Bale Bio - A Case Study on Connecting Rural Forestry with Urban Construction for a Regenerative Built Environment

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Abstract. This paper presents a case study on linking rural agroforestry systems with rapidly urbanising regions in Indonesia, supporting multiple Sustainable Development Goals across the material value chain. It focuses on the Bale Bio, a demonstration pavilion developed within the Bauhaus Earth Rebuilt initiative, which explores regenerative building practices in four regions including Bali. The project investigates the potential of bio-based materials, particularly structural engineered bamboo, as a carbon-neutral or even carbon-negative alternative to conventional construction materials. Due to its fast growth and capacity for local sourcing, bamboo presents a viable solution for reducing reliance on imported, carbon-intensive materials in urban development.

Developed through collaboration between public and private sectors, academia, and local communities, the pavilion demonstrates the practical application of regenerative design principles that aim to create a built environment with net positive environmental outcomes. Bale Bio serves as a real-world prototype showcasing the feasibility of engineered bamboo in urban construction.

This study applies a mixed-methods approach, including bamboo value chain mapping from harvest to assembly, life cycle assessment comparisons with conventional buildings, documentation of construction processes, and semi-structured stakeholder interviews. Findings highlight value chain gaps, emissions reduction potential, material quality standards, and social dynamics influencing adoption, as well as recommendations on how to scale up regenerative practices.

By highlighting both the opportunities and challenges of integrating sustainable, locally sourced materials into urban construction, this research contributes to the advancement of a regenerative built environment in Indonesia. Furthermore, it offers actionable insights for policymakers, architects, and industry stakeholders seeking to accelerate the transition to low-carbon, circular construction.

1. Introduction

1.1 Background

The world is experiencing a climate emergency, with global temperatures already exceeding 1.1°C above pre-industrial levels (Climate Action Tracker, 2024). The construction sector is a significant driver, accounting for nearly 40% of global CO_2 emissions from building activity, materials production, and transport (Sobek, 2022). Achieving net-zero emissions by 2050 will require a sustained annual reduction of 8%, a pace not yet realised (UNEP & Yale, 2023). Despite the urgency, transformative change in construction practices remains limited.

Indonesia, with over 270 million people and the second highest biodiversity globally (UNEP-WCMC, 2023), faces increasing socio-environmental pressures from deforestation and rapid urbanisation. Over 24 million hectares of its forest area is degraded (Bamboo Village Initiative, 2020), and emissions continue to rise. Yet, the country's vast renewable resources; particularly bamboo, offer a path towards regenerative development. Bio-based materials can simultaneously lower emissions, restore ecosystems, and foster more resilient urban environments.

Bali exemplifies these challenges and opportunities. Nearly 70% of Denpasar has urbanised in the past 30 years (Kecamatan Denpasar, 2023), replacing local building materials with carbon-intensive alternatives. Bamboo, as a fast-growing, carbon-sequestering species, presents a low-carbon alternative aligned with several Sustainable Development Goals (INBAR, 2015).

1.2 Research Aim and Objectives

This study explores how rural agroforestry systems can be integrated into urban construction through a case study of the Bale Bio Pavilion in Bali. It investigates the use of bamboo in laminated, split, pole, and slat forms, alongside reclaimed materials, to assess their viability as low-carbon construction alternatives. The study's objectives are to:

- Map the full value chain of bamboo, from harvesting to post-consumer use;
- Assess the socio-ecological and structural performance of engineered bamboo in urban contexts;
- Contribute to the SDGs by promoting regenerative, locally sourced solutions.

The paper presents a theoretical framework, methodology, case study, and practical recommendations for scaling regenerative practices in Indonesia.

