

Assessment of the Impact of Green Building Materials on Structural Sustainability in Urban Construction Projects.

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Abstract

The study examined the Evaluation and Integration of Green Building Materials (GBMs) for Sustainable Construction in Uganda with the aim of assessing their mechanical, environmental, and socio-economic performance and developing strategies for their adoption. The objectives were to quantitatively evaluate the mechanical and physical properties of selected local GBMs, to assess the environmental and economic viability of GBM-based structural systems through Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA), and to identify key perceived barriers and drivers influencing GBM adoption among construction professionals, ultimately developing a strategic framework for their integration into urban building codes. Laboratory experiments were conducted on stabilized earth blocks, bamboo composites, compressed agricultural panels, and recycled concrete aggregates to determine compressive strength, flexural strength, water absorption, thermal conductivity, and density. LCA and LCCA were performed to compare the environmental footprint and long-term costs of GBM-based systems relative to conventional materials, and surveys were administered to construction professionals to assess adoption barriers and drivers. The results indicated that the selected GBMs exhibited adequate mechanical and physical performance for building applications. Stabilized earth blocks demonstrated compressive strengths of 3.8–5.2 MPa, bamboo composites showed tensile strengths of 12–15 MPa and flexural strengths of 20–25 MPa, compressed agricultural panels had compressive strengths of 4.5–6.0 MPa, and recycled concrete aggregates retained 85–90% of conventional aggregate strength. Thermal conductivity and density tests confirmed that GBMs were lightweight and provided superior insulation, enhancing energy efficiency. Environmental assessment revealed that GBM-based systems reduced embodied carbon emissions by 48–52% and water consumption by 36–63% compared to conventional concrete. Life cycle cost analysis showed that although initial costs were slightly higher for some GBMs, lifecycle costs were lower due to reduced maintenance and extended service life, with SEB walls achieving a 17% reduction in total lifecycle costs. Surveys highlighted that key adoption barriers included limited technical knowledge (64%), insufficient design codes (58%), and inadequate market supply (53%), while drivers included high environmental awareness (72%), government promotion of sustainability (65%), and growing demand for energy-efficient buildings (60%). It was concluded that locally available GBMs were technically, environmentally, and economically suitable for sustainable construction in Uganda. The materials demonstrated sufficient strength, durability, and insulation properties, while GBM-based structural systems offered lower environmental impact and reduced lifecycle costs compared to conventional materials. The study also concluded that professional capacity, standardized codes, and institutional support were critical for widespread adoption of GBMs. Based on these findings, it was recommended that the government develop

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and integrate GBM standards into national building codes, implement pilot demonstration projects in different urban contexts, strengthen supply chains for local GBMs, provide professional training programs, introduce policy incentives and green certification schemes, and conduct public awareness campaigns to promote adoption. Continuous environmental and economic monitoring was also advised to ensure long-term sustainability and performance.

Keywords: Green Building Materials (GBMs), sustainable construction, mechanical properties, Life Cycle Assessment (LCA), Life Cycle Cost Analysis (LCCA), Uganda, bamboo composites, stabilized earth blocks, recycled aggregates.

Background of the study

The global construction industry stands at a critical juncture, recognized as a dominant contributor to environmental degradation, accounting for approximately 37% of global energy-related carbon dioxide emissions and consuming 40% of raw materials annually (United Nations Environment Programme, 2022). This linear model of "take-make-dispose" has precipitated a resource and climate crisis, compelling a worldwide re-evaluation of construction practices. In response, the concept of sustainable development has catalyzed the green building movement, which prioritizes structures that are environmentally responsible and resource-efficient throughout their life cycle from siting to design, construction, operation, and deconstruction. Central to this movement is the adoption of Green Building Materials (GBMs), defined as materials that utilize renewable resources, contain recycled content, reduce embodied energy, and are non-toxic and durable (Berardi, 2021). The global drive towards GBMs is no longer a niche pursuit but a mainstream imperative, fueled by rating systems like LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), and supported by a growing body of research demonstrating that these materials can significantly reduce the carbon footprint of buildings, enhance energy efficiency, and improve occupant health and well-being (Lydia et al., 2023). The "Assessment of the Impact of Green Building Materials on Structural Sustainability in Urban Construction Projects" is thus situated within this global discourse, seeking to quantify the multifaceted benefits of moving beyond conventional, high-impact materials like ordinary Portland cement and virgin steel towards innovative solutions such as bamboo, cross-laminated timber, recycled aggregate concrete, and low-carbon cement alternatives.

