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Research paper

Structural suitability of bamboo for screenhouse construction in the humid tropics

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Abstract

The growing need of structures for controlled environment agriculture in the face of climate change cannot be overstated. While year-round crop production is possible in greenhouse farm-ing, procurement costs for conventional greenhouses is high. The use of readily-available local materials such as bamboo in the construction of greenhouses can help reduce construction costs. The objective of this study was therefore, to develop a bamboo-framed greenhouse (BfG) and to evaluate its structural suitability and micro-climate in comparison with an existing greenhouse (ExG) framed with mild steel. Climatic factors (temperature, humidity, and light) and vapour pressure deficit (VPD) were measured in BfG, ExG, and ambient. Using tomato as test crop, evaluation of crop performance was based on stem girth, number of leaves and yield, monitored in comparison with open field cultivation in a nearby plot. Temperature ranges in the BfG, ExG and ambient were 27.03 – 33.32 oC, 29.81 – 38.89 oC, and 25.27 – 28.33 oC, respectively, while relative-humidity ranged between 65.78–83.25%, 56.47–78.86% and 78.13–91.83%, respective-ly. The bamboo framed screenhouse performed satisfactorily and withstood several storm events for close to three years. Farmers in the humid tropics are advised that service life of bamboo-framed screenhouses is about two and half years.

Keywords: *Bamboo; Climate; Greenhouse; Screenhouse; Temperature.*

1. Introduction

Controlled Environment Agriculture (CEA) is increasingly becoming popular in 21st century food production, and this has cemented its appeal among many wealthy farmers and agro-allied investors. Technologies around controlled agriculture permit climate control in order to create optimal conditions, thereby protecting crops from various external environmental hazards such as high solar radiation, high wind speed, excessive rainfall, and invasion of pests and insects (Ajwang and Tantau, 2005; Teitel, 2007, Al-Mulla et. al., 2011, Zakir et. al., 2022). Structural stability is critical in the construction of greenhouse structures. Therefore, the materials that make up of the frame of the structure and method of jointing are very important in preventing failure. Greenhouses can be constructed from a variety of materials, including wood and metal, and their glazing materials can include plastic film and glass. The type of glazing material used in the greenhouse, as well as the surrounding outer environment, influence a greenhouse's micro-climate (Akpenpuun, 2022).

Screenhouses are structures for protected agriculture in which the side walls are covered with screens for the purpose of excluding insects. Screenhouses provide effective protection against insect invasion while consuming little or no energy, thereby enabling the cultivation of crops in an environmentally friendly manner (Mahmood et al., 2018). Moller et al. (2004) reported that the first mention of the use of insect-proof screenhouses as a substitute for conventional greenhouses was in the late 1970s. Screenhouses offer the potential to prevent heat build-up without the use of cooling, resulting in energy costs savings (Santos et al., 2006). A screenhouse can be partially screened, in which the roof is covered and sidewalls are screened; or completely screened at the roof and sidewalls (Tanny et al., 2006; Tanny et al., 2010; Dicken et al., 2012, Teitel et al., 2014; Teitel et al., 2019).

Screenhouses eliminate negative effects on plants while also providing necessary protection for crops against biotic and abiotic stresses. Inas et al. (2017), reported that the use of screenhouses has become more crucial due to its capacity to maximize water savings of up to 30 percent without causing a substantial decrease in the production level. Moller et al., (2003) also highlighted the reduction in crop water use by screenhouse sweet pepper, as compared to the open field samples. Evapotranspiration generally decreases under screens, as would be expected given the reductions in solar radiation, wind speed, and turbulent air exchange rates within the building (Tanny, 2013). The attributes of screens used for covering such as material texture, permeability and color impact the visual and aerodynamic properties of the constructed screenhouse (Villagran et al., 2020).

The cost of greenhouse construction is a major barrier for small, rural, and marginal farmers, who account for the vast majority of farmers (Rajender et al., 2017). Because of the high expense of purchasing a greenhouse for rural farmers in sub-Saharan Africa, its adoption has mostly been limited to researchers and wealthy farmers. Farmers can avoid the high initial investment costs associated with greenhouse construction if for instance, savings can be made on construction materials. Using a steel-framed greenhouse as an example, Saltuk

(2019) reflected on structural analysis, concluding that a reduction in the total amount of steel materials used in greenhouse building will lower the overall cost of greenhouse construction.