2. Theoretical Framework

2.1 Regeneration: A Step Beyond Sustainability

The concept of sustainability has guided global development for over three decades, focusing on minimising harm and increasing efficiency (Brundtland, 1987; Camrass, 2023). However, the escalating climate and biodiversity crises reveal its limitations, often maintaining the status quo rather than addressing systemic ecological degradation (Reed, 2007). In response, a more ambitious paradigm, Regenerative Development, has emerged. Regeneration seeks to restore and enhance ecosystems through proactive approaches such as agroforestry, rewilding, and carbon sink expansion (Du Plessis, 2012). It promotes net-positive built environments that actively improve ecological and social systems (Churkina et al., 2020) and encourages co-evolutionary relationships between urban and rural landscapes (Mohan et al., 2021).

2.2 The Role of Bamboo in Regenerative Development

Bamboo, though technically a grass, provides ecosystem services comparable to trees. With rapid growth, high biomass, and annual regrowth, it is an efficient carbon sink (Yiping et al., 2010).

When engineered into durable products such as laminated bamboo, it stores carbon and reduces reliance on fossil fuel-intensive materials (INBAR, 2015). Technological innovations now allow bamboo to meet structural standards, making it a viable, low-carbon alternative for urban construction while supporting rural livelihoods.

2.3 Urban-Rural Linkage in Sustainable Development

Despite growing interest in bamboo architecture, much research overlooks the spatial dynamics of its value chain. Urban–rural linkages (URLs); the flows between rural bamboo producers and urban construction markets, remain underexplored (Utomo et al., 2021). Recognising these connections is essential for integrated governance. Embedding URL perspectives can align bamboo cultivation with ecological conservation, rural economic development, and sustainable urban growth (UNCCD & UN-Habitat, 2024), reinforcing regeneration as a cross-scalar, systems-based strategy for future development.

3. Research Methodology

3.1 Practice-Based Research

This study presents the Bale Bio Pavilion, a prototype developed through the Bauhaus Earth Rebuilt Project, which explores regenerative architecture across four regions, Berlin-Brandenburg, Paro-Thimphu, Western Cape and Bali. Employing a practice-based research approach grounded in iterative experimentation, stakeholder engagement, and material innovation, the project integrates locally sourced bamboo to model low-carbon alternatives to conventional construction. As a testbed, the pavilion brings together public, private, academic, and community actors, offering a real-world platform for collaborative research and application.

A mixed-methods framework was employed to evaluate the technical, social, and environmental outcomes of the Bale Bio. This included resource supply chain mapping to trace the environmental and socio-economic impacts of bamboo as it moves from forest to construction. A cradle-to-gate life cycle assessment (LCA) to measure the embodied carbon of the pavilion, from extraction and production through to transport and assembly, enabling comparison with conventional building methods. Field observations and documentation were across Denpasar and surrounding rural areas to examine the spatial and logistical dynamics of the bamboo industry. Finally, semi-structured interviews and focus groups with government officials, NGOs, practitioners, and community members offered insights into the implementation and perception of regenerative practices. This helped to identify systemic barriers and opportunities for mainstreaming bio-based materials within Bali's construction sector.

4. Case Study: The Bale Bio Pavillion

4.1 Introduction to the Bale Bio and its design

The Bale Bio Pavilion, developed through the Bauhaus Earth ReBuilt Project, serves as a prototype for regenerative architecture in Indonesia. Located in Bali, the 84-square-metre structure showcases the use of locally sourced bio-based and reused materials. Beyond construction, it functioned as a platform for stakeholder engagement through community consultation, design, and activation to promote dialogues on regenerative development. Its design is inspired by the *Bale Banjar*; a traditional open-air meeting hall central to Balinese village life. Once made of timber and local materials, these communal structures are being replaced with concrete structures. Reimagining this typology in local sustainable materials offered a culturally grounded way to initiate conversations on regenerative design.

A key aim of the project was to explore how local bio-based materials, particularly bamboo, could be integrated into urban contexts. Despite Indonesia's deep tradition of bamboo craftsmanship and Bali's renowned bamboo architecture (Widyowijatnoko, 2012), widespread adoption remains limited due to material variability, lack of standardisation, and social perceptions (Flander, 2008). The Bale Bio aimed to overcome these barriers by demonstrating the structural potential of laminate bamboo within a contemporary architectural context.