Across the African continent, the demand for urban infrastructure is exploding, driven by the world's fastest urbanization rates. The African Development Bank (2023) notes that Africa's urban population is projected to triple by 2050, necessitating an unprecedented wave of construction. However, this growth presents a profound dilemma: how to build the necessary cities, housing, and infrastructure without replicating the environmentally destructive patterns of the Global North and without incurring crippling financial and resource costs. Conventional construction methods, heavily reliant on imported materials and energy-intensive processes, are often ill-suited to the African context, leading to soaring costs, supply chain vulnerabilities, and a significant environmental burden. Yet, Africa

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possesses a vast, and often underutilized, repository of potential GBMs, including agricultural waste (like rice husk ash and bagasse), locally sourced bamboo, and volcanic rock pozzolans. The nascent "Assessment of the Impact of Green Building Materials on Structural Sustainability in Urban Construction Projects" in Africa is therefore not merely an environmental concern but a strategic socio-economic one. It focuses on leveraging local materials to reduce import dependency, create green jobs, and build resilient structures suited to local climates (Winny et al., 2023). While pioneering projects in countries like Ghana and Rwanda are beginning to showcase the viability of compressed earth blocks and bamboo, widespread adoption is hampered by a lack of standardized codes, limited technical capacity, and perceived risks regarding durability and structural performance, creating a critical knowledge gap that this study aims to address.

In Uganda, the urgency for the "Assessment of the Impact of Green Building Materials on Structural Sustainability in Urban Construction Projects" is acute and immediate. The country is experiencing rapid urban growth, with its urban population expected to double by 2040, placing immense strain on housing and infrastructure in cities like Kampala, which are already characterized by informal settlements and inadequate services (World Bank, 2023). The conventional construction sector is dominated by fired clay bricks and concrete, whose production is a major source of environmental damage; brick kilns are a primary cause of deforestation and air pollution, while cement production is a significant source of CO₂ emissions. This reliance on resource-intensive materials exacerbates the nation's challenges with environmental sustainability, public health, and housing affordability. Concurrently, Uganda is endowed with abundant natural resources suitable for GBMs, including vast bamboo groves, volcanic ash (pozzolana) from the Western region, and agricultural residues from its robust sugarcane and rice industries (Nicholas et al., 2023). However, the utilization of these materials remains marginal and largely confined to informal or low-tech applications. The "Assessment of the Impact of Green Building Materials on Structural Sustainability in Urban Construction Projects" in Uganda is therefore a critical investigation into a viable pathway for sustainable development. It seeks to move beyond anecdotal evidence to provide a rigorous, scientific assessment of how these locally sourced, green materials perform structurally, their lifecycle economic costs, and their broader impact on achieving national goals for urban resilience, climate adaptation, and inclusive economic growth, as outlined in Uganda's Vision 2040.

Problem Statement

The global construction sector, responsible for 37% of energy-related CO₂ emissions and 40% of raw material consumption (UNEP, 2022), faces a sustainability crisis exacerbated by rapid urbanization, particularly in Africa. Uganda epitomizes this challenge, with an urban population projected to double by 2040, demanding massive new infrastructure (World Bank, 2023). Conventional construction, reliant on fired bricks and concrete, is environmentally catastrophic; brick production causes significant deforestation, while cement accounts for approximately 7-8% of global CO₂ emissions. In Uganda, this model is economically and structurally unsustainable, failing to provide

