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Mechanical evaluation of lumber as a material for floating houses: Flood resilience in Mozambique

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Abstract

This study investigates the suitability of various wood species available in Mozambique for constructing floating houses in the country, which is highly vulnerable to climate change impacts such as rising sea levels and intense storms. The research focuses on Ironwood (*Swartzia madagascariensis*), Messassa (*Julbernardia globiflora*), Panga Panga (*Millettia stuhlmannii*), and Chanfuta (*Afzelia quanzensis*), evaluating their properties through humidity, dimensional stability, density, compressive strength, and tensile strength tests. Ironwood demonstrated superior performance with the lowest moisture content and highest dimensional stability, making it less prone to environmental damage. Its high compressive and tensile strength further supports its suitability for floating house construction, ensuring structural integrity and safety. However, its higher density requires careful design to maintain buoyancy. The study also highlights the importance of balancing wood density and platform design to ensure the floating house's stability. While high-density woods like Ironwood provide strength, they may reduce buoyancy, necessitating precise design considerations. Conversely, low-density woods like Messassa offer better buoyancy but may lack the necessary strength for long-term durability. The findings underscore Ironwood's potential as a viable material for constructing resilient floating house platforms in Mozambique's flood-prone coastal areas, aligning with initiatives aimed at developing climate-resilient home building techniques and offering a sustainable and adaptable housing solution to mitigate the impacts of climate change.

Keywords: Floating Houses; Flood Resilience; Lumber; Mechanical Evaluation; Mozambique

1. Introduction

Mozambique is a country located on the southeastern coast of Africa, with a population of approximately 31 million people, 60% of whom live in low-lying coastal areas [1]. These regions are particularly vulnerable to the impacts of climate change, such as rising sea levels and frequent intense storms [2], [3], [4] . These climatic events cause flooding, erosion, landslides, threatening communities, homes, and businesses. Traditional houses, often built with low-quality materials, are easily damaged by these events, contributing to a cycle of vulnerability and poverty [5], [6].

Like the innovative approach of utilizing solar energy for refrigeration systems in rural Mozambique, as demonstrated by Nhambiu and Chichango [7], the construction of floating houses using locally available and sustainable wood species can significantly enhance flood resilience in coastal areas. Just as solar cooling systems provide an efficient and cost-effective solution for preserving medicines, floating houses built with materials like Ironwood (*Swartzia madagascariensis*) offer a robust and adaptable housing solution to mitigate the impacts of climate change. Both approaches underscore the importance of leveraging local resources to develop sustainable and resilient infrastructure, promoting environmental preservation and economic resilience in vulnerable communities [8].

The choice of this topic is justified by the need to find housing solutions that are sustainable and resilient to climate change. Floating houses could offer an innovative solution to this problem. These houses are designed to float on water,

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making them resistant to flooding. They are built on buoyant platforms and can withstand heavy storms, providing a safe and comfortable living environment even during the rainy season [5].

In a similar vein to the innovative approach of utilizing alternative materials for solar water heaters in Mozambique, as demonstrated by Chichango et al. [9] the construction of floating houses using locally available and sustainable wood species can significantly enhance flood resilience in coastal areas. Just as the solar water heaters provide an efficient and cost-effective solution to energy needs, floating houses can offer a robust and adaptable housing solution to mitigate the impacts of climate change. Both approaches underscore the importance of leveraging local resources to develop sustainable and resilient infrastructure, promoting environmental preservation and economic resilience in vulnerable communities.

In the face of these challenges, initiatives such as USAID's Coastal City Adaptation Project (CCAP) have been launched to develop climate-resilient home building techniques. These techniques are designed to withstand intense storms and provide clean, reliable water supply to residents. However, the acceptance of floating houses as an alternative residential solution in coastal areas is still quite low. This is due to factors such as the cost of building a floating house, legal restrictions on building on water, and the reluctance of landowners to build legal houses on their land. To improve the social acceptance of floating houses, these factors need to be addressed. While floating houses offer potential benefits (such as adaptability to rising sea levels), addressing these challenges is essential for wider acceptance. Research and community engagement are key to promoting this alternative housing solution [8].

Beyond that, the concept of circular economy, which involves reusing agricultural waste to produce valuable products, can be applied to the construction of floating houses in Mozambique. Just as banana peels are repurposed for bioethanol production to reduce environmental impacts and enhance community health and income, similar approaches can be adopted for building materials. Utilizing locally available and sustainable resources for constructing floating house platforms aligns with the principles of circular economy. This approach not only addresses the housing challenges in flood-prone areas but also promotes environmental sustainability and economic resilience in rural communities [10] .

1.1. Objectives and justification of the article

The construction of floating houses in rural areas of Mozambique, particularly those prone to flooding, would require materials that are both resilient and locally available. The present study investigates the affordable materials for constructing floating houses in rural areas of Mozambique. As justification for the study, it aims to contribute to the reduction of the recurrent and intensified issue of displaced families due to heavy rains, leading to the loss of property and, sometimes, lives. Measures to alleviate the suffering of the population and reduce the financial burden for the government and its partners in the resettlement of displaced families are necessary.

1.2. State-of-the-Art

1.2.1. Global Perspective

Floating houses, or houseboats, have been gaining popularity worldwide due to their potential to address housing challenges in flood-prone areas:

- **Scandinavia and the United States:** These regions showcase numerous examples of stunning floating homes that offer a sense of adventure and harmonious coexistence with nature [11].
- **Flood-Resistant Architecture:** Floating houses use buoyant foundations that allow them to rise and fall with changing water levels. They are designed for quick assembly and disassembly, making them adaptable to varying water conditions [12].
- **Bangladesh and Cambodia:** These countries have embraced floating houses as a viable solution to annual monsoons and river flooding [11].
- **Amsterdam and Venice:** These cities have explored floating houses as a modern solution that respects architectural heritage while embracing innovative flood-resistant practices [13].

1.2.2. Global Impact and Case Studies

The Float House has made a significant impact in the riverine regions of Asia, where annual monsoons and river flooding pose substantial challenges. Countries such as Bangladesh and Cambodia have adopted The Float House as a viable solution. In urban waterfronts across Europe, The Float House has become a symbol of resilience against rising sea levels [12].

1.2.3. Comparative Study

A study comparing different types of flood-resilient buildings (elevated, amphibious, and floating) at the Vistula River in Warsaw, Poland, confirmed the general characteristics of these resilient typologies. It revealed technical problems with buoyant structures and challenges with mooring on semi-wild freezing rivers [12].

