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Climate-Responsive Vernacular Architecture: A Measured Study of Limboo Houses in Eastern Sikkim, India

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Abstract

This paper presents one of the rare remaining typologies of traditional vernacular architecture found in the fragile, cold-climate terrains of the Eastern Himalayas. In this context, houses serve not only as shelters for humans but also as spaces for accommodating cattle and supporting livelihood practices, thereby establishing domestic architecture as a vital element of the socio-ecological system.
Constructed primarily from locally sourced natural materials, these buildings demonstrate a construction logic that is inherently sustainable, climate-responsive, and resource-efficient. This research documents traditional vernacular construction practices through measured drawings, offering a detailed architectural record of a mud house that is increasingly at risk of disappearing, especially in the eastern Himalayan state of Sikkim.
The study emphasizes the relationships among levels, plinths, retaining walls, and internal spatial organization, illustrating how the house adapts to sloped terrain and contributes to its stabilization. The drawings also highlight the integration of living, working, and storage spaces, reflecting seasonal cycles and the daily practices of the inhabitants.
Collectively, the drawings present the mud house as a resilient architectural system that embodies continuity among humans, habitat, and land, and provides insights into sustainable construction practices grounded in vernacular knowledge.
Keywords: Limboo houses, vernacular architecture, climate-responsive architecture

1. Introduction

Vernacular architecture in the Eastern Himalayas represents a deeply contextual and adaptive response to extreme climatic conditions, fragile terrain, and socio-cultural practices (Oliver P. , 1927). In regions such as Sikkim, characterized by steep slopes, heavy rainfall, and cold climates, architectural forms develop through an ongoing negotiation among land, livelihood, and daily life, rather than as isolated design acts (Rapoport, 1969).
Settlements are shaped through a layered relationship between built and unbuilt elements, houses, agricultural terraces, forests, and circulation systems that form an integrated human habitat (Jefferson, 1926). Vernacular settlements in the Eastern Himalayas, especially domestic architecture, are organized around livelihood practices and typically occur in small, closely knit clusters.
A community in eastern Sikkim demonstrates close ethnolinguistic and cultural affinities with Nepali populations. However, their presence should not be understood solely as a result of migration. Rather, it reflects the historical territorial expansion of the Gorkha Kingdom across the eastern Himalayas, which at its height included significant portions of present-day Sikkim, particularly in the eastern region. This historical context complicates conventional migration narratives and underscores the influence of shifting political geographies on contemporary demographic patterns (Wielpton, 2005). The architecture of the Limboo community serves as a living expression of cultural identity, embedding indigenous Kirati beliefs. Kirati refers to a group of indigenous Himalayan communities, including the Limboo, whose cultural, spiritual, and architectural practices are rooted in the Mundhum tradition and a deep ecological relationship with their environment.
The **Limboo houses of Eastern Sikkim** exemplify this relationship, as domestic spaces extend beyond shelter to accommodate livestock, storage, and livelihood activities. These houses, whether individually or in clusters, demonstrate a dominant trait of community living and a strong connection among humans, houses, and habitat. Constructed from locally available materials such as mud, bamboo, timber, and stone, these structures reflect a construction logic that is

inherently climate-responsive and resource-efficient (Fathy, 1986). The study of these typologies provides critical insights into sustainable building practices rooted in traditional knowledge systems.

1.1 Vernacular Architecture and Climate Zone

Vernacular architecture in cold-climate regions is characterized by its ability to respond to environmental constraints through locally evolved construction practices. (Koenigsberger, 1 January 1975)Vernacular architecture in the Eastern Himalayas is shaped by climatic conditions characterized by low temperatures, heavy rainfall (2000–3000 mm annually), and steep terrain. (sikkim.gov.in, 2026)

Buildings respond with compact forms, insulated walls of stone-heavy masonry, raised plinths above the ground, and sloped roofs, using local materials such as timber, stone, straw, and bamboo to ensure thermal comfort and structural resilience. (Oliver P. , 2006) In the Eastern Himalayan context, buildings are designed to withstand low temperatures, heavy rainfall, steep topography, frequent earthquakes, and thermal comfort and structural stability. The use of thick earthen walls, compact forms, and minimal openings helps retain heat, while sloped roofs facilitate drainage during prolonged monsoon periods. (Olgyay, 2015) In Eastern Sikkim, vernacular houses represent a synthesis of climatic adaptation and cultural practices, in which materials such as mud, timber, and bamboo provide thermal insulation, structural flexibility, and local availability, reinforcing the ecological and contextual responsiveness of the built form.