Figure 1. The Bale Bio Pavillion. (Iwan Sastrawan)

4.2 Mapping Bamboo Value Chains

The adoption of regenerative building practices depends on strengthening supply chains between rural and urban areas (Mohan et al., 2021). Bale Bio aimed to activate a regenerative bamboo value chain by sourcing and processing structural laminate bamboo through a partnership with local manufacturer Indobamboo. As the first building in Bali to use this material, the project demonstrated how multiple Sustainable Development Goals (SDGs), including forestry, industry, livelihoods, and sustainable cities can be implemented through regenerative construction.

Indonesia has around 24 million hectares of degraded forest (Bamboo Village Initiative, 2020), which could be revitalised through bamboo agroforestry (Rabik, 2024). Unlike timber, bamboo matures in 3–4 years and can be harvested annually (Flander, 2008). Processing bamboo into preserved strips near the point of harvest enables rural cooperatives to add value locally and improve efficiency, supporting economic resilience and contributing to SDGs 1, 2, 5, 8, 13, and 15.

For Bale Bio, structural bamboo was sourced from Flores, where Indobamboo works with smallholder village cooperatives cultivating *Dendrocalamus asper*. After harvest, culms are locally split, treated with borax, and transported to Bali for further drying and lamination. Larger beams and custom-curved arches were fabricated using cold-press techniques and bespoke jigs, illustrating the implementation of SDGs 9 and 12 through innovation in sustainable manufacturing.

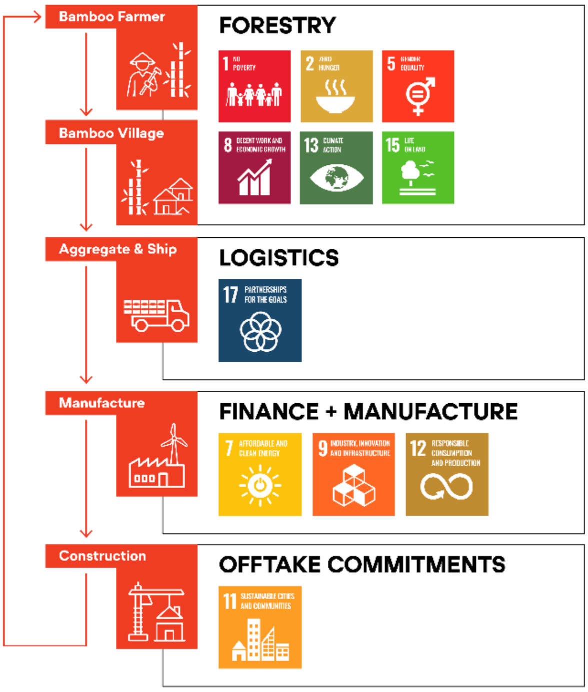

Figure 2. Laminate bamboo value chain and associated SDGs (Cave Urban)

4.3 Constructing the Bale Bio

The Bale Bio Pavilion was developed through a collaborative effort involving Bauhaus Earth, Bamboo Village Trust, Kota Kita, Warmadewa University, Cave Urban, Indobamboo, Eco-Mantra, and Atelier One. The design process was iterative, integrating feedback from research, testing, and stakeholder engagement. The final design was presented to the Mayor of Denpasar in August 2024, with local community participation aiding land and building approvals.

Given limited technical data on laminate bamboo, material testing was carried out through factory trials and at the National Research and Innovation Agency (BRIN), informing the structural design. A Life Cycle Assessment (LCA) was conducted during the construction process, allowing sustainability data to guide design decisions in real time. Construction took place between September 2024 and February 2025 and concluded with an opening ceremony attended by Banjar representatives, Denpasar officials, and stakeholders.

