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Development of water hyacinth reinforced jackfruit-seed-starch bi-layerd composites for sustainable thermal insulation

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Abstract

This study investigates the development of biodegradable composite materials using water hyacinth pulp and jackfruit-seed-starch as a binder, aimed at providing an eco-friendly solution for thermal insulation applications. The composites were fabricated using a compression molding process with varying starch contents (10%, 20%, 30%, and 40%) under controlled temperature and pressure. Mechanical properties such as tensile strength, flexural strength, impact strength, hardness, and thermal conductivity were evaluated. The results indicated that composites with 30% jackfruit seed starch exhibited the best mechanical performance, including tensile and flexural strength, along with favorable thermal conductivity. However, water absorption remained a challenge, with higher starch content leading to increased moisture uptake. The findings highlight the potential of these composites for thermal insulation, particularly in extremely cold countries, where they could serve as a sustainable alternative to conventional materials. Further studies are needed to reduce water absorption and enhance the durability of the composites for long-term use.

Keywords: Water hyachinth composites, Jackfruit seed starch, Biocomposites, Thermal insulation, Biodegradable composites

1. Introduction

The rapid growth of urbanization and the associated demand for construction materials has led to an increasing interest in sustainable building materials [1, 2]. Water hyacinth, an invasive aquatic plant, has been identified as a promising raw material due to its abundant availability and various beneficial properties [3]. Several studies have explored the potential of water hyacinth in the development of eco-friendly composite materials for construction, focusing on its thermal insulation, sound absorption, and mechanical propertie [4, 5]. Salas-Ruiz et al. [6] developed binder-less insulation panels using water hyacinth petioles (WHP) and explored their thermal insulation properties, highlighting the plant's aerenchyma structure, which enhances insulation performance. However, the challenge remains in optimizing mechanical strength for broader applications. Similarly, Abral and Hartono [7] investigated the incorporation of water hyacinth fiber pulp (WHF) into tapioca starch biopolymers (TSB) to create biocomposites. Their findings revealed significant improvements in tensile strength, thermal resistance, and moisture resistance with higher WHF content, though an increase in fiber content resulted in a reduction in fracture strain. This trade-off between strength and flexibility is a critical consideration for practical applications. In another study, Flores Ramirez et al. [8] examined the use of water hyacinth fibers in polyester resin composites, which demonstrated lightweight and excellent acoustic insulation properties, though mechanical performance was somewhat compromised compared to synthetic alternatives. Sruti et al. [9] explored the use of water hyacinth powder combined with corncob ash to create biocomposite boards. Their results showed high thermal insulation properties, with the composite material exhibiting superior mechanical strength, making it a viable alternative for cool boxes. Chaireh et al. [10] developed biodegradable starch-based foams reinforced with water hyacinth powder and coated with beeswax, demonstrating improved mechanical properties and structural integrity. Similarly, Philip and Rakendu [3] research on water hyacinth-cement composite thermal insulation panels suggested that while these composites had lower flexural strength, their thermal conductivity was favorable compared to conventional materials like MDF and plywood. In a related study, David et al. [11] investigated bio-based composite insulation materials made from water hyacinth and rice straw, which exhibited low thermal conductivity and high porosity, further proving the plant’s suitability as a sustainable insulation material. Pongsa et al. [12] used coconut residue to reinforce biodegradable foam composites made from cassava starch, highlighting the potential of natural fibers in enhancing the mechanical and thermal properties of biofoams. Nugroho et al. [13] work on cassava starch and water hyacinth fiber (WHF) biofoams found that increasing the polyvinyl alcohol (PVA) content enhanced the material's compressibility, water absorptivity, and biodegradability, offering an alternative for eco-friendly packaging. Additionally, Motaleb et al. [14] examined the potential of water hyacinth and sugarcane bagasse fibers in epoxy resin composites, exploring the effects of surface treatments on mechanical properties and water absorption. Anjani et al. [15] study on composites of water hyacinth

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and bagasse fibers reinforced with epoxy resin highlighted their thermal conductivity and bending strength, suggesting their application in insulation materials. Ratchakrom and Rodvinij [16] research on water hyacinth-reinforced adobe bricks showed that the inclusion of water hyacinth fibers enhanced durability and reduced shrinkage, although compressive strength decreased. These studies highlight the growing body of research focused on utilizing water hyacinth as a reinforcement material in various biocomposite applications [17].

