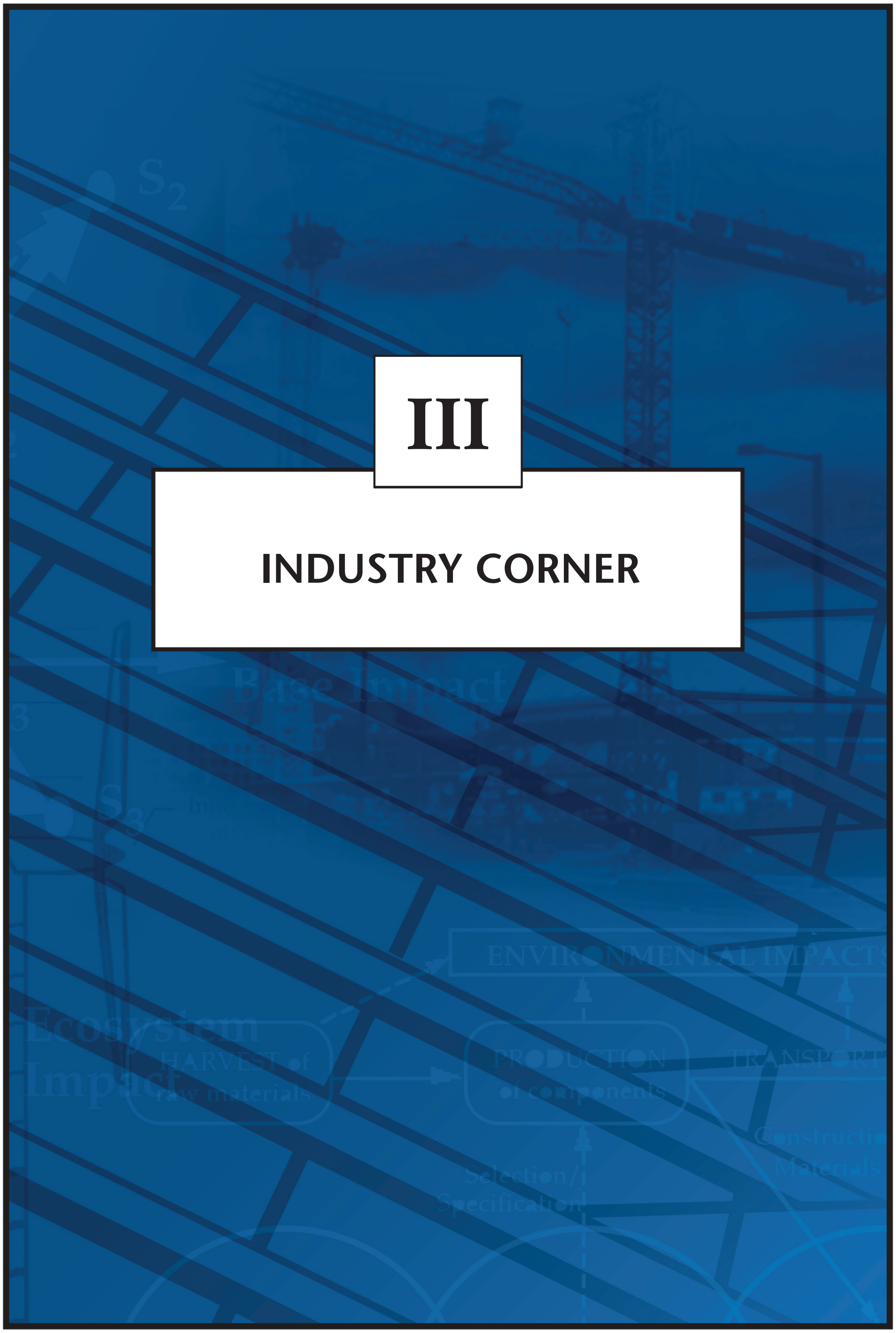

III

INDUSTRY CORNER

DESIGN CONCEPTS FOR THE INTEGRATION OF BAMBOO IN CONTEMPORARY VERNACULAR ARCHITECTURE

Shahryar Habibi[1]

ABSTRACT

This paper discusses the development of design concepts for a row of typical bamboo houses, including the layout configuration and the function/aesthetics properties that are important from an architectural perspective. The purpose of this paper is to discuss the role of bamboo in investigations of structural and sustainability benefits and to highlight key research ideas that are important for industrialized production and cultural systems. The development of bamboo housing systems can advance efforts directed at securing home ownership for low-income families through lowering the construction costs to levels that are within their budgets. This paper aims to demonstrate approaches for using bamboo as a structural material for low-income and affordable housing. Bamboo housing can improve the financial stability and economic sustainability of low-income families. This paper presents a review of examples of vernacular architecture and building elements and then highlights the design of two bamboo-structure residential houses based on bio-climatic design strategies.

KEYWORDS

bamboo, vernacular architecture, sustainable housing design, cultural conformity

1. INTRODUCTION

Consistent with the sustainability movement, bamboo has been identified as a green construction material. Bamboo is currently not being used as one of the main structural materials in the design and construction practice. It is the contention of the author that bamboo can be used as a suitable substitute for more commonly used building materials in this context—concrete blocks, natural stones, and burnt bricks. In order to increase the uptake of bamboo in the housing sector, it is necessary to highlight the importance of bamboo from a low-cost, aesthetic and eco-friendly building material perspective. For example, bamboo due to being devoid of toxicity, and great resistance to rupture can be used in the construction of low-cost sustainable houses and initiatives. This paper discusses the importance of creating sustainable homes, especially by using bamboo-based materials and focuses on the conceptual design of two typical housing units for an average size family (85 m² and 30 m²) with the consideration of low-cost as an objective.

Increasing global attention to limited resources has led to attempts to focus on the potential impact of sustainable development goals in the construction industry. Selection of building

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materials that have minimum environmental impacts represents a key strategy in achieving sustainable building objectives. In this context, bamboo is a renewable, low cost, and environment enhancing resource with great potential to improve sustainable development goals (Adhikari et al., 2015). The environmental properties of bamboo (e.g. high durability, local availability, easy fabrication, multi-purpose usage) makes it a remarkable material to meet a wide range of sustainable development objectives (Nguyen et al. 2011). Bamboo grows quickly and is the fastest-growing and most versatile plant on earth (Liese & Michael, 2015). Furthermore, it is relatively lightweight and can be easily harvested and transported. Sustainable development has resource efficiency/environmental stewardship, social justice and economic components. Developing a bamboo-based building material value chain can contribute to the realization of these outcomes.

Bamboo is a more biodegradable and eco-friendly (Banik et al, 2017) than most building materials. The use of sustainable and low-cost environmentally friendly building materials such as bamboo or timber as construction materials can help achieve the housing-related component of sustainable development.