1.2.4. Mozambique Context

While there is growing interest in floating houses globally, the concept is still relatively new in Mozambique. The country, with its low-lying coastal areas and vulnerability to climate change, could greatly benefit from such innovative housing solutions. However, there is currently no specific information available on the state-of-the-art of floating houses in Mozambique [11].

In other hand, the concept of utilizing locally available and sustainable materials to enhance energy efficiency can be applied to the construction of floating houses in Mozambique. Just as alternative materials are used to reduce the production and installation costs of solar water heaters, similar approaches can be adopted for building materials in floating house construction. This aligns with the principles of sustainability and environmental preservation, promoting the use of resources that are abundant and accessible in the region. Implementing such strategies not only addresses the housing challenges in flood-prone areas but also contributes to the diversification of the energy matrix and reduces dependence on non-renewable resources [9].

Mozambique has significant potential for renewable energy, particularly solar power, which can be harnessed to provide electricity to floating houses. The government aims to achieve universal electrification by 2030, with efforts focused on expanding the grid and developing off-grid solutions. Additionally, the Mozambique Energy Fund Institute (FUNAE) prioritizes rural electrification, making small, off-grid projects feasible. This can ensure that floating houses have access to reliable and sustainable energy sources [14].

Water supply and sanitation in Mozambique are characterized by low levels of access, particularly in rural areas. However, ongoing efforts by organizations like UNICEF and the World Bank are improving access to safe water and sanitation facilities. Integrating these facilities into the design of floating houses can enhance the living conditions of residents, ensuring they have access to clean water and proper sanitation [9].

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2. Literature Review

2.1. Design Philosophy

Floating Houses are designed with a keen understanding of flood-prone environments. It introduces a dynamic approach to elevation, inspired by nautical principles. The architects have ingeniously incorporated buoyant foundations that allow the house to rise and fall with changing water levels [12], [15].

2.1.1. Buoyant Foundations and Structural Stability

The Floating House uses buoyant foundations, often made from lightweight and durable materials, which provide structural stability while allowing the house to stay afloat during flooding events [16].

2.1.2. Difference between Floating Houses and Houseboats

Although many people use the terms "houseboats" and "floating houses" interchangeably due to their ability to be on the water, they are distinct structures. The differences are based on the following aspects:

Floating Houses

Floating Houses A floating house is a type of residence moored to a dock on a body of water, such as a river or a lake. Unlike a conventional boat, it functions as a full-fledged home, connected to local sewer and utility lines. The floating house alternatives under consideration are designed to circumvent the need for resettlement during the rainy season. These are not necessarily located on the seashore but rather in areas prone to flooding or where the water table is near the surface [12], [17].

Floating houses are typically characterized by their modern designs, featuring sleek lines, and often making use of repurposed materials. Many floating houses are designed with two levels, boasting large windows to maximize the enjoyment of the surrounding views. They prioritize outdoor living, with a focus on deck and patio spaces. Floating houses designed as solutions to flooding issues differ from these pleasure-oriented floating houses. These houses are constructed using local materials, such as bamboo and distinct types of wood, as discussed in this study. Their design and construction are tailored to withstand the challenges of living in flood-prone areas. They cannot move independently, are tied or anchored to the shoreline or a dock [18].

Floating houses offer an alternative lifestyle, combining the tranquility of the water with the comforts of home. Floating houses for populations affected by climate change are primarily for survival, prioritizing safety and resilience over comfort [19].

Modular Design for Quick Assembly

A key feature of floating houses is their modular design, allowing for swift assembly and disassembly. This adaptability ensures that communities in flood-prone areas can respond promptly to changing water conditions. To counteract the forces of currents and tides, the Floating House incorporates anchor systems that provide stability in floating conditions [20].

Houseboats

A houseboat is a boat that allows owners to live aboard permanently. It does not need to be connected to local sewer or utility lines. Houseboats come in various sizes and styles, from smaller ones to larger vessels. They often have engines, which means owners can move their homes around lakes or rivers at their discretion. Houseboats are mobile and can be moved to different locations. The purpose of houseboats is for both recreational use and permanent living [21].

2.1.3. Environmental Impact and Sustainability

Both floating houses and houseboats have unique environmental impacts. Floating houses, especially those designed for flood-prone areas, often use sustainable materials and construction methods to minimize their ecological footprint. Houseboats, while mobile, can also be designed with eco-friendly features such as solar panels and waste management systems to reduce their impact on the water bodies they inhabit.

2.1.4. Economic Considerations

The cost of building and maintaining floating houses and houseboats can vary significantly. Floating houses, particularly those designed for flood resilience, may require specialized materials and construction techniques, potentially increasing costs. Houseboats, depending on their size and features, can range from affordable to quite expensive. Additionally, the mobility of houseboats can lead to varying maintenance costs based on their usage and location.

2.1.5. Social and Cultural Aspects

The adoption of floating houses and houseboats can also be influenced by social and cultural factors. In some regions, living on water is a traditional practice, while in others, it may be seen as a novel or luxurious lifestyle. Understanding these cultural contexts is crucial for the successful implementation of floating housing solutions.

In summary, the main difference between floating houses and houseboats is that houseboats can move freely, while floating houses cannot. Floating houses rely on local utilities, whereas houseboats do not need to be connected. Floating houses, which are the focus of this study, tend to be smaller and may be less expensive, but this can vary depending on the individual houseboat.

3. Material and methods

3.1. Material

In this study, four species of lumber, as illustrated in Table 1, were collected from different regions in the central part of the country and evaluated for their suitability in floating house construction. These lumber species were subjected to both compression and tensile tests to determine their structural properties and performance.

Table 1 Lumber subjected to compression and tensile test

Chanfuta (*Afzelia quanzensis)*	**Panga Panga** (*Millettia stuhlmannii)*	**Messassa** (*Julbernardia globiflora)*	**Ironwood** (*Swartzia madagascariensis)*
			

For the compression and tensile tests, a range of precise instruments and equipment were employed (Fig. 1)

Figure 1 Universally testing machines

Universally testing machines were utilized to conduct the tests, ensuring accurate measurement of the samples' strength and durability. The samples were weighed using a precision balance, and their dimensional variations were meticulously measured with a caliper. To assess the impact of water absorption, the samples were immersed in a reservoir filled with distilled water. All measurements and observations were carefully recorded using a notepad and ballpoint pen.

The woods were collected from different geographical origins in the country and are typically used for different applications. Wood is known by a common name and scientific name. The summary of these data is presented in Table 2.