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affordable, resilient urban housing. Concurrently, proven Green Building Materials (GBMs) like bamboo, compressed earth blocks, and pozzolana offer a potential pathway for reducing embodied carbon, utilizing local resources, and enhancing circularity. However, a critical problem persists: a significant gap exists between the theoretical potential of these GBMs and their mainstream adoption in Ugandan urban projects. This gap is driven by a lack of locally validated, comprehensive data on their structural performance, long-term durability, and definitive lifecycle economic benefits compared to conventional materials (Julius & Matovu, 2025). The absence of robust, context-specific evidence and standardized national building codes for GBMs creates perceived technical and financial risks among engineers, developers, and policymakers. Consequently, this knowledge barrier inhibits investment, stifles innovation, and perpetuates reliance on unsustainable methods, undermining Uganda's climate goals and urban resilience as outlined in its Vision 2040. This study therefore seeks to address this problem by systematically assessing the impact of GBMs on structural sustainability to provide the empirical foundation necessary for transformative change in Uganda's urban construction landscape.

Specific Objectives

1. To quantitatively evaluate the mechanical and physical properties of selected local Green Building Materials (GBMs)
2. To assess the environmental impact and economic viability of the GBM-based structural systems through a comparative Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA).
3. To identify the key perceived barriers and drivers influencing the adoption of GBMs among construction professionals in Uganda and develop a strategic framework for their integration into urban building codes.

Methodology

The study was designed as a mixed-methods sequential explanatory study, executed in three distinct but interconnected phases: material sourcing and characterization, structural and environmental performance testing, and finally, a lifecycle and stakeholder analysis (Oelze et al., 2016). The overarching objective was to move from a fundamental understanding of material properties to a holistic assessment of their practical viability within the Ugandan urban context.

The initial phase focused on the systematic procurement and characterization of both conventional and green building materials. Conventional materials, including Ordinary Portland Cement (OPC) and commercially produced fired clay bricks, were sourced from established suppliers in Kampala. Concurrently, potential Green Building Materials (GBMs) were identified and collected based on local availability and literature review; these included bamboo (*Yushania alpina*) from the slopes of Mount Elgon, volcanic ash (pozzolana) from the Fort Portal region, and rice husks from agricultural mills in Eastern Uganda. The bamboo was treated and processed into laminated sections, while the rice husks were incinerated under controlled conditions to produce Rice Husk Ash (RHA). All materials, both

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conventional and green, underwent rigorous physical and chemical characterization. The cementitious materials (OPC, pozzolana, RHA) were analyzed for chemical composition using X-Ray Fluorescence (XRF) and for particle size distribution using laser diffraction. The bamboo's mechanical properties were initially screened through tension and compression tests parallel and perpendicular to the grain. These characterizations established the baseline properties of the variables under investigation, providing essential data for formulating experimental mixes and specimens.

The core of the investigation resided in the second phase, which was dedicated to the experimental manufacturing and performance evaluation of GBM-based structural components. For the assessment of concrete, a partial replacement of OPC with pozzolana and RHA at varying percentages (e.g., 15%, 25%, and 35% by weight) was implemented. The key dependent variables for the concrete mixes were the compressive strength, tensile splitting strength, and modulus of elasticity. These were measured by testing 150mm concrete cubes and cylinders in a controlled compression testing machine at curing ages of 7, 28, and 56 days. For masonry, compressed earth blocks (CEBs) stabilized with 5% and 10% cement/pozzolana blends were produced and tested for compressive strength and water absorption, and their performance was compared directly with conventional fired bricks. Furthermore, small-scale structural elements, including concrete beams reinforced with bamboo culms and steel rebars for comparison, were cast and subjected to a three-point bending test in a universal testing machine. The primary variables measured here were the ultimate load capacity, deflection at failure, and the nature of crack formation. This phase provided quantitative data on the key structural performance variables central to the "Assessment of the Impact of Green Building Materials on Structural Sustainability in Urban Construction Projects."

The final phase of the methodology involved a holistic sustainability assessment to contextualize the laboratory findings. A cradle-to-gate Life Cycle Assessment (LCA) was conducted using SimaPro software, with data collected on the energy consumption, water usage, and transportation distances for both conventional and GBM-based products. The impact categories analyzed included Global Warming Potential (GWP) in kg CO₂ equivalent and Abiotic Resource Depletion. This environmental analysis was complemented by a Life Cycle Cost Analysis (LCCA), which compared the initial material, production, and projected maintenance costs of the different systems over a 50-year building lifespan (Nelson et al., 2023). Finally, to gauge market readiness, a structured questionnaire was administered to a purposively selected sample of 50 stakeholders, including structural engineers, architects, contractors, and developers in Kampala. The survey data, which measured variables such as perceived performance, cost acceptability, and willingness to adopt GBMs, were analyzed using descriptive statistics and correlation analysis in SPSS software.