Bamboo is regarded as a suitable construction material with applications in building construction (Xu et. al., 2014). This is because of a variety of reasons, including its weight-to-strength ratio, an important mechanical characteristic which makes bamboo unique as a suitable alternative material that may be used to replace wood in buildings. Bamboo's mechanical properties are in significant agreement with the number of mechanical properties possessed by wood, just as both wood and bamboo are heterogeneous and anisotropic material (Ogunwusi and Onwualu, 2013; Ribeiro et al., 2017). Bamboo's strong characteristics make it an ideal building material, particularly in terms of tensile strength, which is very important in construction (Moroz et al., 2014; Gomes et. al., 2021). The mechanical qualities of bamboo, according to Van der Lugt et al., (2006), have been demonstrated to be comparable to those of conventional construction materials, and the availability of bamboo throughout the world indicates that it has the potential to be used as an alternative building material. Joint failure, however, is the most common cause of collapse of structures (Chaokun et al., 2019). Despite the fact that bamboo fibres have a tensile strength that is generally higher than that of steel, they have a disadvantage when it comes to the development of connections for bamboo joints that may transfer their tensile stress (Auwalu and Dickson, 2019). The mechanical properties of joints are complicated, and they are influenced by a wide range of conditions such as material properties, temperature and pressure. It is therefore essential that structural design of joints is properly done to ensure safety and durability, in order to promote the use of bamboo structures.

An increase in population has led to sharp increase in food demand. Moreover, the effect of climate change is gradually threatening open field cultivation due to heat stress, drought and desertification. Open field cultivation is prone to environmental hazards and infestation by insects. In some cases, open-field cultivation does not encourage production of hybrid varieties of crops. Therefore, in order to widen the adoption of greenhouse farming, especially to farmers who may not be able to afford conventional greenhouse systems, a cheaper alternative is desirable. This study was therefore set up to develop and evaluate a Bamboo (*Bambusa vulgaris*, Schrad) framed screenhouse in comparison with an existing steel-framed greenhouse covered with polycarbonate sheets, as well as open field cultivation.

2. Methodology

2.1. Determination of strength properties of bamboo

The properties include density, flexural test (to determine MOR and MOE), compression parallel to fibre (C_s), and shear strength (τ_s). These were determined in line with recommendations of ISO Standards DIS 22157 (2009). All the tests were carried out on the Universal Testing Machine (UTM) OKH-600 digital display. Samples for the test were prepared in three replicates from three main sections of the bamboo culms (i.e. top, middle and bottom). The values were calculated as follows:

i) Density, $\rho = \frac{\text{mass}}{\text{volume}}$ (1)

Where; ρ = density of the bamboo sample in kg/m^3,
mass = mass of the bamboo sample in kg, and
volume = volume of the bamboo sample in m^3.

ii) Modulus of Rupture and Modulus of Elasticity: MOE and MOR were both determined simultaneously from each sample on the UTM. The breaking loads (minimum and maximum) were recorded for each of the three trials and substituted into equation 2 and 3:

$$\text{MOR or } F_s = \frac{1.5 P_{max} L}{[\frac{\pi(D^2 - d^2)}{4}]^2} \quad (2)$$

Where; F_s = Flexural strength or MOR (kN/mm^2),
P_{max} = Fracture load at maximum (kN),
L = Effective length of the sample or distance between support points (mm),
D = Sample external diameter (mm),
d = D – 2t, d = Sample diameter (mm) and t = thickness of the sample (mm)

$$\text{MOE} = \frac{P_{min} L^3}{48 I \delta} \quad (3)$$

Where; MOE = Modulus of elasticity (kN/mm^2,
P_{min} = Fracture load at minimum (kN),
L = Effective length of the sample or distance between support points (mm),
δ = Sample displacement (mm)
I = Inertia moment of the sample (mm^4) where.

$$I = \frac{\pi D^4}{64} \quad (4)$$

iii) Compressive Strength: The compressive strength was based on the following equation.