5. Findings and Discussion

5.1 Supply and Value Chain

Bamboo is a promising regenerative material due to its fast growth, ability to be harvested annually, and potential to support rural economies (Bredenoord, 2024). When engineered into laminated structural components, it functions as a long-term carbon sink, making it attractive for low-carbon construction (Flander, 2008). In Indonesia, bamboo is sourced from village plots, community forests, and state-managed lands, with six main species used in construction (Widjaja, 2000). While Bali is known for bamboo architecture, its cultivation capacity is limited compared to regions like Java and East Nusa Tenggara, highlighting the importance of understanding material value chains to connect rural supply with urban demand.

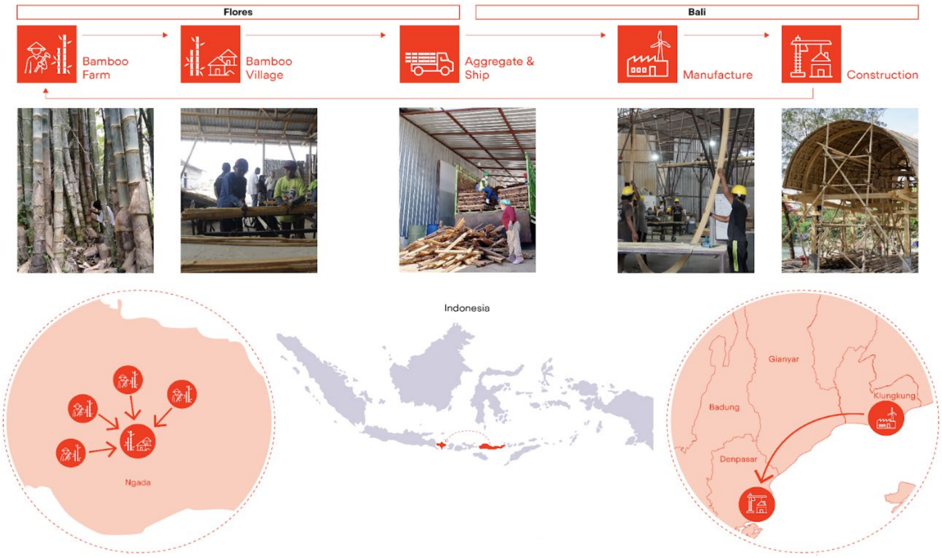

Figure 3. Bamboo Supply Chain for Indobamboo (Cave Urban)

The Bale Bio project revealed several challenges in developing stable bamboo supply chains: inconsistent quality control, multi-island logistics, limited data on informal agroforestry, irregular supply linked to low demand, and farmer scepticism from past market failures. High infrastructure costs and small production volumes hinder economies of scale, while manufacturing inconsistencies and limited competitiveness with Chinese producers further constrain growth. Addressing these issues requires investment, policy alignment, and market stability. A key recommendation is to stimulate demand through low-spec bamboo products, such as panels and furniture, following China's successful model of gradually scaling toward structural applications (Trujillo, 2024).

5.2 Structural Properties and Construction

Interest in structural laminated bamboo has grown over the past decade, supported by the development of international standards such as ISO 23478 and ISO 7567 (Trujillo, 2018). However, data on the performance of Indonesian species like *Dendrocalamus asper* remains limited. To address this, Indobamboo, Cave Urban, Bamboo Village Trust, and Atelier One codeveloped a testing protocol. Preliminary testing informed the Bale Bio Pavilion's design but revealed significant variation in manufacturing quality. Key issues identified included variable bending strength, often linked to joint placement in beams, and brittle failures occurring where plank joints aligned with maximum deflection zones. The modulus of elasticity was influenced by the presence of nodes in small specimens, while untreated or poorly dried strips showed signs of borer damage. Given these findings, the structural design was based on a combination of the project's initial test results and comparable data from other laminate bamboo products.

