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Bridging Housing and Climate Needs: Bamboo Construction in the Philippines

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Abstract: The Philippines faces a significant shortage of affordable housing, and with the growing urgency brought by climate change, there is a pressing need for more sustainable and affordable building solutions. One promising option is cement bamboo frame buildings, which blend traditional bamboo building methods with modern materials. This approach is already being implemented in social housing projects in the Philippines. Dynamic lifecycle assessment (DLCA) calculations show that these bamboo buildings can effectively reduce overall CO_2 emissions. Before a building's end of life, biogenic effects offset approximately 43% of its total production emissions, while the temporary carbon storage afforded by these biogenic materials further reduces total emissions by 14%. In comparison to concrete brick buildings, bamboo constructions reduce emissions by 70%. Transforming an unmanaged bamboo plantation into a managed plantation can potentially triple the capacity for long-term CO_2 storage in biogenic materials and further reduce net emissions by replacing concrete with bamboo as the main construction material. Thus, bamboo construction offers a potent, economically viable carbon offsetting strategy for social housing projects.

Keywords: bamboo; biogenic; dynamic; CO_2; LCA

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1. Introduction

As of 2022, approximately 23.7% of the population in the Philippines lives below the poverty line [1]. This is accompanied by a staggering number of homeless people, which is approximately 4.5 million, and these people generally reside in informal settlements [2]. This type of housing is especially problematic in the Philippines, which is situated in a highly earthquake- and typhoon-prone area. Recent estimates predict that by 2030, the housing shortage will reach approximately 6.5 million homes [3]. This situation highlights the urgent need for affordable housing in the Philippines to meet this increasing demand.

However, the process of upscaling construction to satisfy this demand results in a significant amount of CO_2 emissions. Currently, the construction industry is responsible for 40% of global CO_2 emissions [4]. Therefore, as construction activity increases, it is important to seek alternatives that result in smaller carbon footprints to alleviate the already pressing issue of climate change. The Philippines is among the countries with the highest risks of extreme weather conditions, and climate change can further intensify that risk [5].

The goal, therefore, is to provide affordable and sustainable housing solutions to meet housing demand while also minimizing greenhouse gas (GHG) emissions. Conventional construction materials such as concrete and steel, while providing robust structures, also come with significant carbon footprints. In many European countries, these materials are partially replaced by biogenic materials, such as wood, to decrease embodied emissions. In the Philippines, bamboo is the prime candidate for the principal construction material of affordable housing projects.

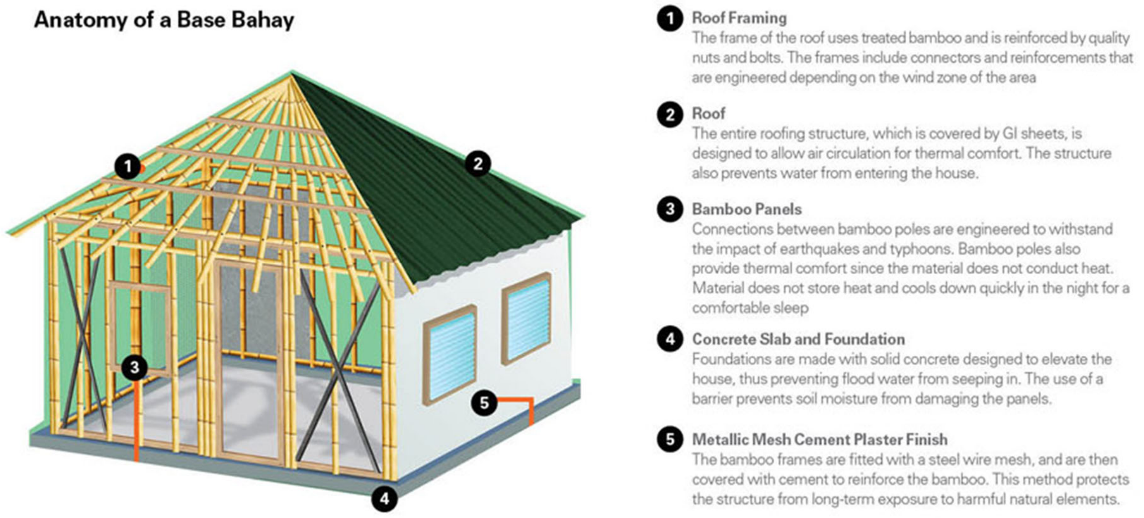
1.1. Bamboo in Construction

The use of bamboo as a building material has a long history in the Philippines. Particularly in regions with naturally occurring bamboo forests, such as Africa, America, and Asia [6], bamboo has traditionally been used for housing. Bamboo displays high tensile strength and elasticity [7] while also being a relatively lightweight material, resulting in a high strength-to-weight ratio. This makes the material especially suitable for construction in areas prone to earthquakes and strong winds [8], which is the situation in the Philippines. Additionally, bamboo is known for its rapid growth speed, which reaches up to 25 cm/day [8], resulting in a much quicker turnover compared to alternative biobased materials such as wood. This results in a rotation period of only 1 to 4 years [7]. The fact that only 25% of bamboo canes are harvested per year means that bamboo can be continuously harvested while still maintaining a standing bamboo forest.

Today, construction with bamboo comes in various forms. Untreated bamboo culms are still used, especially for short-term applications in instances where the material is abundant [9]. For more long-term construction, the poles are treated with chemical substances to help them withstand biological attacks [10,11], thus ensuring a longer lifespan for the bamboo material. It is estimated that today, more than one billion people live in some form of housing that uses bamboo, further highlighting the importance of bamboo as a construction material. The most common structural bamboo construction system is the composite shear wall system, which uses a combination of bamboo poles, cement, and wood. For the cladding of the walls, flattened bamboo is used, which is most commonly sourced by manually opening regular bamboo poles [12]. A similar building method, referred to as the cement bamboo frame (CBF) technique, is employed by the NGO BASE-Bahay in the Philippines. Similar to a building made with conventional materials, the foundation is made of concrete to ensure that the building can withstand lateral loads and to keep the bamboo away from ground moisture. The building itself is primarily constructed from treated bamboo poles and cement plaster. The main wall structure consists of frames with vertical bamboo poles supported by horizontal wood beams. Diagonal steel flat bars provide additional stability for the wall panels, which are then covered with a steel mesh to support the mortar plaster used for cladding. Recently, BASE has replaced the steel mesh used in wall panels with flattened bamboo. This substitution significantly reduces both the amount of steel in the building and the mortar necessary for the cladding. For the roof, bamboo poles are used to create the structure and are then covered by GI sheets [13]. A more detailed overview of the construction method can be seen in Figures 1 and 2. Almost two thousand housing units had been constructed using this technology in the Philippines over the last decade. These buildings are engineered to be disaster resilient, following international standards for structural design with bamboo such as ISO 22156 [14]. Their remarkable performance under external loads and price point increases their acceptance by low-income communities with each passing year.

1.2. Life Cycle Assessment (LCA)

To accurately assess the environmental impact of a construction system, properly quantifying that environmental impact is essential. Life cycle assessment (LCA) is a widely utilized tool for this purpose. The LCA methodology is designed to account for all the relevant ecological impacts across a product's life cycle, from the production of raw materials to its end-of-life treatment. The initial LCA phase involves defining the goal and scope of the analysis, which sets the parameters and objectives for the assessment. Then, an inventory analysis is conducted to identify and quantify all the relevant material and energy inputs and outputs that are associated with the system under study. Following the inventory analysis, an impact assessment is conducted, wherein the potential environmental effects associated with the identified inputs and outputs are evaluated. Finally, the LCA results are interpreted to ascertain their relative significance and to provide a clear and comprehensive understanding of the environmental implications associated with the product or process under evaluation [16] (Figure 3).



1 Roof Framing
The frame of the roof uses treated bamboo and is reinforced by quality nuts and bolts. The frames include connectors and reinforcements that are engineered depending on the wind zone of the area

2 Roof
The entire roofing structure, which is covered by GI sheets, is designed to allow air circulation for thermal comfort. The structure also prevents water from entering the house.

3 Bamboo Panels
Connections between bamboo poles are engineered to withstand the impact of earthquakes and typhoons. Bamboo poles also provide thermal comfort since the material does not conduct heat. Material does not store heat and cools down quickly in the night for a comfortable sleep

4 Concrete Slab and Foundation
Foundations are made with solid concrete designed to elevate the house, thus preventing flood water from seeping in. The use of a barrier prevents soil moisture from damaging the panels.

5 Metallic Mesh Cement Plaster Finish
The bamboo frames are fitted with a steel wire mesh, and are then covered with cement to reinforce the bamboo. This method protects the structure from long-term exposure to harmful natural elements.

Figure 1. Structure of a building using the cement bamboo frame technique, as proposed by BASE [15].