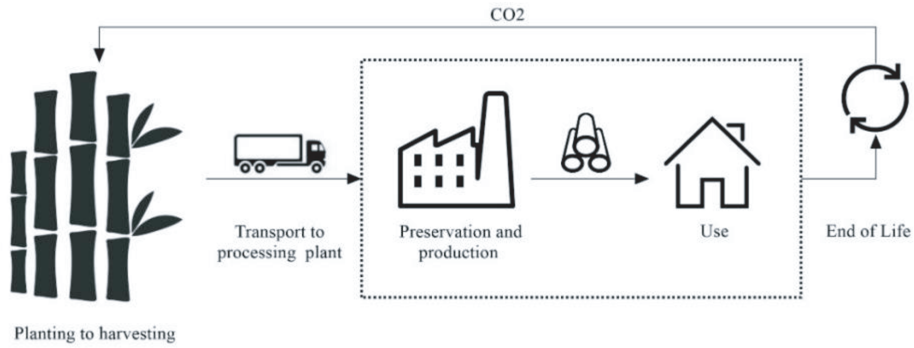
It is important to mention that the incorporation of the 3R principles (reducing, reusing and recycling) can have a major impact on achieving sustainable development (Samiha, 2013). Furthermore, it is essential to reduce the effect of volatile organic compounds (VOCs) in the indoor environment, which has adverse effects on building occupants. Accordingly, the deployment of renewable materials during the construction process is one of the main strategies toward improvements in environmental sustainability. Bamboo is a full natural and sustainable resource in the tropics and subtropics (Fang et al, 2018) and has great potential to supplement timber (Parkkeeree et al., 2014).

Investigation of regional conditions and determination of sustainability indicators of material use are critical success factors for a framework being developed by the author for optimizing the decision-making process for sustainable bamboo-based building materials development. The production and processing of bamboo in response to the prevailing local conditions and sustainability performance indicators can lead to a reduction in environmental and economic impacts (Atanda, 2015).Therefore, the author strongly advocates for a more concerted effort directed at increasing the uptake of bamboo as a material in building construction. Such a drive will provide a strong incentive for farmers to keep growing bamboo trees. This paper addresses this need by discussing concepts and methods for simplifying the specification of bamboo as a low cost, rapidly renewable structural material and green building element, which is comparable in strength to modern structural materials and is available globally(Sharma et al., 2015).

2. THE ENVIRONMENTAL SUSTAINABILITY OF BAMBOO

Environmental sustainability assessment of bamboo structural components (bamboo axial and flexural members) should be an integral part of the design process and relate directly to construction needs and aims. In the case of critical structural systems, bamboo needs to ensure that it has the potential to be used as a substitute for wood-based and timber structures, adobe and masonry buildings (Chaowana, 2013). The environmental sustainability assessment of bamboo is one of the most important factors to determine whether it can meet green building goals and practices. To measure the environmental sustainability performance of a material, it is important to promote the use of life cycle assessment (LCA) as a decision-making tool. For example, the environmental LCA can be used as a methodological framework to calculate

FIGURE 1. Assessing CO_2 balance of bamboo products.

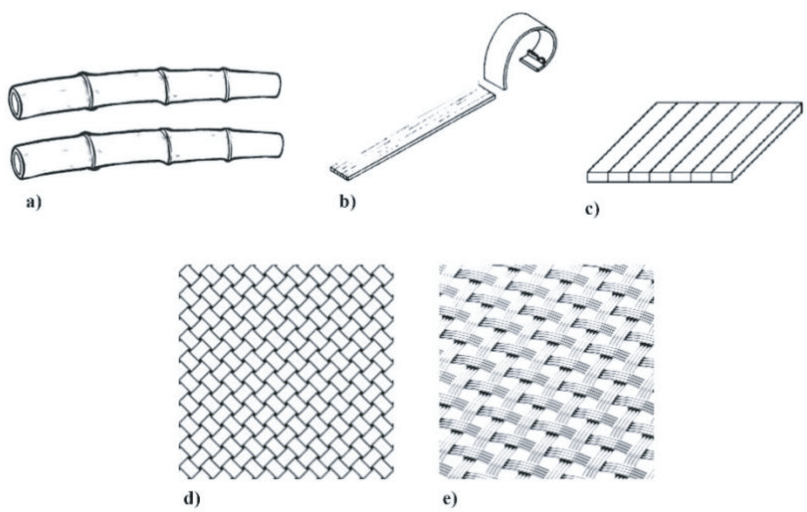


CO_2 emissions from the production and incorporation of bamboo in agriculture to the end of its life cycle (Figure 1). In the environmental LCA of the bamboo, all the lifecycle phases such as harvesting in sustainably managed plantations, transport to processing, storage, and usage need to be considered.

Lugt et al. (2006) performed a cradle-to-grave LCA for bamboo in the Netherlands. They also compared its performance in different structural applications to that of steel, timber, and concrete. They rated bamboo culm as 20 times more favorable. A study by Huang et al. (2018) analyzed the adaptability of applying natural bamboo fiber and bamboo charcoal as construction infills in building envelopes within the context of local climate and building conditions. The results showed that the application of these materials is beneficial for both bamboo resource utilization and building physical performance improvements.

Vogtländer et al. (2010) analyzed the environmental impact and sustainability of bamboo materials for local and Western European applications. The yield of bamboo is higher than other wood species. In another study, Escamilla & Habert (2014) studied the life cycle assessment

FIGURE 2. Bamboo-based construction materials. a) Bamboo poles, b) Flattened bamboo, c) Glue laminated bamboo, e) Woven bamboo mat. e) Woven bamboo mat panels.



of five bamboo-based construction materials such as a bamboo pole, flattened bamboo, woven bamboo mat, glue-laminated bamboo and woven bamboo mat panels (Figure 2). The authors argued that inputs related to the harvesting and transport of bamboo have a very limited contribution to environmental impact, but the nature and amount of energy used in the production process are important parameters. The proposed methodology can provide accurate data for LCAs of bamboo-based construction materials.

A study by Yu et al. (2011) showed that over its life cycle, a bamboo-structure, residential building requires less energy and emits less carbon dioxide to meet envelope insulation and structure supporting requirements in comparison with a typical brick-concrete building. Consequently, most bamboo products can promote environmental protection and rural economic development as integral parts of sustainable development (environmental, economic, and social).

3. OPPORTUNITIES AND CONSTRAINTS FOR BAMBOO USE

Bamboo has been shown (Nurdiah, 2016) to be a potential building material for home construction and has received increased attention for linking sustainable development goals in the local context. Bamboo is a self-regenerating natural resource and can be used as an alternative material to timber, especially in tropical and subtropical regions. Using bamboo-based products can develop vital local economic services and accomplish sustainable development goals. For example, bamboo can be effortlessly prefabricated, assembled, dismantled, and replaced. These specifications might include indicators considering all dimensions of development: economic, environmental, and social.