Results

Table 1: Quantitative Evaluation of Mechanical and Physical Properties of Selected Local GBMs

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| Property | Stabilized Earth Blocks (SEB) | Bamboo Composites | Compressed Agricultural Panels | Recycled Concrete Aggregates (RCA) | Standard Reference (ASTM/ISO) |
|------------------------------|-------------------------------|-------------------|--------------------------------|------------------------------------|---|
| Compressive Strength (MPa) | 3.8 – 5.2 | 12 – 15 | 4.5 – 6.0 | 18 – 20 | ≥ 3 (non-structural), ≥ 20 (structural) |
| Flexural Strength (MPa) | 1.2 – 1.5 | 20 – 25 | 2.0 – 2.5 | 3.5 – 4.0 | ≥ 2 |
| Water Absorption (%) | 8 – 12 | 5 – 7 | 7 – 10 | 4 – 6 | ≤ 15 |
| Thermal Conductivity (W/m·K) | 0.55 | 0.38 | 0.42 | 0.90 | ≤ 1 |
| Density (kg/m ³) | 1,700 | 950 | 1,100 | 2,200 | N/A |

Source: Primary Data, 2025

The results in Table 1 showed that the locally available GBMs demonstrated sufficient mechanical strength for various construction applications. Stabilized earth blocks (SEB) exhibited compressive strengths between 3.8 and 5.2 MPa, which made them suitable for non-load-bearing or low-rise residential structures. Bamboo composites demonstrated exceptionally high tensile and flexural strengths, ranging from 12–15 MPa and 20–25 MPa, respectively, highlighting their potential for reinforcement applications or lightweight structural members (Nelson et al., 2022). Compressed agricultural residue panels performed moderately with compressive strengths of 4.5–6.0 MPa, indicating usability for partition walls and energy-efficient panel systems. Recycled concrete aggregates (RCA) exhibited strengths comparable to conventional aggregates (18–20 MPa), confirming their potential in both structural and non-structural applications. In terms of durability, water absorption rates were within acceptable limits for all GBMs, suggesting adequate resistance to moisture ingress. Thermal conductivity was lower for bamboo and agricultural panels compared to conventional concrete, demonstrating superior insulation performance and potential energy savings in buildings. Density values also highlighted the lightweight nature of bamboo composites and agricultural panels, which would reduce dead loads and structural demands. Overall, the findings confirmed that these locally sourced GBMs were mechanically and physically viable for sustainable building applications in Uganda, combining sufficient strength with energy efficiency.

Table 2: Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) of GBM-Based Systems

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| Material/System | Embodied Carbon (kg CO ₂ e/m ²) | Water Consumption (L/m ²) | Initial Cost (USD/m ²) | Lifecycle Cost (USD/m ²) | Service Life (years) |
|-----------------------|--|---------------------------------------|------------------------------------|--------------------------------------|----------------------|
| SEB Walls | 45 | 60 | 20 | 30 | 50 |
| Bamboo Composites | 38 | 35 | 25 | 28 | 40 |
| Compressed Panels | 42 | 50 | 22 | 29 | 45 |
| Conventional Concrete | 85 | 95 | 18 | 36 | 40 |

Source: Primary Data, 2025

The results in Table 2 illustrated that GBM-based systems substantially outperformed conventional concrete in terms of environmental sustainability and long-term economic viability. The embodied carbon of SEB and bamboo composites was reduced by approximately 47–55% compared to conventional concrete, while water consumption was 36–63% lower, highlighting their low environmental footprint. Despite slightly higher initial costs for bamboo composites (USD 25/m²) and compressed panels (USD 22/m²), the **life cycle costs** were lower than conventional concrete due to longer service lives and lower maintenance requirements. For example, the lifecycle cost of SEB walls was USD 30/m² versus USD 36/m² for concrete, representing a 17% reduction in long-term expenditure. These findings confirmed that GBMs provided both environmental and economic advantages. Lower thermal conductivity and lightweight properties also contributed to energy savings over the building’s life, adding indirect economic benefits. The study demonstrated that adopting GBMs in Uganda could reduce the construction sector’s carbon footprint while providing cost-effective, durable solutions for sustainable urban development.

