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Case study

Sustainable solutions for low-cost building: Material innovations for Assam-type house in North-East India

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ABSTRACT

Assam-type houses, traditionally constructed using bamboo, timber, and mud, have long served as climate-adapted, affordable Building in North-East India. With growing demands for low-cost and sustainable Building, this review evaluates material innovations that can enhance the affordability, durability, and sustainability of Assam-type houses. The paper examines traditional materials such as bamboo and thatch, alongside modern innovations like Compressed Stabilized Earth Blocks (CSEB), fly ash bricks, and agro-waste products. Emerging materials, including ferrocement and hempcrete, are assessed for their potential in providing eco-friendly alternatives. Key challenges in the region, such as economic constraints, environmental threats like floods and earthquakes, and material transportation issues, are addressed. Technological advancements, such as prefabricated Building and 3D printing, are discussed for their role in sustainable construction. The review concludes with a focus on policy support, particularly the Pradhan Mantri Awas Yojana (PMAY), and future directions for scaling sustainable, low-cost Building solutions in the region.

1. Introduction

Assam-type houses are a distinctive architectural style prevalent in the northeastern state of Assam, India. These houses were developed during the British colonial period but incorporate traditional Assamese building techniques that are well-suited to the region's climate and seismic conditions. They are designed to address Assam's frequent heavy rains, high humidity, and earthquake-prone environment, making them both functional and resilient [15,16]. A key feature of Assam-type houses is their lightweight structure. The buildings are typically constructed with a wooden or bamboo frame, which gives them flexibility and durability in the face of earthquakes. The walls are made from a combination of bamboo, wood, reeds, or even brick and plaster, depending on the resources available and the intended permanence of the building. This lightweight construction reduces the risk of severe damage during seismic activity [51]. These houses are often built on raised stilts or a plinth, which helps protect against flooding during the monsoon season and promotes air circulation, preventing dampness and rot.

The roofs are another significant feature, usually made of corrugated iron sheets or traditional thatch. The steep, sloping design helps shed rainwater quickly, preventing water accumulation and leakage. Verandas often wrap around the house, offering shaded outdoor spaces that protect the interiors from direct sunlight while facilitating ventilation. This natural ventilation is crucial in Assam's

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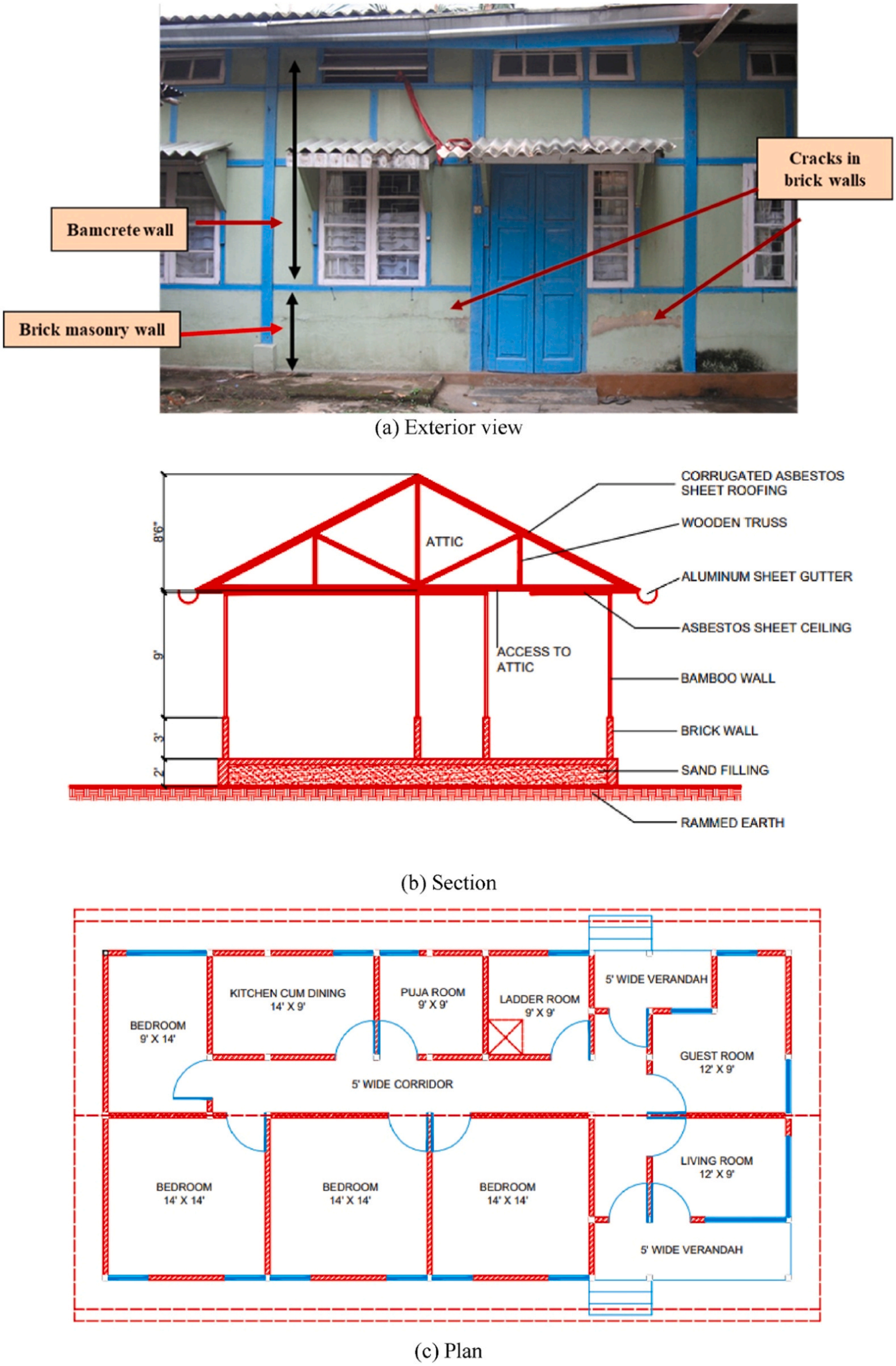

Fig. 1. A 40 years old Assam-type house at Guwahati, Assam (India) [17].

humid climate, helping to keep the interior cool and comfortable. Assam-type houses are known for their adaptability and sustainability [10,49]. They make use of locally available materials, which keeps construction costs low and minimizes environmental impact. Additionally, their simple design allows for easy maintenance and repairs, which is essential in a region frequently affected by natural forces. Despite their practical advantages, modern construction methods using concrete are gradually replacing Assam-type houses. However, they remain an important symbol of Assam's architectural heritage, reflecting a deep understanding of the region's environmental challenges. Fig. 1 shows a 40 years old Assam-type house at Guwahati, Assam (India).

The need for sustainable low-cost Building is increasingly urgent as populations grow and urbanization accelerates, particularly in developing countries. Affordable Building solutions are critical to addressing the global Building crisis, where millions of people live in inadequate or unsafe conditions. Sustainability in Building not only lowers costs but also reduces environmental impact, making it essential for long-term urban planning [1,21,29]. Sustainable low-cost Building focuses on using locally sourced, eco-friendly materials and energy-efficient designs that minimize resource consumption. This reduces the overall cost of construction and maintenance, making Building more accessible to low-income communities. Additionally, incorporating renewable energy sources, like solar panels, and sustainable practices, such as rainwater harvesting and proper insulation, further decreases utility costs for homeowners, promoting long-term financial and environmental sustainability. Moreover, sustainable Building helps mitigate climate change by reducing carbon emissions, waste, and reliance on non-renewable resources [12,39,60]. It also promotes healthier living conditions through better ventilation, natural lighting, and resilient structures that can withstand environmental challenges such as floods or extreme temperatures. With global demand for affordable Building on the rise, the integration of sustainability in Building development is not only a moral imperative but also a practical solution for creating resilient, equitable, and environmentally conscious communities.

This study stands out by comprehensively examining both traditional and modern materials for Assam-type houses, going beyond previous research that primarily focused on conventional materials like bamboo and thatch. It assesses innovative alternatives such as Compressed Stabilized Earth Blocks (CSEB), fly ash bricks, ferrocement, and hempcrete for their sustainability, affordability, and durability. Additionally, it explores the impact of technological advancements like prefabrication and 3D printing on low-cost housing solutions. The study also considers critical regional challenges, including economic constraints and disaster resilience, while highlighting the role of policy initiatives like Pradhan Mantri Awas Yojana (PMAY) in promoting sustainable construction.

The objective of this review paper is to explore sustainable material innovations for low-cost Building, specifically focusing on Assam-type houses in North-East India. It aims to analyse current advancements in eco-friendly building materials and construction techniques that enhance affordability, durability, and environmental sustainability. The scope includes evaluating both traditional and modern materials suited to the region's climate and seismic challenges, while identifying gaps in research and potential future directions. By synthesizing existing studies, the review seeks to guide policymakers, architects, and builders in developing sustainable, cost-effective Building solutions for Assam and similar regions.

2. Assam-type houses: tradition and sustainability

2.1. Historical and cultural significance

Assam-type houses have been in use since the late 19th century, during the British colonial period in India. Their development was closely tied to the establishment of tea plantations in Assam, where British settlers needed structures that could withstand the region's challenging environmental conditions, such as heavy rainfall, humidity, and frequent earthquakes. Initially, these buildings were designed for colonial tea garden managers and estate workers, combining local construction techniques with elements of British architecture. Over time, the Assam-type style spread beyond tea estates and became popular in urban and rural settings across Assam. Its adaptability, cost-effectiveness, and suitability for the local climate made it a lasting architectural choice in the region [11,31,52]. Today, Assam-type houses are considered a blend of colonial and indigenous influences, and they continue to be valued for their historical and cultural significance. Many of these buildings, especially those over a century old, serve as reminders of Assam's colonial past and its integration of traditional knowledge into practical design solutions.

The most notable features of Assam-type houses are their lightweight structures, typically made from local materials like bamboo, wood, and corrugated iron sheets [8,44]. Raised plinths, sloping roofs, and wide verandas provide natural ventilation and protect the interiors from flooding and extreme weather [34,45]. These buildings also reflect the social and economic history of Assam, as they were primarily used for homes, offices, schools, and tea garden bungalows.

Assam-type houses are a vital part of Assam's cultural heritage, embodying the region's architectural identity and connection to its environment. These structures reflect the ingenuity of Assamese craftsmanship, blending indigenous techniques with colonial influences. Designed to adapt to Assam's challenging climate—characterized by heavy monsoons, high humidity, and seismic activity—these buildings are a testament to the local community's harmonious relationship with nature. Culturally, Assam-type houses are more than just practical dwellings; they serve as symbols of Assamese resilience and sustainability. Constructed primarily from locally sourced materials like bamboo, wood, and thatch, these structures highlight the community's reliance on natural resources while minimizing their environmental impact. The wide verandas, sloping roofs, and elevated floors not only provide functional benefits but also foster a sense of openness and social interaction, reflecting the communal way of life typical in Assamese society.

2.2. Traditional building techniques

Assam-type housings are a hallmark of vernacular architecture in Assam, India, known for their adaptability to the region's extreme climatic conditions, including high rainfall, flooding, and earthquakes. These buildings reflect a sustainable, cost-effective construction method that has been perfected over generations, utilizing locally sourced materials and techniques suited to the region's challenges. The foundation of Assam-type houses is typically elevated above ground level, often using wooden or bamboo stilts. This design helps protect the structure from flooding, which is common during Assam's heavy monsoon season, and keeps the house dry by preventing direct contact with the damp ground. The plinth is usually made of mud, stone, or brick, reinforced to ensure stability.

The walls are traditionally constructed from bamboo or reed, bound together and coated with a mixture of mud and cow dung, or in some cases, lime plaster for added durability. Bamboo, a lightweight and flexible material, is abundantly available in Assam and is an excellent choice for this earthquake-prone region. The flexibility of bamboo allows these buildings to absorb and dissipate seismic forces, reducing the risk of collapse during an earthquake. The roof is another critical feature of Assam-type houses. Typically, it is steeply pitched and made from corrugated iron sheets, thatch, or even tin to allow rainwater to run off easily. This sloping design prevents water accumulation and minimizes the chances of leaks, which is essential in Assam's high-rainfall environment. Large overhanging eaves provide shade and natural cooling, enhancing ventilation inside the house, which is crucial for comfort in the region's hot and humid climate. Wide verandas encircling the house serve both functional and social purposes, offering space for outdoor activities while providing extra protection from rain. Overall, the traditional building techniques of Assam-type houses showcase a perfect blend of resilience, simplicity, and environmental harmony, making them well-suited to the region's unique conditions.

Figs. 2 and 3 illustrate a typical frame of an Assam-type house, highlighting various connections and their locations. The primary vertical posts and wall plate beam exhibit significant lateral deformation capacity. One main post connection (Joint B) with the foundation allows for rotation, while the corresponding connection (Joint A) restrains this rotation, providing stability and the necessary stiffness to resist lateral loads. This asymmetrical connection is uncommon in traditional timber houses worldwide. Joint C, linking the main posts to the top wall plate beam, uses an open mortise and tenon joint. Additionally, the horizontal stud connections (Joints D and E) further enhance the frame's deformability, as shown in Fig. 3a, b, c, d, and e.