The construction process was highly iterative, shaped by the lack of standardised data and the complexity of the design. The pavilion's ambitious design including pronounced cantilevers and expressive roof-column connections exacerbated deflection issues. For instance, a 15mm deflection occurred in the horizontal beam under load. This was due to square joint between the roof and column wasn't acting as a moment connection, causing rotation. To rectify this, acro-props were used to remove the deflection, and a steel rod was added to redistribute the load.

Labour challenges further complicated construction. Local craftsmen were reluctant to engage with laminated bamboo, and the team had to depend on one experienced worker. Inexperienced labourers introduced errors such as misaligned plates and incorrect drilling, causing delays. These setbacks underscored the need for detailed construction documentation, experienced on-site supervision, and skills training to build local capacity. Post-construction inspections also found mould on some planks due to inconsistent treatment, requiring antifungal and protective coatings to ensure durability.

5.3 Life Cycle Assessment (LCA)

Regenerative design, unlike sustainability, seeks a net-positive ecological impact (Du Plessis 2012). To evaluate this, we partnered with Eco-Mantra to conduct a Life Cycle Assessment (LCA) of the Bale Bio Pavilion, focusing first on cradle-to-gate (Stage A) emissions.

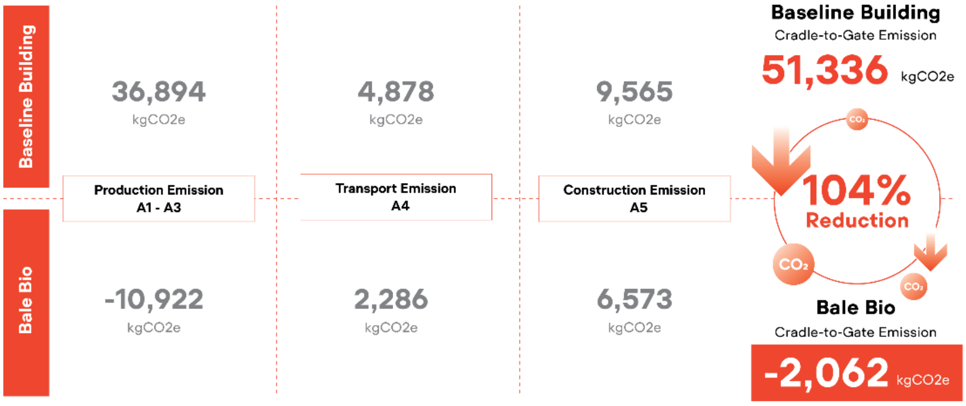

Figure 4. Comparison of Stage A emissions of the Bale Bio vs baseline structure (Eco-Mantra)

Findings showed a 104% reduction in carbon emissions (-2,062 kgCO2e) compared to an equivalent structure built with conventional materials (51,336 kg C02e). Accounting for biogenic carbon storage resulted in a net-carbon negative footprint, demonstrating the ecological benefits of bio-based construction. However, the LCA process revealed data limitations for bio-based materials in Indonesia, insofar that there was limited emission factors or Environmental Product Declarations (EPDs) for Indonesian bamboo products, which resulted in a reliance upon proxy data from China and the Philippines. Despite these gaps, comparative analysis and calibration enabled reliable conclusions. The largest contributor to emissions was the carpet rubber waterproofing membrane used in the roof. This impact could be reduced by sourcing lower-emission alternatives. Production emissions were otherwise dominated by the lamination process, which was offset by the bamboo's carbon sequestration. Simpler bamboo components—round poles, splits, and *pelupuh*—offered strong environmental performance due to minimal processing. Concrete foundations also contributed to emissions but were considered essential given Bali's extreme climatic conditions. Post-construction, we have developed a maintenance manual to inform future assessments for Stages B, C, and D, which are ongoing.

From our experiences conducting the LCA, we found that varying emission factors are provided for the carbon sequestration potential of bamboo products (Sujarwo 2015, Ibrahim 2022, Bundi 2024), this leads to varying results for the potential carbon impact or benefit of the construction process. The absence of an EPD for the bio-based building materials created a challenge when analysing the data as the use of alternative data sources required continual calibration and comparison to ensure consistency and accuracy in our analysis.