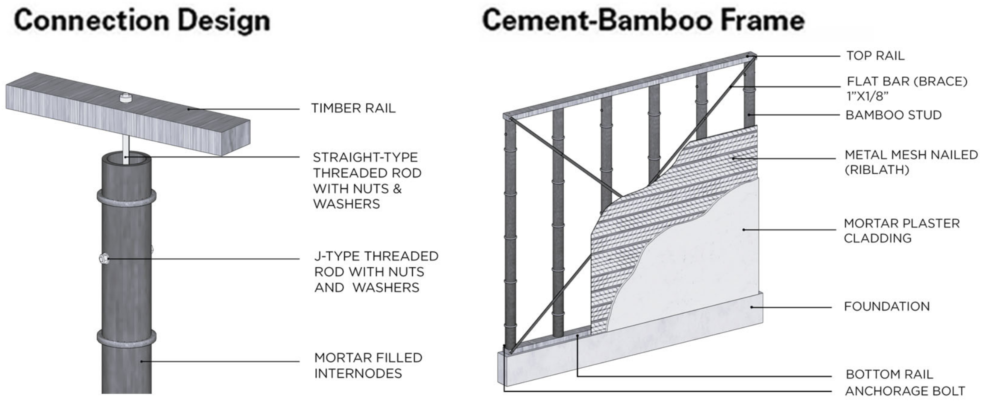
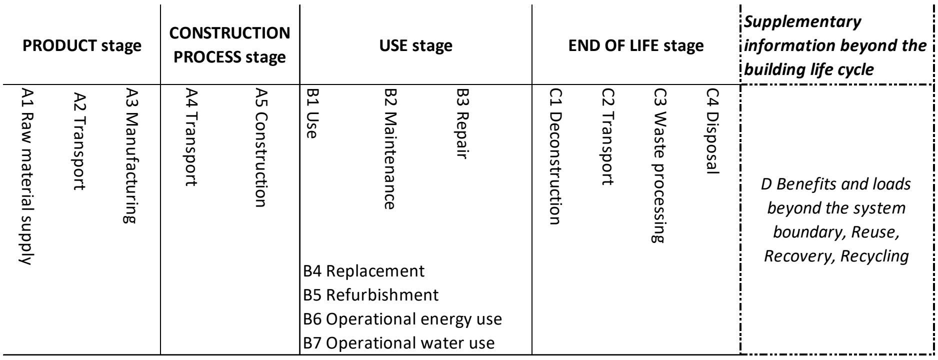


Figure 2. Connection design and wall structure of a cement bamboo frame building as proposed by BASE [15].



PRODUCT stage	CONSTRUCTION PROCESS stage	USE stage	END OF LIFE stage	*Supplementary information beyond the building life cycle*
A1 Raw material supply A2 Transport A3 Manufacturing	A4 Transport A5 Construction	B1 Use B2 Maintenance B3 Repair B4 Replacement B5 Refurbishment B6 Operational energy use B7 Operational water use	C1 Deconstruction C2 Transport C3 Waste processing C4 Disposal	*D Benefits and loads beyond the system boundary, Reuse, Recovery, Recycling*

Figure 3. Overview of the relevant product stages based on EN 15978 [17].

In many LCA studies, the B, C, and D modules are frequently excluded due to the high level of uncertainty associated with predicting the future stages of a product's life. When these stages are omitted, the LCA is referred to as employing a "cradle-to-gate" approach. In contrast, an LCA that encompasses not only the production phase but also the use phase of the product, as well as its end-of-life processes, is termed a "cradle-to-grave" approach. This distinction is crucial, as it significantly impacts the scope and potential insights that can be derived from the LCA. In the context of biobased construction materials, such as bamboo, LCA can play a pivotal role. For example, it enables a meticulous comparison between the environmental impacts of conventional construction materials, such as steel or concrete, and more environmentally friendly alternatives, such as bamboo. This quantitative analysis can inform builders, policymakers, and stakeholders of the potential advantages and trade-offs associated with adopting environmentally friendly building practices and materials, thereby facilitating more informed and sustainable decision-making [18].

1.3. LCA and Bamboo

The ecological impacts of bamboo construction materials have been quantified through LCA in several studies. Due to the high versatility of these products and the variability in their production processes, the LCA calculation results can notably vary among studies [19]. In the case of LCAs conducted on traditional bamboo construction, specifically, the use of treated bamboo poles rather than highly processed EBPs, Zea Escamilla and Habert [19] examined the production emissions of bamboo poles in comparison to those of EBPs, emphasizing the uncertainties in the production stage. Their results indicate that further processing bamboo poles into engineered products approximately doubles the initial emissions [19]. Moreover, social housing solutions using different construction materials in Colombia have found that traditional bamboo and EBPs outperform more industrialized building materials, with CBF construction slightly outperforming EBPs for single-story buildings [6]. A parametric LCA approach was developed by Eleftheriou et al. [20] to examine the influence of various building parameters, such as building dimensions, on the overall environmental impact. This research also included a detailed comparison of CBF buildings with concrete brick buildings, revealing a significant reduction in emissions when using cement bamboo frame constructions rather than concrete brick.

1.4. Methodologies for Carbon Storage Quantification

In the standard LCA approach, all emissions throughout a product's lifecycle are scrutinized. However, this approach overlooks temporary carbon storage in biobased construction materials, such as bamboo, which sequesters significant carbon during its growth phase [21]. This carbon remains stored until the end of the material's life, when it is rereleased into the atmosphere. Accounting for this temporary carbon storage in LCA calculations is a contentious issue, which has resulted in the development of various methodologies over time [22]. The prevalent methodologies include the 0/0 approach, where the biogenic CO_2 flows are excluded, and the $-1/+1$ approach, which accounts for CO_2 sequestration during production (-1) and emission at end-of-life (+1). Although both approaches yield the same net environmental impact, they allocate emissions differently [22]. Levasseur et al. suggested incorporating the temporal profile of emissions into LCA calculations to enhance consistency across different time horizons [23]. This proposal led to the development of dynamic lifecycle assessment (DLCA), where the timing of emissions influences the calculated global warming potential (GWP) [23]. DLCA, as later extended by Levasseur, enables the nuanced quantification of temporary carbon storage effects in biogenic materials [24]. Furthermore, the work of Pittau and Habert revealed noticeable discrepancies between DLCA and static approaches, with DLCA often offering more refined results. However, DLCA is less frequently employed due to its intensive modelling requirements and its need for dynamic lifecycle inventories [25]. To simplify DLCA, Cherubini introduced the GWP_{bio} approach [26], which was subsequently further refined by Guest in 2013 [27]. This method is used to quantify temporary carbon storage effects based on specific rotation periods in forests or plantations and specific storage times in durable products, such as construction materials. Lastly, Vogtlander introduced a distinct approach used to calculate the benefits of carbon storage based on global carbon cycles and land-use changes [28]. This methodology posits that only long-term shifts in overall carbon storage should influence the ecological footprint of a product. It gauges the benefits of carbon storage by considering the net change in land use and the additional storage in plantations and products that result from increased construction activity.

1.5. Carbon Storage and Bamboo

Compared to the research on wood, there is a relative scarcity of research examining the biogenic carbon storage effects of bamboo [29]. Many studies aiming to assess the environmental impact of bamboo employ the 0/0 approach, thereby overlooking the biogenic storage capacity of bamboo in their analyses. Some cradle-to-gate studies have adopted a −1/+1 approach that considers the benefits of bamboo biogenic storage. In such instances, since the end-of-life emissions (module C) are not accounted for, the biogenic storage is effectively treated as negative emissions in the overall environmental impact. For example, Xu et al. investigated engineered bamboo products [30] and yielded net negative CO_2 balances. A similar approach was applied for the production of bamboo scrimber flooring, which also resulted in net-negative emissions [31]. The global flows approach, formulated by Vogtlander et al., has been adapted to bamboo in select instances [28]. Lugt and Vogtlander examined the environmental impact of industrial moso bamboo products within China [32], while Phuong and Viet applied this methodology to engineered bamboo products in the Vietnamese market [33]. In both studies, the combination of carbon storage and the avoidance of emissions from substituting fossil fuels at the end-of-life stage contributed to net-negative global warming impacts for most of the products analysed.

1.6. Economic Assessments and Bamboo

While a significant portion of the research related to bamboo-based construction is focused on environmental impacts, there is a notable scarcity of economic assessments on the use of bamboo in the construction sector. When the economic aspects are examined, they typically involve the monetization of environmental damage, which is often assessed through the "eco-costs" approach. Eco-cost is a common LCA indicator used to quantify the environmental burdens associated with a product's impacts [34]. Zuraida and Larasati employed this assessment method to compare various bamboo preservation techniques [35]. To date, there are no studies that juxtapose the requisite investment costs for traditional bamboo buildings with the prospective returns derived from carbon crediting schemes. Such an analysis can inform decisions concerning the transition from current unmanaged bamboo forests to managed plantations, where bamboo culms are harvested purposefully for the construction of affordable housing.

With this article, we aim to present the potential of bamboo-based construction systems, not only to provide low-carbon housing solutions but also to serve as carbon sinks, while addressing the existing research gap on the economic aspects of bamboo construction. The integration of ecological and economic analyses enables the assessment of bamboo-based social housing as a potential carbon offsetting strategy.

2. Materials and Methods

This assessment consists of two primary components: an ecological assessment and an economic assessment. Input data are categorized into industry and building levels, with building data sourced from a specific case study project and industry data obtained from bamboo supply chain insights and expert interviews. The material flow analysis (MFA) provides an initial overview of the bamboo construction industry's material flows. A dynamic MFA, integrated with an LCA based on an adapted ecoinvent dataset [36], is employed to gauge the long-term impacts of increased bamboo construction and to calculate the benefits of temporary carbon storage through a DLCA. Concurrently, economic data collected at the building and industry levels for the case study are used to evaluate the necessary investments for such operations. The integration of ecological and economic analyses enables the assessment of bamboo-based social housing as a potential carbon offsetting strategy. To address potential strategy adjustments and variable uncertainties, scenarios were developed, and their impacts on economic and ecological outcomes were assessed.