Table 1 outlines the key elements of traditional Assam-type houses, highlighting the materials used, construction techniques, and associated benefits. It covers aspects like foundations, walls, roofing, and ventilation, emphasizing the use of sustainable, local

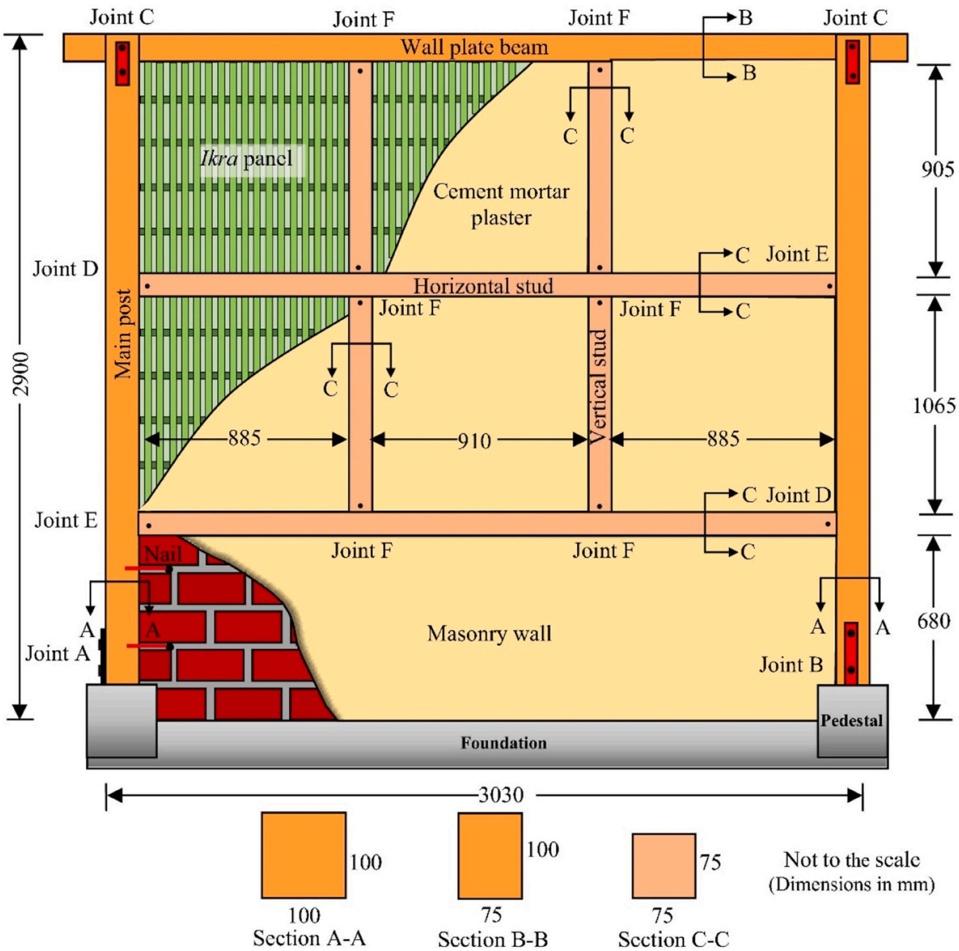

Fig. 2. Details of a typical frame of Assam-type house [9].

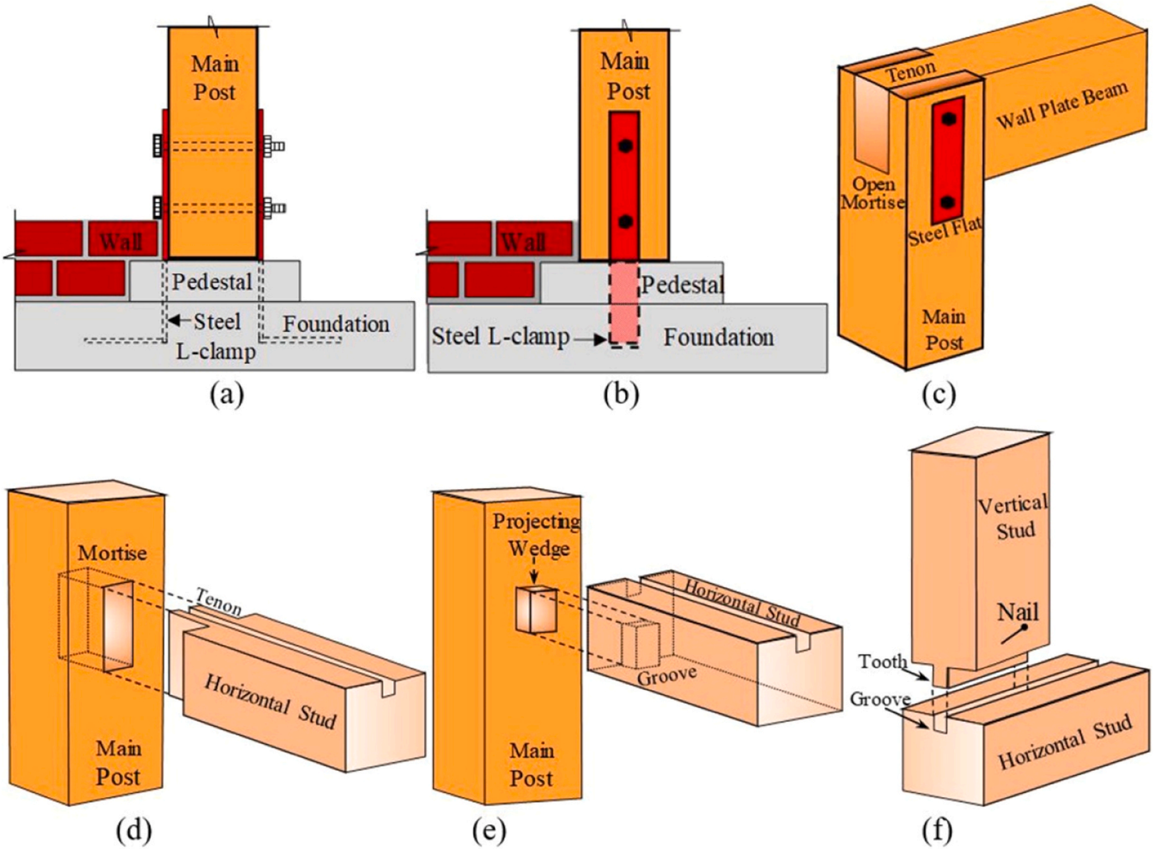

Fig. 3. Details of joints used in typical Assam-type houses: (a) Joint A, (b) Joint B, (c) Joint C, (d) Joint D, (e) Joint E, and (f) Joint F [9].

Table 1
Traditional building techniques in Assam-type architecture.

Building Element	Materials Used	Construction Techniques	Benefits
Foundation	Stone, brick, wooden posts	Raised foundation with wooden posts driven into the ground	Protection from floods, minimizes moisture damage
Walls	Bamboo, reed, plaster	Bamboo woven panels with mud or lime plaster	Lightweight, flexible, resistant to seismic activity
Roof	Corrugated iron sheets, thatch	Thatched roof or corrugated iron on wooden rafters	Good ventilation, heat insulation, rain protection
Flooring	Bamboo, timber	Bamboo mats or wooden planks on elevated structure	Natural cooling, moisture protection, easy maintenance
Windows and Ventilation	Wood, bamboo, iron grills	Wide wooden windows with bamboo lattice or iron grills	Maximizes airflow, natural lighting, and enhances ventilation
Doors	Timber, bamboo	Simple wooden frames with bamboo or wooden panels	Durability, natural insulation, traditional aesthetics
Ceiling	Bamboo mat, cloth, timber	Bamboo mat ceilings with wooden beams	Provides thermal comfort, reduces heat from the roof
Veranda/Portico	Bamboo, timber, thatch roof	Open or semi-open verandas with bamboo or wooden posts	Encourages airflow, provides shade, and outdoor living space
Structural Frame	Timber, bamboo	Timber or bamboo posts and beams with simple joinery	Flexible structure resistant to earthquakes
Plastering	Clay, mud, cow dung, lime	Earth plaster mixed with straw or cow dung applied to walls	Natural insulation, eco-friendly, cost-effective
Drainage System	Bamboo pipes, natural slope	Water drainage through sloped surfaces and bamboo drainage pipes	Prevents waterlogging, reduces moisture in the foundation
Fencing/Compound Walls	Bamboo, timber, thatch	Bamboo fencing tied together with jute or wooden stakes	Eco-friendly, inexpensive, and blends with natural landscape

materials like bamboo and timber, which provide earthquake resilience, thermal comfort, and environmental harmony.

2.3. Adapting to climate and geography in North-East India

Assam-type houses are a remarkable example of architectural adaptation to the unique climate and geography of Northeast India. This region experiences heavy monsoon rains, high humidity, and varied topography, which significantly influence building design. One of the most distinguishing features of these structures is the Chang Ghar, an elevated platform that raises the living space above the ground. This design is critical for preventing water damage during the intense monsoon season, as it protects the interiors from flooding and moisture-related decay. A typical Chang Ghar is shown in Fig. 4.

Constructed primarily from locally sourced materials such as bamboo, timber, and thatch, Assam-type houses exemplify sustainable practices. Bamboo, known for its strength and flexibility, is extensively used in walls, floors, and ceilings, while thatch roofs are both economical and effective at shedding rainwater. The steeply pitched roofs not only facilitate efficient rain runoff but also minimize water accumulation, which can lead to structural issues. Additionally, the use of natural insulation materials keeps the interiors comfortable during the hot summers and cool winters. The architectural layout often features large verandas and open spaces, promoting airflow and ventilation essential for combatting humidity. These spaces also provide shade, enhancing comfort during the sweltering months. The placement of these buildings is strategically chosen, often located near rivers or elevated areas to reduce flood risks and take advantage of the natural landscape. Furthermore, the use of traditional craftsmanship reflects the cultural heritage of the Assamese people. The incorporation of artistic elements in design showcases a deep connection to the local environment and a commitment to harmony with nature. In essence, Assam-type houses represent a perfect blend of functionality and aesthetic appeal, demonstrating a profound understanding of environmental adaptation that has been refined over generations.

3. Challenges of low-cost building in North-East India

3.1. Economic and socio-cultural constraints

In North-East India, low-cost building faces several economic and socio-cultural constraints that affect the adoption of affordable housing solutions. Economically, the region's underdeveloped infrastructure, limited access to raw materials, and high transportation costs pose significant challenges. Construction materials are often sourced from distant areas, making them expensive. The region's high rainfall and seismic vulnerability also require specialized, costlier construction techniques, further inflating building expenses.

Socio-cultural constraints also play a crucial role. The indigenous communities of North-East India have diverse cultural practices and traditional construction methods, which may not always align with modern low-cost housing solutions. Traditional houses, often made from locally sourced bamboo and wood, are seen as both sustainable and culturally significant. However, modern materials like concrete are often viewed as a symbol of progress, leading to a conflict between preserving cultural heritage and adopting cost-effective, modern techniques. Additionally, land ownership patterns in the region are often governed by tribal laws, making it difficult to implement large-scale housing projects. The reluctance of communities to accept non-traditional building designs, coupled with limited awareness of sustainable, low-cost alternatives, further hampers efforts to promote affordable housing solutions in North-East India. These factors together create a complex environment for low-cost building initiatives.

3.2. Environmental challenges

Environmental challenges in North-East India, particularly floods, earthquakes, and climate change, pose significant threats to the region's sustainability and resilience. Floods are a recurring issue, exacerbated by the region's heavy monsoon rains. Rivers overflow, leading to widespread inundation of agricultural land, homes, and infrastructure. The frequent flooding not only disrupts livelihoods

Fig. 4. A typical Chang Ghar [6].

but also leads to soil erosion and the loss of arable land, impacting food security and economic stability. Earthquakes are another critical concern, as North-East India is situated in a seismically active zone. The region experiences significant seismic activity, with earthquakes leading to loss of life, property destruction, and long-term economic consequences. The vulnerability of buildings and infrastructure to earthquakes poses challenges for urban planning and development, necessitating the integration of earthquake-resistant designs in construction.

Climate change compounds these issues, altering weather patterns and increasing the frequency and intensity of extreme weather events. Rising temperatures, shifting rainfall patterns, and increasing droughts threaten agricultural productivity and water availability. Communities, often reliant on subsistence farming, face heightened risks to their livelihoods. Moreover, climate change can trigger migration as people flee from affected areas, leading to urban overcrowding and increased pressure on resources in cities. Addressing these environmental challenges requires comprehensive strategies that incorporate sustainable practices, disaster preparedness, and community resilience-building efforts to safeguard the region's future.

Economic constraints play a crucial role in shaping material adoption in Assam-type houses. Limited financial resources force homeowners to prioritize affordability over sustainability, often leading to the use of cheaper, less durable materials such as tin sheets, bamboo, and locally available wood instead of modern, eco-friendly alternatives. The high cost of sustainable construction materials, like treated bamboo, stabilized mud blocks, or reinforced concrete, makes them inaccessible to many households. Additionally, fluctuating income levels, particularly in rural areas, hinder long-term investments in durable housing solutions. Lack of access to credit and financial assistance further limits homeowners' ability to adopt costlier but resilient materials. As a result, economic constraints not only affect material choices but also contribute to increased maintenance costs, structural vulnerability, and reduced environmental sustainability. Addressing these challenges requires targeted subsidies, financial incentives, and awareness programs to promote cost-effective yet sustainable construction practices in Assam-type houses.

3.3. Availability and transportation of materials

The availability and transportation of construction materials in North-East India present significant challenges that impact the region's housing development and infrastructure projects. Availability of construction materials is often limited due to the region's geographical characteristics. North-East India is endowed with rich natural resources, including timber, bamboo, and clay; however, the extraction and processing of these materials are often hindered by regulatory frameworks and conservation policies aimed at protecting the environment. Moreover, the lack of industrial infrastructure leads to an over-reliance on traditional building materials, which can be insufficient for modern construction needs. This scarcity often drives up costs, making affordable housing projects less feasible.

Transportation further complicates the situation. The region is characterized by hilly terrains and narrow roads, which can impede the movement of heavy machinery and materials. Poor infrastructure, coupled with seasonal weather disruptions such as monsoon rains, can delay transportation and inflate costs. The long distances from material sources to construction sites exacerbate these challenges, as materials must often be sourced from outside the region, adding to the expenses and time required for projects. To mitigate these issues, local governments and stakeholders need to invest in improving infrastructure, promoting sustainable material sourcing, and developing logistical frameworks that can enhance the availability and transportation of construction materials. This would facilitate more efficient and cost-effective building practices, supporting economic growth and housing development in North-East India. Table 2 provides a comprehensive overview of the availability and transportation of materials essential for Assam-type houses. It outlines various construction materials, their sources, and logistical considerations for transport. This information is

Table 2
Assessment of material availability and transportation for Assam-type houses.