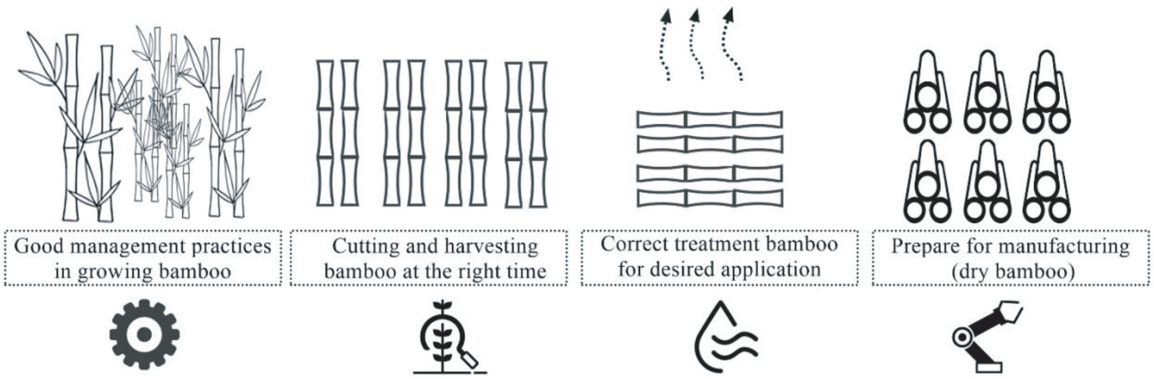
However, there are several constraints to the development of a global bamboo-based industry. For example, local farmers and producers lack an understanding of the industrial potentials of bamboo. Although bamboo-based enterprises require lower capital, it is difficult to establish its role as a substitute for wood in major applications for economic growth. Therefore, an efficient use of bamboo may be helpful in providing incentives to encourage its cultivation.

3.1 Sustainable bamboo processing and treatment

Bamboo trees come in various shapes and sizes with different mechanical characteristics. Therefore, it is important to investigate strategies to standardize bamboo processing and treatment. For example, the drying of the bamboo is a step in the manufacturing process that increases its structural properties. The drying of bamboo before use is necessary since dry bamboo is stronger and less susceptible to biological degradation than moist bamboo (Liese & Michael, 2015). Furthermore, it is important to develop a bamboo-processing industry based on sustainable and eco-friendly approaches to add value to bamboo as a sustainable building material.

Bamboo is treated with a preservative and different drying methods to ensure that it is high quality and resilient. Sustainable and environmentally friendly approaches can be considered the key operations to achieve these goals. For example, Burger et al. (2017) identified steps such as good management practices, cutting, and treating before the bamboo could be used for manufacturing (Figure 3). Additionally, initiatives to create successful bamboo manufacturing can be established by creating sustainable planting and harvesting programs. There are certain traditional techniques like applying heat and pressure that can be used in each step to bamboo processing.

FIGURE 3. The key strategies to standardise bamboo for the manufacturing process.



Bamboo should be treated properly before being used for structural purposes to enhance its natural durability and to protect it from insects, worms, and fungal pathogens. There are various methods of preserving bamboo such as leaching bamboo, chemical bamboo preservation, and drying bamboo poles that are dependent on initial moisture content, bamboo wall thickness, environmental humidity, the quantity of solar radiation, the absence or presence of rain, and the speed of the surrounding air.

A study by Bui et al. (2017) investigated different methods (different oils, different temperatures, different treatment durations, and different cooling methods) for bamboo treatment. The results showed that the treatment duration influenced the properties of treated bamboos. Wahab et al. (2004) studied tropical bamboo treated in palm oil (temperatures 140, 180, and 220 °C, during 30, 60, and 90 min). The results showed that the treatment decreased mechanical properties. In the context heat-treatment influences on the bamboo, Lee et al. (2018) revealed that the treatment temperature and duration imposed a significant effect on the surface color and contact angle of the bamboo.

3.2 Physical and mechanical properties of bamboo

To incorporate local tradition and design into the bamboo manufacturing process, it is important to know the physical, chemical, and mechanical properties of the bamboo species. Bamboo has an anisotropy biological origin, and several factors such as direction, moisture content, diameter, wall thickness, distance to node, height, and age affect its performance. Kamruzzaman et al. (2008) analyzed some physical and mechanical properties (at different heights and three ages) of four bamboo species (Bambusa balcooa, Bambusa tulda, Bambusa salarkhanii,and Melocanna baccifera), Bambusa balcooa had the highest moisture content in its green condition.

Physical properties of bamboo are often referred to in terms of environmental indicators measure factors such as moisture content, mass per volume or density, specific gravity, shrinkage, and fiber saturation point. In this context, fiber saturation point (FSP) has an important role to play in guiding the evaluation of bamboo processing and utilization. The evaluation of a basic concept of FSP is necessary to clarify the physical, mechanical and rheological properties of wood. According to the wood handbook (2010), the fiber saturation point of wood averages about 30% moisture content. Individual species may differ from the average.

Mechanical properties of bamboo are influenced greatly by compression, bending, and stiffness, which may have a significant application in a subjected structure. Bamboo has often been called "green steel" and in some mechanical characteristics, like its surface tensile strength, is stronger than steel (582 MPa v. ~350 MPa) (Shao et al., 2010). International ISO 22157 (2019) has been developed to determine the mechanical properties of bamboo. The mechanical properties of bamboo are commonly determined by properties of compression, tension strength, and elasticity modulus. Various research studies have focused on the mechanical properties and the tensile properties of bamboo (Lo et al., 2004; Tan et al., 2011; Hojo et al., 2014).

To demonstrate an understanding of bamboo as a potential material for use in structural applications, it is necessary to provide the properties of bamboo in comparison with other construction material such as timber, masonry, concrete, and steel. The properties of interest are compressive strength, tensile strength, shear strength, modulus of elasticity, and Poisson's ratio. A study by Xu et al. (2017) was undertaken to investigate the compressive and tensile properties of a bamboo scrimber at elevated temperatures. The results showed that tensile stress-strain relationships of a bamboo scrimber perpendicular to grain direction were linear from the beginning of loading to failure. In a study related to an investigation of the mechanical properties, *Bambusa Vulgaris*, *Dendrocalamus Asper*, and *Gigantochloa Scortechinii*, as species of treated bamboos, had excellent mechanical properties in compression and tensile strength especially in construction works (Awalluddin et al, 2017). The literature shows that bamboo has strong mechanical properties compared with other construction materials, however, the use of bamboo for construction proposes should be standardized.

3.3 Engineered bamboo products

The processing of the primary resource into engineered bamboo presents additional opportunities for promoting the structural use of the material in high-end applications (Xiao, 2016). Examples of specific products include laminated bamboo and bamboo scrimber (Cui et al., 2018).

It is important to note that the lack of effective management interventions in growing bamboo poles and harvesting methods can result in a reduction in quality and quantity of engineered bamboo products. For example, to improve engineered bamboo technologies, it is necessary to focus on the unique characteristics of bamboo. In the context of traditional bamboo construction, diversity of bamboo-based knowledge and processing skills can provide the basis for the industrial development of engineered bamboo products.

The development of bamboo products such as composite boards, reconstituted panels, and laminated flattened culm products from bamboo has risen significantly. To form and bend laminated bamboo into the desired shape, thermal processing techniques can be taken into consideration. Ramage et al. (2017) used a manufacturing process to modify the shape of laminated bamboo to achieve new forms. They investigated the thermal modification of laminated bamboo in shape forming and design.