Table 2 Lumber investigated for floating house

#	Common name	Scientific name	Primary Source	Main Uses
1	Messassa	*Julbernardia globiflora*	Zambezia, Sofala, Manica	Furniture, varnish, architectural items
2	Ironwood	*Swartzia madagascariensis*	Cabo Delgado, Zambezia	Tember, medicine, insecticide
3	Panga Panga	*Millettia stuhlmannii*	Cabo Delgado, Sofala, Manica	Varnish, decorative mobiliary, grocery furniture
4	Chanfuta	*Afzelia quanzensis*	Cabo Delgado, Nampula, Inhambane	Poles, furniture production, parquet flooring and railway sleepers

3.2. Methods

For the mechanical evaluation of lumber for use in the construction of flood-resistant floating houses, three laboratory tests were conducted as described in [22]:

- Humidity.
- Dimensional stability.
- Density.
- Compression parallel to the fibers.
- Traction parallel to the fibers.
- Buoyancy of the prototype house.

Beyond the proposed tests, there are additional considerations and tests that are typically mandatory for floating houses, such as: Buoyant Foundations and Structural Stability, Dynamic Elevation for Water Adaptability, Modular Design for Quick Assembly, and Environmental Impact. However, the Mechanical tests with wood consider the dry or saturated state of the lumber.

3.2.1. Sample Preparation

The wood samples underwent a process of labeling, weighing, and measurement of their linear dimensions. Each test was conducted using a sample that comprised three specimens, all sourced from the same species of lumber. The samples were then placed in a water bath for about 30 days in a controlled environment to ensure their saturation, as illustrated in Figure 2. After 30 days, the samples were observed, measured, and weighed. The data were recorded in the same table as the initial data before the test

Figure 2 Samples in the water bath

3.2.2. Humidity test

The humidity test is done to adjust the mechanical properties of strength and stiffness. According to NBR 1790:2022 the moisture content is determined by formula (1)

$$U(\%) = \frac{mi - md}{md} \times 100 \qquad \text{…………..(1)}$$

Where: U (%) – is the moisture content, m_i – is initial mass of the specimen, m_d – is dry mass of the specimen.

The specimen dimensions in cross-section are recommended to be 2.0 cm x 3.0 cm and a length along the fibers of 5.0 cm, as shown in figure (3a).

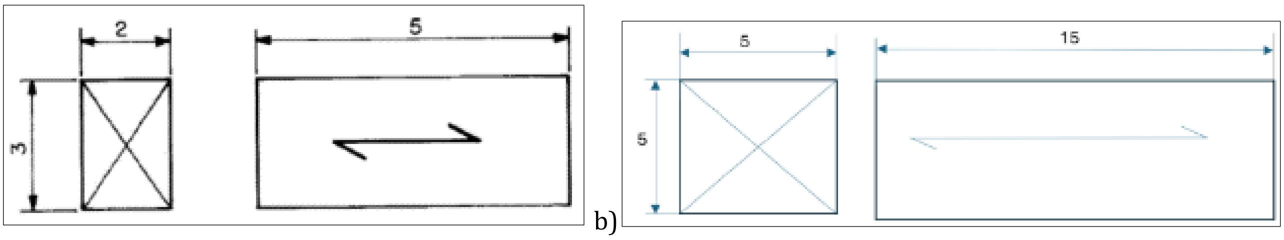
a) b)


Figure 3 a) Sample dimension for compression test; b) Sample for parallel to the fibers according to the standard applied

For general guidelines, the acceptable moisture levels of wood and lumber range from 6% to 8% for indoor use and 9% to 14% for outdoor use or for building envelope components within constructed assemblies. Wood is hygroscopic, meaning it gains or loses moisture as the surrounding air's relative humidity (RH) changes [18]. The safest conditions for most types of wood are between 60- and 80-degrees Fahrenheit and 30% to 50% RH [23].

3.2.3. Test Procedures

The initial mass (mi) of the specimen is determined with an accuracy of 0.01 g. The specimen dried in the chamber at a maximum temperature of 103°C ± 2°C. The mass of the specimen is measured every 6 h until there is a variation between two consecutive measurements less than or equal to 0.5%, the last mass measured should be considered as dry mass (md). Once the md of the specimen is known, the moisture content on the dry basis is determined by the expression (1).

3.2.4. Density Test

Reduced moisture content can lead to a decrease in wood density, thereby making it more appropriate for constructing floating houses. Density is a conventional specific mass. This is defined by the ratio of mass to saturated volume, given by formula (2).

$$\rho = \frac{md}{Vsat} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where: m_d is the dry mass of the specimen in kilograms and V_sat is its saturated volume in cubic meters. According to the standard in question, the saturated volume is determined by the final dimensions of the specimen submerged in water until it reaches a constant mass or with a maximum variation of 0.5% in relation to the previous measurement.

3.2.5. Dimensional stability test, and resistance to decomposition in water

Wood, like many natural materials, is hygroscopic, meaning it absorbs moisture from the surrounding environment. The exchange of moisture between wood and air depends on the relative humidity and temperature of the air, as well as the current moisture content of the wood. This moisture relationship significantly influences the properties and performance of wood [24].

Many challenges in using wood as an engineering material arise from changes in its moisture content or an excess of moisture within the wood [25].

Dimensional stability refers to the degree to which the dimensions of a piece of wood change in response to variations in its moisture content [26]. This property indicates how much a piece of wood shrinks or swells due to changes in its moisture content or the moisture in its environment. The degree of shrinkage and swelling is crucial for determining the suitability of wood for different applications [24].

This property is particularly important for wood used in floating houses, as dimensional changes can lead to issues such as cracking, distortion, and potentially a loss of function (e.g., jammed doors and windows) [26].

The specimens used for the test have initial dimensions of 5 cm, 3 cm, and 2 cm for length, width, and thickness, respectively, as required by the Brazilian Regulatory Standard (BRS 1790:1997). According to this standard, specific shrinkage deformations (ε_r) and swelling (ε_i) are considered indices of dimensional stability and are determined for each of the preferred directions (axial, tangential, and radial). These directions are represented in Figure 4 by 1, 2, and 3, depending on the respective dimensions of the wood measured in situations of saturation and drought.

