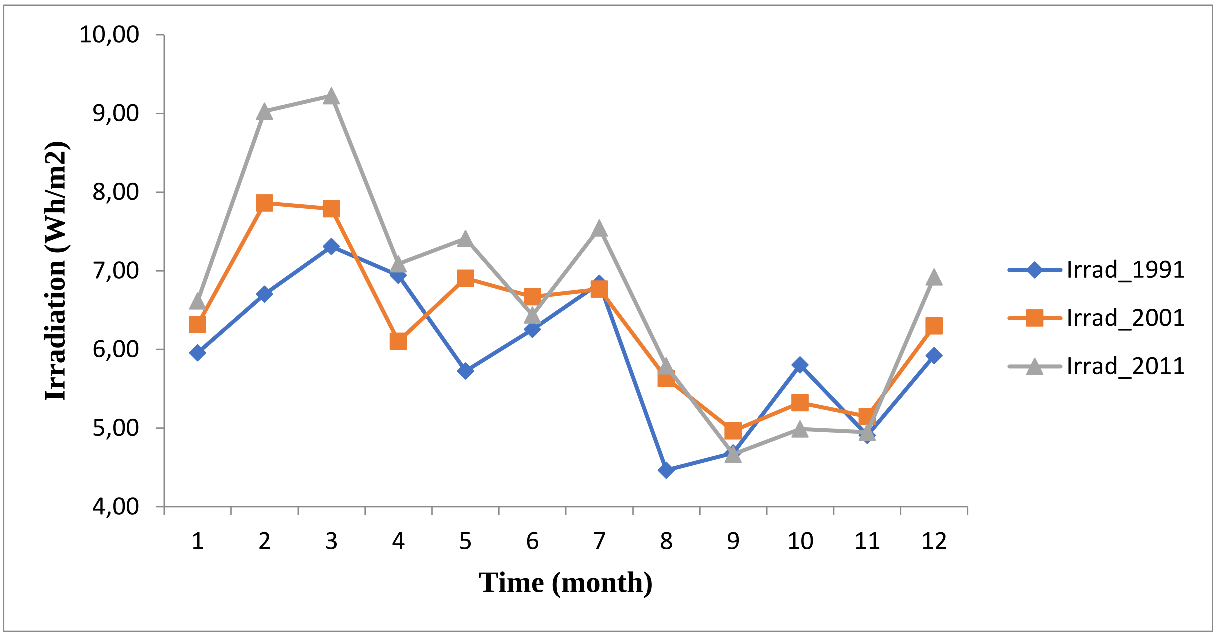

Figure 7: Graph of variation in ten-year mean solar irradiance.

3.2. Housing Typology and Construction Practices

The field survey provides valuable insights into the typology of buildings in Bangui. Out of the 2,000 distributed questionnaires, 1,783 valid responses were collected, representing a response rate of 89.15%. Figure 10 summarizes the distribution of housing categories. Collective housing was found to dominate the urban fabric, surpassing individual, semi-collective, and marginal dwellings. This predominance justifies the choice of collective housing as the primary model for detailed characterization in subsequent analyses.