4. A REVIEW OF STRUCTURAL APPLICATION OF BAMBOO IN BUILDINGS

The review discussed here examines the use of bamboo in building construction from the perspective of the architects who provide oversight over the design process. Examples relevant to the context of the current study methodology include the prototype houses designed by Ingvartsen Architects in the Tanga region of Tanzania. The units were erected using lightweight permeable materials (bamboo, shade net, and timber) (Figure 4).

FIGURE 4. A prototype bamboo house designed by JBK (Ingvartsen Arkitekter, Copenhagen, Denmark) in the village of Magoda, in the Tanga region of Tanzania. Reprinted [adapted] from ArchDaily (2016).

The overarching goal here was minimizing the spread of vector-borne diseases (VBD) such as Malaria Housing units erected using earthen masonry techniques that have been linked to increases in the risk of being bitten by mosquitoes. To prevent these problems, and to create a comfortable home microclimate, strategies using cross-ventilation through the openings in the materials were considered.

Low-cost bamboo housing in Vietnam by H&P architects is a single-family house that has been designed based on the local climate and regional materials (Figure 5). To make the form similar to what is considered to be the vernacular architecture, the house was built with

FIGURE 5. BB (Blooming Bamboo) home designed by H&P architects. Reprinted [adapted] from ArchDaily (2013).

local materials such as bamboo, fiberboard, and coconut leaf. It is located in a flood-prone area. The performance of the building system was considered more resilient to flood damage than conventional ones.

The Pemulung House in Bali, Indonesia, explores the fantastic potential of bamboo as a sustainable building material (Figure 6). The overall goal of the project is to develop a series of modular bamboo homes for garbage collectors who earn their livelihood by collecting and selling recyclable waste. All the surfaces (floors and walls) in this project are made of bamboo, and the roofing and insulation are covered by recycled materials such as bottles and tetra pack packaging. The project is a set of 14 housing units of 18 m^2. The houses are created as modules with main living spaces on the first floor and a mezzanine sleeping area above. They are intended to be assembled as terrace-style houses using bamboo and recycled materials.

A social-housing prototype in rural Mexico is another example of the use of bamboo as a renewable structural building material (Figure 7). The project seeks to engage in public and private partnerships for the construction of a housing project that would use the two existing bamboo species of the region. Furthermore, basic bioclimatic principles such as thermal protection of the building, applying techniques of natural ventilation, interior height and chimneys for hot air exhaust were integrated to make the home comfortable.

The project has been developed based on modular prefabricated systems and panels made with bamboo. It has optimum environmental performance and the sheets used for the roof are based on food-grade aluminum waste, which gives thermal, acoustic and antibacterial properties.

The design and technology of a bamboo house may vary among different cultures and countries. However, the methods for the utilization of bamboo should consider key aspects such as scientific, aesthetic, social, economic, usability, and durability in the design process. Furthermore, it should be noted that constructional usage of bamboo depends on conditions, such as available bamboo species, cultivation and harvesting methods, and maintenance.

Some initiatives have been directed at creating awareness of specific ways through which bamboo-based products can help develop vital local economic services and support the accomplishment of sustainable development goals. These include efforts directed at developing an integrated value chain to ensure sustainable production of bamboo housing economically, and to address the challenges and limitations of using bamboo as the main material in the construction process (Mekonnen et al., 2014). For example, the International Network for Bamboo

FIGURE 6. Pemulung House designed by BUKU. Reprinted [adapted] from ArchDaily (2017).

FIGURE 7. Social Production of the Habitat designed by Comunal Taller de Arquitectura. Reprinted [adapted] from ArchDaily (2019).

and Rattan (INBAR), a founding member of the UN-Habitat-coordinated Global Network for Sustainable Housing, together with the Ministry of the Environment, the Kenya Forestry Research Institute (KEFRI) and the Kenya Forestry Service (KFS), organized a bamboo in housing-focused workshop in 2015. The goal was framing the development of an integrated national bamboo sector policy for Kenya in 2015. Some supply chain recommendations were formulated for bamboo-based housing applications according to key national goals, such as Kenya's Vision 2030. Although bamboo has a lot of potential for an affordable housing project, the treatment and proper jointing of bamboo need to be ensured (Hannula, 2012).

Bamboo-sector development is a high priority focus for the KEFRI, which is the only government institution that supports training on the use of bamboo-based materials (Figure 8). They have played a lead role in the identification of the key impediments to the development of a bamboo-based building materials industry in Kenya. These include a lack of a full appreciation of the revenue-generating opportunities related to among the low-income producers of the primary resource (local farmers). Although bamboo-based enterprises require modest capital investments, it is difficult to establish its role as a substitute to wood in major applications for economic growth because of a lack of context-specific design codes and manuals that can be used by built environment professionals.

The required design targets for bamboo-based building materials must consider physical factors such as location, topography, vegetation, and climate. The location of land and the layout of building site has a direct bearing on its response to deterioration agents such as excessive heat and moisture as well as biological agents such as termites. For example, the performance of building systems in Kenya is mostly influenced by the fact that the most densely populated areas are within a strip located a few degrees north and south of the equator. The temperatures are mild, but warmer months sandwich seasonal tropical storms. The country has also been dealing with *El Niño* rains on a regular basis. There is a need for context-responsive design strategies that empower built environment professionals in Kenya to use bamboo-based building materials in a way that allows them to deliver both sustainable and resilient building envelopes.

FIGURE 8. One example of bamboo construction in Kenya. Reprinted [adapted] from Kenya Tobacco Control Research Group (2019).