2.1. Case Study—The Philppines

The selected case study was provided by the BASE Bahay foundation [13] in the Philippines. The project is aimed at providing a sustainable village for orphaned children and housing units for underprivileged families in the Batangas region, with a focus on 30 duplex houses built using cement bamboo frame technology. The bamboo, specifically Bambusa blumeana (locally known as Kawayan Tinik), was locally sourced. Two construction methods were deployed, with one using flattened bamboo cladding and another using steel mesh walls. The primary construction data, such as building plans and bills of materials, were directly provided by the BASE Bahay foundation. A field trip was conducted to gather insights into the bamboo supply chain, which included visits to a harvesting site, treatment facility, ongoing construction project, and a finished project. This trip did not include the end-of-life phase. For insights into the harvesting and treatment processes of bamboo, a facility in Negros Oriental, called Kawayan Collective, was studied. This facility, although not directly linked to the primary case study, is a recurring supplier for similar projects by BASE Bahay and was chosen due to the comprehensive data availability that it provides regarding the treatment process [10]. The documented bamboo treatment process includes cutting, manual washing to remove imperfections, starch removal via submersion in water, sun-drying, preservation through boric acid treatment, and final storage through sale. The treatment facility also produces various bamboo products, such as furniture and floor panels, that are constructed from the waste generated during the initial cutting of poles [10].

2.2. Mass Flow Model

The initial component of the paper is the mass flow model, which serves as the foundation for the subsequent dynamic material flow analysis (DMFA) and DLCA. Material flow analysis (MFA) is pivotal for understanding resource efficiency and environmental impact, as it tracks the movement and lifespan of materials within ecosystems and human economies. It provides critical insights for sustainable management, enabling the identification of key intervention points to reduce carbon emissions and optimize resource use [37]. A mass flow model comprises both flows and processes, with each process having specified inflows and outflows. Each outflow is associated with a transfer coefficient, which is used to quantify the percentage of that outflow relative to the total inflow. For a process, p, with an outflow, i, and a number of inflows, n, the transfer coefficient, k, is calculated as follows [38]:

$$k_{p,i} = \frac{Outflow_{p,i}}{\sum_n Inflow_{p,n}} \tag{1}$$

In accordance with the principle of mass conservation, the following boundary condition is established for each process:

$$\sum_i k_{p,i} = 1 \tag{2}$$

In this paper, only the material flows of bamboo are modelled. Consequently, the material flows of other materials utilized in the construction have not been modelled.

Five primary processes were identified for the construction of buildings utilizing composite bamboo shear [12]: (i) harvesting, (ii) treatment, (iii) flattened bamboo production, (iv) waste processing, and (v) construction. The subsequent sections of this paper detail each process, its underlying assumptions, and the calculated transfer coefficients obtained through Equations (1) and (2).

During the harvesting phase, the inflow is characterized by harvested culms. The principal outflow consists of bamboo culms transported to the treatment site upon completion of this phase. The residues that remain on site include the culm's base, which connects to the plant, branches and leaves that are removed by the harvester, and pole rejects that do not match the desired specifications. Harvesters trim useful culms at approximately

2.5–3 m in height, since the base is not optimal for construction [10]. Given that the average height of mature culms is 15 m [39], the transfer coefficient is deduced as:

$$k_{1,1} = \frac{3\text{ m}}{15\text{ m}} = 0.2 \tag{3}$$

The uppermost part of the culm is also removed due to its small diameter [39]. The branches and leaves, which represent approximately 15% of the total aboveground mass, are also pruned on-site [21,40]; thus:

$$k_{1,2} = 0.15 + \frac{1\text{ m}}{15\text{ m}} = 0.217 \tag{4}$$

Furthermore, the poles undergo an inspection by the treatment facility's buyer, resulting in a rejection rate that varies from 2–10%, depending on the harvester's proficiency [39].

$$k_{1,3} = 0.05 \tag{5}$$

Factoring in the aforementioned losses and adhering to the conservation of mass principle (Equation (2)), the resultant output of acceptable bamboo culms is:

$$k_{1,4} = 1 - 0.2 - 0.217 - 0.05 = 0.533 \tag{6}$$

In the treatment phase, the inflow is denoted by bamboo culms sourced from the harvester. The outflows include water, waste, and treated bamboo poles. Water loss references the bamboo pole production data from ecoinvent [36]. It is posited that for each kilogram of bamboo culm input, there is a net water weight loss of 0.33 kg.

$$k_{2,1} = 0.327 \tag{7}$$

Waste, which emerges from the initial cutting of culms and removal of imperfections, is combined with waste that also contains parts of the culm that are deemed unusable, such as those with insufficient diameter [39]. The resultant 24.8% waste ratio is then multiplied by the water loss weight (Equation (7)):

$$k_{2,2} = 0.248 \times (1 - 0.327) = 0.167 \tag{8}$$

Considering the weight losses and the conservation of mass (Equation (2)), the resulting output of bamboo poles is:

$$k_{2,3} = 1 - 0.167 - 0.327 = 0.506 \tag{9}$$

Other inputs, such as the boric acid used during the treatment, are considered negligible by weight and hence are excluded from the MFA. Flattened bamboo originates from bamboo poles, implying that the input consists of poles from the preceding phase. This process produces two outputs: flattened bamboo and the resultant waste.

$$k_{3,1} = 0.251 \tag{10}$$

Subsequently, considering Equation (2), the output for flattened bamboo is:

$$k_{3,2} = 1 - 0.251 = 0.749 \tag{11}$$

The waste emerging from the treatment, such as that from pole cutting or the portions unfit for construction, is processed into products such as furniture or floor panels. Hence, the input stems from the waste produced in the treatment phase. The outputs include finished long-term bamboo products, the waste produced during the process, and the waste used for short-term products, which are typically found in households near the facility. Kawayan Collective provided a waste mapping file that was utilized to estimate the amounts in a representative batch [10].

Stated below are the coefficients for final waste (Equation (12)), short-term products (Equation (13)), and long-term products (Equation (14)):

$$k_{4,1} = 0.519 \tag{12}$$

$$k_{4,2} = 0.2 \tag{13}$$

$$k_{4,3} = 0.281 \tag{14}$$

Acknowledging that these products are crafted based on demand implies that the waste ratios fluctuate depending on orders. Considering their marginal impact on the overall results, the representative order values were deemed adequate. In the construction phase, flattened bamboo and bamboo poles from the treatment facility are employed as inputs. The ratio between them is elucidated in the subsequent chapter and hinges on the calculated building variant. The outputs from this phase include the waste from on-site pole and flattened bamboo cutting and the material integrated into the building. Waste generation is ascertained through an overlay of supplied pole lengths versus the lengths needed for actual buildings, as provided by BASE Bahay [41]. This results in a 5.4% waste value. Given the data limitations, the waste arising from flattened bamboo during construction was assumed to be equivalent. We assume that waste is split equally between disposal (5,1) and short-term product use (5,2) [41]:

$$k_{5,1} = 0.027 \tag{15}$$

$$k_{5,2} = 0.027 \tag{16}$$

As derived from the conservation of mass principle (Equation (2)), the proportion of bamboo integrated into the building is:

$$k_{5,3} = 1 - 0.027 - 0.027 = 0.946 \tag{17}$$

2.3. Bill of Materials

The foundation of the material flow analysis is established by the material requirements needed to construct a building, as specified by the bill of materials. This bill was supplied by BASE for a project site located in Batangas. Currently, BASE is involved in the construction of two distinct building types at this site, namely, a standard model featuring steel mesh walls and an alternative model with flattened bamboo walls accompanied by a higher concrete hollow block (CHB) configuration. To facilitate a fair comparison, changes associated with the larger CHB block configuration have been isolated and are excluded from consideration. In Table 1, the material requirements for each of these building variants are detailed and the bill of materials for a comparable concrete structure is presented.

Table 1. Overview of the material requirements for different building variants in kg.

Variant	Bamboo Poles	Flattened Bamboo	Wood	Concrete	Reinforcement	Cement Mortar	Fired Clay Bricks
Flattened bamboo	967	489	535	28,375	609	8074	0
Steel mesh	967	0	535	28,375	746	11,784	0
Concrete + CHB building	0	0	0	82,703	4169	1009	2402

Aside from bamboo materials, the quantities for all other components were computed using the parametric approach developed by Eleftheriou et al. [20]. The building dimensions, which were sourced from construction plans, were input into this tool. To ensure accuracy when applying the tool to a duplex house, several additional adjustments were made to the calculation method. The baseline results are derived using the flattened bamboo variant, as indicated in the first row of results.

2.4. Dynamic Mass Flow Model

While a static material flow model elucidates the resources needed to construct a bamboo building and the waste generated in the process, it does not provide insights into the carbon stock accumulating in the Anthropocene because of these buildings and products. As these entities have defined lifetimes, they only temporarily persist in the Anthropocene. In scenarios representing continuous construction activity, building and product stocks grow until a balance is established, which occurs when the number of demolitions equals the number of new constructions. Figure 4 presents the natural carbon storage in plantations (in light green), then its material flows into the Anthropocene (light tan) in the form of buildings, temporary, and long-term products. This stock accumulation signifies an augmentation in carbon storage within the Anthropocene.