Material	Availability	Source Locations	Transportation Considerations
Bamboo	Widely available, especially in rural areas	Local forests, bamboo farms	Lightweight, easy to transport; may require special vehicles for bulk transport.
Thatch	Commonly found, particularly in flood-prone areas	Local vendors, agricultural areas	Easy to transport; often sold in bundles, but care is needed for preservation.
Timber (Sal, Teak)	Moderately available; dependent on regulations	Forest reserves, local sawmills	Heavy; requires flatbed trucks; availability may vary due to environmental regulations.
Brick	Readily available in many regions	Local brick kilns	Bulk transport can be costly; stacking needs to be done carefully to prevent damage.
Stone	Available but location-dependent	Quarry sites in hilly regions	Heavy and requires specialized equipment for transport; may have limited access in remote areas.
Cement	Available through various suppliers	Cement factories in Assam	Heavy; transported via trucks; ensure proper storage to prevent moisture damage.
Sand	Generally available, often from riverbeds	Local riverbanks, quarries	Easily transported but can be subject to environmental regulations on sourcing.
Steel	Available from regional distributors	Steel manufacturing units	Heavy; requires special handling equipment; bulk purchases can reduce costs.
Clay	Readily available for brick making	Local clay pits	Easy to transport in bulk, but requires care during wet conditions to avoid damage.
Paint/Finish	Available at hardware stores	Urban centres, local suppliers	Lightweight; standard transportation methods are adequate; needs careful handling to avoid spillage.

crucial for builders and architects to ensure efficient procurement and sustainability in construction practices in Assam.

Tackling logistical challenges in transporting innovative building materials to remote areas for Assam-type house construction requires a multi-pronged approach. First, local sourcing should be prioritized by identifying and utilizing regionally available sustainable materials, reducing transportation costs and delays. For essential non-local materials, strategic supply chain partnerships with regional suppliers and transporters can streamline distribution. Improving road and river transport infrastructure is crucial, as many remote areas in Assam have poor connectivity. Utilizing waterways—a natural transport route in Assam—can be cost-effective and efficient. Additionally, modular prefabrication of building components at nearby hubs can minimize on-site material requirements, reducing bulk transport needs. Incorporating community participation by training local artisans and builders in sustainable construction techniques ensures long-term feasibility. Lastly, government incentives and policy support for sustainable transport and storage facilities can further ease logistical constraints, making innovative building materials more accessible for Assam-type house construction.

4. Traditional sustainable materials in Assam-type houses

4.1. Bamboo

Bamboo has long been a traditional sustainable material in Assam-type houses, reflecting the region's rich cultural heritage and ecological practices. Known for its rapid growth and renewability, bamboo is an eco-friendly alternative to conventional building materials like wood and concrete. In Assam, where bamboo is abundantly available, it serves not only as a primary construction material but also as a symbol of local identity.

Assam-type houses, characterized by their unique architectural style, often utilize bamboo in various structural elements, including walls, roofs, and flooring. The lightweight nature of bamboo allows for flexible and innovative designs, making it particularly suitable for the region's seismic activity and heavy rainfall. Bamboo's natural resilience and insulation properties also contribute to energy efficiency, keeping interiors cool in the hot season and warm during the cooler months. The primary bamboo-based structures predominantly consist of bamboo roof trusses and bamboo-reinforced clay walls (Fig. 5). In humid and rainy regions, traditional farmhouses often feature triangular roofs [37], which can be constructed using bamboo materials. Bamboo-reinforced clay walls are framed with round bamboo and finished with a combination of bamboo basketry and clay. These walls may also be used as triangular gables or interior partitions. Additionally, using bamboo in construction promotes sustainable practices by reducing carbon footprints and minimizing deforestation. The integration of bamboo into contemporary architectural designs can enhance aesthetic appeal while respecting traditional craftsmanship. However, challenges such as a lack of awareness about its potential and the need for improved treatment techniques to enhance durability must be addressed. Overall, bamboo remains a vital resource in Assam's architectural landscape, offering sustainable solutions for the future.

Bamboo, despite its resilience, faces significant challenges in humid climates due to its susceptibility to pests and moisture-related issues. High humidity creates a favourable environment for mold, fungi, and decay, accelerating bamboo's deterioration. Constant exposure to moisture weakens its structure, leading to warping, cracking, and reduced durability. Pests such as termites and powder post beetles pose another serious threat. These insects bore into bamboo, compromising its strength and longevity. Additionally, bamboo's natural starch content attracts pests, making it even more vulnerable. Without proper treatment, infestations can quickly spread, causing extensive damage. Preventative measures like chemical treatments, varnishing, or kiln drying help mitigate these risks, but they require regular maintenance. Poor ventilation and prolonged exposure to rain further exacerbate degradation. Sustainable solutions, including natural preservatives and proper storage, are crucial to enhancing bamboo's durability in humid regions while maintaining its eco-friendly appeal.

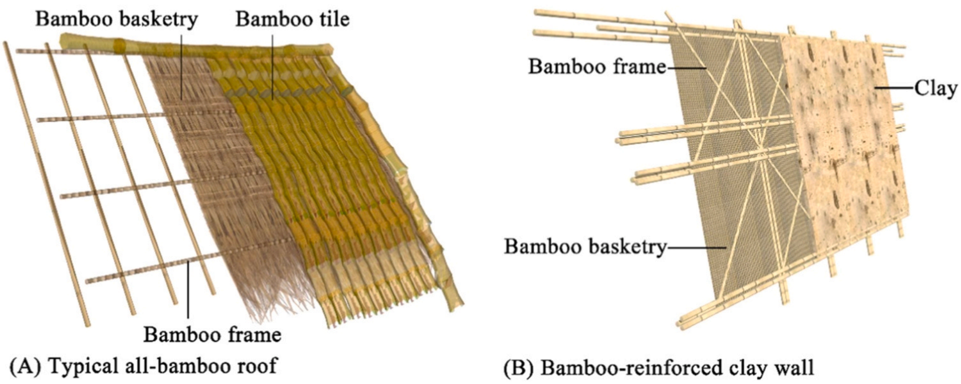

Fig. 5. Traditional bamboo-bearing structures [20].

4.2. Timber

The development of timber structures in China has a long history, reaching its peak during the Tang and Song Dynasties. The Chuan-dou timber structure is predominantly used in southwestern China. It consists of Chuan-dou timber frames connected by tie beams known as Dou-fang, as shown in Fig. 6. The enclosure walls are typically made of wooden panels, adobe panels, or wattle and daub panels, similar to Ikra construction in India. To improve kitchen and bathroom conditions and meet modern living requirements, newly built or renovated Chuan-dou timber structures often feature brick walls at the base, with gypsum or wooden panels used for the upper portions.

Timber, particularly species such as Sal and Teak, plays a vital role as a traditional sustainable material in Assam-type houses. These hardwoods are renowned for their durability, strength, and natural resistance to pests, making them ideal for constructing robust structures in the region's diverse climatic conditions. In Assam, timber has been used for centuries in traditional architecture, offering

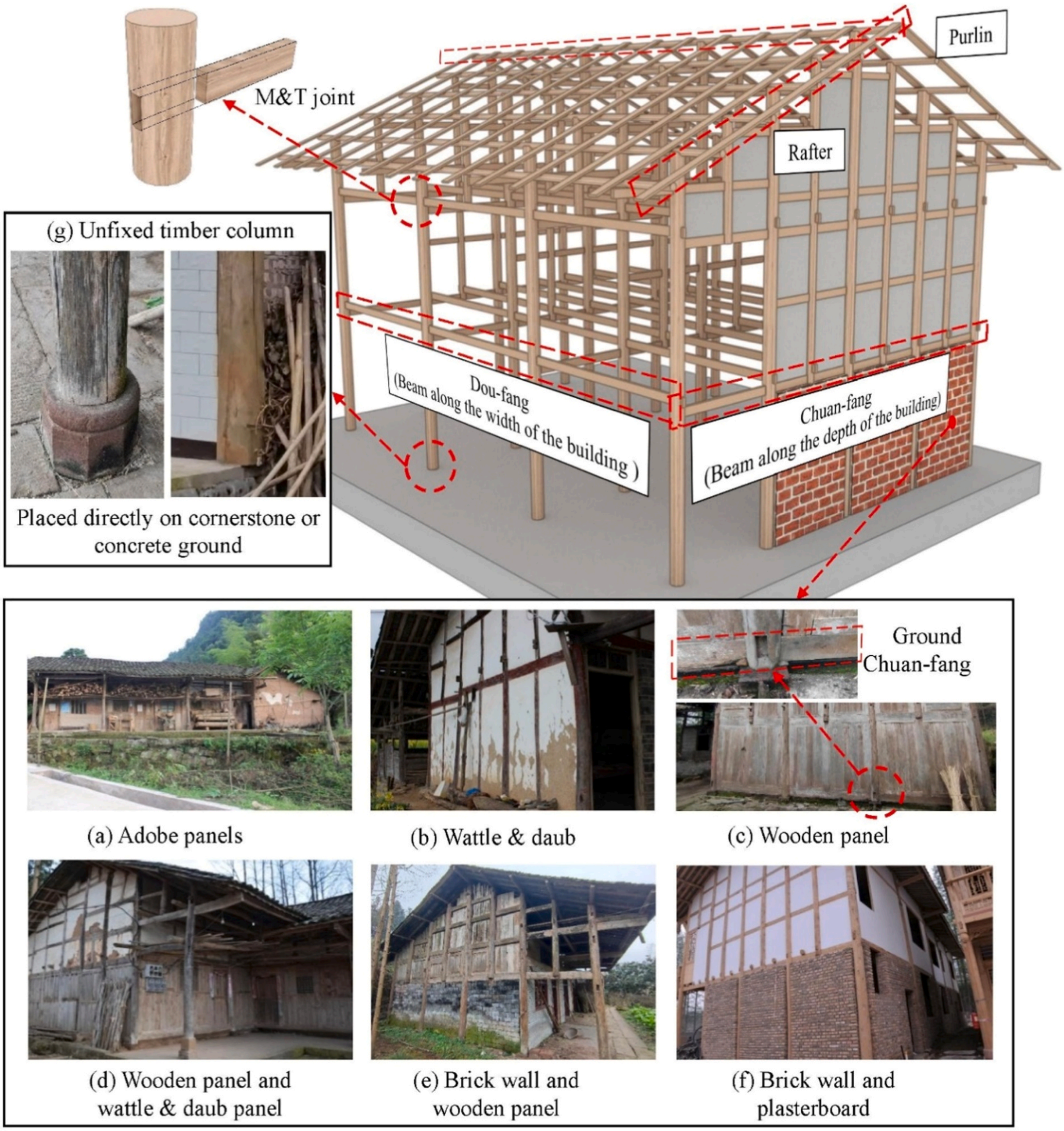

Fig. 6. The construction form and common wall types of Chuan-dou timber structures [36].

aesthetic appeal and functional benefits. The intricate carvings and designs often found in timber elements reflect the rich cultural heritage of the region, showcasing local craftsmanship. Sal wood, known for its density and resistance to decay, is commonly used for structural components like beams and columns, while Teak, valued for its beauty and workability, is frequently used in doors, windows, and furniture.

Sustainably sourced timber helps in reducing the carbon footprint, as it sequesters carbon dioxide throughout its lifecycle. Additionally, the cultivation of these trees supports local economies and promotes forest conservation practices when managed responsibly. However, challenges such as illegal logging and deforestation threaten the sustainability of timber resources. Promoting responsible harvesting and reforestation initiatives is crucial to ensure that timber remains a viable, sustainable building material in Assam-type architecture, blending traditional practices with modern sustainability principles.

4.3. Thatch, straw, and palm leaves

Thatch, straw, and palm leaves are traditional sustainable materials that have been used extensively in Assam-type houses, showcasing the region's rich cultural heritage and ecological consciousness. These materials, derived from local resources, offer an affordable and environmentally friendly alternative to conventional construction materials. Thatch, made from dried grass or reeds, is commonly used for roofing in Assam-type structures. Its lightweight nature allows for easy handling and installation, making it a practical choice for traditional bamboo frameworks. Thatch provides excellent insulation, effectively regulating indoor temperatures by keeping homes cool during the hot season and warm in colder months.

Many straw bale buildings are typically low-rise, consisting of single or two-story constructions (Fig. 7). The limited structural capacity of straw bales makes them suitable for load-bearing walls primarily in residential settings. However, incorporating an alternative structural system, such as timber framing with straw used as in-fill insulation, allows for greater design flexibility. Although straw bale construction remains a niche industry compared to other construction methods, with only an estimated few thousand buildings worldwide, recent innovations have led to significant advancements and increased acceptance in recent years.

Thatched roofs blend seamlessly with the natural surroundings, enhancing the aesthetic appeal of rural architecture. When properly maintained, thatch can last for several years, providing a cost-effective roofing solution. Straw is another sustainable material often utilized in construction, particularly as a byproduct of agricultural activities. Straw bales can be used as wall insulation, offering thermal benefits and contributing to energy efficiency. This approach not only reduces the carbon footprint of buildings but also promotes a circular economy by repurposing agricultural waste, reducing the environmental impact of construction. Palm leaves, frequently used for roofing and wall cladding in rural homes, are lightweight and readily available, making them an ideal choice for local builders. They are naturally resistant to moisture and pests, contributing to the longevity of structures. Palm leaves also offer flexibility in design, allowing for creative architectural expressions that reflect the local culture.

Together, thatch, straw, and palm leaves not only enhance the sustainability of Assam-type houses but also embody the region's rich cultural practices and ecological values. Their use in construction supports local economies, promotes biodiversity, and fosters a deeper connection between communities and their natural environment. As awareness of sustainable practices grows, these traditional materials continue to offer innovative solutions for contemporary architecture in Assam.

4.4. Mud, Adobe, and Earth-Based Materials

Mud, adobe, and earth-based materials are foundational elements in the construction of Assam-type houses, reflecting the region's sustainable architectural practices and cultural traditions. These materials, sourced from the local environment, provide numerous

Fig. 7. Load-bearing straw bale wall under construction [59].

Fig. 8. Mud house design in Assam (Housing.com).

benefits, including thermal insulation, affordability, and a reduced ecological footprint. Mud is one of the oldest building materials used globally, and in Assam, it is commonly employed in the construction of walls and plaster (Fig. 8). The use of mud not only enhances the thermal properties of buildings but also creates a comfortable indoor climate by regulating humidity levels. Mud is abundant and inexpensive, making it an ideal choice for low-cost housing. Its natural composition ensures that it is biodegradable, reducing environmental impact.