5. THE STRUCTURAL USE OF BAMBOO-BASED MATERIALS

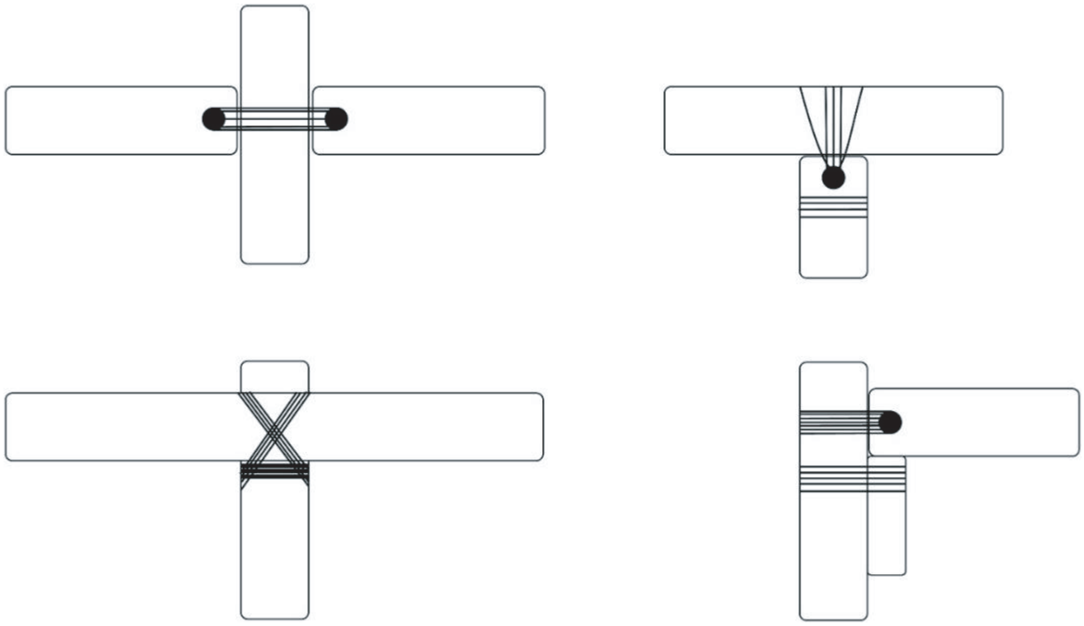
As mentioned before, the mechanical and physical properties of bamboo materials are different from each other. It is important to note that the lack of effective management interventions during both the growing phase and harvesting phase can result in a reduction in quality and quantity of engineered bamboo products. Strategies during bamboo processing and treatment must take into account the unique characteristics of bamboo that can be impacted by source and/or extraction method. The drying of the bamboo should be carefully monitored to ensure that the structural properties of the end product are optimized. The drying of bamboo also makes the end-product a more sustainable and eco-friendly structural material in building (Yang et al., 2018).

In a previous section, the author highlighted example uses of bamboo-based materials in various building components such as floor, roof, beam, wall-panels, columns, etc. The structural integrity assessment of bamboo is one of the most important factors to determine whether it can meet construction performance objectives. Awoyera and Adesina (2017) highlighted that bamboo has excellent mechanical properties for construction purposes. A study by Asamoah et al. (2017) investigated the flexural performance of bamboo reinforced concrete beams with the application of self-compacted concrete (SCC) in the construction industry. The result of the study showed that bamboo can be used as the transverse reinforcement and as ties for seismic action in concrete and could potentially minimize the demand for steel reinforcement.

Bamboo is being used in the walls and composite members for beams and columns (Shen et al., 2010)—that constitute the main structural load support system for buildings. Bamboo-based building materials have also been used in scaffolding, bridges, and roofs. Bamboo can also be used as a roofing material due to its properties such as strength, durability, and being lightweight. Furthermore, the benefits of bamboo as a building material are diverse and can lead to improvements in structural performance with respect to fire resistance, safety, and elasticity.

The use of bamboo as a structural material should be compatible with recognized engineering principles. Sassu et al. (2016) conducted experimental tests and developed assessments for a simple bamboo framed structure with an innovative low-cost and low technology joint. In

FIGURE 9. Examples of traditional joint of bamboo houses.



this study, the structural system involved only natural materials (bamboo canes, plywood plate, wooden pins, canapé ropes) and three different types of bamboo joints.

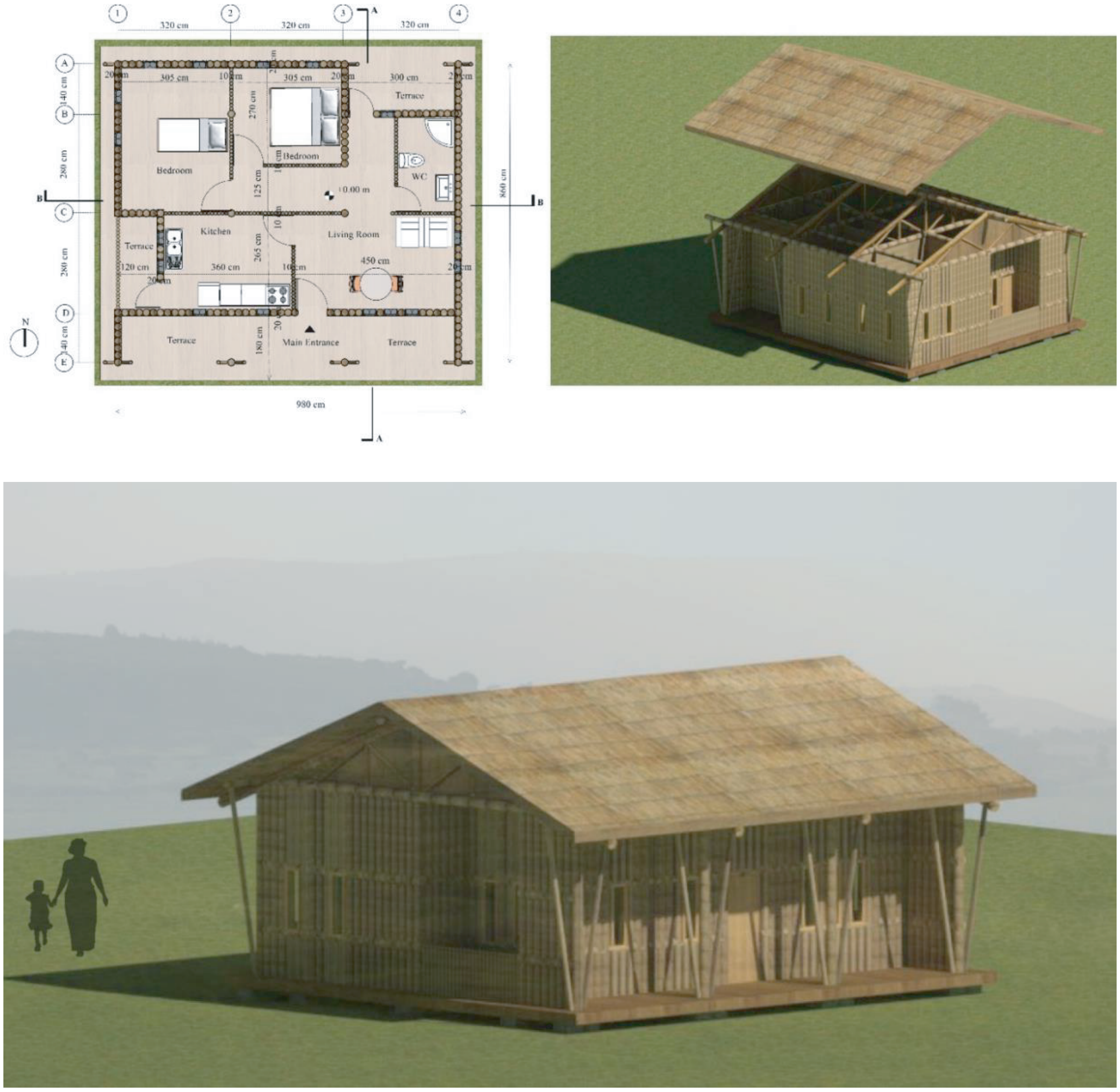
Bamboo can be used as a structural material with efficient mechanical properties against compression and bending. Adherence to context-specific design codes and manuals can result in the framing of structural members and details of construction of the bamboo in a way that meets load-bearing requirements (dead, imposed and environmental loads). Joints and connections are of great concern as they have a direct bearing on the systemic performance of building systems. Therefore, bamboo structural and joint systems should be properly investigated before any construction. The aesthetical goals of the design process play a critical role in driving adoption of bamboo-based building materials. Joints and connections that have been adopted in traditional bamboo construction are to have superior aesthetic appearance compared to systems erected using conventional materials (Figure 9).