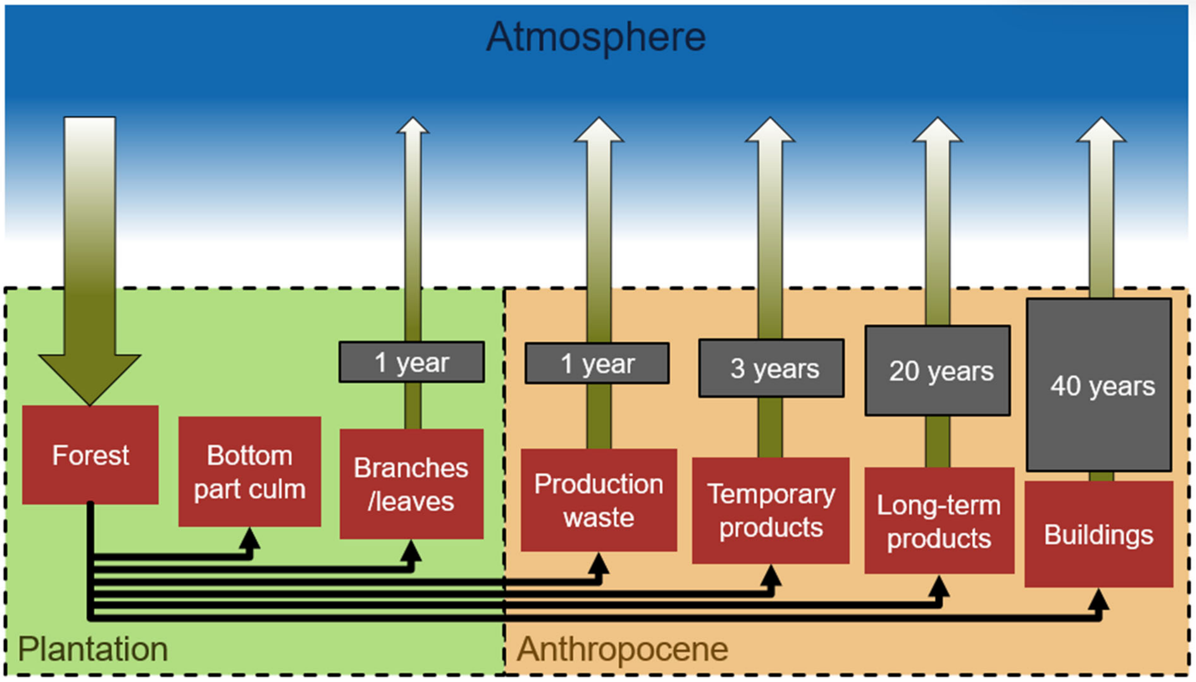


Figure 4. Carbon dynamics from bamboo plantations to the Anthropocene over a period of 1 to 40 years. CO_2 is captured from the atmosphere by the plants and transformed into cellulose. These molecules are the building blocks of all biomasses. By processing the biomass into durable products, the carbon that was captured in the forest is move into the Anthropocene as building materials and other products.

The assumptions concerning the lifespans of various components are outlined in this conceptual representation. A Dirac-delta distribution was employed to depict these lifespans, which implies that all products from a given year are demolished after their defined lifespan within that specific year. The branches and leaves are anticipated to decompose completely within one year, as are the production wastes [42]. Temporary products, such as untreated poles used for fencing, are expected to have a lifespan of 3 years. In contrast, long-term products, which are treated, are projected to have significantly longer lifespans. In terms of the buildings themselves, a 40-year lifespan is posited as a realistic baseline assumption [41]. This assumption considers not only the durability of the construction materials but also the urbanization and economic dynamics in the context of the Philippines. In recognition of the fact that the actual lifespan of a building is difficult to predict and is likely influenced by external factors (e.g., changes in land use), a sensitivity analysis was conducted on this factor.

To assess the additional amount of CO_2 stored in the building/product stock, the CO_2 stored in biomass must first be determined using the equations described in EN 16449:2014 [43] that account for the carbon content of the biomass, the biomass content in product, the moister content in product, and the ratio between the molar masses of carbon and carbon dioxide. Sohel et al. found the carbon content of oven-dried bamboo to be approximately 55% [44]. Considering the expected water content of 11% in treated bamboo poles [39], this yields an adjusted carbon content of 50% for bamboo. To estimate the potential amount of CO_2 that this bamboo carbon content can capture, we use Equation (18):

$$C\ content_{bamboo} = 0.55\ \mathrm{kgC/kg} \times \left(\frac{0.11}{(1+0.11)} + 1\right) \times 3.667\ \mathrm{kgCO_2/kgC} = 1.835\ \mathrm{kgCO_2/kg} \tag{18}$$

The carbon content, C, per kg of biomass, described in Equation (18), is defined in terms of the amount of CO_2 that can be generated from the carbon stored in the biogenic material. Since the variations in carbon content among the different parts of the plant (e.g., culm, leaves) are minimal, a consistent value is applied throughout the analysis [44]. Similarly, for wood (Equation (19)), the CO_2 emissions from biogenic sources are calculated using the same formula. The carbon content of wood is estimated to be approximately 50% for dry wood [45], resulting in:

$$C\ content_{wood} = 0.5\ \mathrm{kgC/kg} \times 3.667\ \mathrm{kgCO_2/kgC} = 1.833\ \mathrm{kgCO_2/kg} \tag{19}$$

This process is calculated in discrete time steps. For this analysis, one-year time steps are considered appropriate. The input is determined by the construction activity, representing the annual amount of material entering the Anthropocene. Given the relevance of carbon storage, this input is multiplied by the previously computed carbon content, as presented in Equation (20).

$$Input(t) = C(t) \times CarbonContent \tag{20}$$

where C(t) describes the construction activity over time. For this analysis, the construction activity is assumed to remain constant over an extended period, enabling an assessment of the effects of a continuous construction operation. The output depends on the lifespan of the products, as represented in the lifespan function L(t − i) in Equation (21). The total output for a specific year is calculated as the sum of each input, which is each multiplied by the lifespan function and offset by the timing of that respective input.

$$Output(t) = \sum_{i=0}^{t} Input(i) \times L(t-i) \tag{21}$$

Combining these equations, we obtain the following formula for calculating the stock at each point in time:

$$Stock(t) = Stock(t-1) + C(t) \times CarbonContent - \sum_{i=0}^{t} C(t) \times CarbonContent \times L(t-i) \tag{22}$$

2.5. Land-Use Calculation

One essential aspect to consider is the land area needed to supply bamboo for buildings. Considering that a bamboo forest contains culms of various ages, only a portion of the forest can be harvested each year. With an assumed rotation period of approximately 4 years, it is estimated that 25% of the culms in the forest reach maturity and are ready to be harvested each year. To be suitable for construction, poles must meet certain criteria, such as low curvature and minimal cracking. Culms failing to meet these criteria are identified through visual inspection and are not harvested. Precisely determining the number of mature culms that are left unharvested is challenging, so this value is indirectly estimated by comparing the projected output of usable construction poles with the calculated culm density of a comparable bamboo forest. Industry experts estimate that approximately 35–50 hectares are needed to produce 2000 treated poles per week (24,000 poles per year) [41]. With an average yield of 1.6 poles per input culm and using the lower estimate of 35 hectares as the requisite forest area, the following mature culm density is calculated:

$$Culm\ density_{hyp} = \frac{24000\ \text{poles}}{1.6\ \text{poles/culm}} \div 35\ \text{ha} = 429\ \text{culms/ha} \tag{23}$$

At the time this paper was written, there are no culm density estimations available for the bamboo species Bambusa blumeana [21]. Due to inherent similarities, Bambusa vulgaris is used as a proxy for this analysis. The literature estimates the culm density of a bamboo forest for Bambusa vulgaris to be approximately 2933 culms per hectare [44]. Considering that only 25% of the forest comprises mature culms, the following mature culm density, as derived from the literature, is applied:

$$Culm\ density_{lit} = 2933\frac{\text{culms}}{\text{ha}} \times 0.25 = 733\ \text{culms/ha} \tag{24}$$

Taking the ratio from the culm density calculated using the output (Equation (24)) and the forest culm density in the literature (Equation (25)) yields the ratio of mature culms being harvested:

$$Ratio\frac{harvested}{mature} = \frac{429\ \text{culms/ha}}{733\ \text{culms/ha}} = 0.59 \tag{25}$$

In this analysis, 59% of the mature culms are harvested each year. The value presented in the literature (Equation (25)) is used to calculate the carbon storage of plantations. Conversely, the culm density calculated from the output (Equation (24)) is used to determine the forest area needed to produce a given output.

2.6. LCA of Bamboo-Based Housing Units

To assess the ecological impact of material production, an LCA is employed. The specific stages of the process under examination shown in Figure 3 are indicated in brackets. The LCA calculations are conducted using the "openLCA" tool and employing the ecoinvent dataset version 3.8 [36]. The selected impact assessment method is IPCC 2013 GWP 100a [46]. Although the emissions derived from transporting materials to the site are considered (module A4), emissions associated with the construction (A5) and use phases (B) of the building are excluded. As most construction work in the Philippines involves manual labour, its environmental impact is assumed to be minimal.

2.6.1. Production of Bamboo (A1–A4)

To adapt the general bamboo pole production data contained in the ecoinvent dataset to the specifics of the Philippine case study, several adjustments based on field inspections and expert interviews were needed. These adjustments include:

- Removing the entry for fertilizers, as none are used in the relevant bamboo forests;
- Deleting the entry for technical wood drying, as such poles are sun-dried;
- Indicating the lack of an electricity requirement for trimming, as this process is manually performed with a knife;
- Removing the need for an air compressor to pump boric acid into the pole, as the poles are instead fully submerged;
- Setting the waste residues to zero, as they are calculated separately;
- Making additional general adjustments in the material flows, such as correcting underestimated amounts of waste in the production of bamboo poles (Villanueva et al., 2022 [39]).

With these adjustments applied, specific values were calculated. The major contributors and their respective contributions are detailed in Table 2.

Table 2. Static LCA values for bamboo poles and flattened bamboo.