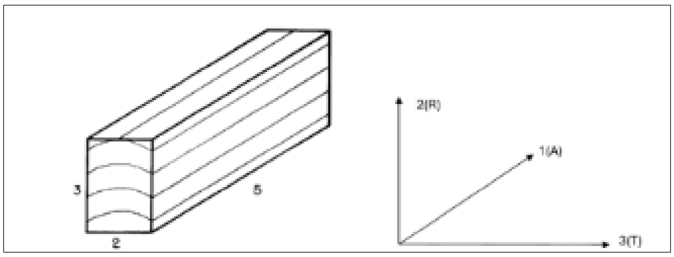


Figure 4 Specimen and orientation directions for determination of shrinkage and swelling indices

The expression of the specific deformations is given by the formula (3) and (3.1).

$$\varepsilon_{swe,i} = \left(\frac{L_{i,Sat} - L_{i,dry}}{L_{i,dry}}\right) X100 \;\; for\; i = 1, 2\; and\; 3 \quad \text{.......... (3)}$$

$$\varepsilon_{shr,i} = \left(\frac{L_{i,Sat} - L_{i,dry}}{L_{i,dry}}\right) X100 \;\; for\; i = 1, 2\; and\; 3 \quad \text{............ (3.1)}$$

Where: L-is the lateral distance, the coefficients i- means direction of orientation (1- Axial, 2- Radial, 3- Transverse), sat, and dry – the statement of the specimen (meaning saturated and dry). $\varepsilon_{swe,i}$ and $\varepsilon_{shr,i}$ are specific deformations of swelling and shrinkage respectively in the i-direction.

The volumetric variation is determined as a function of the specimen dimensions in the saturated and dry states in the specific directions given by formula (4)

$$\Delta V = \frac{V_{sat} - V_{dry}}{V_{dry}} \text{....................(4)}$$

Where: $V_{sat} = L_{1,Sat} x\, L_{2,Sat} x\, L_{3,Sat}$ and $V_{dry} = L_{1,dry} x\, L_{2,dry} x\, L_{3,dry}$

3.2.6. Density test

Lumber density tests are crucial for selecting the right wood for specific applications, ensuring safety, durability, and performance. Key benefits include:

- Structural Integrity: Stronger and more durable wood for construction.
- Moisture Content: Determines moisture levels, affecting dimensional stability.
- Workability: Denser woods offer better stability but are harder to cut.
- Pest Resistance: More resistant to termites and fungi.
- Weight: Essential for calculating the weight of structures.
- Fire Resistance: Better fire resistance properties.
- These tests help ensure the wood chosen meets the necessary criteria for various uses

Lumber density tests can be conducted using standardized methods to ensure accuracy and consistency. One widely used standard is ASTM D2395 [27], which outlines several test methods for determining the density and specific gravity (relative density) of wood and wood-based materials, and another is NBR 1790:1997 and NBR 1790:2022.

3.3. Methodology

- **Volume by Measurement**: The specimen's length, width, and thickness are measured. The initial mass is recorded before oven-drying. After drying, the mass is measured again to determine moisture content.
- **Volume by Water Immersion**: The specimen is submerged in water, and the volume of water displaced is recorded to calculate the specimen's volume.
- **Flotation Tube**: The specimen is placed in a cylinder filled with water and allowed to float. The submerged portion's length is recorded to determine moisture content.
- **Forstner Bit**: A hole is bored into the wood with a Forstner-type bit. The volume of the specimen is calculated based on the diameter and depth of the hole. The mass is recorded before and after the oven drying.

- **Increment Cores**: A core sample is taken using a standard increment borer. The volume and mass of the core are measured before and after oven drying.
- **Chips**: Wood chips are submerged in water and placed in a centrifuge. The volume of water equal to the volume of chips is measured. The chips are oven-dried to determine moisture content.
- **Full-Size Members**: The specimen's dimensions are recorded to determine its volume.

For this issue, the density test was conducted using the methodology of submerging the specimen in water and calculating the volume of water displaced.

3.3.1. Compression and tensile test

Compression and tensile tests are essential for understanding the mechanical properties of wood and other materials. These tests help determine the stress-strain behavior of wood under various loads [28]. And tensile tests are ideal for applications where tensile forces are applied. They measure the force required to pull something, such as a structural beam, to the point of breaking. The tensile strength of wood is the maximum stress that can be sustained by a wood sample along its length until it breaks [29].

Compression tests, on the other hand, are more suitable for applications involving pressure forces [30]. They measure the ability of a material, like wood, to withstand compressive loads that reduce its size. In the context of wood, the compression strength is the maximum stress that can be sustained by a wood sample while being compressed along its length until it fails [23].

In addition to these tests, other tests such as bending, sharing, torsion, and cleavage are also used to determine the strength properties of wood [31]. Although these tests are important for calculating and sizing wood products, they were not included in this study. However, the compression and tensile tests of lumber for the construction of flood-resilient houses were conducted in accordance with Brazilian standards (NBR 1790:1997 and NBR 1790:2022) Figure (2b).

Before placing the sample in the machine, it must be ensured that the specimen has moisture above the saturation point of the fibers, placing it in a saturated environment, with a temperature of 20°C ± 5°C, until the dimensional variation stabilizes around the difference of 0.02 mm between two successive measurements. The maximum compressive force is given by the formula (05).

$$\sigma_{Comp} = \frac{F_{N\_max}}{A} \quad \text{.............}(05)$$

Where:

- $F_{N\_,max}$. is the maximum compressive force applied to the specimen during the test, in Newtons.
- A - is the initial area of the compressed cross-section, in square meters.
- σ_{Comp} is the compressive strength parallel to the fibers, in Megapascals [29].

3.3.2. Tensile test and procedures

Using the same standard, the tensile strength and stiffness parallel to the wood fibers of a homogeneous lot are determined. The tensile strength parallel to the fibers is given by the maximum stress corresponding to the maximum force that can be applied to a specimen until rupture in the central section of a given cross-sectional area A, represented by the formula (06):

$$\sigma_t = \frac{F_{t\_max}}{A} \quad \text{............}(06)$$

where:

- Ft_{max} is the maximum tensile force applied to the specimen during the test in the normal direction, in Newtons.
- A is the initial area of the tensile cross-section of the central section of the specimen, in square meters.
- σ_t is the tensile strength parallel to the fibers, in Megapascals [32].

The modulus of elasticity is determined under the same conditions as the compression test. Figure (5a) illustrates the specimen under parallel fiber compression and Figure 5b) presents prepared specimens and dimensions for the tensile test.