1.2 Climate-Responsive Architecture

Climate-responsive architecture refers to design strategies that respond to local environmental conditions to enhance comfort, efficiency, and sustainability. (Olgyay, 2015) In vernacular settings, such strategies are embedded within traditional knowledge systems developed over generations.

Across India, vernacular architecture demonstrates distinct climate-responsive approaches aligned with the 16 types of climatic zones. In hot-dry regions such as Rajasthan and Kutch, compact settlement forms, thick earthen walls, internal courtyards, and minimal external openings reduce heat gain and create cooler microclimates. For instance, the circular *bhunga* houses of the Banni grasslands in Kutch use mud walls and thatched roofs to resist extreme heat, wind, and seismic activity, while their clustered arrangement enhances social interaction and environmental protection (Soladhara, 2025). In warm-humid regions like Kerala and coastal areas, buildings employ elevated plinths, large overhangs, sloped roofs, and cross-ventilation to manage heavy rainfall and humidity (Ar. Vishnu P Prakash, 2023). In composite climates such as Delhi, architecture combines seasonal adaptability through courtyards, shaded verandahs, and flexible spatial use. In trans-Himalayan regions such as Ladakh, Spiti, and Lahaul, houses are built with thick earthen-stone walls, compact forms, minimal south-facing openings, and black-colored walls to maximize solar gain and retain heat. Flat roofs and clustered settlements further enhance thermal efficiency and protect against harsh winds in the cold desert climate. (None Prajwal, 2014/10)

Within this broader framework, Limboo houses in Eastern Sikkim demonstrate climate-responsive features such as solar-orientation, the use of thermal-mass materials like mud, and elevated plinths to prevent moisture ingress. Wattle-and-daub construction further provides flexibility and resilience, particularly in seismic zones (Hugo Houben, 1994). These strategies are not isolated design decisions but part of a larger environmental logic where materiality, form, and spatial organization respond simultaneously to climate, terrain, and livelihood needs.

Such vernacular responses align closely with contemporary sustainable architecture principles, particularly in terms of low embodied energy, passive thermal regulation, and adaptability (IPCC, 2022). As a result, vernacular architecture offers not only historical insight but also a critical framework for rethinking climate-responsive design in present-day architectural practice.

1.3 House Form and Socio-Ecological Systems

House form in vernacular contexts is deeply embedded within socio-ecological systems, where architecture responds to both environmental conditions and social organization. (Rapoport, 1969)

In Limboo settlements, houses serve as multifunctional units that integrate domestic life, agriculture, and livestock management. The spatial organization reflects daily routines and seasonal cycles, where kitchens, storage areas, and livestock spaces are arranged to support livelihood practices. This integration aligns with Lefebvre's concept of lived space, where everyday practices shape spatial production (LEFEBVRE, 1974).

Limboo houses can be understood as dynamic entities within a socio-ecological system, mediating between human needs, environmental conditions, and cultural practices, keeping climate resilience at the core of the architecture. Rather than functioning as static shelters, these houses evolve through continuous adaptation to terrain, climate, and livelihood requirements. The use of locally available materials such as mud, bamboo, timber, and stone enables thermal regulation, structural flexibility, and ease of repair, ensuring long-term sustainability in a fragile Himalayan environment, thermally as well as seismically. Spatial configurations integrating domestic, agricultural, and livestock-related functions respond to seasonal cycles and daily practices, reinforcing the interdependence between built form and livelihood systems.

Figure 1. Limboo House Site Visuals.

At the settlement scale, the positioning of houses along contours, combined with features such as plinths, retaining walls, and terraces, contributes to slope stabilization, the ability to have multiple crops, and efficient water management. Collectively, these strategies demonstrate that climate resilience is not an added feature but an inherent characteristic of vernacular architecture, in which environmental responsiveness, cultural continuity, and functional adaptability are seamlessly integrated.

2. Methodology

This research adopts a qualitative and field-based architectural documentation approach focused on the measured drawing study of a traditional Limboo mud house in Chalamthang village, East Sikkim. The methodology combines measured drawings, site observations, contour studies, photographic documentation, and indoor environmental monitoring to understand how the built form responds to terrain, climate, and livelihood practices within the Eastern Himalayan context. The selected house is particularly significant as it functions as the epicenter of a larger socio-spatial ecosystem comprising residential spaces, cattle shelters, poultry areas, agricultural land, water bodies, utility spaces, and a shared open courtyard. Together, these elements form an integrated habitat system where domestic life, livelihood activities, ecological resources, and community interactions coexist within a unified spatial framework.