Adobe, a building material made from sun-dried mud bricks, is also prevalent in Assam's traditional architecture. Adobe bricks are known for their excellent thermal mass, which helps maintain stable indoor temperatures throughout the year. This energy efficiency is particularly beneficial in the region's variable climate. Adobe structures are also highly durable and can withstand the heavy rainfall common in Assam. Furthermore, adobe is easy to work with and can be shaped into various forms, allowing for creativity in design. Earth-based materials encompass a variety of natural substances, including cob (a mix of clay, sand, and straw) and rammed earth. These materials offer strong structural integrity and excellent insulation properties, making them suitable for traditional Assamese architecture. The use of earth-based materials not only supports sustainable building practices but also fosters a deep connection to the land and the community. Incorporating mud, adobe, and earth-based materials into Assam-type houses promotes local craftsmanship, supports sustainable resource management, and reflects the region's cultural identity. As interest in eco-friendly construction grows, these traditional materials continue to offer innovative solutions for sustainable architecture, bridging the gap between past practices and modern environmental consciousness.

5. Material strengths and overall stability of Assam-type houses

5.1. Material strengths

Bamboo is one of the primary materials used in Assam-type houses, known for its flexibility, strength, and sustainability. Bamboo has a high strength-to-weight ratio, making it ideal for construction in earthquake-prone regions. Its ability to withstand tension and compression allows it to absorb seismic shocks effectively. Additionally, bamboo grows quickly and is readily available, making it an economically and environmentally viable choice. Timber, often used for the house frame and flooring, adds structural stability. Durable hardwood species like Sal or Gamari are preferred due to their resistance to decay and ability to bear loads effectively. Timber also offers excellent thermal insulation, keeping the interiors comfortable during the region's hot and humid summers.

The roofing and walls of Assam-type houses often use thatch or Ikra (a reed-like plant). These materials are lightweight and provide good insulation against both heat and cold. Their lightweight nature is particularly beneficial in minimizing the overall load on the structure, an essential feature for earthquake resistance. In modern adaptations, corrugated iron sheets are used for roofing. These sheets are durable, weather-resistant, and cost-effective. While not as insulating as thatch, they offer better resistance to prolonged exposure to heavy rains and are easier to maintain. The walls of traditional Assam-type houses are often coated with mud plaster. This provides an additional layer of thermal insulation and protection against the elements. Mud plaster is also eco-friendly and easy to repair.

5.2. Stability and resilience

The design of Assam-type houses inherently enhances their stability. These houses are typically built on raised stilts or plinths to protect against flooding, a common occurrence during the monsoon season. This elevated foundation also safeguards the structure from termites and other pests. The lightweight materials used in construction ensure minimal inertia during seismic activity, reducing the risk of collapse. Bamboo and timber frameworks are tied together with strong joints, allowing the structure to sway but remain intact during earthquakes. This flexibility is crucial for withstanding tremors, as Assam falls in a high-seismic-risk zone. Proper ventilation is another key feature of these houses, aiding in moisture control and preventing the deterioration of organic materials like bamboo and timber. Sloped roofs allow rainwater to drain off quickly, reducing the risk of waterlogging and structural damage. While traditional materials offer numerous benefits, modern adaptations incorporate reinforced concrete plinths and steel reinforcements to improve durability. Hybrid designs combine traditional aesthetics with modern engineering, ensuring that Assam-type houses meet contemporary safety and durability standards.

5.3. Relevant codes and standards

Given the seismic vulnerability of Assam, located in Seismic Zone V, several Indian Standards are relevant to ensuring the structural safety of Assam-type houses. IS 1893 (Part 1): 2016, which provides criteria for earthquake-resistant design, offers foundational principles that can be adapted for lightweight structures like these houses. Similarly, IS 4326: 2013 and IS 13827: 1993 provide practical guidelines for enhancing earthquake resistance in buildings using traditional materials. Techniques like bracing, strong joint connections, and anchorage are particularly useful for the bamboo and timber framework commonly used in Assam-type houses. These materials are inherently flexible and lightweight, characteristics that reduce the risk of structural failure during seismic events.

Bamboo, a primary material in these houses, benefits from standards like IS 6874: 2008, which outlines methods for treating bamboo to resist decay and pests, and IS 15912: 2018, which provides structural design practices specific to bamboo. Timber, another essential component, is guided by IS 883: 2016, which specifies permissible stresses and design parameters for timber structures. These codes ensure that the materials used in construction are both durable and safe for the region's specific conditions.

Assam-type houses are also designed to withstand the region's frequent flooding. Elevated on stilts or plinths, they mitigate the impact of waterlogging and protect against pests. IS 15498: 2004 and the National Building Code of India (NBC) 2016 provide guidelines for flood-resilient construction, offering recommendations on raised foundations, use of water-resistant materials, and structural reinforcements. For roofing, particularly with corrugated iron sheets now widely used in modernized versions of these houses, IS 3007 provides specifications for installation and weather resistance. These adaptations enhance the durability of Assam-type houses against prolonged exposure to heavy rains.

The thermal insulation properties of traditional materials like thatch, bamboo, and mud plaster are complemented by their lightweight nature, which contributes to overall structural stability. In addition to these material benefits, the design of Assam-type houses prioritizes ventilation, sloped roofs for efficient rainwater drainage, and modular layouts that accommodate repairs and upgrades easily. Modern adaptations often incorporate reinforced concrete plinths and steel reinforcements while preserving the aesthetic and functional elements of traditional designs.

Although no single code exclusively addresses Assam-type houses, their construction can draw from a combination of Indian Standards, disaster-resilience guidelines, and vernacular knowledge. Institutions like the National Institute of Disaster Management (NIDM) and UNESCO have also documented best practices for preserving the traditional architecture of Assam while integrating modern safety standards. This approach ensures that these houses continue to serve as a sustainable and resilient housing solution in the face of environmental and geological challenges.

6. Innovative sustainable materials for Assam-type houses

6.1. Compressed stabilized earth blocks

Compressed Stabilized Earth Blocks (CSEBs) are increasingly recognized as a sustainable alternative to traditional building materials due to their environmental benefits and cost-effectiveness, particularly in low-cost housing. These blocks utilize locally available earth materials combined with stabilizers like lime or cement, enhancing their strength and durability. Studies by González-

Fig. 9. A typical cured CSEB [22].

López et al. [25] demonstrated that optimal compaction improves compressive strength, while Malkanthi et al. [40] highlighted lime stabilization's role in enhancing block performance with reduced clay content. The incorporation of waste materials, such as crushed brick waste, further contributes to sustainability. Kasinikota & Tripura [32] found that using such materials improves block properties, while Malkanthi et al. [41] showed how construction waste can modify soil grading, reinforcing the environmental advantages of CSEBs. However, challenges remain, particularly regarding their performance in harsh conditions. Chaibeddra & Kharchi [7] noted potential durability issues in sulphate-rich environments. Overall, CSEBs offer a viable solution for addressing housing shortages, especially in developing countries, aligning with sustainable construction goals. Their ability to utilize local resources and minimize waste positions them as an important element in future sustainable building practices. Continued research and innovation are essential to maximize their potential.

CSEB are increasingly recognized as a sustainable building material in Assam, particularly in the construction of Assam-type houses. These blocks, made from a mix of soil, cement, and water, are compressed under high pressure, resulting in strong and durable building units. Their use aligns well with the traditional architecture of Assam, characterized by raised wooden platforms, sloping roofs, and ample use of local materials. A typical cured CSEB is shown in Fig. 9.

The integration of CSEB in Assam-type houses enhances thermal comfort, as earth blocks naturally regulate indoor temperatures, keeping homes cool in summer and warm in winter. This reduces reliance on artificial heating and cooling systems, promoting energy efficiency. Furthermore, CSEBs are eco-friendly, as they utilize locally sourced materials and require less energy for production compared to conventional fired bricks. In addition to their environmental benefits, CSEBs also offer cost advantages. They can be produced on-site with minimal machinery, reducing transportation costs and labour expenses. The durability and low maintenance of CSEBs contribute to the long-term viability of constructions. As Assam seeks to address housing challenges while preserving its cultural heritage, the adoption of CSEB technology in Assam-type houses presents a promising pathway towards sustainable and resilient construction practices.

CSEBs offer durability and sustainability when properly manufactured and maintained. Their long-term performance depends on factors such as soil composition, stabilization materials (e.g., cement or lime), and construction techniques. Proper curing enhances strength and weather resistance, ensuring structural stability over decades. To maintain CSEB structures, periodic inspections are essential to detect erosion, cracking, or moisture infiltration. Applying protective coatings, such as lime or cement-based plasters, helps resist water damage and prolongs lifespan. Proper roof overhangs and foundation drainage prevent excessive water exposure, reducing deterioration risks. Environmental conditions influence CSEB durability, necessitating region-specific maintenance strategies. In high-humidity areas, sealing techniques minimize moisture absorption, while in seismic zones, reinforcement improves resilience. Regular cleaning and minor repairs prevent long-term degradation. With adequate care, CSEBs remain a cost-effective, eco-friendly building material, ensuring longevity and structural integrity for sustainable construction projects.

6.2. Fly ash bricks and blocks

Fly ash bricks and blocks represent a significant innovation in sustainable construction, offering an eco-friendly alternative to

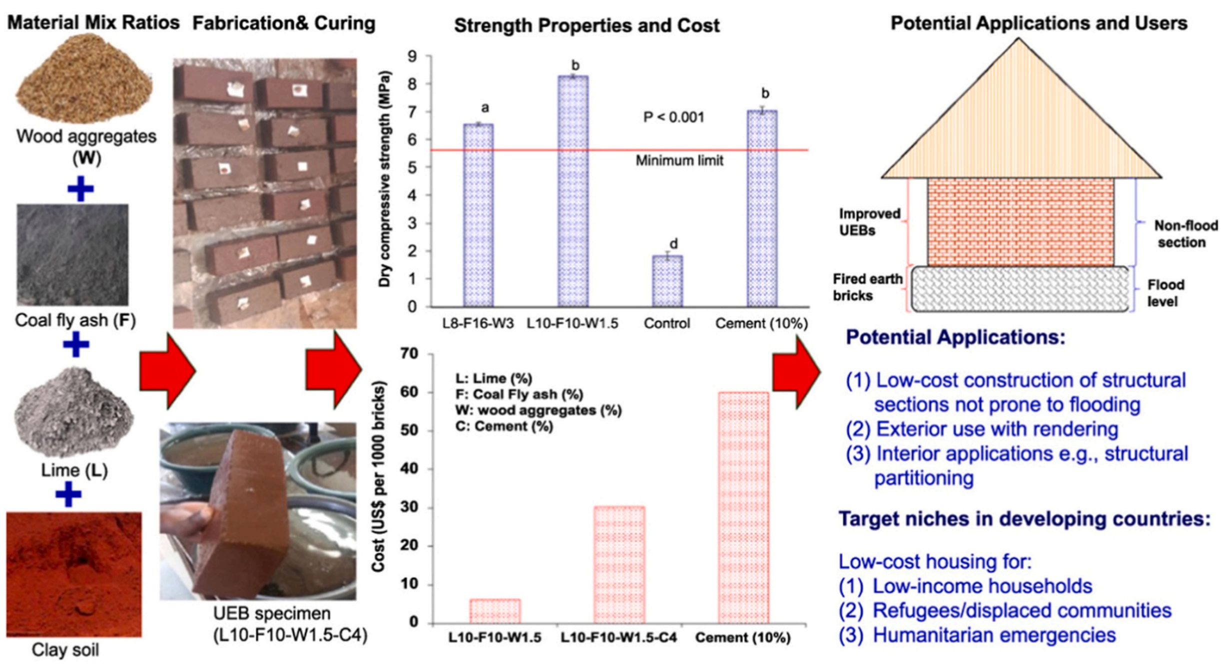

Fig. 10. Development, Evaluation and Potential Application of Improved Unfired Earth Bricks [42].

traditional clay bricks. Their production utilizes waste materials, primarily from coal combustion, thereby addressing waste disposal issues while reducing environmental impact. Research by Freidin & Erell [23] highlighted the feasibility of using coal fly ash and slag in brick manufacturing, demonstrating comparable performance to conventional bricks when cured appropriately. Kumar [33] emphasized the potential of fly ash-lime-gypsum bricks in low-cost housing, which can enhance affordability and accessibility in construction. Moreover, Cicek and Çinçin [14] explored the advantages of using fly ash in lightweight building materials, contributing to energy efficiency and reduced transportation costs. The study by Uygunoğlu et al. [58] further elucidated the effects of fly ash content on the properties of interlocking blocks, indicating that optimal formulations can enhance durability and structural integrity. However, concerns regarding the leaching behaviour of fly ash bricks, as investigated by Gupta et al. [28], underline the importance of assessing environmental safety alongside performance. Overall, while fly ash bricks present numerous benefits in sustainability and cost-effectiveness, ongoing research is necessary to ensure their safety and performance in construction applications. Fig. 10 shows the development, evaluation and potential application of improved unfired earth bricks.

One of the primary advantages of using fly ash bricks in Assam-type constructions is their superior thermal insulation properties. This helps maintain comfortable indoor temperatures, reducing energy consumption for heating and cooling. Additionally, the high strength of fly ash bricks allows for thinner walls, optimizing space and material usage without compromising structural integrity. The production of fly ash bricks requires less water and energy compared to traditional clay bricks, making them a more sustainable option. Their use also contributes to reducing landfill waste, as fly ash, often considered an industrial byproduct, is effectively repurposed. Moreover, fly ash bricks are resistant to moisture, pests, and fire, enhancing the longevity of the structures built with them. As Assam seeks to modernize its housing solutions while preserving its cultural heritage, integrating fly ash bricks and blocks into Assam-type houses represents a progressive step toward sustainable construction practices, promoting both ecological and economic benefits.

Fly ash bricks offer excellent long-term performance due to their high durability, low water absorption, and resistance to weathering. They are stronger than conventional clay bricks and improve over time due to pozzolanic reactions, enhancing their load-bearing capacity. These bricks do not shrink, reducing the risk of cracks, and they maintain structural integrity even in harsh environmental conditions. For maintenance, fly ash bricks require minimal upkeep, but proper construction practices are essential to maximize their longevity. Regular inspection of mortar joints, periodic surface coatings, and waterproofing treatments help prevent moisture penetration. Although they are less prone to efflorescence, occasional cleaning may be needed to remove salt deposits. Using high-quality cement mortar and ensuring adequate curing during construction further enhance their lifespan. With proper maintenance, fly ash bricks can sustain structural efficiency for decades, making them an eco-friendly and cost-effective choice for construction.