5.4 Stakeholder Perspectives

The Bale Bio Pavilion's use of laminated bamboo highlights the potential for integrating engineered bamboo into mainstream construction in Bali. To explore scalability, focus group discussions were held with stakeholders from government, NGOs, and the construction sector. Their insights revealed both opportunities and systemic challenges.

A central theme was the need for workforce development. Since laminated bamboo has not been used in permanent buildings in Bali, construction teams lack experience with the material. Consequently, skilled labour must often be sourced externally, increasing costs. Government and practitioner groups stressed the importance of local training programs to upskill Balinese craftsmen, reduce reliance on outside expertise, and boost local employment.

Maintenance was another concern. Practitioners noted that engineered bamboo currently requires specialised knowledge for upkeep, posing a barrier to wider adoption. Stakeholders recommended simplified maintenance protocols and community training to empower users and reduce long-term service costs. Public perception also plays a role. Bamboo, whether traditional or engineered, is not widely accepted as a primary housing material in Bali. By making it more affordable and easier to maintain, there is greater potential for mainstream adoption, particularly in residential construction.

Finally, stakeholders raised concerns about supply chain limitations. Bali's bamboo sector relies heavily on smallholder farms and artisanal producers, which restricts its capacity to meet increasing demand. Government representatives advocated for a coordinated strategy involving farmers, industry, and policymakers to ensure sustainable sourcing and prevent ecological degradation. Hence, stakeholders called for a holistic approach ensuring long-term regenerative bamboo construction by combining innovation, training, engagement and policy coordination.

6. Recommendations and Future Directions

6.1 Scaling the Use of Structural Laminated Bamboo in Indonesia

The construction of the Bale Bio Pavilion provided practical insight into the systemic change required for mainstreaming regenerative construction in Indonesia. Though a single structure, it serves as a prototype for systems-level change, demonstrating that regenerative architecture is feasible, sustainable, and socially impactful- if supported by coordinated cross-sectoral action.

Our findings demonstrate that Indonesia has the potential to scale a regenerative manufacturing industry centred on structural laminate bamboo for urban construction. As a bio-based fast-growing resource, laminate bamboo offers a viable alternative to timber. While small producers are emerging, significant work is still needed to expand technical infrastructure, strengthen supply chains, and build the multilevel collaborations essential for broader adoption.

6.2 Supply Chains

This study affirms prior research (Tropenbos Indonesia, 2023) identifying systemic barriers to bamboo-based agroforestry. Key challenges include complex supply networks, limited financial viability, fragmented policies, weak institutional support, and a general lack of knowledge and innovation. Additional obstacles such as unreliable offtake, inadequate incentives for agroforestry, and restricted access to finance further complicate efforts to scale production. Field observations confirmed these issues, particularly in rural areas where bamboo is grown by smallholder cooperatives. Quality assurance remains a persistent concern due to inconsistent harvesting practices and fluctuating demand, often requiring repeated retraining of farmers. These findings underscore the urgent need for capacity-building programs that address not only cultivation techniques but also storage, treatment, and coordinated supply chain management.

While there is a risk that scaling demand may lead to monoculture plantations, such a trajectory could be mitigated through integrated landscape management approaches. Incentives linked to conservation practices can support sustainable harvesting and socio-economic upliftment, especially in rural and remote communities. When embedded within a broader regenerative development strategy, these approaches contribute not only to ecological restoration but also to inclusive rural-urban partnerships (UNCCD & UN-Habitat, 2024).

Additionally, the unpredictable offtake market deters investment and undermines continuity in rural livelihoods. Strengthening market linkages between rural producers and urban developers is essential. Discussions from stakeholder focus groups revealed that targeted financial mechanisms such as government-backed incentives or reimbursement schemes could support wider bamboo adoption in commercial and tourism sectors. However, the governance of such mechanisms remains unclear. A coordinated, multi-actor approach is essential to ensure that incentive structures are socially equitable, economically viable, and tailored to regional contexts.