Detailed plans, sections, elevations, and construction details were prepared to analyze the spatial hierarchy, material systems, climatic responsiveness, and the relationships among domestic, livestock, and utility spaces. Indoor thermal monitoring of air temperature and humidity was also undertaken to evaluate the passive climate-responsive performance of the house. The recorded data indicated relatively stable indoor thermal conditions with limited diurnal variation, demonstrating the thermoregulatory capacity of vernacular materials such as mud, bamboo, and timber. The measurements were taken at 9:00 AM, 12:00 PM, 3:00 PM, and 6:00 PM.

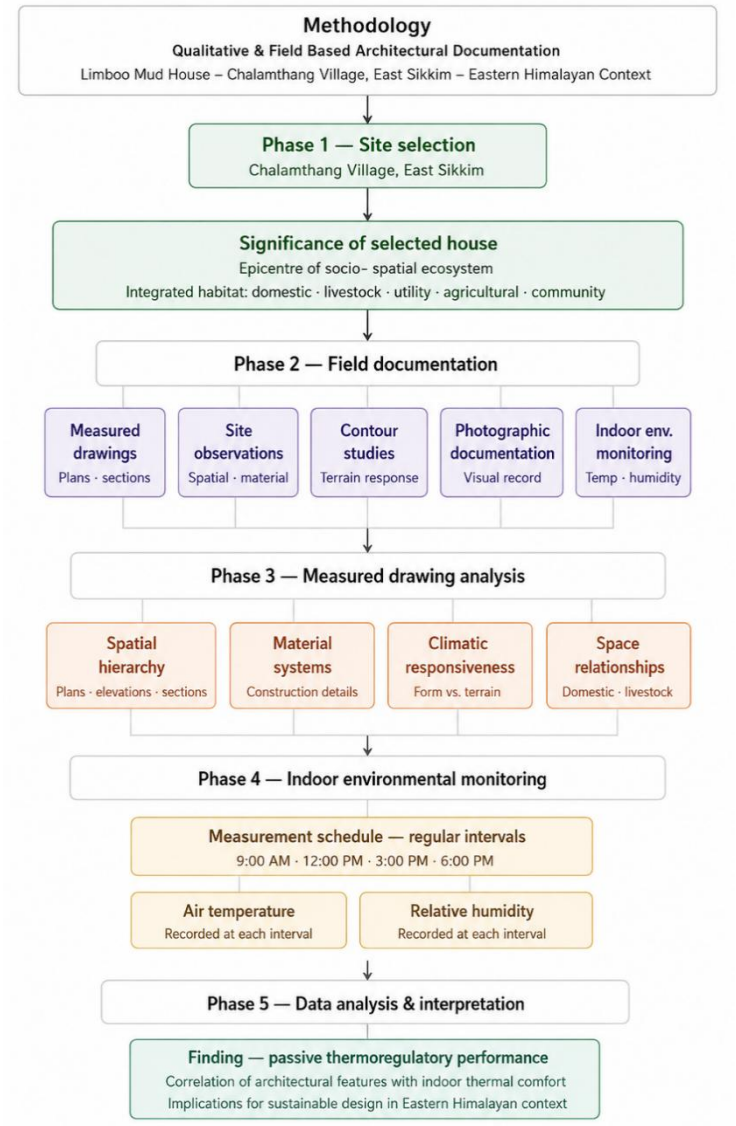

Figure 2. Methodology.

3. Architectural Documentation of the Limboo House

3.1 Site Planning and Orientation of Limboo Houses: Spatial Organization, Resource Integration, and Community Relationships

The site planning and orientation of Limboo houses demonstrate a highly contextual response to climate, terrain, resource availability, and socio-cultural organization. Houses are clustered across the terrain's contours, along with cattle shelters and farms.

Figure 3. Vernacular Limboo house and the cluster plan.

Structures are typically elevated on robust stone plinths, ensuring visibility from the site facing the valley. The predominant north-south orientation, with door and window openings aligned accordingly, facilitates controlled solar exposure and natural ventilation, contributing to thermal comfort. The Houses are typically constructed with the central idea of climate resilience, community living, and access to resources, including water, sun, and the scope of agriculture.
A clear spatial hierarchy is maintained within the built form, wherein level differences distinguish areas occupied by humans from those designated for livestock, ensuring both functional efficiency and hygienic separation. Ancillary spaces, including toilets and utility areas, are located as distinct yet integrated components within the domestic setting, reflecting a systematic approach to spatial organization.
In Chalamthang, as in comparable Himalayan settlements, water is a key environmental determinant of settlement morphology, with dwellings preferentially situated near reliable water sources. The earliest houses are located in close proximity to natural springs, reflecting the foundational role of water in the formation of early settlements. As families expanded over generations, new clusters of dwellings developed progressively along the water source and extended downslope towards the valley. (Lodson, 2018).This pattern of growth follows the natural trajectory of water, with the spatial expansion of the settlement unfolding along its flow, thereby reinforcing the intrinsic relationship between resource availability, topography, and settlement development.
At the settlement scale, the clustering of houses reflects strong kinship networks, where neighboring households operate as extended familial units, reinforcing social cohesion and interdependence. Collectively, these organic evaluations of the settlements illustrate an integrated architectural response in which environmental adaptation, spatial organization, and community structure are intrinsically interlinked.