6. DESIGN PROCESS OF AFFORDABLE BAMBOO HOUSES

In order to encourage the use of bamboo in building affordable houses, the author has developed conceptual designs for bamboo-based housing. The purpose of these projects is to design and build two affordable bamboo houses in which the growth and development of bamboo make possible different approaches to shape, structure, typology, gross area and architectural philosophy. The first house was envisaged as a residence for low-income families (85 square meter—915 square feet) and adapted to local soil and hot-humid tropical climate conditions (Figure 10).

In order to take advantage of scenic views and available wind resources, the house is located and oriented in a landscape comprised of hills. The outer terraces provide a physical connection to the outside. They also provide the occupants with a cool place to relax during warmer days. The kitchen and the bathroom are positioned towards the east and west sides to

FIGURE 10. Architectural illustration of the first bamboo-based house.

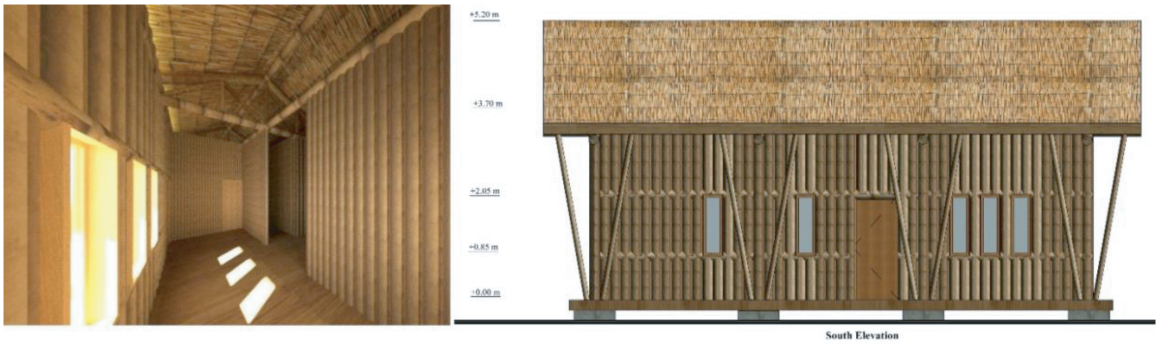


promote an open floor plan. The ground floor consists of a living room with a closed-concept kitchen, two bedrooms, one bathroom with toilet, and three terraces with panoramic views of the adjacent hills.

The premise here is that the entire building envelope is made from bamboo-based materials. Round bamboo poles are considered as a primary construction material in structural components such as roof and walls. The roofing system consists of a set of timber trusses, which are made up of bamboo, and arranged into triangular shapes (on a slope of 21 degrees). In similar tropical cultures, bamboo has been used as the base for thatch panels and roofing. This house is designed as a simple and traditional building that uses thatch as an outer covering to provide insulation (Figure 11).

The second project aims to create new styles of vernacular architecture and its area is 30 square meters. It is considered a tiny house in a forest setting (Figure 12). The composition is

FIGURE 11. Illustration of indoor space and south elevation.



structured around curved axes in the space. The horizontally curved axes prevent the contraction of space and provide a fluidity at the same time. They form the areas of movement, kitchen, living room, and wc (including building's mechanical room) on the first floor and one bedroom with a bathroom on the second floor. The spaces offer volume and scenic views to the forestland. The project aims to create an economically modest built form abstraction of forestland. It also aims to cover less surface area of forestland and rises along an upward curve. The shape of the roof is evolved from the form of a topographic profile—a feature of a hill.

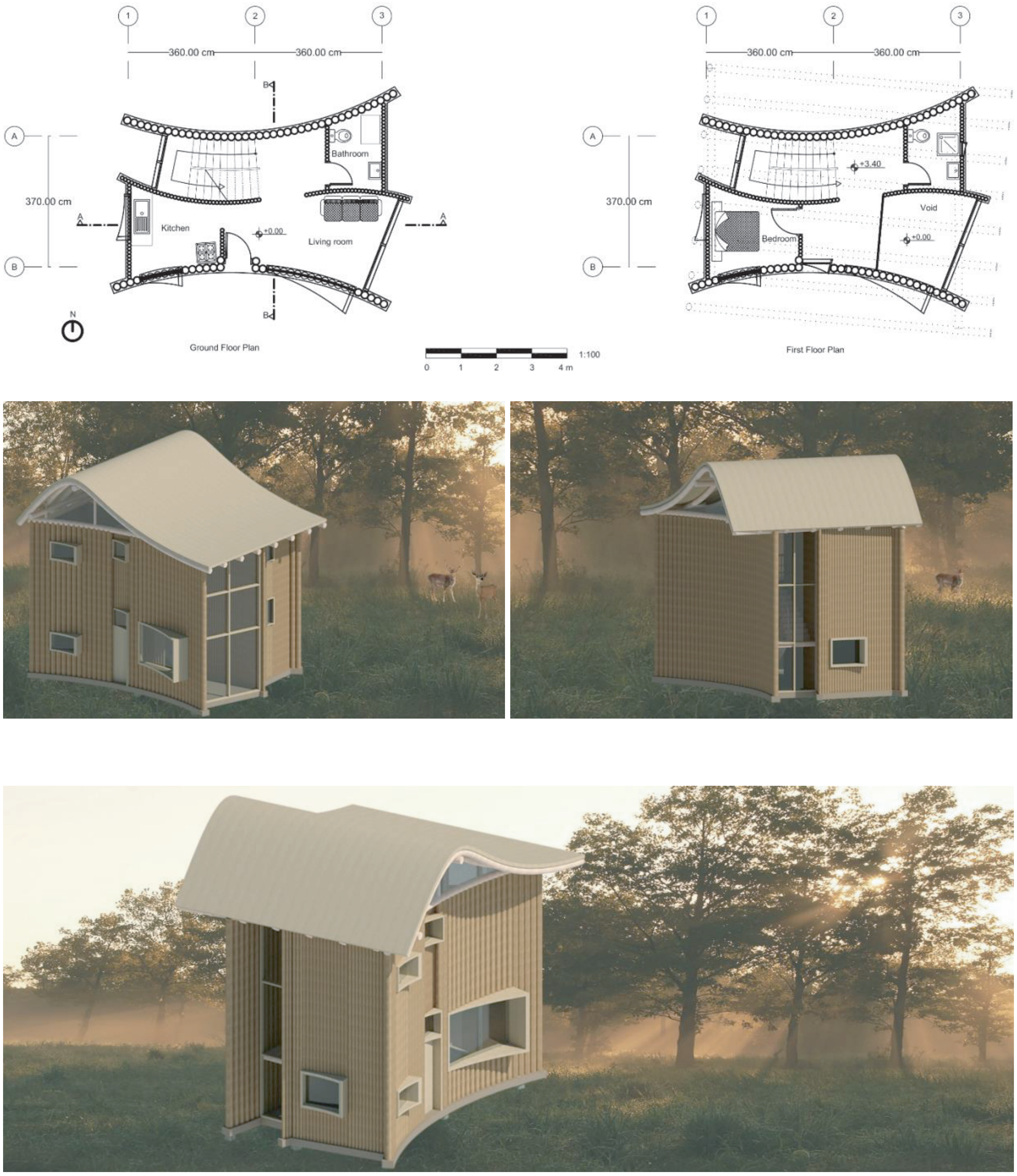
This project highlights the feasibility of introducing bamboo as a sustainable material for minimizing the financial and environmental impacts attributed to climate change and carbon emissions, from the initial planning to the final construction. It shows that the use of a bamboo-based material should be considered as a technological improvement especially in the design and construction process using indigenous material.