	Total	**Main Contributors**			
Product	Production emissions [kg CO_2-eq]	Transportation to construction site	Transportation to treatment facility	Power sawing	Other
Bamboo pole	0.041	71%	17%	11%	1%
Flattened bamboo	0.050	65%	20%	14%	1%

Most of the emissions are generated during transportation to and from the treatment facility, as the production process itself predominantly involves manual labour. The additional material inputs in the system, such as tap water and boric acid, have a negligible overall impact.

2.6.2. End-of-Life (C)

For end-of-life emissions, only the transportation of materials from the building site to the disposal site was considered (C2). It is assumed that both mineral and biogenic materials are disposed of in a manner that results in negligible emissions. Emissions from the carbon stored in the biogenic materials are not considered to be a part of the end-of-life emissions but are rather treated separately. Emissions from the demolition of the building (C1) are also assumed to be negligible. Due to a lack of data regarding the average transportation distance for materials to the disposal site in the Philippines, an approximation was used. The transportation distance was assumed to be 50 km, which is approximately twice the distance assumed for transportation from the harvesting site to the treatment facility for bamboo in the ecoinvent dataset. For more reliable results, a detailed analysis of the waste management system in the Philippines would be necessary, which was beyond the scope of this project.

2.7. Dynamic Life Cycle Assessment (DLCA)

The dynamic life cycle assessment (DLCA) methodology, which was first introduced by Levasseur et al., is employed to examine the temporal distribution of emissions [23]. The primary goal is to quantify the benefits of temporary carbon storage in the building stock and other products. This is accomplished using a convolution of time-dependent emissions and a substance-specific decay function. The DLCA calculation begins with a dynamic lifecycle inventory, which is used to outline the varying emissions over time. This analysis focuses on the carbon sequestration and biogenic emissions of bamboo and wood. Since production emissions are concentrated in the first year, they remain unchanged in both dynamic and static calculations. Bamboo sequestration is assumed to occur annually, as mature culms harvested each year are replaced by younger culms in the subsequent year. For wood, a rotation period of 60 years is applied, with sequestration assumed to remain constant throughout this period. The second component of DLCA involves calculating the temporal behaviour of different emission substances. This is captured through a substance-specific impulse response function, which describes the decay time of a substance in the atmosphere, or the time needed until it is reabsorbed into natural carbon sinks. The DLCA enables a separate examination of carbon dioxide and methane emissions. Due to the minimal presence of other emission types in the LCA, these are integrated into the CO_2 emissions as CO_2 equivalents. As introduced earlier, another methodology for quantifying the effects of temporary carbon storage in biogenic materials is the GWP_{bio}, which was initially introduced by Cherubini et al. [26] and later expanded by Guest et al. [27]. The GWP_{bio} factors are derived using the DLCA methodology outlined above. The DLCA calculations are executed for various storage times and rotation periods, yielding the semi-static factors presented in the subsequent table. To obtain these semi-static factors, a fixed time horizon is set, which, in this case, is 100 years. For a longer time horizon, such as 500 years, the benefits of carbon storage diminish, leading to a decrease in the

GWP_{bio} factors. In addition to the DLCA calculations outlined above, the GWP_{bio} factors are directly applied to the system to assess potential variations in the results.

2.8. Economic Model

To calculate the relevant economic flows for bamboo material construction we used the MFA-based method developed by Ioannidou [47]. The initial step was to determine the total construction costs per building. This includes the material and labour costs from the bill of materials and the indirect costs, such as planning and temporary facilities, which are sourced on a project basis and allocated to individual buildings by dividing by the total number of buildings constructed in the respective project. The repair costs, as informed by past projects, are similarly allocated based on the overall project size. The investment considerations are based on values from the literature and expert interviews. These values are normalized into sensible functional units, e.g., per hectare investments for the plantation or the cost of building a single treatment facility. Investments are then standardized along the supply chain based on the modelled material flow analysis (MFA). For example, the average output of a treatment facility informs the necessary input at the plantation level, thus enabling the calculation of the needed plantation area and associated investments. Likewise, the output from the treatment facility is used to establish the economic input needed for subsequent construction activities.

In the analysis, the environmental impacts and economic costs of two wall panel variants—steel mesh and flattened bamboo—are compared. To quantify the benefits of switching from steel mesh to flattened bamboo, the CO_2 sinking costs are calculated via Equation (26). These costs represent the expense associated with reducing a specific quantity of CO_2 emissions, which are typically measured per ton. This value is calculated when transitioning from a standard strategy (1) to an alternative strategy (2), as described by the formula below:

$$\mathrm{CO_2}\ sinking\ cost\ \frac{\$}{t\ \mathrm{CO_2}} = \frac{Cost_2 - Cost_1}{Emissions_2 - Emissions_1} \tag{26}$$

Lastly, we include a brief assessment of the potential for bamboo construction in the CO_2 certificate market. CO_2 certificates are credits obtained from reducing CO_2 emissions, which can be traded on either regulated or voluntary certificate markets. To assess the viability of investments in this context, the period for a full return on investments (ROI) is calculated. Initially, yearly avoided emissions are monetized using a predefined CO_2 certificate price. The necessary investment is then divided by the potential returns from the certificates of the yearly avoided emissions, thus yielding the return period:

$$Return\ period\ [\mathrm{Years}] = \frac{Investment\ [\$]}{Avoided\ emissions[t\ \mathrm{CO_2}] \times Price\ of\ Certificate[\frac{\$}{t\mathrm{CO_2}}]} \tag{27}$$

3. Results

The first subsection is focused on the building-level results. Initially, the MFA results are presented to establish the needed input at the plantation level to supply materials for a building. This is followed by the presentation of the static LCA for different building variants. Subsequently, the DLCA results, which highlight the effects of temporary carbon storage using the GWP_{bio} approach, are explored. Finally, the results of the economic calculations at the building level are presented. The second subsection is aimed at ascertaining the effects of bamboo construction at an industry level for a specified construction scenario. Initially, the results of the dynamic MFA are illustrated, detailing how the total carbon storage in the building stock evolves over time. Following this, the necessary investments for a construction operation based on a single treatment facility are computed. The subsection wraps up with a summary of the overall CO_2 emissions and requisite investments. In this subsection, the results are scaled to a standard cement factory to ascertain the relative impacts of adopting bamboo materials as an alternative.

3.1. Material Flows

Table 3 presents the description of the MFA and coefficients of transfer from forest to buildings.

Table 3. Overview of the inputs and outputs and their respective transfer coefficients.

Process	Input	Output	Transfer Coefficient
Harvest	Harvested culms	Bottom part	$k_{1,1} = 0.2$
		Branches/leaves	$k_{1,2} = 0.217$
		Rejects	$k_{1,3} = 0.05$
		Cut culms	$k_{1,4} = 0.533$
Treatment	Cut culms	Water	$k_{2,1} = 0.327$
		Bamboo waste	$k_{2,2} = 0.167$
		Poles	$k_{2,3} = 0.506$
Flattened bamboo production	Poles	Bamboo waste	$k_{3,1} = 0.251$
		Flattened bamboo	$k_{3,2} = 0.749$
Waste processing	Waste from treatment	Final waste	$k_{4,1} = 0.519$
		Temporary products	$k_{4,2} = 0.2$
		Long-term products	$k_{4,3} = 0.281$
Construction	Bamboo poles Flattened bamboo	Final waste	$k_{5,1} = 0.027$
		Temporary products	$k_{5,2} = 0.027$
		Bamboo in building	$k_{5,3} = 0.946$

Using the factors listed in Table 3, combined with the building bills of materials from Table 1, the material flows of a single bamboo building can be computed. The material flow analysis for a building with flattened bamboo walls is shown in Figure 5.

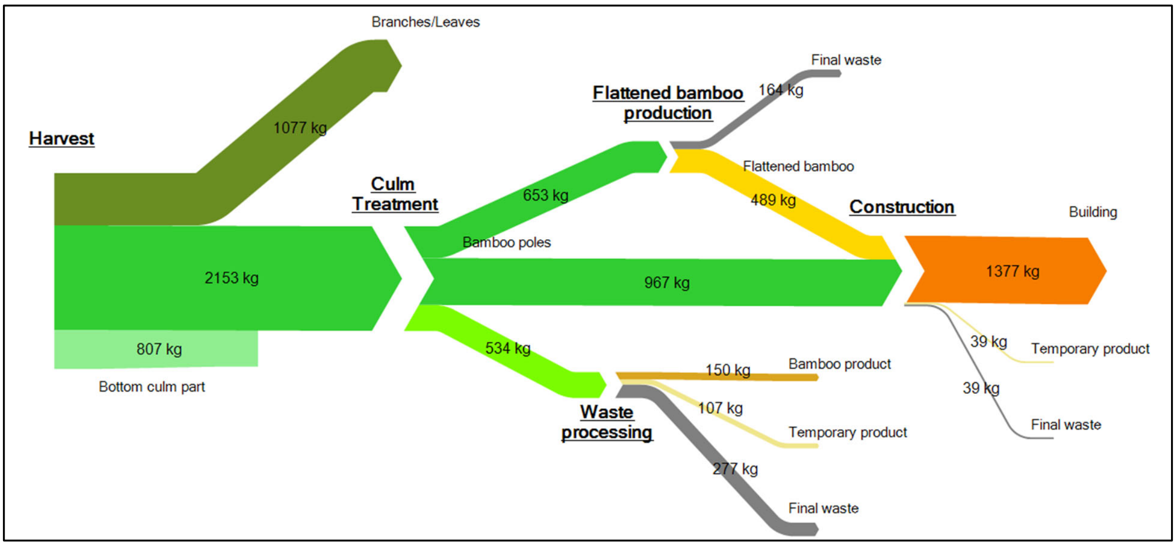


Figure 5. Bamboo material flows of a single building with flattened bamboo used for the wall panels.