$$C_s = \frac{P}{A} \quad (5)$$

Where.
c_s = Compression parallel to fibre or compressive strength kN/mm^2 and,

P = compressive load in kN,

$$A=\frac{\pi D^2-(D-2t)^2}{4} \quad (6)$$

Where; $A=$ Area of the bamboo section (mm^2),
D = External diameter of the bamboo culm sample (mm^2) and
t = Wall thickness of the bamboo culm sample (mm^2

iv. Shear Strength: The shear strength was determined in relative manner to that of compression parallel to fibre. The shear load was recorded for each of the three trials and substituted into equation 7:

$$\tau_s=\frac{P}{4\,L\,t} \quad (7)$$

Where; τ_s = Shear parallel to fibre and,
P = Shear load (kN)

2.2. Bamboo-framed screenhouse construction

The design of the structural members of the screenhouse was based on Allowable Stress Design (ASD) method, through load estimation, truss analysis using method of joints, and column design. The dimension of the screenhouse was 5.8 × 4 × 2.5 m (length × width × height) as shown in Fig 1. Table 1 presents other basic details about the screenhouse.

Table 1: Dimensions of the Screenhouse

S/N	Element	Dimension (mm)	Qty
1	Columns at the edges	3000	9
2	Rafters	2150	8
3	King pole	800	3
4	purlins between truss	2000	6
5	Tie beams for collection at sides	3000	8
6	Tie beams for collection at back	2000	6
7	Truss tie beam	2000	6
8	Door frame column	2100	2
9	Door frame beam	900	2

The plastic screen mesh size of 50 microns was chosen because of its capacity to prevent insects from gaining entry as well as its suitability for natural ventilation as smaller mesh sizes reduce airflow. High Density Polyethene (HDPE) glazing material was used to cover the roof because of the protection it provides against ultra-violet (UV) radiation.
The bamboo culms were treated to prevent attack from insects. The foundation of the screenhouse was 4.4 by 6.2 m, arrived at by adding 0.4 m to the actual length and width of the screenhouse. The depth of the foundation was 0.5 m, and the foundation wall thickness was 0.150 m. The foundation was of strip type which was made of 50 mm thick concrete. The mixing ratio of the concrete blinding for the foundation was a nominal type concrete of 1:3:6 mix, typically used for low load surface or slab. The sandcrete blocks used for the structure was prepared using mixing ratio 1:8 (sand-cement) and the plastering of the wall was based on a mixing ratio of 1:5 (sand-cement).
The frame of the structure consists of 8 columns of 3000 mm length (including 500 mm buried into the foundation), while the roof of the structure is made of A-frame trusses – which consist of rafters, tie beam and king pole. The columns were first erected into the foundation for stability, after which other members (purlins, trusses, side beams, and door) were connected to the columns. The length of each purlin and side beam are 2850 mm while the dimensions of the door was 2100 by 900 mm. At each joint, fastening of structural members was achieved by using 50 mm long nails of 2 mm diameter, after which rattan strips were used to bind the member, a method known as lashing joint. Both were attached to the frame using locking profiles (U-channel) and wiggle wire. The locking profiles were fixed to the structure at the edges of the structure in all sides including the roof using screws.
Load estimate of the screenhouse includes roof covering load, installation load, roof accessories load, and self-weight of bamboo for a truss. Table 2 shows the estimated loads for the screenhouse.

Table 2: Estimated Loads for the Screenhouse

S/N	Section	Value (N)	Type of load
1	Roof covering load	225	Dead
2	Installation load	1785.42	Live
3	Roof accessories load	225	Dead
4	Self-weight of bamboo for a truss	21.68	Dead
	Total load	2257.1	

Truss analysis: Estimating tributary load for each point on the truss as shown in Figure 1
Total load (W) = 2257.1 N

$W=\frac{1}{2}w+w+\frac{1}{2}w$ (Olorunnisola, 2018); Point A = $\frac{1}{2}w$, Point B = $(\frac{1}{2}w+\frac{1}{2}w)=w$ and Point C = $\frac{1}{2}w$

Therefore, using Joint Analysis method, forces acting on the members of a truss is presented in the Table 3.

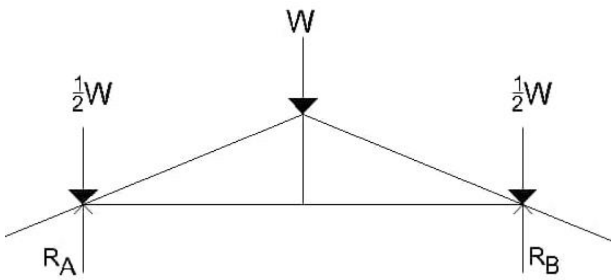

Fig. 1: Truss Section.