3.3 Structural Elements

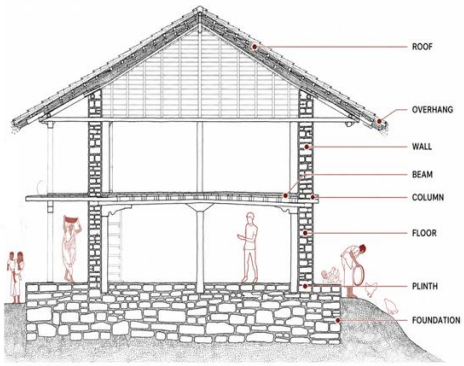

Figure 4. Section of the Mud House.

The **foundational** element of Limboo houses lies in their robust stone plinths, which provide structural stability within the steep and fragile terrain of the Eastern Himalayas. Constructed using locally available stone predominantly composed of slate and mica, the foundations are carefully laid and compacted with soil infill to enhance load distribution and ground stability. This construction technique demonstrates a contextually evolved response to the region's sloping topography and seismic sensitivity. The elevated stone base not only anchors the structure securely to the terrain but also protects the earthen superstructure from moisture ingress, surface runoff, and ground instability. Through the use of locally sourced materials and indigenous construction knowledge, the foundation system reflects a resilient and climate-responsive architectural approach deeply rooted in the environmental conditions of the region.
The **plinth** of the Limboo mud house is constructed using locally sourced stone and gravel, carefully compacted to create a stable base capable of negotiating the steep Himalayan terrain. The upper surface is finished with layers of mud plaster reinforced using a traditional mixture of animal dung, local soil, and finely cut hay fibres, which improves binding strength and surface durability. Beyond functioning as a structural base, the elevated plinth protects the earthen superstructure from moisture ingress, surface runoff, and ground dampness during heavy monsoon conditions. The raised platform also mediates level differences across the sloping site, ensuring stability while establishing a transitional threshold between the ground and inhabitable spaces. Due to its continuous exposure to water, soil erosion, and everyday physical abrasion, the plinth remains one of the most maintenance-intensive components of the house, particularly during the monsoon season. Periodic repair and re-plastering are essential to maintain surface integrity, moisture resistance, and level stability, reflecting an ongoing cycle of care embedded within vernacular construction practices.
The **wall system** demonstrates a climate-responsiveness rooted in locally available natural materials and indigenous knowledge systems. The walls are primarily composed of mud infill integrated with stone timber and bamboo frameworks, creating a lightweight yet thermally efficient enclosure. Thick earthen walls provide thermal mass that helps regulate indoor temperatures by reducing heat loss during cold periods and limiting excessive heat gain during the day. The layered composition of mud, bamboo lattice, and timber framing also contributes to seismic flexibility, an important consideration within the earthquake-prone Himalayan region.
This wall system undergoes a distinct transformation in its material composition and structural character at the uppermost level of the house. At the third level, particularly along the north–south orientation, the walls are constructed using a traditional wattle-and-daub system composed of woven bamboo lattice infilled and plastered with mud. This lightweight construction technique reduces structural load on the upper levels while simultaneously improving thermal performance and seismic flexibility. The walls at the second level additionally function as a structural base supporting the extended roof overhang, thereby contributing to load transfer, climatic protection, and the overall stability of the roof assembly.

Wall sections reveal the integration of structural stability, insulation capacity, and material economy within a single construction system.

The **beam** system primarily consists of locally sourced timber and bamboo members spanning across structural walls and columns to support upper floors and roof loads. Timber beams are carefully placed to distribute loads two way evenly while maintaining flexibility within the structural framework. Their relatively lightweight nature reduces overall structural stress and enhances seismic responsiveness. In addition to their structural role, exposed timber beams contribute to the spatial character of the interiors and reflect the craftsmanship embedded within vernacular construction traditions. The projecting timber beams extending outward from the walls serve multiple functional purposes within the house's architectural system. Structurally, these projections create deep overhangs that protect the earthen walls from direct exposure to rainwater, thereby reducing moisture penetration and weathering during heavy monsoon conditions. Simultaneously, the extended beams provide shaded peripheral spaces that are often utilized for temporary storage, drying agricultural produce, and everyday utility activities. In several instances, the protruding beam system is integrated with suspended wooden platforms that support hollow timber logs used for traditional bee cultivation practices

Figure 5. Storage Space in various places of the house.