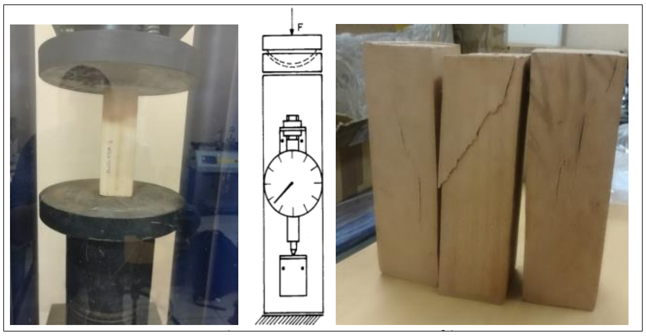
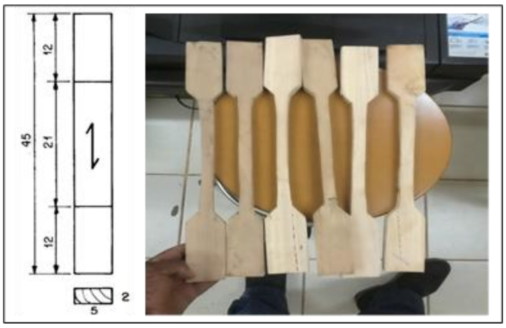
	
a	b

Figure 5 a) Specimens under parallel fiber compression; b) Specimen and dimensions for the tensile test

3.3.3. Buoyancy test of the prototype

A floating house stays afloat due to buoyancy, which is the upward force exerted by a fluid (like water) on an object submerged in it. According to Archimedes' principle, a body immersed in a fluid experience an upward force equal to the weight of the fluid displaced by the body. If the density of the house is less than that of water, it will float. After conducting the tests, the species of wood that proved to be viable in terms of mechanical resistance will be used for the construction of the prototype, which will be supported on the house base shown in figure (6).

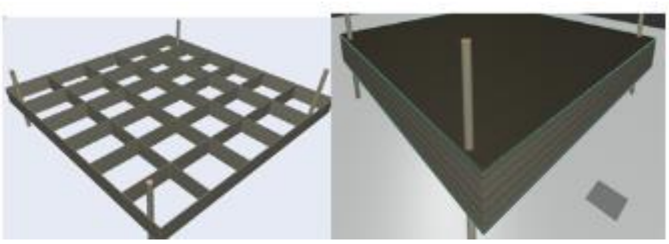


Figure 6 Prototype of floating house base for buoyancy testing

The floating house base for buoyancy as dimensions: C= 1,18m; L=1,20m; H= 0.15 m; thicknesses e=5cm (Admission submersion (H/2).

Buoyancy is the tendency of an object to float or sink when placed in a fluid. If the buoyancy is greater than the weight of the object, the object will float because the upward force (buoyancy) outweighs the downward force (weight). If the buoyancy is less than the weight of the object, the object will sink. Therefore, the buoyancy of an object is determined by the buoyant force acting on it. If the buoyant force is sufficiently large, the object will float; if it isn't, the object will sink. Thus, it can be said that buoyancy is a manifestation of Archimedes' principle [33].

The buoyancy test procedure consisted of calculating the Buoyancy Force (F) using the water density, gravity acceleration, and the volume displaced from the water, which is equivalent to the cross-sectional area of the base and the height that will be submerged in the water (Eq. 07).

$$F = \rho_f \cdot g \cdot V \text{ …………..(07)}$$

Where:

- Buoyancy force.
- ρf.–density of the fluid (water).
- g–acceleration of the medium's gravity.
- V- Displaced volume of fluid given by Eq (8)

$$V = d\_im \cdot A \quad ....(08)$$

Where:

- d_im - is the immersed depth,
- A - is the cross-sectional area over the water.

On the other hand, the houseboat has its own weight, which includes the weight of the materials used in its construction, as well as the weight of the infrastructure, furniture, and occupants. When the water level rises, the houseboat will either be supported by the water or become flooded. This outcome depends on the comparison between the buoyancy force and the weight of the floating house. The weight of the floating house is given by (Eq. 9).

$$P = m_{fh} \cdot g \quad ....(09)$$

Where

- P — is the Weight of the floating house.
- m_{fh} - is the total mass of the floating house.
- g is the gravity acceleration.

Required data

Mass of the house: The volume of the house, as the shape is irregular, it was considered to divide the house into simpler parts and calculate the volume of each part separately. And The weight (P).

$$\rho = \frac{m}{V} \quad \text{and} \quad P = \rho_{house} \times V_{house} \times g ....(10) \text{ and } (11)$$

Where:

- ρ - is water density (kg/m^3). The density of water is approximately 1000 kg/m^3.
- m – mass (kg) of the house
- V – volume (m^3) occupied by the house

The Buoyancy (E) is given by:

$$E = \rho_{fluid} \times V_{fdisp.} \times g ....(12)$$

Where:

- ρ_{house} — specific house mass.
- ρ_{fluid} — specific mass of the fluid.
- V_{fluid} — fluid volume displaced.

Note: Given that the gravity and the fluid volume remain constant, if the density of the floating house is less than the density of water, it will float.

4. Results and discussion

4.1. Humidity test

The results of the humidity test indicate that Ironwood (Swartzia madagascariensis) exhibited lower moisture content compared to the other species tested (Figure 7a). Wood with low moisture content tends to be more stable and durable. Excessive humidity can lead to deformations, cracks, and mold growth, while insufficient humidity results in fragility and loss of structural integrity [34].

Wood with lower relative humidity is less susceptible to attacks by fungi and insects. Additionally, dry wood is lighter and has better workability, making it ideal for indoor use and furniture manufacturing. Among the four specimens tested, Ironwood was the driest and demonstrated the greatest dimensional stability. The variation in dimensions during the test was minimal after the water bath.

Considering a relative humidity range of 9% to 14% for outdoor use or building, particularly for floating house walls and platforms, it is crucial to evaluate the wood's durability, resistance to moisture, and stability. Ironwood (Swartzia madagascariensis) is known for its termite resistance and durability. The results obtained align with the findings of Orwa et al. (2009), which confirm that Ironwood is suitable for outdoor use, especially in areas with moderate humidity. This makes it an excellent choice for applications where stability and resistance to environmental factors are critical, such as floating houses.

4.2. Dimensional stability test results

The dimensional stability tests were conducted on four wood species: Messassa (Julbernardia globiflora), Ironwood (Swartzia madagascariensis), Panga Panga (Millettia stuhlmannii), and Chanfuta (Afzelia quanzensis). Among these, Ironwood exhibited the lowest variability in the dimensions, indicating superior dimensional stability (Figure 7b).