Table 3: Forces Acting on the Members of the Truss

Members	Forces (N)	Type of forces
F_{AC}	3002	Compression
F_{AD}	2787	Tension
F_{BC}	3002	Compression
F_{CD}	0	Redundant
F_{BD}	2787	Tension

The screenhouse was constructed at the Department of Agricultural and Environmental Engineering, Faculty of Technology, University of Ibadan, Nigeria, situated at Latitude 7 26'23.6" and Longitude 3 53'32.9" at about 227 m height above the mean sea level. As at July 2021, the cost of constructing the bamboo-framed screenhouse was ₦336,320 ($773.2 US) compared to that of the metal framed greenhouse which cost ₦771,820 ($1,774.3 US), both of which are of the same dimensions.

Three-week old tomato seedlings were transplanted in August, 2021 into buckets inside the screenhouse, and also planted in the open field near the screenhouse for comparison. Ten tomato seedlings were randomly selected from the screenhouse and the open field to monitor stem girth and number of leaves. Data were collected from the ambient environment, the bamboo-framed screenhouse and the existing greenhouse. Dataloggers (Lascar EL-USB-2, USA) were programmed to collect data at an interval of 5 mins in the screenhouse while a weather station (Ambient Weather WS-1200 Console, Ambient LLC, USA) at the experimental site was used to take the readings of macroclimate parameters (temperature), humidity and solar intensity (W/m^2) of the ambient environment. A light meter was used to measure the solar intensity (W/m^2) in the greenhouse and screenhouse. VPD was calculated using the following equation provided in Arellano et al. (2006):

$$VPD = 0.61078\exp\left(\frac{17.269 * T_a}{T_a + 273.3}\right) x\ (1 - \frac{RH}{100})$$

Where T_a is air temperature in °C and RH is relative humidity either inside or outside in %.

Data obtained was processed using Microsoft Excel and then subjected to statistical analysis using Minitab 19. Sigmaplot12 was used for visualization.

3. Results and discussion

3.1. Strength properties

The following results are presented:

3.1.1. Density

A mean density of 1009.53 ± 58.22, 969.81± 81.93 and 929.73 ± 92.28 kg/m^3 were obtained for bottom, middle and tops sections of the bamboo respectively. This is similar to the findings of Sadiku et al. (2016), who worked on the same species of bamboo. The result of one-way ANOVA at 5% level of significance of bamboo density from the three sections show that there was no significant difference among the sections with a p-value of 0.05. This confirms the maturity of the bamboo. The mean of the density data of the three sections was analyzed using Tukey Honestly Significant Difference test and it showed that there were no significant differences.

3.1.2. Compressive strength

The compressive strength results obtained from the mechanical testing for the three sections of the bamboo culm; top (T), middle (M) and bottom (B) showed that the highest value was at the bottom section with 39.2 N/mm^2 and the lowest at the top with 14.1 N/mm^2. The thickness of the bamboo at the bottom section accounts for the higher strength. Mean values were 26.3±4.1, 17.0±3.6 and 13.31±3.3 N/mm^2 for bottom, middle and top, respectively. The mean compressive strength for all sections of the bamboo was 18.86±14.4 N/mm^2, and this was adopted for the design of columns and truss members of the screenhouse. The values obtained for the three sections for compressive strength of bamboo were lower when compared with 67.62 N/mm^2 reported by Awalluddin et al., (2017). The result of statistical analysis; one-way ANOVA at 5% level of significant of bamboo compressive strength from the three sections shows that there was no significant difference between the sections at a p-value of 0.05. The result of the ANOVA was further analyzed with Tukey comparison which shows that there were no significant differences among the three sections when compared against each other.

3.1.3. Shear strength

At the bottom section, the mean shear strength was 12.81 ± 2.68 N/mm^2, while the middle and top sections were 12.62 ± 7.57 and 15.53 ± 1.32 N/mm^2 sections respectively. For the purpose of construction, the overall average from the three sections; 13.65 ± 3.86 N/mm^2

was used. Mean shear strength across the three sections were greater than value (9.6 N/mm^2) reported by Bautista et al. (2021). One-way ANOVA for the shear stress in different sections shows that there was no significant difference with a p-value greater than 0.05. Tukey comparison of shear stress at different sections shows that there was no significant difference in the shear strength between the sections.