Timber **columns** form an important vertical structural element within the house, transferring loads from the upper floors and roof systems onto the stone plinth and foundation below. Positioned strategically within the internal spatial layout, the columns help define circulation and functional zones while maintaining open and adaptable interior spaces. The use of timber columns also allows a degree of structural flexibility, enabling the building to respond more effectively to seismic movement and settlement shifts associated with sloping terrain. The timber columns are anchored on robust stone footings integrated within the foundational plinth system, ensuring structural stability and effective load transfer to the ground. At floor level, the bases of the columns are raised above the finished surface and protected by a mud-plastered pedestal, minimizing direct moisture exposure to the wood.

The joinery system of the Limboo mud house demonstrates a refined understanding of structural behavior, material efficiency, and climatic responsiveness developed through indigenous construction knowledge. Timber beam–column connections are primarily achieved through traditional interlocking wooden joinery techniques, minimizing reliance on metal fasteners and allowing a degree of structural flexibility essential in the seismically sensitive Himalayan terrain. The primary timber beams transfer roof and floor loads onto vertical timber columns, which are anchored into the stone plinth system, ensuring stability and continuity of load transfer throughout the structure.

Floor of the lower level, mezzanine level, and the third level

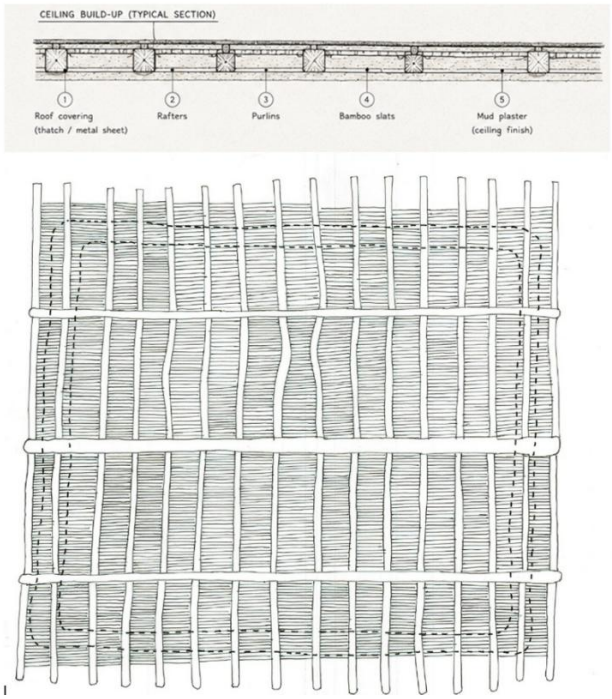

Figure 6. Reflected ceiling plan and floor details.

The **roof** is characterized by a steeply sloping profile designed to efficiently drain monsoon rainwater and reduce moisture accumulation. Traditionally, roofs were constructed from locally available materials supported on bamboo frameworks, providing natural insulation and a lightweight structure. However, over time, many houses have transitioned towards corrugated metal sheets and other contemporary roofing materials due to reduced maintenance requirements and increased durability. The roof structure is organized through a hierarchy of primary and secondary timber members. Large primary beams span across the principal structural grid and support secondary rafters and purlins that establish the roof slope. The roof is intentionally designed with a steep pitch to facilitate rapid drainage of monsoon rainwater and prevent moisture accumulation on the thatch surface. Extended roof overhangs project significantly beyond the wall plane, protecting the earthen walls from direct rain exposure while also creating shaded peripheral spaces around the house.

Figure 7. Roof of Mud house.

Bamboo elements are intricately integrated within the roof assembly through tied and interwoven joineries connected to timber rafters and purlins. Split bamboo members function as secondary lattices and support systems for the thatch covering, distributing loads evenly while maintaining lightweight construction. The bamboo–timber joinery system also contributes to structural flexibility, ventilation, and ease of maintenance. Collectively, the roof joineries reflect a construction logic that balances climatic adaptation, material availability, structural resilience, and craftsmanship within the vernacular architectural tradition of the Eastern Himalayas.