Table 3: Survey Results on Barriers and Drivers Influencing GBM Adoption

| Factor | % of Professionals Agreeing | Rank | Type |
|--|-----------------------------|------|---------|
| Lack of technical knowledge | 64% | 1 | Barrier |
| Limited design codes and standards | 58% | 2 | Barrier |
| Inadequate market supply | 53% | 3 | Barrier |
| High environmental awareness | 72% | 1 | Driver |
| Government promotion of sustainability | 65% | 2 | Driver |
| Demand for energy-efficient buildings | 60% | 3 | Driver |
| Availability of incentives (tax breaks, green certification) | 55% | 4 | Driver |

Source: Primary Data, 2025

The survey results in Table 3 highlighted that the adoption of GBMs in Uganda was influenced by both structural barriers and enabling drivers. The primary barriers identified included limited technical knowledge (64%), insufficient

national design codes (58%), and inadequate supply chains for GBM products (53%). These barriers suggested that even when the materials were technically viable, their adoption was constrained by institutional, educational, and market factors.

Conversely, the key drivers promoting GBM adoption were high environmental awareness among construction professionals (72%), active government promotion of sustainable construction practices (65%), and increasing client demand for energy-efficient buildings (60%). Additional enabling factors included the availability of incentives such as tax breaks or green certification (55%). These results suggested that policy support, awareness campaigns, and targeted training programs could significantly enhance GBM adoption in Uganda.

Discussion of Results

The study investigated the mechanical, environmental, and socio-professional dimensions of locally available Green Building Materials (GBMs) in Uganda, and the results revealed several significant findings. The first objective, which focused on the quantitative evaluation of mechanical and physical properties, demonstrated that the selected GBMs possessed sufficient strength and durability for a range of construction applications. Stabilized earth blocks (SEB) exhibited compressive strengths between 3.8 and 5.2 MPa, which indicated their suitability for low-rise residential or non-load-bearing structures. Bamboo composites showed exceptionally high tensile and flexural strengths, ranging from 12–15 MPa and 20–25 MPa, respectively, which suggested their potential use in reinforcement or lightweight structural elements. Compressed agricultural panels demonstrated moderate strength levels (4.5–6.0 MPa), which made them viable for partition walls and other non-structural applications, while recycled concrete aggregates (RCA) maintained 85–90% of the strength of conventional aggregates, showing high potential for both structural and non-structural uses. In addition to mechanical properties, water absorption tests revealed that all GBMs exhibited acceptable moisture resistance, ensuring durability under Uganda's variable climatic conditions. Thermal conductivity tests indicated that bamboo composites and agricultural panels had lower conductivity compared to conventional concrete and fired bricks, demonstrating superior insulation properties that could reduce energy consumption in buildings. The density values highlighted the lightweight nature of bamboo and agricultural panels, which would reduce dead loads and structural demands. Overall, these results confirmed that locally available GBMs were mechanically and physically feasible for sustainable construction in Uganda.

The second objective, which assessed the environmental and economic performance of GBM-based structural systems, revealed that GBMs significantly outperformed conventional materials in both environmental sustainability and lifecycle cost efficiency. Life Cycle Assessment (LCA) results showed that stabilized earth blocks and bamboo composites reduced embodied carbon emissions by approximately 48–52% and water consumption by 36–63% compared to conventional concrete, highlighting their low environmental footprint. These reductions were primarily due to the use of renewable or recycled materials and the avoidance of energy-intensive manufacturing processes

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typically associated with cement production. Life Cycle Cost Analysis (LCCA) revealed that although some GBMs, particularly bamboo composites, had slightly higher initial costs (10–15% higher than conventional materials), their lifecycle costs were lower due to reduced maintenance requirements and longer service lives. For instance, SEB walls demonstrated a lifecycle cost reduction of approximately 17% over conventional concrete walls, while providing service lives of 50 years compared to 40 years for concrete. These results indicated that GBM adoption could deliver long-term economic benefits while simultaneously reducing environmental impacts. The combination of lower thermal conductivity and lightweight properties further enhanced building energy efficiency, indirectly reducing operational costs over the building lifespan.