6.3. Recycled and upcycled materials

The use of recycled and upcycled materials in construction has gained traction as a sustainable alternative to traditional building materials. Various studies highlight the potential benefits and challenges of integrating these materials into construction practices. Parece et al. [48] presented a qualitative methodology for selecting upcycled materials from urban and industrial waste, emphasizing the need for careful material assessment to ensure sustainability. This aligns with Guo et al. [26], who advocated for a full life cycle perspective, suggesting that recycling building materials can significantly enhance the quality and sustainability of green buildings. Roberts et al. [50] further illustrated the practical application of upcycled materials by exploring innovative designs like the "bottle house," which effectively mitigates overheating in tropical climates, showcasing how upcycling can address specific environmental challenges. Messahel et al. [43] expanded this concept by reviewing the upcycling of agricultural and plastic waste, highlighting the versatility of materials available for construction. However, the quality control and long-term performance of these upcycled materials remain crucial concerns [24]. As Zhao et al. argued, upcycling plastics not only reduces waste but also fosters a circular economy. Overall, the integration of recycled and upcycled materials presents a promising pathway toward sustainable construction, provided that rigorous methodologies and standards are established.

The use of recycled and upcycled materials in Assam-type houses is a forward-thinking approach that aligns with sustainable development and environmental conservation. Assam-type houses, traditionally characterized by raised wooden platforms and sloping roofs, can significantly benefit from incorporating materials like recycled plastics, rubber, and metal. Plastics, particularly from household waste, can be transformed into construction materials such as blocks, panels, and insulation. These plastic components are lightweight, durable, and resistant to moisture and pests, making them ideal for the humid climate of Assam. By using recycled plastics, builders can reduce the environmental impact of waste while creating functional and aesthetically pleasing structures. Moreover, the integration of colourful plastic elements can enhance the visual appeal of Assam-type houses. Rubber, often sourced from discarded tires, can be upcycled into flooring, wall panels, and roofing materials. Rubber is resilient, provides excellent insulation, and is impervious to water, making it suitable for the region's monsoon conditions. The use of upcycled rubber not only diverts waste from landfills but also reduces the need for new raw materials, contributing to a circular economy.

Recycled metals, such as aluminium and steel, can be utilized in various structural components, including frames, roofing, and decorative elements. Utilizing these metals not only strengthens the building but also reduces the demand for virgin materials. The lightweight nature of recycled metals simplifies transportation and construction, making them a practical choice for rural areas. Incorporating recycled and upcycled materials into Assam-type houses promotes sustainability and reflects an innovative approach to architecture. By embracing these materials, builders can create environmentally responsible homes that are resilient, cost-effective, and visually appealing. This shift not only preserves the region's cultural heritage but also fosters a more sustainable future.

6.4. Agro-waste-based building products

Agro-waste-based construction materials offer significant sustainability potential by reducing environmental impacts and utilizing renewable resources. Madurwar et al. emphasized that agro-waste, such as rice husk, sugarcane bagasse, and coconut coir, can replace traditional materials, enhancing the eco-efficiency of the construction industry. They argue that these materials reduce reliance on non-renewable resources while also mitigating waste disposal issues. Similarly, Sangmesh et al. highlighted the development of sustainable alternatives using agricultural residues to promote green building solutions. They stress the dual benefits of waste reduction and lower carbon footprints in construction. Singh et al. [55] investigated the performance of agro-waste-based gypsum hollow blocks, revealing that these materials offer comparable structural properties to conventional materials, making them suitable for partition walls. However, they note that further testing is needed for widespread adoption. Liuzzi et al. [38] focussed on the Mediterranean region, where agro-waste integration into building materials shows promise for enhancing thermal and acoustic insulation. However, they caution that inconsistent material properties and lack of standardized guidelines hinder large-scale application. Maraveas (2020, 2024) underscored the potential for transforming agricultural residues into valuable construction materials. He highlights the need for technological advancements and policy support to ensure the durability, safety, and market viability of agro-waste-based products.

The incorporation of agro-waste-based building products such as rice husk ash and coconut fibre in Assam-type houses represents a sustainable and innovative approach to construction. Assam, being an agricultural state, generates significant amounts of agro-waste, making these materials both accessible and environmentally friendly. Rice husk ash, a byproduct of rice milling, is increasingly used in construction due to its pozzolanic properties, which enhance the strength and durability of concrete. When mixed with cement, rice husk ash improves the workability and reduces the overall weight of the building materials. This lightweight concrete is particularly beneficial in Assam’s humid climate, where traditional materials may be prone to moisture damage. Moreover, the use of rice husk ash contributes to reducing carbon emissions associated with cement production, aligning with sustainable building practices.

Coconut fibre, or coir, is another valuable agro-waste material that can be utilized in Assam-type houses. Known for its strength and resilience, coconut fibre can be used in various applications, including insulation, roofing, and wall panels. The fibrous nature of coir provides excellent thermal insulation, helping to regulate indoor temperatures and enhance energy efficiency. Additionally, coir is biodegradable and has a lower environmental impact compared to synthetic insulation materials. The use of these agro-waste materials not only helps reduce waste but also supports the local economy by creating new markets for agricultural byproducts. By integrating rice husk ash and coconut fibre into construction practices, builders can create homes that are both cost-effective and environmentally responsible. This innovative approach not only preserves Assam’s rich cultural heritage through traditional building styles but also promotes sustainability, ensuring a greener future for the region’s architecture.

Table 3 presents a comparative analysis of four sustainable building materials: Compressed Stabilized Earth Blocks (CSEB), Fly Ash Bricks and Blocks, Recycled and Upcycled Materials, and Agro-Waste-Based Building Products. Key parameters such as composition, primary applications, strength, thermal insulation, environmental impact, cost, durability, and production requirements are examined. The table highlights the diverse properties and applications of these materials, emphasizing their potential to reduce environmental impact while meeting construction needs. CSEB and agro-waste products are cost-effective for rural projects, while fly ash and recycled materials suit urban settings. This comparison provides insights for informed decision-making in sustainable construction.

Integrating emerging materials like hempcrete in Assam-type housing, especially in regions prone to high humidity and flooding, presents both opportunities and challenges. Hempcrete, a bio-composite made from hemp fibres, lime, and water, offers excellent thermal insulation, breathability, and mold resistance, making it suitable for Assam’s humid climate. However, its vulnerability to prolonged water exposure raises concerns in flood-prone areas. To enhance feasibility, hempcrete structures should incorporate elevated plinths, waterproof coatings, or hybrid construction with water-resistant materials at the base. Additionally, periodic maintenance and protective treatments can mitigate moisture absorption. While hempcrete is not load-bearing, it pairs well with

Table 3
Comparison of sustainable building materials based on key parameters.

Parameter	Compressed Stabilized Earth Blocks (CSEB)	Fly Ash Bricks and Blocks	Recycled and Upcycled Materials	Agro-Waste-Based Building Products
Composition	Mix of soil, stabilizer (e.g., cement, lime)	Fly ash, sand, lime, gypsum	Waste materials (e.g., glass, plastic)	Agricultural residues (e.g., rice husk, coconut fiber)
Primary Applications	Walls, foundations	Walls, partitions	Flooring, walls, decorative elements	Walls, insulation, partitions
Strength	Moderate to high (depends on stabilizer)	High (due to controlled production)	Varies widely depending on material	Moderate to low (depending on process)
Thermal Insulation	Good	Moderate	Varies (depends on material properties)	High
Environmental Impact	Low to moderate (if locally sourced)	Moderate (uses industrial waste)	Low to moderate (recycling reduces waste)	Low (utilizes agro-waste effectively)
Cost	Affordable (dependent on local resources)	Moderate	Moderate to high (depends on material)	Affordable (readily available waste)
Durability	High (with proper stabilization)	High	Moderate to high	Moderate
Production Requirements	Local, manual or semi-mechanized	Industrial, highly mechanized	Industrial or artisanal	Manual or semi-mechanized

bamboo or timber framing, aligning with Assam's traditional construction methods. The main challenges include sourcing raw materials, higher initial costs, and limited awareness. However, with research-driven adaptations and policy support, hempcrete can be a sustainable alternative for eco-friendly housing in Assam's climate-sensitive regions.

7. Technological innovations in sustainable building

7.1. Prefabricated modular building

Prefabricated modular buildings are innovative construction solutions designed for efficiency and sustainability. These structures are manufactured off-site in controlled environments and then transported to the final location for assembly. This method reduces construction time and waste, as components are produced simultaneously, minimizing delays caused by weather and other on-site issues. Modular buildings can be customized for various uses, including residential, commercial, and educational facilities. Their versatility allows for easy expansion or relocation, making them an attractive option for developers. Additionally, prefabricated modular buildings often incorporate sustainable materials and energy-efficient technologies, contributing to a reduced environmental footprint.

Aluminium, timber, precast concrete, and steel are essential materials for producing modular units as cab seen in Fig. 11. While aluminium shows promise due to its light weight and strength, its brittle nature and high costs hinder widespread adoption. Timber is limited to low-rise structures, whereas steel and precast units dominate high-rise applications. Steel modules are 25–30 % lighter than precast, offering superior durability, simpler jointing, and higher strength-to-weight ratios. Their self-supporting strength ensures stability during transport and reduces costs. Additionally, steel's resistance to lateral forces makes it ideal for high-rise buildings, providing flexibility in design and larger opening spans compared to precast alternatives.

The possibility of using prefabricated modular buildings in Assam-type architecture presents a unique opportunity to blend traditional aesthetics with modern construction techniques. Assam's distinctive architectural style, characterized by sloping roofs and

Fig. 11. Prefabricated volumetric modular (PFVM) units with different construction materials [13].

wooden structures, can benefit from modular designs that are customizable and efficient. By utilizing locally sourced materials and prefabricated components, builders can create sustainable homes that reflect Assam's cultural heritage while enhancing durability against the region's climatic challenges. Additionally, modular construction can significantly reduce construction time and labour costs, making it an attractive option for addressing housing shortages in Assam. This fusion can promote economic growth and innovation in the region.

The major barriers to implementing prefabricated construction technology in Assam-type housing projects include high initial costs, lack of skilled labour, and resistance to change. Prefabrication requires specialized equipment and trained workers, which are scarce in Assam. Additionally, limited awareness and skepticism among local builders and homeowners hinder adoption. Transportation challenges due to Assam's geographical conditions, including floods and poor road infrastructure, also pose difficulties. Furthermore, regulatory hurdles and inadequate government incentives slow down progress. The region's preference for traditional bamboo and timber construction adds to the reluctance, making it difficult to integrate prefabrication into Assam's housing sector.

7.2. 3D Printing for low-cost sustainable homes

3D printing has emerged as a transformative technology for low-cost, sustainable housing, offering potential to address global housing shortages while reducing environmental impacts. [18] emphasize the potential of 3D printing in Brazil's social housing sector, citing the use of local, sustainable materials to reduce construction costs. However, they highlight challenges, such as ensuring material durability and developing regulations for widespread adoption. Similarly, Moghayedi et al. [46] explored 3D printing's role in affordable housing across Africa, noting its ability to streamline construction processes and lower costs. However, they caution that infrastructural limitations and the high initial costs of 3D printers present obstacles. Yemesegen & Memari [61] advocated for integrating natural materials like cob, hempcrete, and bamboo into 3D-printed homes, promoting sustainability and reducing carbon emissions. While these materials show promise, further experimentation is required to optimize their use in 3D printing processes. Bazli et al. [3] explored 3D printing's benefits for remote housing, particularly in disaster-prone or hard-to-reach areas. They identify material challenges, such as ensuring structural integrity in extreme conditions. Batikha et al. [2] and Bhattacherjee et al. [5] focussed on the sustainability of 3D concrete printing, highlighting its potential to reduce material waste and carbon emissions. However, they stress that material selection and process efficiency must be improved for broader application.

The option of using 3D printing technology for low-cost sustainable homes in Assam-type houses offers a transformative approach to addressing housing needs in the region. Assam, known for its unique architectural style characterized by sloping roofs and wooden structures, can greatly benefit from the precision and efficiency of 3D printing. This method allows for the rapid construction of homes while significantly reducing labour costs and material waste. 3D printing utilizes additive manufacturing techniques, where layers of materials are added to create structures. This method can produce intricate designs that mimic traditional Assam architecture while incorporating modern sustainable practices. By using locally sourced materials such as clay, bamboo, or recycled plastics, 3D-printed homes can maintain cultural integrity and reduce transportation costs and carbon footprints. One of the most significant advantages of 3D printing is its ability to create customized homes tailored to the specific needs of families in Assam. The technology allows for flexibility in design, enabling builders to adapt structures to varying site conditions and personal preferences. This adaptability is

Fig. 12. Examples of projects based on 3DCP: (a) Bridge, Nijmegen, the Netherlands (PERI 3D Construction); (b) Two storey house, Beckum, Germany (PERI 3D Construction); (c) House Zero, East Austin, USA, 2022 (ICON Build).

crucial in rural areas, where land topography and environmental factors can vary widely. 3D printing techniques have been utilized in the construction of various structures, including bridges, walls, curved surfaces, houses, villages, and even buildings. Fig. 12 illustrates some examples. Currently, many of these applications are emerging in developed countries.

Implementing 3D printing and prefabrication in Assam requires strategies that address its specific socio-economic conditions, ensuring these technologies align with the region's challenges and opportunities. Assam's complex terrain and frequent floods demand robust transportation networks to enable the seamless movement of raw materials and prefabricated components to remote areas. Strengthening road, rail, and waterway connectivity is essential to reduce delays and maintain efficiency in supply chains. The availability of materials is another critical factor. Sourcing local materials such as aggregates, sand, and binding agents can lower costs while promoting sustainability. Establishing regional manufacturing hubs for 3D printing filaments and prefabricated components can minimize reliance on external suppliers and mitigate supply chain disruptions. Additionally, the adoption of these advanced technologies requires a skilled workforce. Investing in training programs, collaborating with technical institutions, and implementing government-backed initiatives can equip local workers with the expertise needed to operate 3D printing machinery, software, and prefabrication systems effectively. Investment models tailored to Assam's socio-economic landscape are vital for success. Public-private partnerships, government subsidies, and flexible financing options can encourage the adoption of these technologies and foster inclusive growth. These strategies can enable Assam to harness the potential of 3D printing and prefabrication to accelerate sustainable development while addressing regional challenges.