Finally, the need to account for end of life during the manufacturing process and post construction was also identified. The bamboo waste stream during production of laminate bamboo is not economically viable, unless waste products such as offcuts and sawdust are captured and monetised as additional products. This has both an ecological and economic benefit.

6.3 Structural Knowledge and Standards Development

A major constraint in advancing the use of laminate bamboo lies in the absence of technical data related to its structural performance. Currently, no formal national testing standards exist for bamboo laminates, although provisional certification can be obtained on a case-by-case basis. This process, however, is costly and time-consuming, hindering broader adoption.

To overcome this barrier, it is essential to develop a national testing and certification protocol aligned with ISO 23478, an international standard for testing engineered bamboo. Several Indonesian universities have expressed research interest in this field, and there is institutional support from both the Ministry of Public Works and Public Housing (PUPR) and the National Research and Innovation Agency (BRIN). The formulation of national building standards (SNI) that integrate international guidelines would create a regulatory framework to facilitate safe, consistent, and scalable application of bamboo in construction.

Knowledge sharing is equally critical. Laminated bamboo behaves differently than timber, requiring specialised design and engineering guidance. Projects such as Bale Bio are essential for experimentation, training, and dissemination, serving as a model for replication and adaptation.

6.4 Knowledge Exchange and Collaborative Governance

Scaling a regenerative bamboo sector demands more than technical innovation, it requires governance models that account for knowledge exchange and collaborative governance. Rural–urban linkages (URL) must be embedded into value chain strategies to improve coordination between farmers, industries, and governments. Furthermore, multistakeholder dialogues are needed to address incentive distribution, value capture, and governance roles.

Decentralised networks, professional training, and public education campaigns are essential to foster a broader understanding of bamboo’s ecological and economic benefits. Hence, regional knowledge ecosystems will help local actors lead future growth.

7. Conclusion

The Bale Bio Pavilion illustrates how regenerative architecture can be rooted in local materials, cultural typologies, and rural–urban collaboration. Reimagining the traditional Bale Banjar with engineered bamboo bridges the gap between vernacular knowledge and contemporary design, demonstrating how rural agroforestry can support resilient urban development.

Developed as part of the Bauhaus Earth Rebuilt Project, the pavilion exemplifies how systems-based approaches; combining community consultation, institutional partnerships, material testing, and life cycle assessment, can inform replicable regenerative frameworks. It also demonstrates the technical viability of laminate bamboo and the critical role of multi-stakeholder collaboration in achieving climate-positive construction aligned with multiple SDGs.

Bale Bio confirms that engineered bamboo, when properly processed, is a viable low-carbon alternative to conventional materials. Indonesia’s rich bamboo resources and craft traditions position it to lead this transition. However, scaling requires addressing persistent challenges such as inconsistent quality control, fragmented supply chains, underdeveloped logistics, and limited structural performance data. Strengthening capacity among smallholder cooperatives and establishing traceable value chains supported by incentives and policy reform are essential.

Another major barrier is the absence of national standards for engineered bamboo. Provisional certification is possible but costly. Aligning Indonesia’s protocols with ISO 23478 and integrating them into building codes would enable market scalability. Projects like Bale Bio play a vital role in this transition by providing platforms for training, research, and dissemination.

A Life Cycle Assessment revealed a 79% reduction in emissions compared to conventional structures and a net-carbon negative footprint with biogenic carbon factored in. However, the lack of Environmental Product Declarations (EPDs) and reliance on proxy data highlight the need for better data infrastructure for bio-based materials in Indonesia.

Finally, the study emphasizes the importance of public engagement, training, and circular strategies such as waste reuse, to shift perceptions, improve performance, and ensure the long-term sustainability of bamboo architecture. The Bale Bio Pavilion thus stands as a prototype for a regenerative future that can be scaled up through coordinated action and inclusive innovation.

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