The main challenge in previous research is the complexity of processes involving multiple chemicals, making them intricate and time-consuming. This highlights the need for greener and simpler methods with minimal chemical usage [18, 19]. Another major challenge is the water absorption tendency of natural fiber/pulp-reinforced composites, which is difficult to control. However, this study proposes the development of a tile-like biocomposite specifically for thermal insulation in extreme cold regions, where the atmospheric moisture levels are naturally low. In such environments, especially at temperatures below 0°C, the air holds very little moisture due to reduced humidity and frozen water content, significantly lowering the risk of moisture uptake by the composite. Therefore, the inherent limitation of higher water absorption in natural composites becomes less critical in these conditions, making the material more suitable for application in cold climate insulation systems. The most significant aspect of this research is the completely chemical-free production process, ensuring a 100% green composite with no harmful waste. The novelty lies in utilizing agricultural waste—water hyacinth and jackfruit seeds—as both reinforcement and matrix materials, adding commercial value to these otherwise discarded resources.

2. Materials and methods

2.1 Materials

The primary material used for the composite samples was water hyacinth pulp, which was obtained through a series of processing steps. Mid-aged stems were collected from a pond, with the roots discarded, and the stems were thoroughly cleaned with water. The stems were then chopped into 4 cm long pieces while maintaining proper size distribution. These pieces were boiled in a furnace without any chemicals for 3 hours to remove impurities and soften the material. The boiled stems were subsequently blended to obtain a consistent pulp. Jackfruit seed starch was used as the matrix material in varying concentrations (10%, 20%, 30%, and 40%) during composite preparation. The jackfruit seeds were collected from ripe fruits harvested from a mid-aged tree. The seeds were cleaned thoroughly, ground in a blender, and soaked overnight in water. The starch content settled at the bottom of the jar and was carefully collected for use. The collected starch was then cooked at 80–85°C for around 20 minutes with continuous stirring until a consistent, gelatinous solution was obtained. During cooking, the viscosity of the starch slurry was visually observed to increase gradually, and based on qualitative assessment, it reached a semi-fluid consistency suitable for uniform application, roughly in the range of 1500–2500 cP as estimated by common laboratory behavior of boiled starch solutions.

2.1.1 Preparation of preforms

Preforms were developed as an intermediate step to shape and consolidate the water hyacinth pulp into a uniform, dimensionally stable structure before the application of the jackfruit-seed starch matrix, which facilitated better handling, ensured consistent fiber distribution, and enhanced the penetration and adhesion of the matrix during final compression molding. This approach also helped to partially remove excess moisture, reduce void content, and improve the overall mechanical integrity and reproducibility of the composite samples. A compression molding machine was employed to fabricate preforms from water hyacinth pulp. The molding was carried out using a specially designed steel template framework to ensure consistent width, height, and thickness across all samples, thereby maintaining dimensional uniformity. During this process, no matrix or binding agent was added, allowing the preforms to be composed solely of compacted water hyacinth pulp. The pulp was subjected to a pressure of 2 tons using the hydraulic press, and a dwell time of 5 minutes was maintained to ensure adequate compaction and moisture expulsion. This pressing condition resulted in cake-like solid preforms that were sufficiently rigid and cohesive to be handled and used in the subsequent composite fabrication steps, where the starch matrix was later introduced.