3D printing can improve construction speed, reducing the time required to build homes from months to just a few days. This rapid deployment is vital in regions prone to natural disasters, as it allows for quicker recovery and rebuilding efforts. Additionally, 3D-printed homes can be designed with energy-efficient features, such as improved insulation and passive solar design, further enhancing their sustainability. By integrating renewable energy solutions like solar panels, these homes can operate off-grid, promoting self-sufficiency in rural communities. 3D printing presents a viable option for creating low-cost, sustainable homes in Assam-type building, merging tradition with innovation and addressing pressing housing challenges in the region.

7.3. Energy-efficient construction techniques

Adopting energy-efficient construction techniques in Assam-type houses is crucial for enhancing sustainability and reducing energy consumption in the region. Assam's unique architectural style, characterized by sloping roofs and wooden structures, can effectively integrate these modern practices. One key technique is natural ventilation, which facilitates airflow to cool interiors without relying on mechanical systems. By strategically positioning windows, vents, and overhangs, buildings can maintain comfortable indoor temperatures in Assam's hot and humid climate. This approach minimizes the need for air conditioning, thereby conserving energy.

Another important method involves using thermal mass materials, such as mud or adobe, which absorb heat during the day and release it at night. This helps to regulate indoor temperatures, reducing the reliance on heating and cooling systems. Incorporating renewable energy sources is also vital. Installing solar panels can harness the abundant sunlight in Assam, powering lighting and appliances, while solar water heaters can significantly lower energy consumption for hot water needs. Moreover, implementing rainwater harvesting systems captures and stores rainfall, conserving water for irrigation and domestic use. This eco-friendly practice aligns perfectly with Assam's climatic conditions. Emphasizing these energy-efficient construction techniques in Assam-type houses

Table 4
Energy-efficient construction techniques for sustainable Assam-type houses.

Technique	Description	Benefits	Challenges
Natural Ventilation	Strategic placement of windows, vents, and overhangs to optimize airflow, reducing the need for air conditioning.	Maintains comfortable indoor temperatures in hot, humid climates without mechanical systems.	Requires careful design and planning to avoid drafts and ensure effective airflow in all areas.
Use of Thermal Mass Materials	Incorporating materials like mud or adobe that absorb heat during the day and release it at night.	Helps regulate indoor temperatures, reducing reliance on heating and cooling systems.	Can increase construction time and may require special skills or knowledge.
Sloping Roofs with Insulation	Insulating the traditional sloping roofs to prevent heat buildup and improve thermal comfort inside the house.	Reduces heat transfer, keeping interiors cooler in summer and warmer in winter.	Installing insulation may increase construction costs initially.
Solar Energy Systems	Installing solar panels and solar water heaters to harness Assam's abundant sunlight for powering appliances and heating water.	Reduces dependence on non-renewable energy sources, lowers electricity bills, and provides a sustainable energy supply.	High initial investment and requires maintenance; needs sufficient sunlight for optimal performance.
Rainwater Harvesting	Capturing and storing rainwater for domestic use or irrigation, especially during the monsoon season.	Conserves water, reducing strain on local water supply systems and aligning with Assam's monsoon climate.	Requires space for storage tanks and filtration systems; initial setup cost may be high.
Shaded Outdoor Spaces	Designing verandas or covered outdoor areas that protect from direct sunlight while promoting natural cooling.	Keeps interiors cooler by reducing heat gain from direct sunlight, enhances outdoor living spaces.	Requires additional space and can slightly increase construction costs.
Local and Sustainable Materials	Using locally sourced wood, bamboo, and other renewable materials in construction, which are common in Assam's traditional architecture.	Reduces environmental impact and supports the local economy, while maintaining cultural heritage.	May not provide the same durability as modern, synthetic materials in some cases.
High-Efficiency Lighting	Installing energy-efficient lighting systems such as LED bulbs, which consume less power compared to traditional lighting.	Lowers electricity consumption, reducing energy costs while providing longer-lasting lighting.	Initial cost of energy-efficient fixtures may be higher than traditional options.

not only reduces energy costs but also promotes environmental sustainability, paving the way for resilient and culturally respectful communities. Table 4 outlines key energy-efficient construction techniques tailored to Assam-type houses, blending traditional architectural elements with modern sustainability practices. Techniques like natural ventilation, thermal mass materials, solar energy systems, and rainwater harvesting help reduce energy consumption, enhance indoor comfort, and promote environmental sustainability in Assam's hot and humid climate.

Assam Type housing, known for its lightweight yet resilient design, must balance traditional craftsmanship with modern building techniques to enhance durability while preserving its heritage. Traditionally, these homes utilize timber, bamboo, and thatch, offering natural insulation and earthquake resistance. However, incorporating modern materials like reinforced concrete for plinths, steel joints, and treated bamboo can significantly enhance structural integrity without compromising aesthetics. Prefabrication methods, such as modular bamboo panels or fibre-reinforced composites, can streamline construction while maintaining the region's vernacular style. Additionally, integrating seismic-resistant designs, such as cross-bracing and flexible joints, ensures longevity in Assam's flood- and earthquake-prone environment. Sustainability remains key; using locally sourced materials combined with modern weatherproof coatings can extend the lifespan of wooden components. By blending indigenous techniques with contemporary engineering solutions, Assam Type houses can evolve into structurally sound, climate-responsive dwellings that honour tradition while meeting modern living standards.

8. Sustainable design practices for Assam-type houses

8.1. Passive solar design and natural ventilation

Passive solar design and natural ventilation are essential components for enhancing the energy efficiency of Assam-type houses, which feature distinctive sloping roofs and wooden structures. Passive solar design utilizes the sun's energy to maintain comfortable indoor temperatures without relying on mechanical heating or cooling systems. In Assam's climate, which includes hot, humid summers and cool winters, careful orientation of windows and the strategic placement of overhangs can optimize solar gain in winter while minimizing it in summer. For example, large south-facing windows can capture sunlight during winter months, warming the interior, while overhangs can provide shade during the summer, reducing the need for air conditioning.

Natural ventilation is equally crucial for maintaining indoor comfort. By designing homes with cross-ventilation in mind, builders can promote airflow that cools spaces naturally. High ceilings, strategically placed windows, and vents allow warm air to escape while cooler air enters, creating a comfortable living environment. This technique not only improves air quality but also reduces energy costs associated with mechanical cooling. By integrating passive solar design and natural ventilation, Assam-type houses can achieve greater energy efficiency, providing residents with sustainable, comfortable living spaces that harmonize with the region's unique climate and architectural heritage. Assam-type houses adapt to cold-cloudy Shillong climate are characterized by high solar absorptance corrugated GI (galvanized iron) roofing with dark green or reddish paints, veranda with reduced depth, large glazing area sunspaces and clerestory for solar heat gain in winter and cross-ventilations in humid summer as can be seen in Fig. 13.

According to Singh et al. [54], vernacular architecture in North-East India has long incorporated passive solar design principles, with an emphasis on maximizing natural lighting and minimizing heat gain during hot periods. The region's solar radiation potential, though underutilized, offers significant opportunities to reduce energy consumption in residential buildings. The traditional sloping roofs of Assam-type houses, if combined with shading devices like overhangs or verandas, can help regulate heat gain and maintain thermal comfort inside the house. This aligns with the bioclimatic principles identified by Singh, Mahapatra, and Atreya [53], who noted that vernacular designs are inherently climate-responsive, although they can be further optimized with modern solar strategies. However, implementing passive solar design in Assam-type houses presents challenges. One issue is the region's highly variable weather, including frequent monsoon rains, which can reduce the effectiveness of solar gain. Tungnung [57] highlighted that in regions with heavy cloud cover and unpredictable sunlight, solar passive elements need to be synergized with other design factors, such as thermal mass and natural ventilation, to maintain indoor thermal comfort. Therefore, while solar passive features are beneficial, their full potential might only be realized in combination with other energy-efficient strategies like natural ventilation.

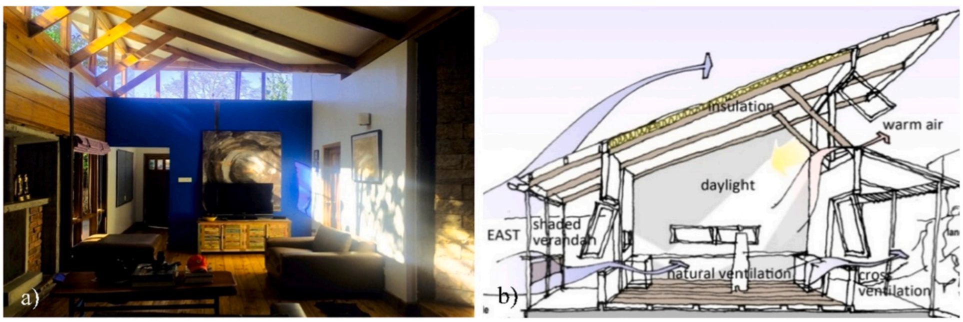

Fig. 13. Nel Sedone house living-room after adaptation to cold-cloudy Shillong, (a) afternoon solar heat gain from South, West glazing and absorption with thermal mass walls and interior elements, (b) section of daylight heat gain and ventilation [27].

Singh et al. [53] emphasized the importance of bio-climatism in North-East India's vernacular architecture, where buildings are designed to be highly adaptive to the local climate. In Assam-type houses, the high-pitched, sloping roofs are particularly effective in promoting natural ventilation, as they encourage air movement and prevent heat buildup under the roof. Additionally, the use of wooden structures, which are porous and breathable, further enhances natural cooling. Chandel et al. [11] reviewed the energy-efficient features of vernacular architecture and highlight that natural ventilation in traditional homes is highly effective in reducing the need for mechanical systems, particularly in regions like Assam where electricity can be unreliable and expensive. The authors also stress that ventilation systems in these homes are highly sustainable, as they do not rely on external energy sources and contribute to improved thermal comfort, even in challenging climates. However, the reliance on natural ventilation alone can have limitations, especially during extreme weather conditions. During the monsoon season, high humidity levels can reduce the effectiveness of natural ventilation. Singh et al. [56] pointed out that while natural ventilation works well in most conditions, additional strategies may be needed in offices and homes to meet adaptive thermal comfort standards in extreme climates. The use of cross-ventilation techniques, adjustable windows, and strategic positioning of vents can enhance the performance of natural ventilation systems, but these must be carefully integrated into the design to avoid overcooling or excessive humidity indoors.

Combining passive solar design and natural ventilation in Assam-type houses offers a holistic approach to improving energy efficiency and sustainability. As Pal et al. [47] suggested, energy-efficient techniques such as solar passive design and natural ventilation can significantly reduce the energy demand for heating, cooling, and lighting, particularly when applied in traditional non-engineered residential buildings in North-East India. The inherent adaptability of Assam-type houses, with their lightweight wooden structures and sloping roofs, makes them well-suited for integrating both techniques. However, as Singh et al. [53] and Tungnung [57] emphasized, these traditional systems must be updated and optimized to meet the needs of modern occupants. This includes addressing the challenges posed by the region's climatic variability and the increased demand for thermal comfort. Implementing passive solar design features such as insulated walls and strategically placed windows can help enhance indoor comfort, while natural ventilation systems can be optimized with modern technologies like adjustable vents and automated window systems to respond to changing weather conditions.

Passive solar design and natural ventilation offer significant opportunities for enhancing energy efficiency in Assam-type houses. By integrating these techniques with modern technologies, it is possible to maintain the cultural integrity of vernacular architecture while reducing energy consumption and improving indoor comfort. However, challenges related to climate variability, construction costs, and the limitations of natural ventilation in humid conditions must be addressed through careful planning and design. The potential for combining passive solar features with natural ventilation remains high, particularly when tailored to the specific climatic and cultural context of North-East India.

8.2. Rainwater harvesting and water management

Rainwater harvesting and effective water management are vital for enhancing sustainability in Assam-type houses, which are characterized by their unique architectural style and adaptation to local climate conditions. Given Assam's abundant rainfall, implementing rainwater harvesting systems can significantly reduce reliance on external water sources. In Assam-type homes, collecting rainwater from rooftops through gutters and directing it into storage tanks can provide a reliable supply of water for domestic use, irrigation, and other needs. This method not only conserves water but also mitigates the risk of flooding and soil erosion in the surrounding environment. By utilizing this natural resource, residents can enhance their self-sufficiency, especially in rural areas where access to clean water may be limited. Furthermore, incorporating effective water management practices, such as greywater recycling and the use of water-efficient fixtures, can maximize the utility of harvested rainwater. Greywater from sinks and showers can be treated and reused for irrigation or toilet flushing, further reducing overall water consumption. Integrating rainwater harvesting and efficient water management strategies in Assam-type houses promotes sustainability, conserves vital resources, and enhances the resilience of communities against water scarcity, making it an essential practice for the region's future.

Rainwater harvesting and effective water management are crucial for sustainable living in Assam-type houses, given the region's heavy rainfall and frequent flooding. Rainwater harvesting systems can capture and store rainwater for domestic use, irrigation, and other non-potable purposes, addressing both water scarcity and flooding challenges. Ji & Punekar [30] highlighted that traditional Assam-type houses, designed with sloping roofs, are well-suited for rainwater harvesting as their roof geometry aids in efficient water collection. Additionally, Deka [19] pointed out that with increasing urbanization, many modern adaptations of Assam-type houses have lost traditional water management features, leading to increased vulnerability to water scarcity and flooding.

To combat these issues, incorporating rainwater harvesting systems can revive these traditional practices. Bhardwaj & Kumar [4] stressed the importance of integrating indigenous knowledge of water management, particularly in disaster-prone areas, where proper water storage systems can mitigate the impact of monsoons and floods. Laskar et al. [35] argued that effective water management, including rainwater harvesting, can enhance flood resilience by reducing surface runoff and improving water retention. Ravishankar and Ji [49] further emphasize the need for integrating modern technologies with vernacular designs, suggesting that rainwater harvesting systems, when coupled with proper drainage, can help Assam-type houses adapt to changing environmental conditions.