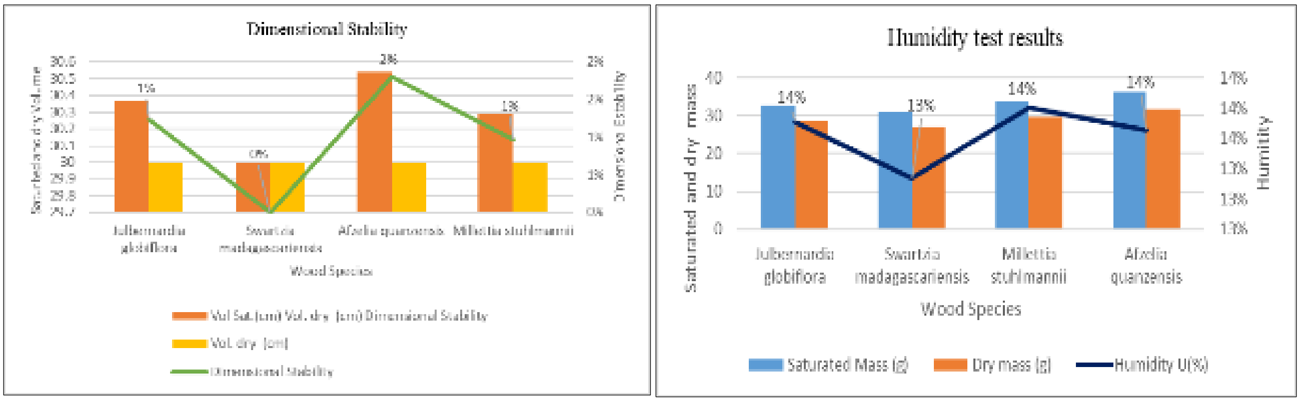


Figure 7 a) Relative humidity of wood by species; b) Dimensional stability of the wood

The results suggest that Ironwood (Swartzia madagascariensis) is less prone to shrinkage and swelling compared to the other species tested, making it a more reliable choice for constructing floating house platforms. The stability of Ironwood can help prevent issues such as cracking, distortion, and functional problems like jammed doors and windows, which are critical for the durability and performance of floating houses. This superior dimensional stability ensures that Ironwood maintains its structural integrity even in varying moisture conditions, making it an ideal material for such applications.

The variability in the dimensions of lumber can be due to natural variations in the wood, the way the wood is cut, or changes in the wood's moisture content [23] [35]. This variability can affect the dimensional stability of the wood, and therefore, the stability of the floating house. For example, if the dimensions of the lumber vary significantly, it could lead to uneven weight distribution, which could impact the balance and stability of the house on the water. Ensuring consistent dimensions and moisture content in the wood used for floating house platforms is crucial to maintaining the overall stability and functionality of the structure.

4.3. Density test results

The density test revealed that among the species examined, Chanfuta (Afzelia quanzensis) exhibited the highest density compared to the others, as shown in Figure 8. This higher density indicates that Chanfuta is likely to have superior structural integrity and durability, making it a strong candidate for applications requiring robust and stable wood. The increased density also suggests better resistance to mechanical stress and environmental factors, enhancing its suitability for demanding construction projects.

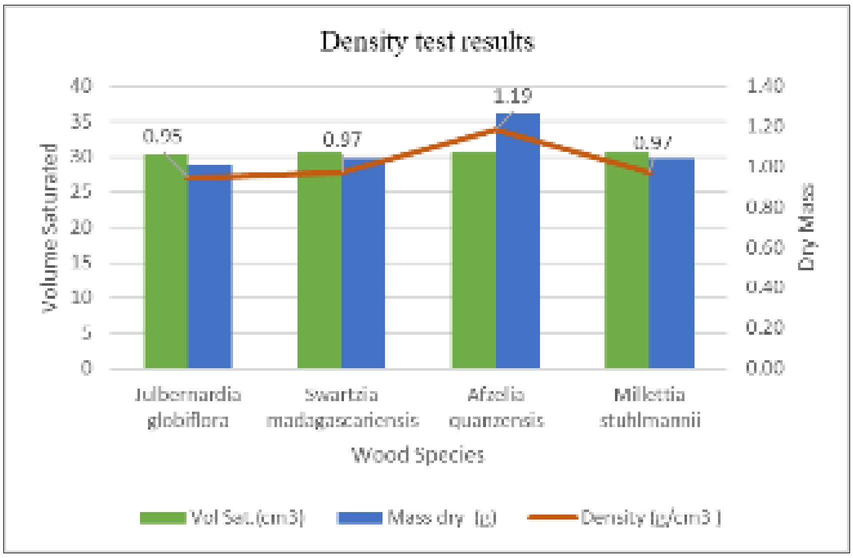


Figure 8 Results of lumber density test

High density lumber is heavier and typically stronger than low density lumber. This can contribute to the overall strength and durability of the floating house. However, because it's heavier, it could potentially decrease the buoyancy of the house. Therefore, the design of the floating house must ensure that the weight of the house (including the high-density lumber) does not exceed the uplift force of the water, which would otherwise cause the house to sink [36].

In other hand, low density lumber is lighter, which can increase the buoyancy of the floating house. This can be beneficial in maintaining the house's stability on the water surface. However, low density lumber may not be as strong or durable as high-density lumber, which could impact on the structural integrity of the house over time.

In both cases, the key is to strike a balance between the weight of the house and its buoyancy. The house's weight should be equal to or less than the water's uplift force to allow it to float. This principle of buoyancy is fundamental to the design of floating houses .

4.4. Compressive strength lumber test results

The compressive strength of wood determines how much load the wood can withstand without deformation or failure. This is crucial to ensure that the floating house can support the weight of the occupants and furniture without structural damage. It also can help assess the quality of the wood. Figure 9 illustrates the specimens under compression test.