2.1.2 Composite fabrication

After the water hyacinth pulp preforms were prepared, a layer of boiled jackfruit-seed starch was uniformly applied to both sides of each preform, ensuring an even distribution of the matrix material. This application was carried out manually using a brush to achieve controlled layering, followed by thorough drying under ambient conditions for 24 hours to remove residual moisture and facilitate strong interfacial bonding between the matrix and the reinforcement. Four distinct composite formulations were developed by varying the concentration of jackfruit-seed starch, applied at 10%, 20%, 30%, and 40% by weight relative to the dry mass of the water hyacinth pulp, as presented in Table 1 and illustrated in Figure 1. Once the starch had sufficiently dried, the matrix-coated preforms were placed in a compression molding machine equipped with heated plates. The molding parameters were set at a pressure of 3 tons and a temperature of 80 °C, with a dwell time of 30 minutes. These conditions were chosen based on the gelatinization range of jackfruit seed starch (65–80 °C), which ensures thermal activation without degrading the matrix, while maintaining fiber integrity. The moderate temperature also reduces energy consumption, aligning with the study's aim of developing environmentally friendly and easily processable materials. The selected pressure facilitates good fiber-matrix contact and consolidation without excessive compaction, and the dwell time allows sufficient heat transfer and curing throughout the composite panel [12, 20]. This step enabled the formation of rigid, thermally stable biocomposites suitable for insulation applications.

2.1.3 Post-Processing and curing

The molded composite samples were allowed to cool at room temperature before being removed from the mold. The samples were then stored under standard laboratory conditions to achieve equilibrium moisture content before testing.

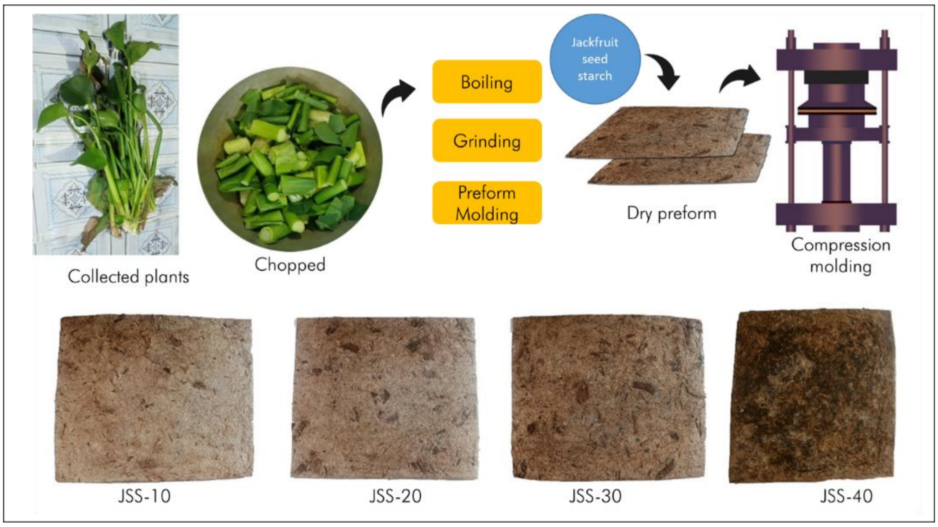

Figure 1 Preform and composite building process and all developed samples

Table 1 Overall properties and nomenclature of the developed composites

Sample Code	Nomenclature	Density (g/cm³)	Thickness (mm)	Void Content (%)
JSS-10	10% JSS Composite	0.85	5.2	10
JSS-20	20% JSS Composite	0.91	5.1	9
JSS-30	30% JSS Composite	0.92	5.0	7
JSS-40	40% JSS Composite	0.94	4.8	5

2.2 Methods

2.2.1 Tensile testing

The tensile test was conducted to evaluate the ultimate strength, elasticity, and elongation of the composite tiles. Specimens with dimensions of 100 × 20 × 4 mm were prepared. The test was performed using a universal testing machine (UTM) at a constant crosshead speed of 5 mm/min. The load was applied until the specimen broke, and the maximum force required for the fracture was recorded. The tensile strength was calculated using the formula:

Tensile Strength (MPa) = $\frac{F_{max}}{A}$

2.2.2 Bending (flexural) testing

The bending strength of the composite tiles was determined using a three-point bending test, in accordance with European Standard 12089. Specimens of size 150 × 75 × 15 mm were placed on a testing machine with a span of 100 mm. A gradually increasing load was applied at the center until failure occurred. The maximum bending stress at failure was calculated using the equation:

Flexural Stress (N/mm^2) = $\frac{3FL}{2bd^2}$

The Modulus of Rupture (MOR) was determined from the flexural stress at the point of fracture. This test is critical in understanding the material's resistance to bending and its suitability for structural applications.