8.3. Waste management and recycling in construction

Waste management and recycling are critical components of sustainable construction practices in Assam-type houses, which are known for their unique architectural features and use of local materials. With an increasing focus on environmental conservation, integrating effective waste management strategies into the construction process can significantly reduce the ecological footprint of building projects. During construction, a considerable amount of waste is generated, including scrap materials, packaging, and unusable remnants. Implementing a waste management plan that prioritizes recycling and reusing materials can minimize this waste. For instance, excess wood from timber construction can be repurposed into furniture or decorative elements, while concrete debris can be crushed and used as aggregate for new structures.

Adopting sustainable practices such as sourcing materials locally can further reduce waste and transportation emissions. Encouraging contractors and builders to choose recyclable materials, such as steel and bamboo, supports a circular economy and reduces landfill contributions. Educating workers and stakeholders about proper waste segregation and recycling practices is also essential. By fostering a culture of sustainability within the construction industry, Assam can promote environmentally friendly building practices that respect its cultural heritage and natural resources, ensuring a healthier future for both communities and the environment.

8.4. Climate resilient construction practices

Climate-resilient construction practices are vital for Assam, a region susceptible to flooding, landslides, and other climate-related challenges. The use of local materials, such as bamboo, thatch, and mud, is encouraged due to their sustainability and ability to withstand extreme weather conditions. These materials are not only readily available but also provide excellent insulation, keeping homes cooler in summer and warmer in winter. Elevated foundations are a common practice in flood-prone areas, ensuring that structures remain above potential floodwaters. Designing buildings with sloped roofs can facilitate efficient rainwater drainage, minimizing water accumulation and preventing structural damage. Additionally, incorporating green spaces and vegetation around buildings can enhance biodiversity while reducing the urban heat island effect.

Passive design strategies, such as maximizing natural ventilation and daylighting, contribute to energy efficiency, reducing reliance on artificial heating and cooling systems. Regular maintenance and adaptive reuse of existing structures can further support resilience by minimizing waste and conserving resources. Community involvement in planning and construction processes ensures that local knowledge and traditions are respected, fostering a sense of ownership and responsibility towards the environment. Implementing these climate-resilient construction practices can significantly enhance the sustainability and safety of Assam's built environment in the face of climate change.

8.5. Retrofitting of Assam type houses

The retrofitting process of Assam-type houses entails a multifaceted approach that addresses structural, thermal, and functional enhancements to extend the lifespan of these traditional homes while making them more suitable for contemporary living. Structural retrofitting prioritizes strengthening the house to withstand natural disasters, particularly earthquakes, which are common in the region. This involves reinforcing wooden frames with additional bracings, using steel connectors to secure joints, and integrating modern anchoring systems that stabilize the foundation. By replacing aged, rusted corrugated sheets with advanced, lightweight, and durable materials such as metal alloys or fibre-reinforced polymers, the structural integrity is further enhanced. These upgrades not only improve the house's resilience but also significantly prolong its durability, making it better equipped to handle environmental stressors.

Thermal retrofitting focuses on improving the energy efficiency and comfort of the home. The addition of insulation layers to walls, ceilings, and roofs minimizes heat transfer, ensuring a stable indoor temperature regardless of external conditions. This reduces the reliance on artificial cooling or heating systems, lowering energy consumption. Improved ventilation systems, like modern louvers or strategically placed vents, optimize airflow throughout the house. These solutions also help in controlling indoor humidity levels, reducing the risk of mold, mildew, and related deterioration, which is particularly critical in the humid climate of Assam.

Functional retrofitting addresses the modernization of essential systems while preserving the aesthetic and cultural heritage of Assam-type houses. Electrical systems are upgraded to meet current safety standards and accommodate increased energy demands, including provisions for renewable energy technologies like solar panels. Plumbing and sanitation systems are redesigned to ensure better water management and hygiene, aligning with modern living requirements. Where possible, these upgrades are implemented in harmony with the original design, retaining the unique character and charm of the traditional architecture.

Sustainability plays a pivotal role in retrofitting, as it allows homeowners to reduce their ecological footprint while benefiting from modern conveniences. The incorporation of renewable energy systems, like rooftop solar panels, enables energy independence and cuts utility costs. Use of eco-friendly materials in structural and thermal upgrades further promotes sustainability, aligning with global efforts to minimize environmental impact. The retrofitting process strikes a balance between preserving the cultural and historical significance of Assam-type houses and adapting them to meet contemporary standards. It offers a cost-effective alternative to complete reconstruction, saving resources while maintaining the essence of traditional craftsmanship. Retrofitted houses are not only more robust and energy-efficient but also better equipped to handle the challenges posed by a changing climate and evolving societal needs. In essence, retrofitting Assam-type houses represents a thoughtful, sustainable approach to blending tradition with modernity, ensuring these architectural gems remain functional and cherished for generations to come.

9. Cost comparisons and lifecycle analysis

Cost comparisons reveal that these houses are more economical than concrete structures due to reduced material and labour expenses. Additionally, they have shorter construction timelines. Lifecycle analyses indicate that these houses, while less durable than concrete, are environmentally sustainable and resilient to the region's seismic and climatic conditions. Maintenance costs, particularly for roofing and bamboo reinforcements, are moderate but necessary for longevity. Innovations like using treated bamboo and metal cladding improve durability, balancing affordability with sustainable living practices.

9.1. Cost comparisons

Assam Type Houses are known for their cost-effectiveness due to the use of locally available materials and traditional construction methods. Bamboo, timber, thatch, and corrugated galvanized iron (CGI) sheets form the primary construction materials. These are significantly cheaper than materials like cement and steel used in reinforced cement concrete (RCC) structures. The availability of bamboo and timber locally reduces transportation expenses, and their affordability makes them a preferred choice. Treated bamboo, though slightly more expensive than untreated, increases durability and remains economical. Labor costs for Assam Type Houses are lower as their construction relies on traditional techniques that require less specialized skills. Local artisans can efficiently build these houses, reducing dependency on expensive skilled labour needed for RCC structures. Additionally, the construction process is quicker, resulting in reduced labour costs and allowing earlier occupancy, which minimizes expenses associated with temporary housing.

Compared to RCC structures, Assam Type Houses are approximately 50–70 % cheaper in initial costs. RCC homes involve higher material expenses and require earthquake-resistant designs to address seismic concerns, increasing their overall cost. Assam Type Houses, with their lightweight framework, are naturally resilient to earthquakes and do not require costly reinforcements. While maintenance costs for Assam Type Houses are higher due to the need for periodic repairs of bamboo and timber elements, their affordability and sustainability outweigh this factor for many. Treated bamboo and CGI roofing reduce the frequency of repairs, offering a balance between upfront investment and lifecycle savings. The biodegradable and renewable nature of materials further adds to their cost-effectiveness by minimizing environmental costs. Assam Type Houses also offer flexibility in terms of customization to fit different budget levels. Unlike RCC homes, which require substantial initial investment, these houses can start as basic structures and be gradually upgraded over time. This adaptability makes them an ideal option for rural and low-income households, where affordability and cultural suitability are critical.

9.2. Lifecycle analysis

The lifecycle analysis of an Assam Type house examines the environmental impacts at each stage of its existence, beginning with raw material acquisition. Materials like bamboo and wood are harvested locally, which minimizes transportation emissions but can lead to deforestation and habitat loss if not managed sustainably. Bamboo, being a renewable resource, is often prioritized, but its extraction can disturb local ecosystems if overharvested. Corrugated galvanized iron (CGI) sheets, commonly used for roofing, require energy-intensive processes involving mining, smelting, and transportation, adding to the overall carbon footprint. Mud and bricks, often used for walls and plinths, are locally sourced with minimal energy input, though their extraction may result in soil degradation.

In the manufacturing phase, raw materials are processed to make them suitable for construction. Bamboo is treated to improve durability, often using natural or chemical preservatives, while wood is sawn, seasoned, and sometimes chemically treated to resist pests. These processes consume energy and may generate chemical waste. CGI sheets are produced in factories that are typically far from construction sites, and transporting them adds to the environmental impact. Chemical treatments for bamboo and wood can introduce pollutants into the soil and water if not properly managed.

The construction phase of an Assam Type house employs traditional techniques with minimal machinery. Lightweight materials such as bamboo and wood allow for quick construction, while mud plastering is labour-intensive but energy-efficient. Local labour and materials reduce emissions associated with transportation and industrial construction processes. Waste generation during construction is minimal compared to modern methods, making it environmentally favourable. During the use and maintenance phase, the house demonstrates high adaptability to the local climate. Bamboo and CGI sheets provide ventilation and protection from heavy rains. However, frequent maintenance is required to address the natural wear and tear of bamboo and wood, which are prone to damage from termites, fungi, and humidity. Replacing materials like CGI sheets, which may rust over time, also contributes to the environmental impact. The ongoing need for resources during maintenance increases the long-term environmental burden.

At the end of its lifecycle, the materials of an Assam Type house are either disposed of or recycled. Bamboo and wood, being biodegradable, decompose naturally or are repurposed for other uses, while CGI sheets can be recycled but often end up in landfills. Improper disposal of treated wood or bamboo can lead to soil and water contamination. Despite the potential for recycling, non-renewable components like CGI sheets introduce challenges in managing end-of-life impacts.

Assam Type houses exhibit several sustainability advantages. They rely heavily on renewable and local materials, reducing the carbon footprint. Their lightweight design and traditional construction methods involve low embodied energy, making them an environmentally conscious choice. Furthermore, their earthquake-resistant structure minimizes damage and waste during natural disasters. However, challenges remain, such as the dependence on energy-intensive CGI sheets, the environmental impact of chemical treatments, and the frequent need for maintenance. Addressing these issues could involve promoting sustainable bamboo cultivation, adopting eco-friendly wood and bamboo preservatives, and exploring alternative materials like clay tiles or solar roofing to replace CGI sheets. By implementing such measures, Assam Type houses can become even more environmentally sustainable while preserving their cultural and functional significance.

10. Government policies and support for sustainable building

10.1. Pradhan mantri awas yojana (PMAY) and other national schemes

The Pradhan Mantri Awas Yojana (PMAY) is a flagship housing scheme initiated by the Government of India in 2015, aimed at providing affordable housing for all. It targets the urban poor and aims to construct over 20 million affordable houses by 2022. The scheme facilitates financial assistance, enabling beneficiaries to access loans at subsidized interest rates, promoting home ownership among economically weaker sections. PMAY aims to provide affordable housing, but it faces challenges in Northeast India regarding sustainability. Limited focus on eco-friendly materials and traditional architecture raises concerns about environmental impact. Difficult terrain and inadequate infrastructure hinder effective implementation. Climate resilience is overlooked, leaving houses vulnerable to floods and landslides. Slow fund allocation and bureaucratic delays affect timely construction. Local indigenous housing techniques are not fully integrated, leading to cultural disconnect. Additionally, affordable financing options for low-income families remain insufficient, making sustainable housing less accessible in the region. Addressing these gaps is crucial for long-term success. Beyond PMAY, the Indian government has implemented several other national schemes that support sustainable building practices. The Smart Cities Mission focuses on urban renewal and sustainable development, encouraging the use of green technologies in construction. The Atal Mission for Rejuvenation and Urban Transformation (AMRUT) promotes infrastructure development, emphasizing the importance of sustainable urban spaces.

Additionally, the National Mission for Sustainable Habitat aims to enhance energy efficiency in buildings and promote the use of renewable energy sources. The Pradhan Mantri Ujjwala Yojana also complements these initiatives by providing clean cooking fuel to low-income households, reducing reliance on traditional biomass fuels. Collectively, these schemes foster sustainable urban development, enhance living standards, and address housing shortages while prioritizing environmental conservation and energy efficiency. Table 5 provides an overview of key national housing and sustainability schemes in India, including the Pradhan Mantri Awas Yojana (PMAY) and initiatives like the Smart Cities Mission and Pradhan Mantri Ujjwala Yojana. It highlights each scheme's objectives, key features, and target beneficiaries, emphasizing their role in promoting affordable housing and sustainable development.

10.2. State-level initiatives for North-East India

State-level initiatives in North-East India are crucial in promoting sustainable building practices, particularly given the region's unique environmental and socio-economic landscape. Several states have recognized the need for sustainable development and have implemented initiatives that focus on green construction and eco-friendly practices. One prominent initiative is the Sustainable Housing Scheme launched by the Government of Mizoram. This scheme encourages the use of locally available materials, such as bamboo and timber, for construction. It emphasizes eco-friendly design principles that reduce energy consumption and environmental impact. By integrating traditional architecture with modern techniques, this initiative not only preserves cultural heritage but also promotes sustainability. In Sikkim, the government has initiated the Sikkim Organic Mission, which indirectly supports sustainable building practices by promoting organic farming and the use of eco-friendly building materials. The focus on organic materials reduces the carbon footprint associated with construction and enhances the overall health of local ecosystems.

Assam has launched the Assam Green Mission, aiming to increase forest cover and promote sustainable land use practices. This initiative includes afforestation programs that encourage the use of native plants in landscaping, contributing to biodiversity and enhancing the aesthetic appeal of new constructions. Moreover, the Nagaland State Eco-Sensitive Zones initiative aims to regulate building activities in ecologically sensitive areas. By enforcing strict building codes and promoting eco-friendly construction practices, Nagaland seeks to balance development with environmental conservation. Additionally, the North-Eastern Council (NEC) has been instrumental in funding various sustainable building projects across the region. By providing financial assistance for green building initiatives, NEC supports state governments in their efforts to promote environmentally friendly construction. Through these state-level initiatives, North-East India is making significant strides toward sustainable building practices, contributing to environmental conservation, economic development, and the well-being of local communities.

Table 5
Summary of housing and sustainable urban development schemes in India.