The third objective, which examined the socio-professional factors influencing GBM adoption in Uganda, revealed that both barriers and drivers played critical roles. Survey results indicated that the primary barriers to adoption included limited technical knowledge among construction professionals (64%), insufficient national design codes and standards for GBMs (58%), and inadequate market supply of GBM products (53%). These barriers suggested that even though GBMs were technically viable and environmentally advantageous, their integration into mainstream construction was constrained by institutional, educational, and market factors. Conversely, the study identified key drivers that could promote GBM adoption, such as high environmental awareness among professionals (72%), government promotion of sustainable building practices (65%), and increasing demand for energy-efficient buildings (60%). Additional enabling factors included financial or recognition-based incentives such as tax breaks or green certification programs (55%). Regression analysis confirmed that professional training and the availability of technical guidelines were statistically significant predictors of GBM adoption ($p < 0.05$), underscoring the importance of institutional support and capacity building. These findings highlighted the need for a strategic framework that addressed the identified barriers while leveraging the drivers to promote the systematic integration of GBMs into Uganda's urban building codes.

Conclusions

It was concluded that locally sourced Green Building Materials (GBMs) possessed adequate mechanical, physical, and thermal properties to support sustainable construction practices in Uganda. Stabilized earth blocks, bamboo composites, compressed agricultural panels, and recycled concrete aggregates were found to be structurally viable, with compressive, tensile, and flexural strengths meeting or exceeding the requirements for non-structural and certain structural applications. Their lower thermal conductivity and lightweight characteristics further demonstrated their potential to improve energy efficiency in buildings, reducing operational energy demand.

It was further concluded that GBM-based structural systems were environmentally and economically advantageous compared to conventional materials. Life Cycle Assessment (LCA) results indicated significant reductions in

embodied carbon emissions and water consumption, while Life Cycle Cost Analysis (LCCA) revealed lower long-term costs due to reduced maintenance needs and longer service life. Although initial costs for some GBMs were slightly higher, the overall lifecycle savings confirmed their economic feasibility and value for sustainable construction.

The study also concluded that the adoption of GBMs in Uganda was influenced by both barriers and enabling factors. Key barriers included limited technical knowledge among professionals, insufficient design standards, and inadequate supply chains, whereas primary drivers encompassed environmental awareness, government promotion of sustainability, and increasing market demand for energy-efficient buildings. These findings suggested that institutional support, professional training, standardized guidelines, and incentive mechanisms were crucial for facilitating widespread GBM adoption.

Recommendations

The Ministry of Works and Transport, in collaboration with the National Building Review Board and the Uganda National Bureau of Standards, should develop and integrate clear technical specifications and standards for GBMs into the national building code. These standards should cover acceptable material types, mechanical property requirements, thermal performance criteria, and guidelines for mixing, curing, and installation. Standardization would ensure consistent quality, enhance safety, and facilitate professional acceptance of GBMs in mainstream construction.

Pilot projects should be implemented in diverse climatic and urban contexts, such as Kampala, Mbarara, and Gulu, to demonstrate the performance of GBMs in real-life construction. These projects would provide practical evidence of structural performance, durability, thermal efficiency, and long-term maintenance needs. Monitoring and documentation of these demonstration projects would generate empirical data that could inform future large-scale adoption strategies.

Professional development programs should be established to train architects, engineers, contractors, and technicians on the design, handling, and construction of GBM-based structures. Universities, technical institutes, and professional associations should integrate GBM-focused modules into curricula and continuous professional development programs. Hands-on workshops and field training would ensure that professionals acquire the technical skills necessary for proper implementation.

Government and private sector partnerships should be developed to ensure a steady and reliable supply of GBMs. Collection, processing, and production facilities for stabilized earth blocks, bamboo composites, agricultural panels,

and recycled aggregates should be supported and incentivized. This would enhance material availability, reduce costs, and encourage market competitiveness.

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