2.2.3 Impact testing

Impact strength was measured to assess the material's ability to absorb energy under sudden loading. The test was conducted using a standard pendulum-based impact tester. Specimens with dimensions of 75 × 15 × 4 mm were placed in the tester, and the energy required to fracture the sample upon impact was recorded. The impact strength was calculated as the energy absorbed per unit cross-sectional area of the specimen:

Impact Strength (J/m^2) = $\frac{\text{Energy absorbed}}{Cross\text{−}sectional\ area}$

This test evaluates the material's toughness and its ability to resist failure under dynamic loads, which is particularly important for applications subject to sudden impacts.

2.2.4 Hardness testing

Hardness testing was carried out to determine the resistance of the composite tiles to surface indentation. A Shore D durometer was used, applying a standard indenter to the surface of the tile under a defined pressure. The hardness value was recorded as the depth of indentation, providing a measure of the material's surface strength. This test is particularly useful for understanding how the composite material will perform under wear and tear conditions.

2.2.5 Water uptake

The water uptake behavior of the composite tiles was assessed by immersing the samples in water at room temperature (22°C) for 24 hours. The samples were weighed before and after immersion, and the percentage increase in weight due to absorbed water was calculated using the following equation:

$$\text{Water Uptake (\%)} = \frac{\mathrm{M_{wet}} - \mathrm{M_{dry}}}{M_{dry}}$$

2.2.6 Thermal conductivity testing

Thermal conductivity was measured using a steady-state method with a PHYWE high-insulating house, equipped with five thermocouples (type K). Samples were pre-dried at 40°C for 24 hours to ensure constant weight before testing. The thermal conductivity was calculated by comparing the temperature gradients between the sample and a reference material of known thermal conductivity. This test provides valuable insights into the material's insulating properties, critical for applications in building construction where energy efficiency is a concern.

3. Results and discussion

3.1 Tensile strength

The tensile strength results show a progressive increase from JSS-10 (2.5 MPa) to JSS-30 (5.2 MPa), followed by a decline at JSS-40 (3.1 MPa), while the tensile modulus follows a similar trend, increasing from 122 MPa (JSS-10) to 136 MPa (JSS-30) before decreasing to 126 MPa (JSS-40) (Figure 2). The compression molding process, carried out at 80°C and 3 tons pressure, perhaps played a role in ensuring proper matrix penetration and adhesion between the fibers, leading to enhanced mechanical properties up to 30% starch content. This level of pressure is commonly reported in natural fiber composite fabrication and is sufficient to promote intimate contact between the hydrophilic starch matrix and the porous water hyacinth fibers, allowing effective interfacial bonding without damaging the fiber network [21]. Too little pressure may lead to inadequate fiber wetting, interfacial voids, and poor load transfer, while excessive pressure can deform or crush the lignocellulosic fibers and force out the starch matrix, reducing fiber content and compromising the structural integrity of the composite. Hence, the selected pressure provided a balance between consolidation and preservation of fiber structure. Although scanning electron microscopy (SEM) could provide additional insight into fiber–matrix interfacial bonding, it was not included in this study due to resource limitations. Given that the primary focus of the research is the thermal insulation performance of the developed composites, the mechanical analysis provided is considered sufficient to support the overall objectives. The failure mechanism in the composites can be understood based on the mechanical test results and findings reported in similar natural fiber–starch systems in the literature [7, 22]. At optimal starch content (around 30%), strong interfacial adhesion between the starch matrix and water hyacinth fibers allows effective stress transfer, resulting in energy absorption through a combination of fiber pull-out, fiber breakage, and matrix cracking. This mixed failure mode helps dissipate impact energy and improve flexural strength. In contrast, at higher starch content (40%), poor fiber-matrix compatibility and possible phase separation weaken the interface, causing brittle failure with cleaner fracture surfaces and reduced mechanical performance. Such behavior aligns with studies showing that balanced fiber-matrix bonding is critical for preventing premature debonding and ensuring composite toughness. The steady rise in both strength and modulus from 10% to 30% starch content suggests that the applied heat and pressure facilitated better cross-linking and bonding between the jackfruit seed starch (JSS) matrix and water hyacinth fibers, improving load transfer efficiency [22]. However, at 40% starch content, the mechanical properties declined due to excessive matrix content, which resulted in a more rigid and brittle structure. The increased starch content likely reduced the effectiveness of fiber reinforcement, leading to poor stress distribution and increased chances of micro-crack formation under tensile loading. The observed decrease in tensile modulus at 40% starch further confirms that an excess matrix content compromises the composite's ability to sustain stress, making it less resistant to deformation. This indicates that while a moderate starch percentage (30%) enhances both strength and modulus, an excessively high matrix content weakens the composite's ability to withstand tensile forces [23].