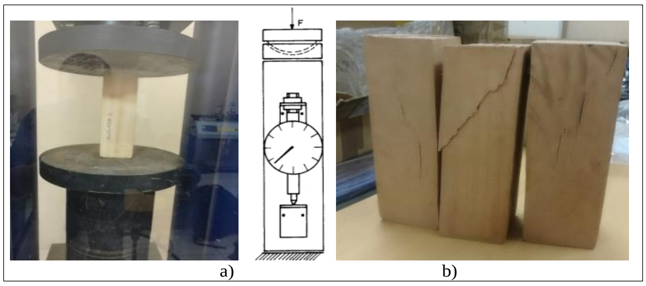


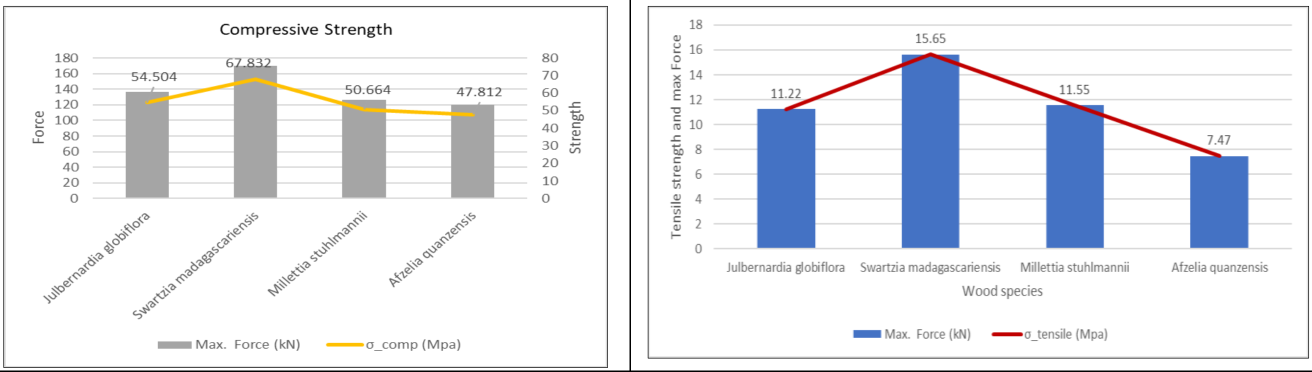
Figure 9 Specimens under parallel fiber compression test

In this test, high-quality wood exhibits higher compressive strength, indicating greater durability and resistance to damage. Different types of wood have varying compressive strengths, which is a crucial factor for the safety of floating houses. Homes constructed with wood of low compressive strength can be unsafe for occupants.

The test results, illustrated in Figure 10a, show that Ironwood (Swartzia madagascariensis) has significant advantages due to its high compressive strength, while Chanfuta (Afzelia quanzensis) is the least favorable. It is important to note that the cross-section of the specimens in this test was 25 m^2, as recommended by standards NBR 1790:1997 and 2022.

4.5. Tensile strength lumber test results

The tensile strength of wood is a critical factor in the design of structural components. Figure 9b shows the results of tensile strength test of the different wood species.



a b

Figure 10 Results of a) compressive test results b) Tensile strength results

From Figure 9b, the tensile strength of the tested wood species can be compared. The results indicate that Ironwood (*Swartzia madagascariensis*) is more resilient than the other species. The summary of test results is presented in table (4) where all the wood species are classified in terms of performance.

Table 3 Wood test summary

Wood Species	**Classification from high to low performances (position)**				
	Humidity	Dimensional Stability	Density	Compressive Strength	Tensile Strength
Messassa (*Julbernardia globiflora)*	Third (3)	Third (3)	Second (1)	Second (2)	Third (3)
Ironwood (*Swartzia madagascariensis*)	First (1)	First (1)	Third (2)	First High (1)	First High (1)
Panga Panga (*Millettia stuhlmannii*)	Fourth (4)	Second (2)	Third (2)	Third (3)	Second (2)
Chanfuta (*Afzelia quanzensis*)	Second (2)	Four (4)	Fourth (3)	Fourth (4)	Fourth (4)

The table 3 shows the good mechanical properties of the species Ironwood *(Swartzia madagascariensis)* for the construction of houses resilient to flooding, followed by the species Panga Panga *(Millettia stuhlmannii)* also have good mechanical properties.

4.6. Floating house prototype construction

After identifying the wood species with the best properties for home resilience to flotation, the prototype of the floating house was built and it weighed 18,345kg, as illustrated in Figure 11.

Figure 11 Floating House Prototype

The floating house prototype was constructed using Ironwood (*Swartzia madagascariensis*). The model features four mooring posts to anchor the house to submerged concrete foundations. When water levels rise, the entire house moves upward and floats.

4.7. Buoyancy test results

The table 4 presents the dimensions of the floating house prototype.

Table 4 Input data for the buoyancy test

Ref	Description	Dimension	Unit
1	Platform Base Area (L =1.18m; W =1.20m)	1,42	m^2
2	Platform height (H)	0,15	m
4	Submerged height (H/2)	0,075	m
3	Wood thickness (for in platform inner volume)	0,02	m
5	Wood Density	1020	kg/ m^3
6	Density of fresh water	1000	kg/m^3

For the buoyancy test, it was considered acceptable for the platform to be submerged up to half its height, and that the wooden platform is made of Ironwood (according to test made before) with density and thickness presented in table 4. The buoyancy results were calculated for the platform without the floating house prototype to determine the maximum weight it care support without sinking. Table 5 presents the buoyance teste.

Table 5 Buoyance test results

Parameter	Value	Unit	Parameter	Value	Unit
Base area	1,416	m^2	Inner Thickness	0,02	m
Submerged height (h/2)	0.075	m	Platform volume extern	0,2124	m^3
Displaced Volume	0,1062	m^3	Platform Volume intern	0,1719	m^3
Displaced Water mass	106,2	kg	Platform mass	41,31	kg
Buoyant Force (Fb)	1041,82	N	Weight of platform	405,13	N

According to Table 5, the buoyant force (1041.82 N) is greater than the weight of the wooden platform (405.13 N), indicating that the platform will float. Additionally, there is an extra capacity to support a mass of 64,9kg (636,69N), which accounts for the floating house prototype and other potential loads the house might be subjected to, such as strong winds, etc. In instance, the floating house prototype built in this research, shown in figure 11 above, has a weight of 18,345 kg, demonstrating that the system can float without any issues.