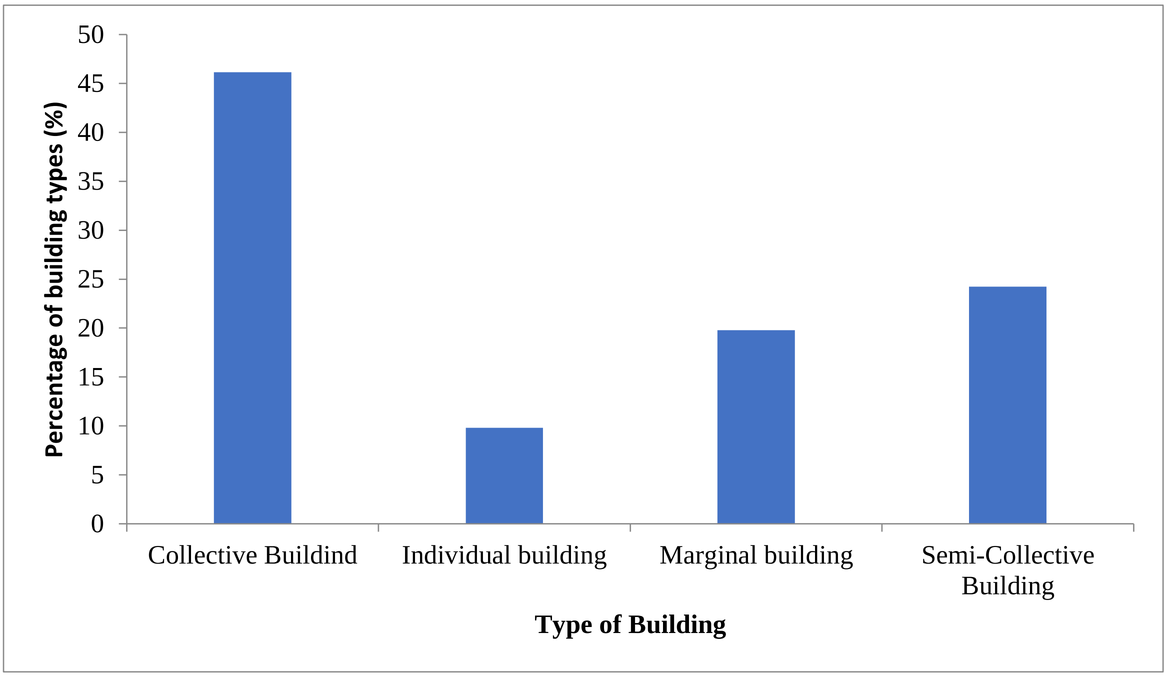

Figure 8: Percentage of building types surveyed

An examination of wall construction materials is shown in Figure 11. Among the 823 surveyed collective buildings, 451 (54.8%) were constructed using mud bricks, while the remainder relied on cement blocks, concrete, or other synthetic materials. The reliance on earth-based materials reflects long-standing traditions and indicates partial alignment with passive design principles, particularly in terms of thermal inertia and reduced embodied energy.

However, the persistence of synthetic materials raises concerns regarding both thermal performance and environmental sustainability.