The plantation is excluded from the MFA (Figure 5) for clarity, and calculations are based on dry bamboo to ensure comparability. For a standard bamboo building containing 967 kg of bamboo poles and 489 kg of flattened bamboo, a total of 4037 kg of culms are utilized. Approximately half of this biomass is removed from the forest, while the rest, including the branches, leaves, and unsuitable culm sections, remains in the plantation.

Culm treatment and flattened bamboo production each generate approximately 25% waste, while the construction process results in approximately 5% waste. The comprehensive process, from harvest to building completion, yields specific outputs, with the ratios to the total input indicated in a subsequent column. Approximately 34% of the originally harvested culms are incorporated into the building, which highlights the significant upstream biomass loss that occurs in the construction process. In total, 58% of the affected biomass is not utilized in any products, either decomposing in the plantation or being categorized as final waste (Anthropocene disposal). Apart from the 34% of bamboo used in buildings, a small fraction is found in temporary untreated products (3.6%) and in treated long-term bamboo products (3.7%), which are generated in the treatment facility from the waste derived from bamboo pole production. Integrating the calculations from the land-use calculations and considering a rotation period of 4 years, the bamboo forest area necessary to source materials for a single building can be determined. This results in a requisite area of 0.29 hectares (approximately 50 × 50 metres) to supply bamboo for one building. Given the rapid rotation period, a new bamboo building can be constructed annually using mature culms harvested from this area. The subsequent calculation of the overall biomass in this area provides the following biomass distribution for a single harvest cycle:

3.2. Classic LCA

The results of the classic LCA of the different variants are presented in Figure 6.

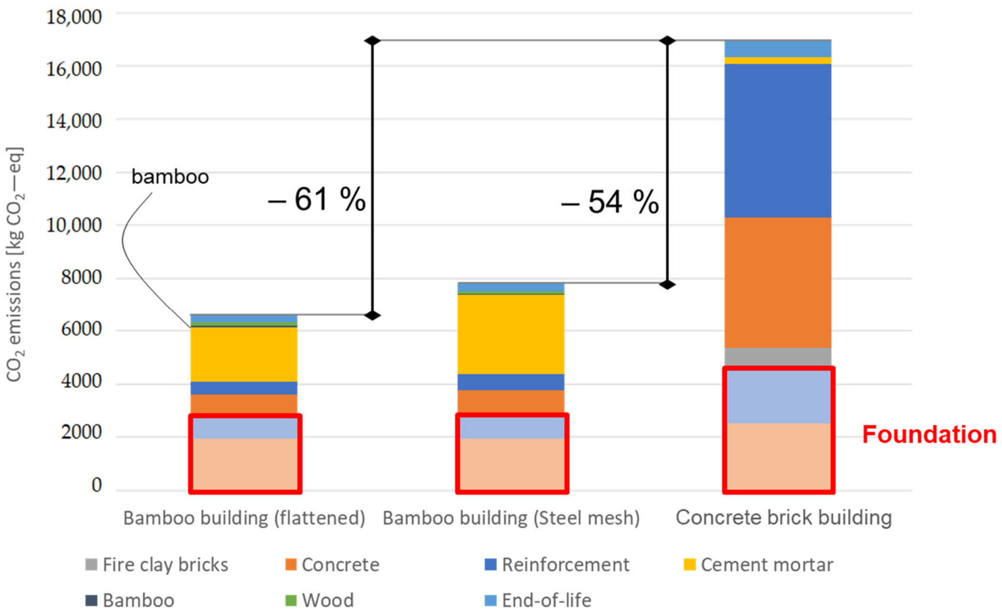


Figure 6. Static LCA results of both building variants and of a comparable concrete building, as sorted by material.

As depicted in Figure 6, bamboo buildings exhibit significantly lower emissions than concrete buildings, amounting to only approximately one-third. Emissions from a bamboo building employing steel mesh for wall cladding are approximately 20% higher than those using flattened bamboo, which is attributed to steel's higher carbon footprint than that of flattened bamboo. Broadly, bamboo and wood production emissions remain relatively low. In the context of flattened bamboo buildings, only approximately 1% of emissions arise from bamboo production. For bamboo buildings, the primary production emission contributor is concrete, which is predominantly employed in foundations and slab-on-grade components. Conversely, conventional buildings necessitate more concrete and reinforcing steel, resulting in it being the dominant emission source for that building type. The emissions originating from transportation to disposal sites at the building's end-of-life account for approximately 4% of the total emissions across different variants.

In the figure, the red box denotes the foundation's relative emissions contribution, which represents nearly half of the total emissions for bamboo buildings with flattened bamboo walls. Cement mortar stands as the primary contributor to the building's main structure emissions. This underscores the fact that to further curtail emissions, the relevant options include identifying an appropriate cement mortar substitute or addressing the foundation. Bamboo, due to its already comparatively low carbon footprint, need not be the central focus here.

3.3. CO_2 Flow Model

Figure 7 shows the CO_2 flow model, which was computed using the carbon content of the respective biogenic flows (Equations (18) and (19)) as well as the emissions computed in the classic LCA.

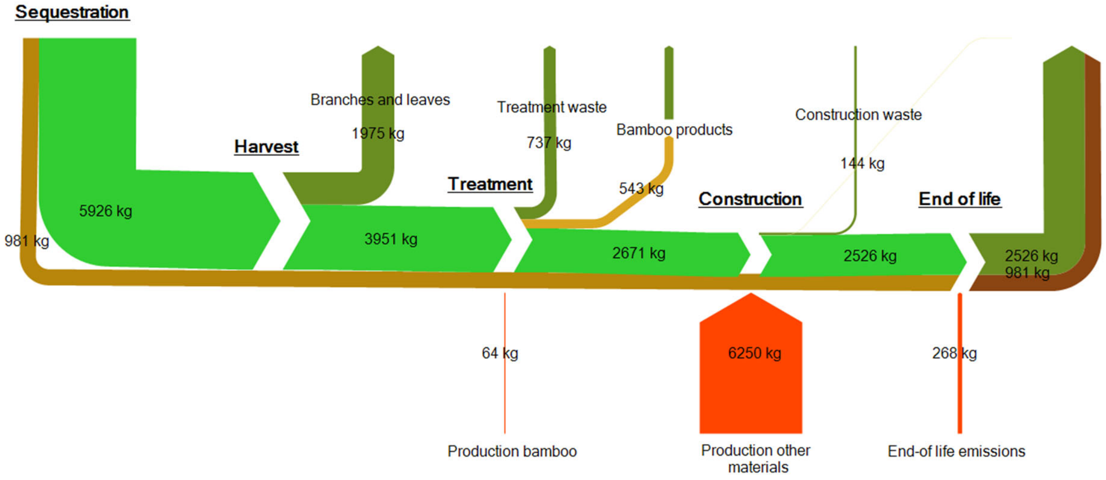


Figure 7. CO_2 flows for a single bamboo building.

The fossil emissions from production and end-of-life phases, which are exclusively considered for the static LCA calculation, are highlighted in red. Subsequently, the green-shaded biogenic emissions will also be incorporated into the DLCA calculations. The biomass harvested for construction undergoes complete restoration in the initial year, which equates to approximately 6 tons of CO_2. Subsequently, the biogenic flows disperse over time based on product lifespans, as outlined in Figure 4. A simplified approach is adopted for wood. An equivalent quantity of wood for a building is presumed to be sequestered throughout the rotation period. However, due to the extended sixty-year rotation period, the waste produced during wood production can adversely affect the DLCA computation, as this waste re-emits captured CO_2 around the first year, while sequestration takes longer. This divergence does not apply to bamboo, given its full sequestration within the initial year. Impacts from wood warrant a distinct MFA to quantify waste in harvesting and production; however, these effects are disregarded due to wood's lower relative quantity and overall minor biogenic influence that stem from the prolonged rotation period for wood. Most emissions, including the sequestration of bamboo, occur within the first year, while biogenic emissions are offset by the lifespan of the building or the respective product. It is important to note that the biogenic emissions from production waste and the biomass left on site are compensated by a part of the sequestration that occurs in the first year, meaning that these parts of the plant do not impact the DLCA calculation. Positive effects only occur for delayed biogenic emissions.

3.4. Dynamic LCA Results

The results for the dynamic calculations are presented in Figure 8.