The **doors** of the Limboo mud house are constructed from locally sourced timber and integrated into a simple yet durable wooden framing system embedded in the earthen wall assembly. The door shutters are generally made of vertical timber planks joined with horizontal battens and traditional wooden joinery techniques, minimizing reliance on industrial hardware. Openings are proportioned modestly to reduce heat loss and maintain thermal efficiency within the indoor spaces, particularly during colder seasons. Elevated thresholds are commonly incorporated at the base of the doorway to prevent moisture ingress, surface runoff, and the entry of dust and insects from the exterior terrain.

The **windows** are designed as climate-responsive openings that balance daylight penetration, ventilation, and thermal comfort within the dwelling, given the house's strategic location on the eastern wall. Timber-framed window systems are generally recessed within thick earthen walls, creating shaded openings that reduce direct exposure to rain while enhancing thermal insulation. The window shutters are fabricated from lightweight timber members and are often operable to regulate airflow according to seasonal requirements and also acts as a kitchen exhaust.

3.4 Indoor Living Spaces

The placement of doors within the Limboo mud house reflects a carefully articulated internal spatial hierarchy, establishing controlled transitions between public, semi-private, and utility spaces. The modest scale of the doors and windows minimizes heat loss during colder months while maintaining visual connectivity with agricultural fields, circulation paths, and the surrounding Himalayan landscape. Particular attention is given to the positioning of openings in relation to domestic activities and environmental responsiveness. A small window located adjacent to the kitchen functions as a multifunctional climatic element, facilitating smoke exhaust, daylight penetration, and passive ventilation. Strategically positioned along the eastern wall, the kitchen space benefits from the morning sun while maintaining a direct visual relationship with the extended living environment, comprising cattle shelters, poultry areas, and adjoining farmland. This spatial arrangement reinforces the interconnected nature of livelihood, domesticity, and landscape within the vernacular habitat.

The house also accommodates a sacred spatial dimension through the placement of a worship area located in the south-east corner, parallel to the kitchen on the ground level. Although the house itself is no longer permanently inhabited, this sacred space remains active within the collective memory and ritual life of the community. As one of the earliest ancestral houses within the settlement, the structure symbolizes the lineage and historical continuity of the community's early settlers. The worship space is therefore used not only by the household's descendants but also by the wider community during festivals, marriages, and other auspicious occasions.

Vertical movement within the house is mediated by compact, anthropometrically responsive circulation systems. A small opening near the ceiling corner on the first level provides access to the upper level, reflecting a spatial configuration optimized for thermal efficiency and material economy. An important example of indigenous construction knowledge is observed in the staircase system, where a single bamboo culm is carved and adapted into a ladder-like element utilizing the natural bamboo nodes as footholds and risers.

The internal organization of the house reveals a seasonal hierarchy of inhabitation closely linked to thermal performance and livelihood practices. The middle and lower levels served as the primary habitable spaces in both summer and winter due to the thermal mass of the thick earthen walls, which helped maintain warmer indoor conditions during cold periods and cooler conditions during warmer months. (Afolabi, 2023)These levels were predominantly used for resting, domestic activities, and storage, depending on seasonal requirements. In contrast, the uppermost attic level primarily served as a storage space for winter provisions, particularly fodder for cattle and agricultural produce. The stacked hay stored within the attic further acted as an additional insulating layer during the winter months, reducing heat loss through the roof assembly. During summer, the relatively open attic space beneath the thatch roof facilitated air circulation and passive ventilation, thereby improving thermal comfort within the lower inhabitable levels. Collectively, the house's sectional organization demonstrates a highly climate-responsive spatial strategy rooted in vernacular knowledge and seasonal adaptation.

Storage practices within the house further reflect adaptive responses to climate, livelihood, and animal coexistence. Storage spaces are integrated beneath roof overhangs, suspended from beams, and positioned above ground level to protect edible materials and agricultural produce from moisture, rodents, and livestock. The extended roof overhang additionally creates a transitional buffer zone between the enclosed wall surface and the exterior open space. This shaded semi-public threshold functions as a social interface visually connected to the settlement pathway, enabling interaction, observation, and passive surveillance within the settlement fabric, closely resonating with the concept of "eyes on the street" in community-oriented environments.

Figure 8. Bamboo stairs, Transition of floor, and inside view.

4. Climate - Responsive Design

Environmental monitoring conducted in the Limboo vernacular house revealed significant evidence of passive climate responsiveness and thermal stability. Monitoring of indoor air temperature, relative humidity, dew point temperature, and wet bulb temperature demonstrated that the indoor environment remained within a narrow thermal range of approximately 20.0°C to 23.8°C across the winter monitoring period, despite the absence of mechanical heating or cooling systems. During late November and early December, the Eastern Himalayan region of Sikkim generally experiences cold weather, with average temperatures ranging from approximately 7.2°C to 14.1°C. (IMD, 2026) The comparatively stable and thermally comfortable indoor environment observed within the Limboo house highlights the effectiveness of the vernacular building envelope in moderating external climatic fluctuations through passive and climate-responsive architectural strategies.