Scheme Name	Objective	Key Features	Target Beneficiaries
Pradhan Mantri Awas Yojana (PMAY)	Provide affordable housing for all	Financial assistance, subsidized loans, home ownership	Urban poor, economically weaker sections
Smart Cities Mission	Urban renewal and sustainable development	Focus on green technologies in construction	Urban areas
Atal Mission for Rejuvenation and Urban Transformation (AMRUT)	Infrastructure development, sustainable urban spaces	Emphasis on water supply, waste management	Urban residents
National Mission for Sustainable Habitat	Enhance energy efficiency and promote renewable energy	Focus on sustainable building practices	General public, building developers
Pradhan Mantri Ujjwala Yojana	Provide clean cooking fuel to low-income households	Distribution of LPG connections	Low-income households

10.3. Financial incentives for green building materials and practices

Northeast India, with its rich biodiversity and unique ecological characteristics, has increasingly recognized the importance of sustainable development through green building practices. To promote the use of environmentally friendly materials and techniques, various financial incentives have been introduced by both the government and non-governmental organizations (NGOs). State governments in Northeast India, particularly Assam, Meghalaya, and Sikkim, offer subsidies and grants for eco-friendly construction practices. These financial aids are targeted at projects that utilize sustainable materials, such as bamboo and other local resources, which reduce environmental impact and support local economies.

Several states provide tax benefits for developers and homeowners who opt for green building practices. These can include property tax exemptions or reductions for buildings that meet specific energy efficiency standards or utilize renewable energy systems, like solar panels. The National Housing Bank (NHB) and various regional banks have launched schemes to offer low-interest loans for green buildings. These loans are aimed at promoting sustainable housing projects that implement energy-efficient designs, water conservation systems, and other eco-friendly technologies. Table 6 outlines various financial incentives promoting green building practices in Northeast India. It details subsidies, tax benefits, low-interest loans, support for local materials, and training programs for construction workers. These initiatives aim to encourage eco-friendly construction, enhance local economies, and foster sustainable development in the region, leveraging abundant resources.

The government has also initiated programs to encourage the use of local, sustainable building materials, often providing financial assistance or credits for the procurement of materials like bamboo, which are abundantly available in the region and have a lower carbon footprint compared to conventional materials. Several incentives exist for integrating renewable energy systems in buildings, including financial support for solar panel installation or biogas units, with programs aimed at reducing the upfront costs associated with these technologies.

Financial incentives are also provided for training programs aimed at construction workers in green building techniques. These programs, often funded by state governments or NGOs, help enhance local capacities while promoting sustainable practices. The combination of subsidies, tax incentives, low-interest loans, and support for renewable energy adoption constitutes a robust framework for promoting green building in Northeast India. These initiatives not only encourage environmentally responsible construction but also contribute to the economic and social development of the region by leveraging local resources and skills. As awareness of environmental issues grows, expanding these financial incentives will be crucial for fostering a sustainable future in Northeast India.

11. Future directions in sustainable low-cost building

11.1. Scaling up material innovations

Scaling up material innovations in Assam-type houses, characterized by their stilted structures, bamboo construction, and local adaptability, presents a unique opportunity for sustainable development in the region. Assam-type houses are traditionally designed to withstand the region's climatic conditions, but they can benefit significantly from modern material innovations. Incorporating eco-friendly materials such as engineered bamboo, recycled plastics, and sustainable composites can enhance the durability and energy efficiency of these structures. For instance, using bamboo laminates can improve tensile strength while maintaining a lightweight profile, making them ideal for the stilted design. Furthermore, integrating local materials with modern technologies can reduce carbon footprints and foster economic growth through local industries.

Scaling up these innovations requires collaboration between local artisans, architects, and policymakers. Training programs focused on sustainable building techniques can empower the workforce and ensure knowledge transfer. Additionally, creating awareness about the benefits of these innovations among homeowners can drive demand. Public-private partnerships can also play a vital role in funding research and development projects. By embracing material innovations, Assam-type houses can not only preserve cultural heritage but also pave the way for resilient, sustainable housing that meets contemporary needs while respecting traditional practices.

Table 6
Financial incentives for green building practices in Northeast India.

Incentive Type	Description	Target Beneficiaries	Examples
Subsidies and Grants	Financial support for eco-friendly construction practices	State governments, developers, homeowners	Offered by Assam, Meghalaya, and Sikkim
Tax Benefits	Property tax exemptions or reductions for green buildings	Developers, homeowners	Tax incentives for energy-efficient buildings
Low-Interest Loans	Loans for sustainable housing projects with eco-friendly designs	Developers, homeowners	Launched by the National Housing Bank (NHB)
Support for Local Materials	Financial assistance for procuring sustainable materials	Builders, local suppliers	Assistance for using bamboo and renewable resources
Training Programs	Training for construction workers in green building techniques	Construction workers	Funded by state governments and NGOs

11.2. Climate-adapted designs for Assam-type building

Climate-adapted designs for Assam-type houses are essential to address the unique environmental challenges faced in Assam, including heavy monsoons, flooding, and humidity. Traditionally, Assam-type structures have evolved to respond to these climatic conditions, characterized by stilted construction, sloped roofs, and the use of local materials such as bamboo and thatch. However, incorporating modern design principles and materials can enhance their resilience and sustainability.

One key feature of climate-adapted designs is the elevation of buildings on stilts. This not only protects the living space from flooding during monsoon seasons but also allows for proper ventilation and air circulation, crucial in humid climates. Additionally, sloped roofs facilitate rainwater drainage, preventing water accumulation and reducing the risk of leaks and structural damage. Modern materials, such as treated bamboo or engineered wood, can enhance the durability of these roofs while maintaining the aesthetic appeal of traditional designs. Another critical aspect is the integration of passive solar design. Orienting buildings to maximize natural light and airflow can significantly reduce the reliance on artificial lighting and cooling systems, leading to energy efficiency. Large overhangs and verandas can provide shade, while strategically placed windows allow for cross-ventilation, keeping interiors cool during hot months.

Sustainable practices, such as rainwater harvesting systems and biofiltration gardens, can be integrated into the design to manage water resources effectively. Using local materials and promoting traditional construction methods also supports the local economy and minimizes the environmental impact associated with transporting building materials. Climate-adapted designs for Assam-type houses hold great potential to enhance the resilience of communities in the region. By blending traditional architectural elements with modern sustainable practices, these structures can effectively address climate challenges while preserving cultural heritage.

11.3. Promoting local entrepreneurship in sustainable building materials

Promoting local entrepreneurship in sustainable building materials for Assam-type houses offers a unique opportunity to blend cultural heritage with environmental sustainability, addressing the region's pressing economic and ecological challenges. Assam-type houses, known for their stilted structures, bamboo construction, and traditional aesthetics, can significantly benefit from innovative, locally sourced materials that enhance resilience and sustainability.

Assam is rich in natural resources, particularly bamboo, which has been traditionally used in construction. By encouraging local entrepreneurs to innovate with bamboo and other indigenous materials, such as thatch, earth, and recycled materials, the region can develop sustainable building solutions tailored to its climatic conditions. Promoting entrepreneurship in this sector can lead to the creation of high-quality, eco-friendly alternatives to conventional materials, reducing reliance on imports and lowering carbon footprints. To foster local entrepreneurship, it is essential to provide training and education on sustainable building practices. Workshops, seminars, and collaboration with local universities can equip aspiring entrepreneurs with the knowledge and skills to innovate and produce sustainable materials. For example, teaching techniques for treating bamboo to enhance its durability or developing composite materials that blend traditional and modern practices can empower local businesses.

Government incentives, such as grants, low-interest loans, and subsidies, can play a significant role in encouraging startups in the sustainable building materials sector. By offering financial support, the government can help local entrepreneurs invest in research, product development, and scaling up operations. Additionally, creating a certification program for locally sourced sustainable materials can boost credibility and encourage builders to choose these options. Facilitating access to markets is crucial for local entrepreneurs. Collaborating with architects, builders, and construction companies to incorporate sustainable materials into their projects can increase visibility and demand. Establishing platforms for networking and partnerships can foster innovation and share best practices among stakeholders, leading to new business opportunities.

Engaging local communities in the promotion of sustainable building materials is vital. Initiatives that encourage residents to support local businesses through campaigns highlighting the benefits of sustainable construction can strengthen community ties and boost local economies. Community-driven projects, such as eco-friendly housing developments using Assam-type designs and materials, can serve as models for others, demonstrating the viability of local entrepreneurship in sustainable building. Promoting local entrepreneurship in sustainable building materials for Assam-type houses not only preserves the region's architectural heritage but also addresses contemporary environmental and economic challenges. By investing in education, financial support, and community engagement, Assam can cultivate a thriving ecosystem of sustainable practices that empower local entrepreneurs and enhance the resilience of its communities.

11.4. Research gaps and areas for further exploration

One significant gap is the lack of comprehensive studies on the long-term durability of traditional materials, such as bamboo and thatch, in varying climatic conditions. Understanding how these materials respond to changes in weather patterns, particularly with increasing instances of flooding and extreme temperatures, is essential for improving their performance. Additionally, there is a need for research on modern construction techniques that can be integrated with traditional designs to enhance structural stability and energy efficiency. This includes exploring hybrid materials that combine local resources with advanced technology, ensuring compatibility with local aesthetics while meeting contemporary building standards.

Another area for further exploration is the socio-economic impact of sustainable building practices in local communities. Investigating how promoting Assam-type houses can create jobs, empower local artisans, and foster economic resilience is vital for developing effective policies. Furthermore, examining the cultural significance of these buildings in the context of climate adaptation can provide insights into community engagement and acceptance of sustainable practices. Overall, addressing these research gaps will support the development of innovative strategies that preserve Assam's architectural heritage while promoting sustainable development.

12. Conclusions

12.1. Summary of Key Insights

The quest for sustainable solutions in low-cost building material innovations for Assam-type houses in North-East India has garnered significant attention. Assam-type structures are characterized by their unique architectural features and adaptability to the region's climate. Key insights into sustainable solutions reveal a focus on using locally sourced, renewable materials to reduce environmental impact while promoting affordability.

Research emphasizes the potential of bamboo, a fast-growing and abundant resource, as a primary building material. Its lightweight nature and high tensile strength make it an ideal alternative to conventional materials like steel and concrete. Additionally, integrating traditional craftsmanship with modern techniques can enhance durability and aesthetic appeal, fostering cultural preservation. Another insight is the incorporation of earth-based materials, such as rammed earth and stabilized mud blocks, which provide excellent thermal insulation and require minimal energy for production. These materials are cost-effective and environmentally friendly, aligning with sustainable building practices. Furthermore, innovative approaches like modular construction and prefabrication are highlighted as means to streamline the building process and reduce waste. By leveraging technology, the construction industry can improve efficiency and lower costs, making sustainable housing more accessible to the population. Overall, the integration of these materials and techniques presents a pathway toward resilient and sustainable architecture in North-East India.

12.2. Recommendations for policymakers and practitioners

Policymakers and practitioners play a crucial role in advancing sustainable building practices in North-East India, particularly regarding low-cost innovations for Assam-type houses. To foster this development, it is essential to promote the use of locally sourced materials such as bamboo and earth-based products. Utilizing these materials supports the regional economy and reduces transportation costs and environmental impact, aligning with sustainability goals.

Investing in research and development for sustainable building materials and technologies is another key recommendation. Collaborations with local universities and research institutions can yield innovative solutions tailored to the unique climatic and cultural contexts of the region. This approach not only encourages innovation but also addresses local needs and challenges effectively. Additionally, implementing financial incentives such as tax breaks or subsidies for builders and homeowners who utilize sustainable materials and practices can significantly lower initial costs, making eco-friendly options more accessible. This incentivization can lead to a broader adoption of green building practices among communities, ultimately contributing to a more sustainable future.

Enhancing training and education is equally vital. Establishing training programs for architects, builders, and local craftsmen that focus on sustainable construction techniques can improve skill levels and promote traditional knowledge. This hands-on training can empower local communities, ensuring they are well-equipped to implement sustainable practices in their building projects. Moreover, developing regulatory frameworks that create guidelines and standards for sustainable building practices is essential. Such frameworks can encourage innovation while ensuring safety and quality, streamlining processes and fostering an environment conducive to sustainable construction. By taking these actions, policymakers can significantly impact promoting sustainable solutions in building practices across the region, ultimately contributing to the environmental, social, and economic resilience of North-East India.

12.3. Future outlook on sustainable buildings in North-East India

The future outlook for sustainable buildings in North-East India appears promising, driven by a growing recognition of environmental issues and the need for resilient housing solutions. As urbanization accelerates in the region, there is an increasing demand for affordable housing that aligns with sustainability principles. Innovative materials such as bamboo, rammed earth, and stabilized mud blocks are gaining traction due to their eco-friendly properties and local availability. These materials not only minimize the carbon footprint but also enhance the cultural identity of the region, blending traditional architecture with modern needs. Additionally, advancements in construction techniques, such as modular construction and prefabrication, are expected to streamline building processes, reducing waste and costs.

Government policies are likely to evolve, emphasizing sustainable building practices through incentives and regulations that promote energy efficiency and environmentally friendly materials. Increased collaboration between local communities, architects, and researchers can foster a culture of innovation, ensuring that sustainable solutions are both practical and culturally relevant. Moreover, the integration of renewable energy sources, such as solar panels and biogas systems, into building designs will enhance energy efficiency and reduce reliance on traditional power sources. Overall, the shift towards sustainable buildings in North-East India is set to create a more resilient, eco-friendly, and culturally rich built environment.

The perspectives of end-users, such as local builders and homeowners, are crucial in evaluating the acceptability, usability, and cultural relevance of proposed innovations. Builders prioritize ease of implementation, cost-effectiveness, and compatibility with existing techniques. Homeowners focus on the practicality, aesthetic appeal, and alignment with cultural preferences. Innovations should address local climate, material availability, and traditional practices to ensure relevance. Open communication, participatory design, and feedback loops can enhance trust and adoption. Demonstrating tangible benefits, such as energy efficiency or cost savings, further supports acceptance. Ultimately, tailoring innovations to local needs fosters sustainability, user satisfaction, and community-wide support for new solutions.

CRediT authorship contribution statement

Barbhuiya Salim: Funding acquisition, Formal analysis, Data curation, Conceptualization. **Adak Dibyendu:** Writing – review & editing. **Marthong Comingstarful:** Writing – review & editing. **Forth John:** Writing – review & editing.

Declaration of Competing Interest

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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Data availability

Data will be made available on request.

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