The current project is designed with the principles of bioclimatic design, utilizing both passive and active solar heating systems and natural cooling (Figure 13). In summary, the current house includes the installation of openings and the glazed areas in the house facing the east and west directions, vertical ventilation through the open spaces, cross ventilation through the roof vents, and minimizing energy losses through insulated bamboo walls. The purpose of the underside of the glazed roof is to allow natural light into the space and to exhaust the hot air out from indoors. Active systems have been used like solar photovoltaic panels, combined with the use of heat pump and fan coil.

7. CONCLUSIONS

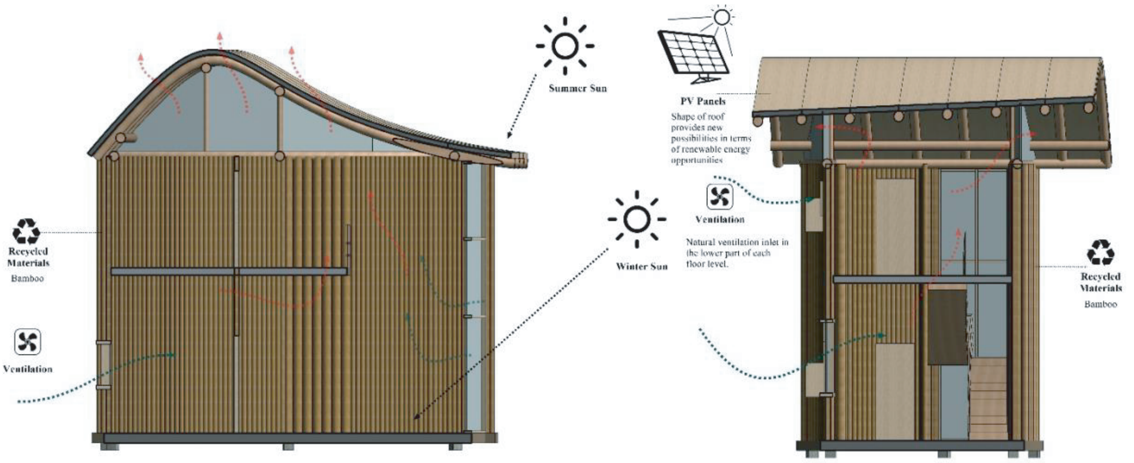
Bamboo housing can improve the financial stability and economic sustainability of families. The development of bamboo housing systems can advance efforts directed at securing home ownership for low-income families by lowering the construction costs to levels that are within their budgets. The successful implementation of the proposed approaches can advance efforts directed at demonstrating the appropriateness of a bamboo housing option for rapidly developing countries. Bamboo is not currently being used as one of the main structural materials in the design and construction practice. This paper demonstrates that bamboo can be used as a suitable substitute for more commonly used building materials (e.g. concrete blocks, natural stones, and burnt bricks). It is necessary to create awareness at the regional and local levels about the potential of bamboo to enhance sustainable development and social sustainability of urban renewal projects.

FIGURE 12. Architectural illustrations of the second bamboo-based house.



In this paper, the author has exemplified approaches for using bamboo as a structural material in low-income housing through strategies that respond to context-specific design constraints and socio-cultural needs. As part of follow-up work, the author will perform a holistic comparison of different building materials, focusing specifically on how bamboo can address sustainability-related issues such as 1) the cost and use of cement-related concerns associated with concrete blocks; 2) the cost and destruction to land associated with the extraction of natural

FIGURE 13. Illustration of indoor space and the principles of bioclimatic design.



stones; and 3) land-use conflict, particularly with farming, reliance on wood fuel systems during the production of fired bricks, which contributes to air pollution and deforestation.

The author's proposed use of bamboo-based building materials is closely aligned with the need for alternative (non-conventional) building materials that can be used to accelerate progress with respect to housing-related targets of affordable building units. Actualizing these design concepts will require the development of design manuals and standards for the use of bamboo as a structural material in buildings.

REFERENCES

Adhikari, R., Wood, D., & Sudak, L. (2015). Low-cost bamboo lattice towers for small wind turbines. *Energy for Sustainable Development, 28*, 21–28.

Archdaily. (2013). Bb Home / H&P Architects. [ONLINE] Available at: https://www.archdaily.com/431271/bb-home-h-and-p-architects. [Accessed 22 July 2019].

Archdaily. (2016). How Combining Traditional Asian and African Design Could Minimize Diseases in Rural Tanzania. [ONLINE] Available at: https://www.archdaily.com/796540/how-combining-traditional-asian-and-african-design-could-minimize-diseases-in-rural-tanzania. [Accessed 10 May 2019].

Archdaily. (2017). Pemulung House / IBUKU. [ONLINE] Available at: https://www.archdaily.com/884519/pemulung-house-ibuku. [Accessed 12 July 2019].

Archdaily. (2019). Social Housing Production: Exercise I / Inhabitants of Tepetzintan + Comunal Architecture Workshop. [ONLINE] Available at: https://www.archdaily.com/920082/social-housing-production-exercise-i-inhabitants-of-tepetzintan-plus-comunal-architecture-workshop. [Accessed 17 July 2019].

Asamoah, A. M., Banahene, J. O., Obeng, J., & Boasiako, E. A. (2017).Bamboo-reinforced self-compacting concrete beams for sustainable construction in rural areas. *Structural Concrete, 18*(6), 1000–1010.

Atanda, J. (2015). Environmental impacts of bamboo as a substitute constructional material in Nigeria. *Case Studies in Construction Materials, 3*, 33–39.

Awalluddin, D., Ariffin, M. A. M., Osman, M. H., Hussin, M. W., Ismail, M. A., Lee, H.-S., & Lim, N. H. A. S. (2017). Mechanical properties of different bamboo species. *MATEC Web of Conferences, 138*, 01024.

Awoyera, P. O., & Adesina, A. (2017). Structural Integrity Assessment of Bamboo for Construction Purposes. *Reference Module in Materials Science and Materials Engineering*.

Banik, N., Dey, V., & Sastry, G. (2017). An Overview of Lignin & Hemicellulose Effect Upon Biodegradable Bamboo Fiber Composites Due to Moisture. *Materials Today: Proceedings, 4*, 3222–3232.