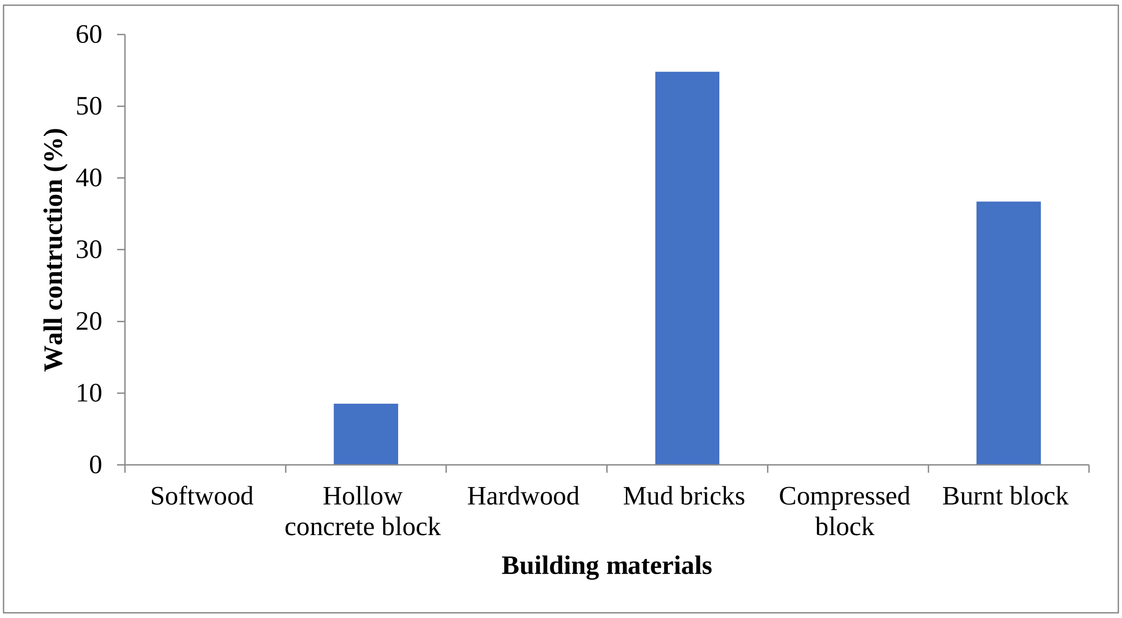

Figure 9: Percentage of wall materials in multi-family dwellings

Orientation practices were analyzed to assess their alignment with passive design requirements. Figure 12 reveals that 36% of the surveyed collective buildings were oriented towards the north-east. Although such orientations can enhance exposure to prevailing winds, the overall distribution appears largely random, reflecting the absence of formal planning or adherence to climatic criteria in design. This randomness limits the potential of natural ventilation and solar control strategies, thereby contributing to suboptimal indoor comfort conditions.

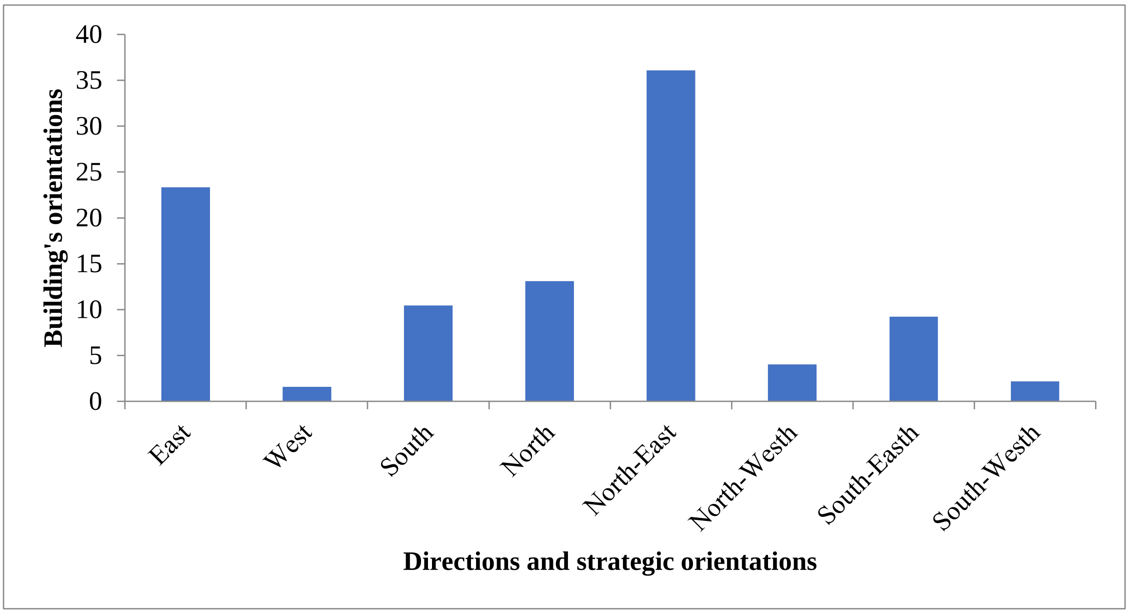

Figure 10: Percentage orientation of multi-family housing buildings

Conditioning practices were also evaluated. As shown in Figure 13, 38% of collective dwellings rely primarily on natural ventilation for thermal comfort. Approximately 23.5% employ air conditioning, while 36.5% depend on mechanical ventilation. These figures illustrate two parallel trends: first, the persistence of traditional reliance on passive airflow, and second, the increasing dependence on energy-intensive mechanical systems, driven by rising temperatures. The adoption of air conditioning in nearly one-quarter of surveyed dwellings confirms that climate change is directly shaping construction choices and energy demand.