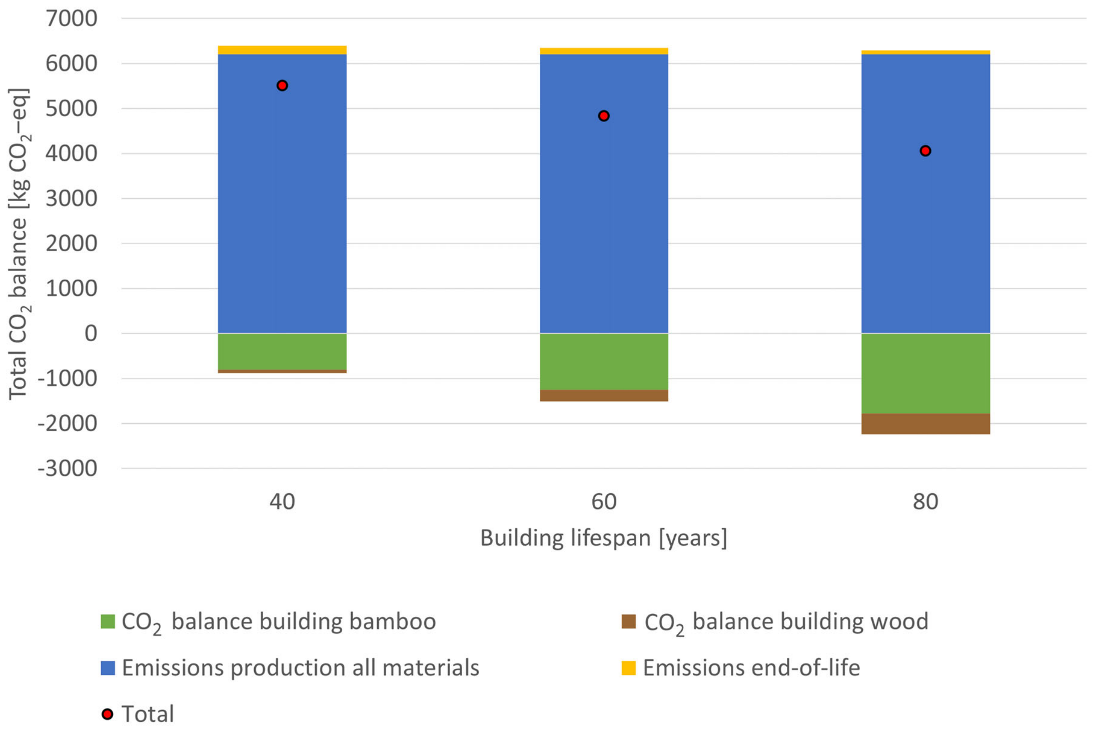


Figure 8. Dynamic LCA results for a forty-, sixty- and eighty-year service life.

Given that the largest balance represents the best option, the DLCA of the bamboo building reveals that the most favourable CO_2 balance occurs at an eighty-year lifespan, where the cumulative biogenic benefits of bamboo are maximized. This finding indicates that as the building ages, the sustained carbon storage advantage of bamboo over conventional materials increases, which contrasts with a prolonged lifespan where the dynamic storage benefits diminish. Concrete buildings, which do not share the carbon benefits of biogenic materials, show their dynamic effects primarily through the decay and delayed release of methane emissions. Initially, methane has a significant impact, but this impact lessens over time as these emissions decay. The updated data from Figure 8 demonstrate that at the end of life—80 years for this study—the emissions from bamboo buildings are significantly lower than those from concrete buildings, and their levels surpass the reductions predicted by static calculations. This highlights the long-term sustainability and carbon sequestration potential of utilizing bamboo as a construction material, thus offering a stark contrast to the emissions profile of traditional concrete buildings.

3.5. Economic Assessment

The bill of materials provided by the BASE-Bahay foundation include the respective estimated costs per building for the project in Batangas as well as the material quantities. The needed economic investments for the construction of a single building are presented in Figure 9, and they are subdivided by cost type and material:

The total cost of a duplex building is just under USD 10,000, with material expenses accounting for nearly 80%. Among these costs, flattened bamboo walls contribute the most to buildings that use such panels, amounting to approximately USD 2000. This item is of great importance as it shows the economic benefit of adding value to a natural resource by processing it. In this case, the transformation of round pole bamboo into flattened bamboo provides an additional flow to the local economy and community. Wood and concrete, both amounting to approximately USD 1200, follow closely in terms of expenditure, yet there is little added value to the local economy as these products are either imported or produced by multinationals. A notable portion of the funds goes towards materials that are not distinctly affiliated with the primary material categories. The bill of materials also encompasses labour expenses on the construction site, approximately USD 1800 or 20% of the overall costs. Additional indirect expenses cover temporary facilities for bamboo panel fabrication and project planning. These costs were estimated for a thirty-house project, which serves as the examined case study. This indirect cost factor includes planning costs (USD 2000), the site engineer's salary (USD 3500), and temporary facility construction (USD 7500). Notably, certain temporary facility components, such as fabrication tables, can be repurposed for future projects, subsequently diminishing the indirect costs per building. The indirect costs also include potential early-project repair costs due to potential bamboo pole replacements. In a similar past project, ten poles needed replacement. This project consisted of 180 buildings, equivalent to approximately USD 36,000, thus indicating a negligible bamboo pole failure rate. With a USD 500 replacement average, the expected per-house cost is a mere USD 16.

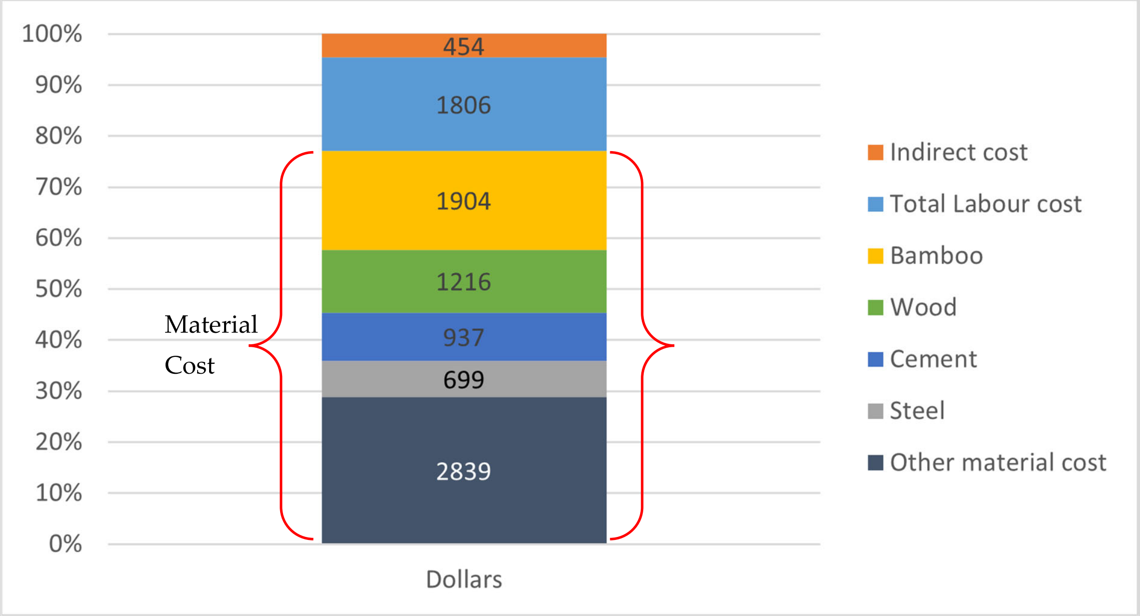


Figure 9. Cost of a single building subdivided by cost type and material in dollars.

3.6. Investment and Outputs

To depict the requisite investments for bamboo construction, the values are proportionally adjusted based on the yield of a single treatment facility. Thus, Figure 10 illustrates the essential input at the plantation level, alongside the ensuing output at the construction level, which are all attributable to a singular treatment facility.

The values in the figure are distributed across the primary components of bamboo construction, namely, plantation, treatment facility, and building construction. An initial investment of approximately USD 20,000 is anticipated for the construction of a treatment facility, encompassing both the facility itself and the cost of washing stations. A single treatment facility is projected to yield approximately 2000 poles monthly, equivalent to 174 tons of bamboo annually. This output necessitates an input of 15,000 culms, which requires a plantation area of 35 hectares. Calculating from the MFA values, the plantation stores a total of 8000 tons of CO_2, entailing an estimated initial plantation investment of USD 900 per hectare, for a total of USD 30,000. Often, however, the local bamboo resources near the treatment facility suffice, preventing the need for additional culm plantations. The facility's output is adequate to supply the necessary materials for 126 buildings per year. With construction costs per building of approximately USD 10,000, the cumulative construction cost per year amounts to USD 1.24 million. The application of these figures to the dynamic MFA indicates that the potential long-term storage for these buildings culminates in an additional 18,000 tons of CO_2. Consequently, a single treatment facility bears the potential to produce enough materials for the construction of approximately

125 duplex houses while amplifying CO_2 storage threefold over what can be stored by a 35-hectare bamboo forest.

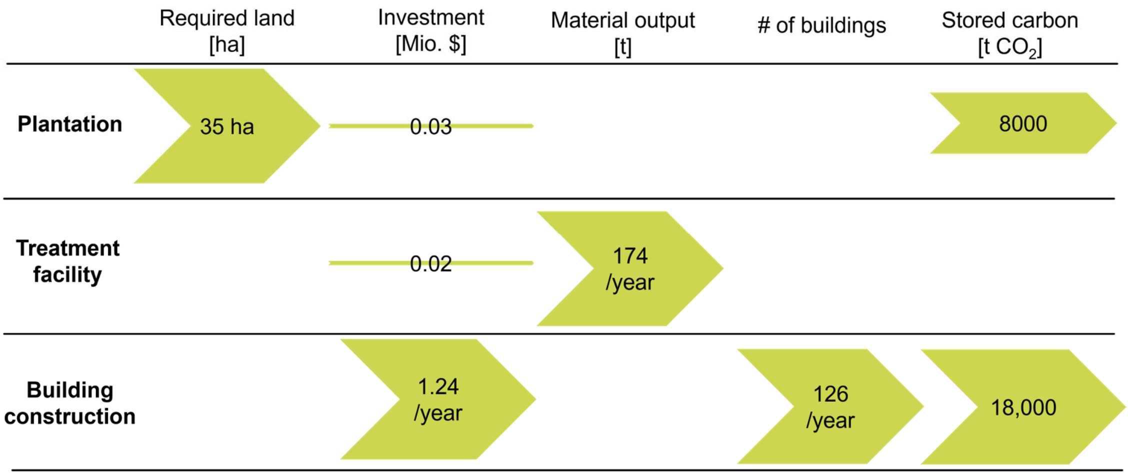


Figure 10. Investments and outputs scaled to a single treatment facility.