Bui, Q.-B., Grillet, A.-C., & Tran, H.-D. (2017). A Bamboo Treatment Procedure: Effects on the Durability and Mechanical Performance. *Sustainability, 9*(9), 1444.

Burger, M., Oosthuizen, G., Oberholzer, J., Wet, P. D., & Ras C. (2017).Strategies to Standardise Bamboo for Manufacturing Process Chains. *Procedia Manufacturing, 8*, 330–337.

Chaowana, P. (2013). Bamboo: An Alternative Raw Material for Wood and Wood-Based Composites. *Journal of Materials Science Research, 2*, 90–102.

Cui, Z., Xu, M., Chen, Z., & Xiang, J. (2018). Experimental study on thermal performance of bamboo scrimber at elevated temperatures. *Construction and Building Materials, 182*, 178–187.

Escamilla, E. Z., & Habert, G. (2014). Environmental impacts of bamboo-based construction materials representing global production diversity. *Journal of Cleaner Production, 69*, 117–127.

Fang, C.-H., Jiang, Z.-H., Sun, Z.-J., Liu, H.-R., Zhang, X.-B., Zhang, R., & Fei, B.-H. (2018). An overview on bamboo culm flattening. *Construction and Building Materials, 171*, 65–74.

Hannula, E.-L. (2012).Going green: a handbook of sustainable housing practices in developing countries. UN-HABITAT, Nairobi, Kenya.

Hojo T., Xu, Z., Yang, Y., & Hamada, H. (2014).Tensile Properties of Bamboo, Jute and Kenaf Mat-reinforced Composite. *Energy Procedia, 56*, 72–79.

Huang, Z., Sun, Y., & Musso, F. (2018). Hygrothermal performance of natural bamboo fiber and bamboo charcoal as local construction infills in building envelope. *Construction and Building Materials, 177*, 342–357.

ISO 22157, (2019).Bamboo structures—Determination of physical and mechanical properties of bamboo culms—Test methods.

Kamruzzaman, M., Saha, S. K., Bose, A. K., & Islam M. N. (2008). Effects of Age and Height on Physical and Mechanical Properties of Bamboo. *Journal of Tropical Forest Science, 20*(3), 211–217.

Kenya Tobacco Control Research Group. [Online]. Available: http://www.tobaccotobamboo.org/index.php?PID=bamboohousing. [Accessed: 03-Feb-2019].

Lee, C.-H., Yang, T.-H., Cheng, Y.-W., & Lee, C.-J. (2018). Effects of thermal modification on the surface and chemical properties of moso bamboo. *Construction and Building Materials, 178*, 59–71.

Liese, W. & Michael, K. (2015). Bamboo: the plant and its uses. Cham, Switzerland: Springer Verlag.

Lo T. Y., Cui, H.Z., &Leung H.C. (2004). The effect of fiber density on strength capacity of bamboo. *Materials Letters, 58*(21), 2595–2598.

Lugt, P. V. D., Dobbelsteen, A. V. D., & Janssen, J. (2006). An environmental, economic and practical assessment of bamboo as a building material for supporting structures. *Construction and Building Materials, 20*(9), 648–656.

Mekonnen, Z., Worku, A., Yohannes, T., Alebachew, M., Teketay, D., & Kassa, H. (2014). Bamboo Resources in Ethiopia: Their value chain and contribution to livelihoods. *Ethnobotany Research and Applications, 12*, 511–524.

Nurdiah, E. A. (2016). The Potential of Bamboo as Building Material in Organic Shaped Buildings. *Procedia—Social and Behavioral Sciences, 216*, 30–38.

Nguyen, A.-T., Tran, Q.-B., Tran, D.-Q., & Reiter, S. (2011). An investigation on climate responsive design strategies of vernacular housing in Vietnam. *Building and Environment, 46*, 2088–2106.

Parkkeeree, T., Matan, N., & Kyokong, B. (2014). Flattening of half tubular bamboo culms and fixation of bamboo boards. *Journal of Tropical Forest Science, 26*, 101–114.

Ramage, M. H., Sharma, B., Shah, D. U., & Reynolds, T. P. (2017). Thermal relaxation of laminated bamboo for folded shells. *Materials & Design, 132*, 582–589.

Samiha, B. (2013).The Importance of the 3R Principle of Municipal Solid Waste Management for Achieving Sustainable Development. *Mediterranean Journal of Social Sciences, 4*(3), 129–135.

Sassu, M., Falco, A. D., Giresini, L., & Puppio, M. (2016). Structural Solutions for Low-Cost Bamboo Frames: Experimental Tests and Constructive Assessments. *Materials, 9*(5), 346.

Sharma, B., Gatoo, A., Bock, M., Mulligan, H., & Ramage, M. (2015). Engineered bamboo: state of the art. *Proceedings of the Institution of Civil Engineers—Construction Materials, 168*, 57–67.

Shao, Z. P., Zhou, L., Liu, Y. M., Wu, Z. M., & Arnaund C. (2010). Difference in structure and strength between internode and node sections of moso bamboo. *Journal of Tropical Forest Science, 22*(2), 133–138.

Shen, H. Y., Li, Y. S., Zhang, Z. W., Jiang, T. Y. & Liu, J. Z. (2010).Application and Prospect of Bamboo/Steel Composite Material in Civil Engineering Structure. *Advanced Materials Research, 113–116*, 989–993.

Tan, T., Rahbar, N., Allameh, S., Kwofie, S., Dissmore, D., Ghavami, K., & Soboyejo, W. (2011). Mechanical properties of functionally graded hierarchical bamboo structures. *Acta Biomaterialia, 7*(10), 3796–3803.

Vogtländer, J., Lugt, P. V. D., & Brezet, H. (2010).The sustainability of bamboo products for local and Western European applications. LCAs and land-use. *Journal of Cleaner Production, 18*(13), 1260–1269.

Wahab, R., Samsi, H. W., Sudin, M., & Moktar, J. (2004). Strength and Durability of Bamboo Treated Through an Oil-curing Process. *Journal of Biological Sciences, 4*(5), 658–663.

Wood handbook: wood as an engineering material. (2010). Washington D.C: U.S. Department of Agriculture.

Xiao, Y. (2016). Engineered bamboo. In *Nonconventional and Vernacular Construction Materials*, 433–452.

Xu, M., Cui, Z., Chen, Z., & Xiang, J. (2017). Experimental study on compressive and tensile properties of a bamboo scrimber at elevated temperatures. *Construction and Building Materials, 151*, 732–741.

Yang, T.-C., & Lee, T.-Y. (2018). Effects of density and heat treatment on the physico-mechanical properties of unidirectional round bamboo stick boards (UBSBs) made of Makino bamboo (Phyllostachys makinoi). *Construction and Building Materials, 187*, 406–413.

Yu, D., Tan, H., & Ruan, Y. (2011). A future bamboo-structure residential building prototype in China: Life cycle assessment of energy use and carbon emission. *Energy and Buildings, 43*(10), 2638–2646.