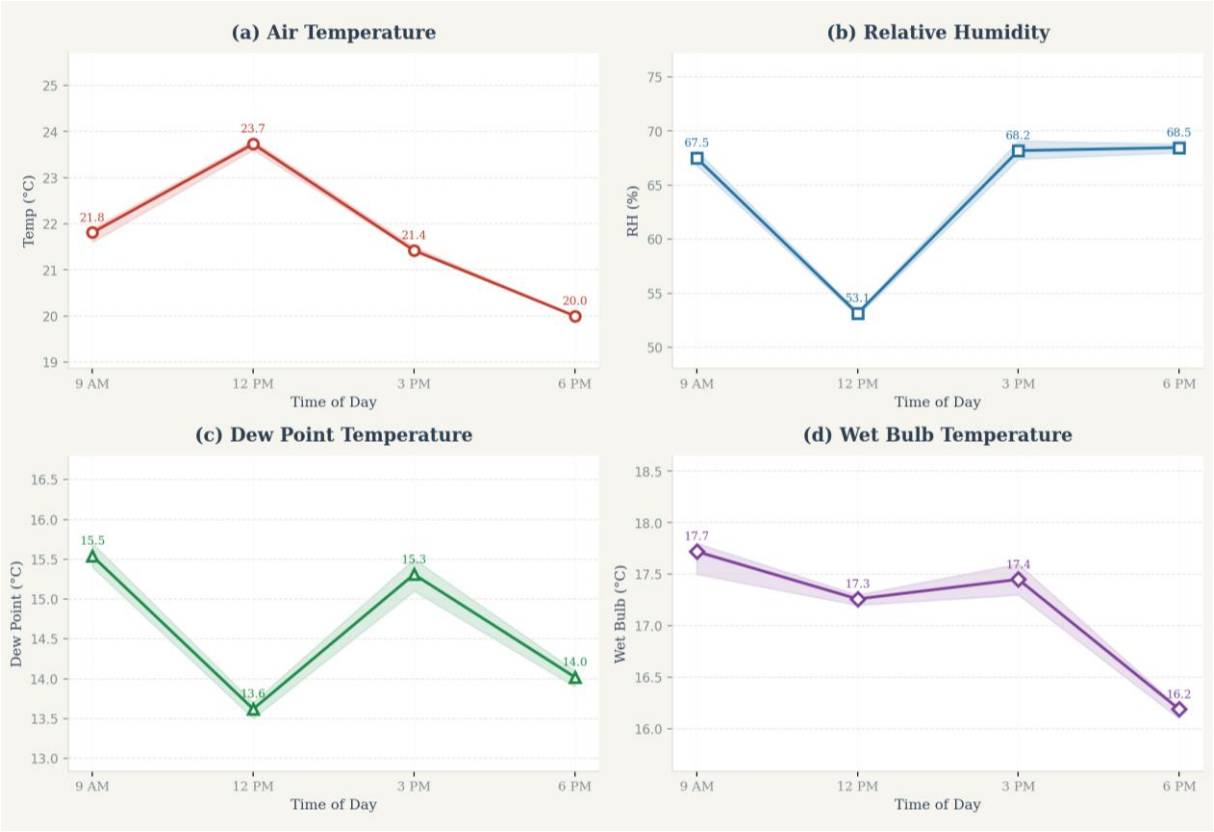

Figure 9. Plot of mean temperature.

Figure 8 presents a scatter plot of mean temperature against mean relative humidity for each of the four daily observation times, with a linear trend line overlaid. The strong inverse relationship is immediately apparent: as temperature increases from 20.0°C to 23.73°C, relative humidity decreases from 68.47% to 53.14%.

The Pearson correlation coefficient between these two parameters is approximately -0.92, indicating a strong negative linear association. The strong inverse correlation ($r \approx -0.92$) between indoor temperature and relative humidity across the four time slots confirms that the indoor air behaves as a near-constant-moisture-content system.

This inverse relationship is a fundamental characteristic of enclosed spaces where the absolute moisture content (specific humidity) remains relatively constant while temperature varies. The Limboo house envelope, through its hygroscopic earthen plaster finish and bamboo wall assembly, appears to moderate both the magnitude of temperature swings and the rate of humidity change, consistent with the hygrothermal buffering properties documented in the literature on vernacular building performance for earthen and bamboo construction.