3.1.4. Modulus of elasticity (MOE) and modulus of rupture (MOR)

The mean values of the MOE were 1756.36 ± 489.35, 1720.43±434.17 and 969.59±354.33 N/mm^2 for bottom, middle and top respectively. Average of the mean values was used for the structural design while the mean values of the MOR were 630.59 ± 517.57, 651.49 ± 527.768, and 375.73 ± 447.96 N/mm^2 for the sections respectively. The mean MOR and MOE values were compared with values reported by Javadian et al., (2019), 23,970 and 158 N/mm^2 for MOE and MOR, respectively. ANOVA analysis for both MOE and MOR showed no significant difference across the sections. The maturity of the bamboo may be responsible for this.

3.2. Microclimate

3.2.1. Temperature and relative humidity

Temperature levels were within acceptable ranges in the bamboo screenhouse when compared with the greenhouse which sometimes went above 45 ºC. The mean temperature in the screenhouse, greenhouse and ambient were 30.23 ± 3.9, 34.1 ± 6.0 and 26.0 ± 1.1 ºC, respectively. The lower temperature in the screenhouse when compared to the greenhouse can be attributed to the effect of the shade which reduced the entry of ultraviolet radiation into the structure, and the larger vent area of about 52.2 m^2, unlike the greenhouse which had no shading, and also fitted with a smaller vent area of about 12.14 m^2. The ANOVA ($\alpha_{0.05}$) shows that there was a significant difference in the temperatures in the screenhouse and the greenhouse. In addition, mean relative humidity in the screenhouse, greenhouse and ambient were 74.2 ± 9.61%, 67.44 ± 15.34% and 76.96 ± 3.08%, respectively, indicating a cooler microclimate in the screenhouse when compared to the greenhouse. When RH data was subjected to ANOVA ($\alpha_{0.05}$), a significant difference in their humidity levels was confirmed. The humidity levels (>60%) recorded in the screenhouse is similar to that which was reported by Tanny et al., (2014). This indicates potentials for low evapotranspiration and minimal water stress for the plants (Liu et al., 2009).

3.2.2. Light

The mean light intensity of the screenhouse, the greenhouse and the ambient were recorded to be 165.8±44.1, 240.9±64.8 and 318.5±47.6 W/m^2, respectively. A significant difference was observed among the three when subjected to ANOVA ($\alpha_{0.05}$). Similar trends were reported by Inas et al., (2017), and Moller and Assouline (2007). Optimal light intensity in the screenhouse was due to the covering material (shade net) which has ultraviolet resistance film. The light intensity in the greenhouse was similar to that of the ambient because it is covered with transparent polycarbonate. However, light received in the screenhouse was adequate for crop growth. Figure 2 presents observations in the structures and the ambient.

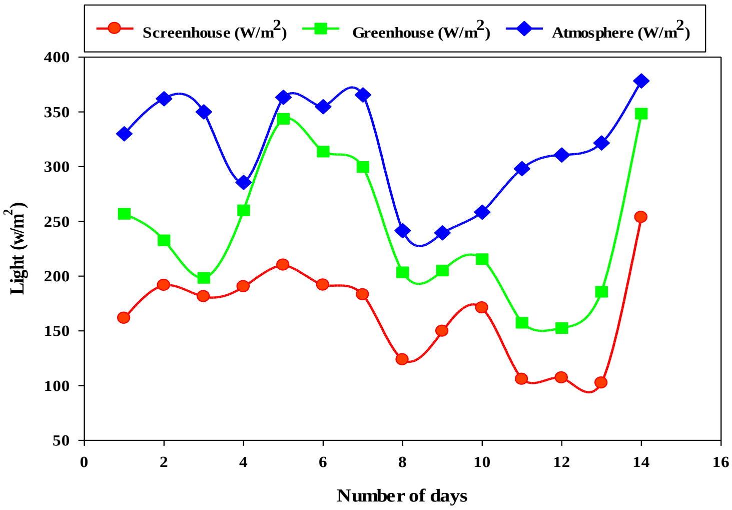

Fig. 2: Light Intensity.