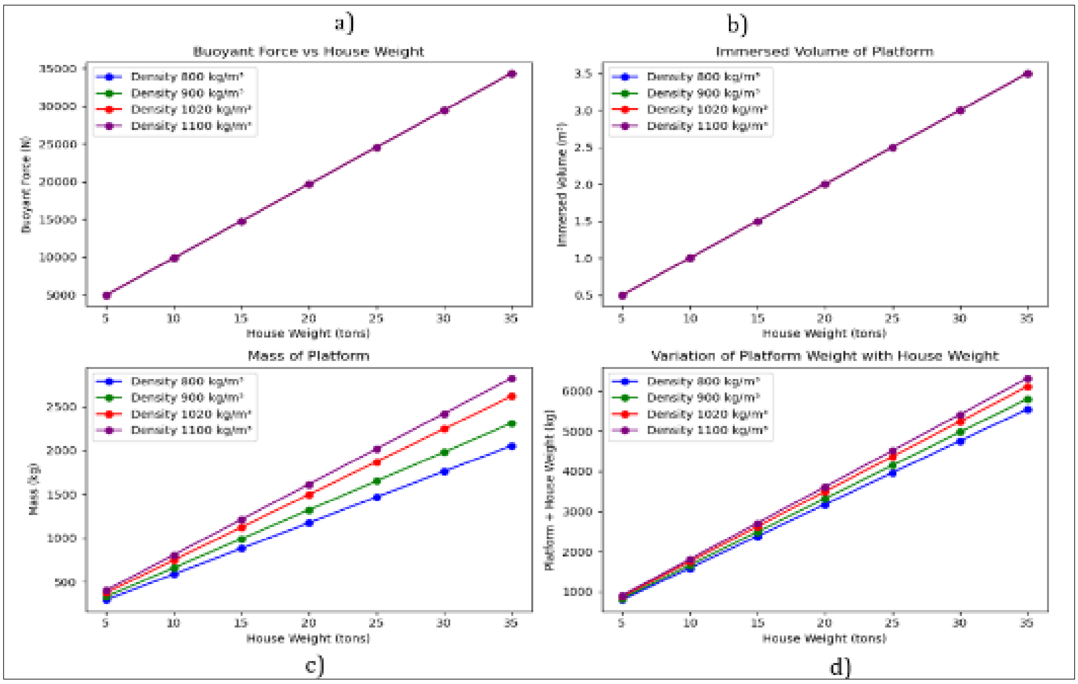


Figure 12 Relationship ship of different variables with impact in house floating. a) Force vs House Weight: Shows how the buoyant force changes with different house weights and wood densities. b) Immersed Volume of Platform: Displays the immersed volume required for different house weights and wood densities. c) Mass of Platform: Indicates the mass of the platform needed to support different house weights and wood densities. d) Variation of Platform Weight with House Weight: Illustrates how the weight of the platform varies with the weight of the floating house

The buoyant force is the force exerted by the water to push the platform upwards, while the platform weight is the force exerted by gravity to pull it downwards. The calculated ratio of approximately 0.389 indicates that the buoyant force is significantly greater than the platform weight, ensuring that the platform floats. This is crucial for stability, as a platform that does not float properly may sink or tilt, compromising its functionality.

The wood density (1020 kg/m^3) is a critical factor. Materials with a density lower than water (1000 kg/m^3) tend to float better. However, the wood used has a slightly higher density than water, meaning the platform needs careful design to ensure the buoyant force is sufficient to keep it afloat. The choice of wood and its density directly influence the platform's buoyancy and stability.

The platform base area (1.416 m^2) is another important factor. A larger area allows the platform to displace more water, increasing the buoyant force. This is beneficial for buoyancy, as the larger the area, the greater the volume of water displaced, resulting in a higher buoyant force. Therefore, the base area must be large enough to ensure the platform can support the weight of the house and any additional loads.

The submerged height (0.075 m) determines the volume of water displaced. A greater submerged height displaces more water, increasing the buoyant force. However, it is important to balance the submerged height to ensure the platform does not sink too much, which could compromise its stability. The submerged height should be calculated to maximize the buoyant force without compromising the structural integrity of the platform.

The relationship between the weight of the house on the platform and the buoyant force is fundamental to ensuring the platform's buoyancy and stability. The wood density, platform base area, and submerged height are critical variables that must be carefully considered in platform design. The buoyant force being greater than the platform weight is a positive indicator that the platform can float properly, supporting the weight of the house and ensuring its functionality.

Considering the variation in wood density, the results may differ. Table 6 below presents the different values of wood density.

Table 6 Wood range Density

Common Name	Scientific Name	Density Range (kg/m^3)
Messassa	Julbernardia globiflora	600 - 650
Ironwood	Swartzia madagascariensis	1090 - 1250
Panga Panga	Millettia stuhlmannii	850 - 900
Chanfuta	Afzelia quanzensis	800 - 850

For a floating platform, wood with a lower density is generally more suitable because it will be more buoyant. Among the options from the table 6, Messassa (Julbernardia globiflora) with a density range of 600 - 650 kg/m^3 would be the most appropriate choice for a floating platform. Higher density woods like Ironwood (Swartzia madagascariensis) with a density range of 1090 - 1250 kg/m^3, are less buoyant and may not be ideal for floating structures.

5. Conclusion

Mozambique, with its low-lying coastal areas, is highly vulnerable to climate change impacts such as rising sea levels and frequent intense storms. These climatic events cause significant flooding, erosion, landslides, threatening communities and traditional housing structures. Floating houses offer a promising solution to these challenges by providing resilient and adaptable housing that can withstand flooding and heavy storms.

The research findings underscore the potential of Ironwood (Swartzia madagascariensis) as a viable material for constructing floating house platforms in Mozambique's flood-prone coastal areas. Ironwood's low moisture content and high dimensional stability make it an excellent choice for maintaining structural integrity and preventing issues like cracking and distortion. This is crucial for the durability and performance of floating houses, which offer a sustainable and resilient housing solution in these regions. Additionally, Ironwood's high compressive and tensile strength further supports its suitability for floating house construction. The wood's ability to withstand significant loads without deformation or failure ensures the safety and stability of the floating house, making it a reliable choice for constructing resilient structures that can endure the stresses associated with floating on water. This aligns with the objectives of initiatives like USAID's Coastal City Adaptation Project (CCAP), which aims to develop climate-resilient home building techniques.

However, the buoyancy test results highlight the importance of balancing wood density and platform design. While Ironwood's higher density provides strength, it requires careful design to ensure adequate buoyancy. Future research should include comprehensive economic viability studies to assess the cost-effectiveness of using Ironwood for floating house construction. This involves analyzing initial costs, long-term maintenance expenses, and potential savings from reduced structural damage and increased durability. Addressing these factors, along with legal restrictions and community engagement and capacity building using specific methodologies mentioned in [37] it is essential for improving the social acceptance of floating houses as a sustainable housing solution in Mozambique.

Compliance with ethical standards

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Disclosure of Conflict of interest

The authors declare that there are no conflicts of interest or competing interests related to the publication of this manuscript.

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