The thermal stability observed in the house can be attributed to the combined performance of thick earthen wall assemblies, bamboo infill systems, raised-floor construction, and ventilated attic spaces beneath the thatch roof. Earthen-plastered walls provide thermal mass and hygroscopic buffering, regulating both heat transfer and indoor humidity, while the attic and roof assembly facilitates seasonal insulation and passive ventilation. The monitoring further revealed a strong inverse relationship between indoor temperature and relative humidity, reflecting the thermal and moisture-regulating properties of natural materials such as mud, bamboo, and timber. Collectively, the findings demonstrate how indigenous Limboo construction practices embody a sophisticated understanding of climate-responsive design, enabling thermal comfort, moisture regulation, and environmental resilience within the challenging climatic conditions of the Eastern Himalayas.

5. Discussion

The documentation of this vanishing architectural typology is particularly significant, as it embodies indigenous vernacular knowledge systems that have evolved over generations in response to harsh climatic conditions and the fragile Himalayan terrain. Constructed from locally available natural materials, the Limboo mud house demonstrates a deeply

sustainable and climate-responsive approach to habitation, in which architecture exists in close continuity with nature. Its spatial organization, materiality, and construction techniques collectively reflect resilience, adaptability, and environmental sensitivity. At a time when such traditional systems are rapidly disappearing under the pressures of modernization and changing aspirations, documenting these houses becomes essential not only for architectural conservation but also for understanding sustainable building practices rooted in local ecological knowledge and cultural continuity.

The study demonstrates that climate responsiveness in Limboo vernacular architecture is achieved not through mechanized systems but through an integrated tectonic and environmental logic embedded in indigenous construction practices. Architectural elements such as thick earthen wall assemblies, elevated stone plinths, ventilated attic volumes, controlled fenestration systems, and deep roof overhangs collectively function as passive environmental regulators that moderate heat transfer, moisture ingress, and indoor air movement. The thermal performance analysis further substantiates the environmental efficiency of the vernacular envelope, indicating that the indoor microclimate remained comparatively stable and thermally comfortable despite substantially colder external winter conditions. The hygrothermal behavior of natural materials such as mud, bamboo, timber, and thatch demonstrates their capacity for thermal mass, moisture buffering, insulation, and passive ventilation, thereby reinforcing the continued relevance of bio-based materials within low-energy and climate-responsive architectural systems.

Beyond environmental performance, the research highlights the spatial and functional interdependence between habitation, livelihood systems, and ecological processes within Limboo settlements. Domestic architecture extends beyond the conventional notion of shelter to incorporate livestock management, agricultural storage, food processing, and ritual functions, forming a continuous socio-spatial system between humans, houses, and habitat. The contour-responsive organization of settlement clusters, the gravity-based integration of water systems, and the strategic positioning of cattle sheds, utility spaces, and communal thresholds collectively demonstrate an ecologically adaptive settlement morphology optimized for resource efficiency, climatic responsiveness, and terrain negotiation. These spatial relationships reveal how vernacular architecture operates simultaneously as environmental infrastructure, livelihood apparatus, and socio-cultural framework within the Himalayan context.

The study additionally identifies the increasing vulnerability of this architectural typology under contemporary socio-economic transformations. The gradual substitution of earthen, bamboo, and timber-based systems with industrialized materials such as reinforced concrete, corrugated metal sheets, and masonry construction reflect shifting aspirations, changing labor economies, declining artisanal knowledge, and evolving perceptions of permanence and modernization. Although such transformations may reduce immediate maintenance demands, they frequently compromise the passive environmental performance, material circularity, seismic adaptability, and ecological integration characteristic of vernacular systems. Consequently, the disappearance of Limboo mud houses represents not only the loss of a regional architectural typology but also the erosion of accumulated ecological intelligence and culturally embedded climate-adaptation strategies developed over generations of empirical environmental engagement.

Within this context, the systematic documentation of Limboo vernacular architecture assumes significant disciplinary relevance. The measured drawings, spatial analyses, tectonic studies, and environmental observations presented in this research contribute toward the preservation and interpretation of an endangered architectural knowledge system with direct implications for contemporary sustainable design discourse. The study demonstrates that vernacular architecture in the Eastern Himalayas embodies principles of low embodied energy, passive thermal regulation, material renewability, ecological integration, and climate resilience that remain critically relevant under present-day environmental challenges. The Limboo house should therefore be understood not as a static remnant of the past, but as a dynamic and contextually adaptive architectural model capable of informing future approaches toward climate-responsive, low-energy, and regionally grounded design practices in fragile mountain environments.

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

All datasets are included within the article

Institutional Review Board Statement

Not applicable

CRediT Author Statement

All authors have read and approved the final version of the manuscript

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