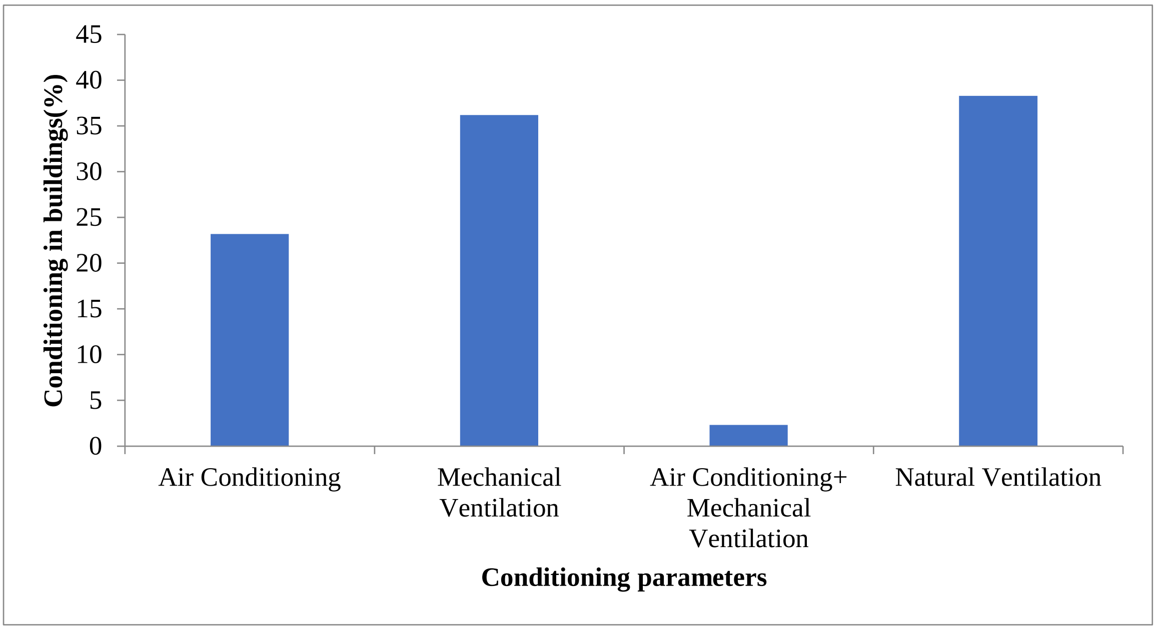

Figure 11: Percentage of conditioned apartment buildings

3.3. Discussion

The combined climatic and typological analyses highlight both opportunities and challenges for the integration of passive design in Bangui. Two of the seven principles—use of local materials and reliance on natural ventilation—are already present to some extent within traditional construction practices. However, the absence of systematic consideration for orientation, shading, roof insulation, or transitional spaces demonstrates the partial and fragmented nature of passive strategies currently in use.

The results also reveal a progressive substitution of passive techniques with mechanical systems, which undermines long-term sustainability. The reliance on air conditioning and mechanical ventilation not only increases household energy bills but also amplifies greenhouse gas emissions, thus perpetuating the cycle of climate vulnerability. Similar patterns have been documented in other tropical regions, such as the Caribbean and Southeast Asia, where partial adoption of passive measures has limited their effectiveness [12].

Importantly, the data suggest that traditional practices—particularly the use of earth-based materials—still hold significant potential for improving thermal performance if integrated within a more holistic framework. Mud bricks, for instance, provide thermal mass that can moderate indoor temperatures when coupled with appropriate ventilation and shading. The random orientation of buildings, however, remains a critical barrier to optimization, as it constrains airflow management and solar control.

The findings underscore the urgency of developing a bioclimatic construction model tailored to the Central African context. Such a model should integrate all seven principles of passive design, adapted to local climate dynamics and cultural preferences. Furthermore, the study provides a baseline for defining optimal thermal comfort thresholds specific to Bangui, moving beyond imported standards (e.g., ASHRAE, ISO) that may not adequately capture adaptive behaviors in tropical Africa.

4. Conclusion

This study assessed the typology of residential buildings in Bangui and their integration of passive design principles under changing climatic conditions. Results show that while local practices incorporate certain strategies—such as the use of earth bricks (55%) and natural ventilation (38%)—most dwellings lack consistent orientation and remain dependent on synthetic materials and mechanical cooling. The absence of regulatory frameworks further contributes to disorganized urban growth and increased vulnerability to climate change. Developing a bioclimatic building model tailored to the Central African context emerges as a priority to improve resilience, reduce energy demand, and enhance the quality of life for residents.

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Competing interests

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

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