3.2.3. Vapour pressure deficit (VPD)

Mean VPD recorded in the screenhouse, the greenhouse and the ambient were 1.33 ± 0.38 kPa, 1.33 ± 0.38 kPa, and 2.94 ±0.13 kPa, respectively. Figure 3 presents the real-time data obtained during the study. Values obtained in both the screenhouse and the greenhouse are optimal for plant growth, fruiting, pollination, because they fall within range of 0.4 to 1.6 kPa, which is recommended for optimal plant growth. They are also comparable to the values obtained (0.5 – 0.8 kPa) by Rosales et al. (2011) and Speetjens et al. (2012). A significant difference was observed between the VPDs in the ambient and those of the microclimate in the structures. Moreover, VPD of the ambient was higher than what was reported by Moller and Assouline (2007); Rosales et al., (2011) and Speetjens et al., (2012).

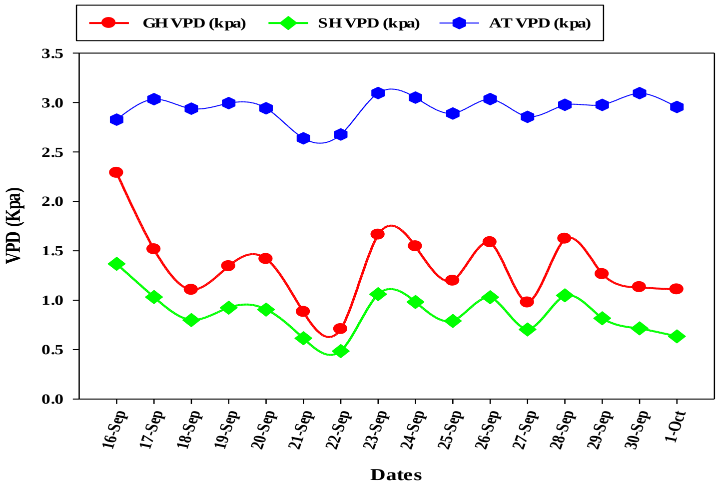

Fig. 3: Vapour Pressure Deficit.

3.2.4. Crop performance (stem girth, number of leaves and yield)

Comparison of data on stem girth of tomato reveal no significant difference between plants cultivated in the screenhouse and those in the greenhouse, however, a significant difference was observed between them and those cultivated in the open field. This poor performance of crops planted in the open field was attributed to the condition of soil (predominantly clay), and the activities of insects in the outside environment. This is a confirmation of the suitability of controlled environment farming on degraded soils. In addition, the average number of leaves of the plants in the screenhouse and greenhouse were comparable (64.5 ± 7.1 and 62.3 ± 3.6 respectively), with no significant difference. The extrapolated yield of tomatoes from the screenhouse and greenhouse was 7.9 and 4.3 tons/ha respectively, while the plants cultivated on the nearby soil had no yield due to stunted growth. The yield of the screenhouse shows potential for quick recovery of investment.

3.2.5. Functional suitability of the bamboo-framed screenhouse

During the study, insect attack on plants within the screenhouse was insignificant, which shows the effectiveness of the anti-aphid net used for covering the screenhouse. Typical wind speeds around the study site, especially during rainstorm events is about 10.9 km/hr and the structure was able to withstand the pressure without failure/structural damage to framing members as well as the glazing materials for a period of about two and half years (July 2021 to February 2024), before the frame got damaged.

4. Conclusion

Strength properties of the bamboo culms show that the bottom section of the bamboo culm gave the best results in terms of density, compressive strength, and modulus of rupture. Nailing of bamboo with 50 mm nail is recommended when constructing with bamboo because splitting did not occur at the joints. Moreover, the lashing joint formed by rattan strips provided additional strength for the joints of the screenhouse members. The non-uniformity of bamboo stem provides entry for insects, but this challenge was overcome by using spray foam to block all gaps and spaces through which insects could enter the screenhouse. Structurally, the screenhouse was found to be adequate as it did not fail during several heavy storms for over two and half years. As expected of all biomaterials, portions of the bamboo close to the foundation eventually degraded substantially, leading to structural damage. Farmers adopting bamboo framed greenhouses in the humid tropics are therefore advised to prepare to change the frame after every two years as part of their investment plans. A comprehensive study on effect of the screenhouse microclimate on selected high value crops' yield and the effect of supplementary lighting on crop productivity can be explored.

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