4. Discussion

The key outcomes from the preceding chapters are consolidated in this section. Figure 11 presents the results of the three strategies, namely, (i) afforestation with bamboo, (ii) afforestation and construction with bamboo, and (iii) conventional construction with concrete and CHB. The results were normalized to the production from an ordinary Portland cement factory. The anticipated output of such a factory (1 Mt cement) [48] was juxtaposed against the average cement amount used in a conventional building, thus determining the potential building output (35,000) from a single facility.

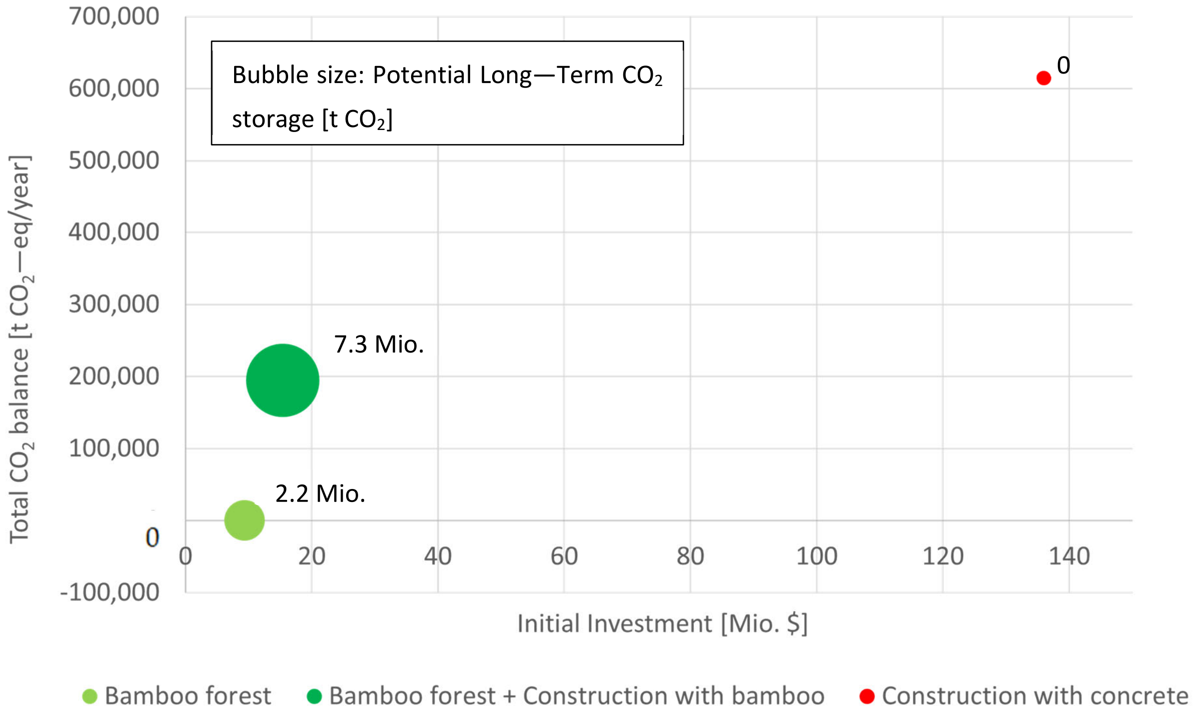


Figure 11. Comparison of the necessary investments, total CO_2 balance, and potential long-term CO_2 storage of different strategies.

In Figure 11, the x-axis showcases the requisite investments for each respective strategy. The investments in bamboo forest and bamboo-based construction were adjusted to align with the building output under consideration. The data point for bamboo-based construction also incorporates plantation values, as plantations often furnish the requisite raw material. The investment costs of an ordinary Portland cement factory are estimated at approximately \$136 million [48]. In this analysis, only the initial investments that are essential for the main building material are factored, and the construction costs themselves are excluded. On the y-axis, the annual total CO_2 balance for each strategy is presented. The bubble size denotes each strategy's maximum potential long-term carbon storage, computed through dynamic MFA results. Notably, this value is zero for concrete buildings, as they lack biogenic materials. Additionally, Figure 11 illustrates bamboo's economic and environmental benefits compared to concrete. Bamboo entails significantly lower factory investments (−90%), a substantially reduced CO_2 balance (−69%), and offers long-term carbon storage within the building stock. While plantations are the optimal choice for the pure offsetting of carbon, addressing the pressing demand for social housing necessitates building construction. Moreover, Figure 11 underscores that the combination of afforestation and bamboo buildings is not only more economically viable but also environmentally advantageous due to their smaller investment requirements and the significantly lower resulting CO_2 emissions. To put these results in the context of CO_2 certificates, we must first distinguish between the mandatory certificate market and the voluntary market. The former is a regulated platform that dictates the permissible CO_2 emissions for companies within the relevant region. An example is the EU CO_2 certificate market, where the current price per ton of CO_2 is approximately EUR 80 [49]. On the other hand, the voluntary market comprises the participation of companies or individuals aiming to offset their own CO_2 emissions through investment in sustainable initiatives, such as afforestation, or the adoption of renewable energy sources. Presently, the price per ton in this sector is notably lower, at approximately USD 10 per ton [49]. Given the absence of mandatory CO_2 certificates in the Philippines, potential compensation would likely stem from the voluntary certificate market. In this industry, widely recognized certification standards such as the Gold Standard or Verra necessitate adherence to specific criteria in the concerned project. Voluntary certificates are chiefly awarded for those endeavours related to afforestation and the promotion of renewable energy usage. However, there are no prevailing certification standards for emissions reduction within construction, or more specifically, for mitigating emissions by transitioning from concrete-based construction to less emission-intensive materials. Correspondingly, the protocols for granting CO_2 certificates for temporary storage, which is an outcome of employing biogenic materials in building construction, are also absent. Consequently, the investments in bamboo construction can officially leverage CO_2 certificates exclusively for the initial bamboo plantation and the utilization of materials at the culmination of a building's lifecycle for energy generation.

In addition to the overall environmental advantages of bamboo construction, the economic viability of this approach is increasingly relevant. To ascertain this, the period needed for complete investment recovery is determined through Equation (27). This formula enables us to calculate the duration needed to offset initial investments through returns generated from carbon credit sales. As mentioned in the results, when the necessary initial plantation investments are scaled to inputs for a single treatment facility, the amount stands at USD 30,000. Assuming a consistent carbon accumulation over six years for the initial plantation, coupled with a carbon price of USD $10/tCO_2$ on the voluntary market, the return period can be calculated as a mere 2.25 years. Thus, the initial plantation investments can be recovered within the first three years. The return on investment for construction activity can be similarly computed. In this analysis, buildings are assumed to be constructed in a cost-neutral manner, implying that expenses for the buildings themselves are covered by charitable organizations or through selling the buildings at a price that covers the costs. Consequently, the sole investment needed for construction activity is the initial treatment facility cost of approximately USD 20,000. The same calculation methodology applies to the potential long-term carbon storage within the biogenic materials of buildings. Over a forty-year span, an accumulation of 18,000 tons of CO_2 as a carbon sink is achieved, assuming steady construction activity over the evaluation period. Again, employing yearly storage accumulation, the investment for a single treatment facility (USD 20,000), and the voluntary carbon certificate price, the return on investment is calculated to be approximately 6.7 years. In the carbon credit market, prevailing certification standards, such as the Gold Standard or Verra, do not presently consider the potential for redeeming carbon credits on the voluntary market in relation to emissions avoidance in construction and the enduring carbon storage within building stock. The inclusion of these aspects can render bamboo construction an immensely appealing investment prospect, particularly considering the brief timeframes needed to realize a full return on investment. Alternatively, trading carbon credits on the voluntary market can additionally reduce building costs, thereby expanding the capacity to offer housing to more individuals in need.

5. Conclusions

The aim of this paper was to assess the viability of bamboo-based construction systems as sustainable, low-carbon housing solutions with the added benefit of acting as carbon sinks while also examining the economic aspects of such construction to address current research gaps. Our study indicated the substantial role that carbon storage in biogenic materials can play in shaping the ecological footprint of bamboo buildings. The incorporation of these effects can lead to emissions reductions that range from 0% to 43%. A comparison of unmanaged and managed plantations reveals that bamboo deployment in construction can significantly enhance long-term carbon storage. The requisite investment for treatment facilities to treat bamboo construction materials remains relatively modest, on the order of USD 30,000. While an unmanaged plantation surpasses pure carbon offsetting due to net positive emissions from building construction, the prevailing housing scarcity prompts the exploration of cost-effective and low-carbon strategies. Bamboo construction not only requires considerably lower investments than other construction types but also markedly reduces the environmental impact compared to that of conventional buildings. Furthermore, bamboo materials boost long-term carbon storage in the building stock, effectively reducing the levels of atmospheric CO_2. This underscores bamboo construction's efficacy as a robust carbon offsetting strategy. Incorporating the construction sector-avoided emissions into carbon crediting frameworks can further minimize building costs, thus enhancing the cost-effectiveness of addressing the housing demand in the Philippines. Bamboo construction emerges as an appealing proposition for external investors, given the expedited investment return timeframe via potential carbon credit trading returns. Utilizing this bamboo forest area for construction can not only considerably elevate overall carbon storage but also mitigate emissions by substituting for carbon-intensive concrete brick buildings.

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