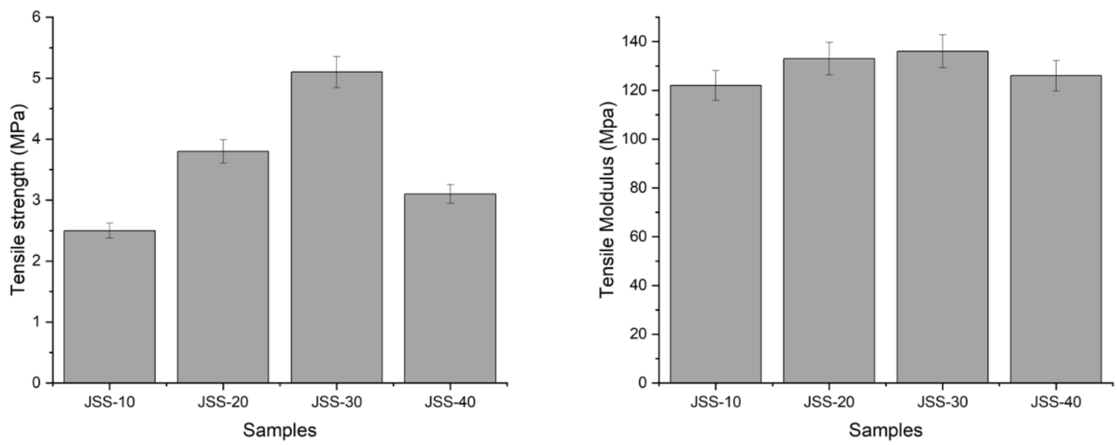

Figure 2 Tensile strength and modulus graph

3.2 Flexural strength and modulus graph

The flexural strength results indicate an initial increase from JSS-10 (8.1 MPa) to JSS-20 (11.2 MPa), followed by a slight decline at JSS-30 (10.4 MPa) and a significant drop at JSS-40 (6 MPa), while the flexural modulus follows a similar pattern, increasing from 900 MPa (JSS-10) to 1121 MPa (JSS-30) before decreasing to 1054 MPa (JSS-40) (Figure 3). The compression molding process, with applied pressure and temperature, contributed to improved bonding between the fibers and matrix, allowing the composites to resist bending forces effectively up to 20% starch content. Although microscopic analysis was not performed, the mechanical test results suggest that failure at 30% starch involved both fiber pull-out and matrix cracking. The flexural tests showed mostly brittle fractures without clear delamination, indicating good fiber-matrix bonding. Impact tests revealed some fiber protrusion, consistent with partial fiber pull-out. Literature reports similar behavior for natural fiber–starch composites, where optimal matrix content improves adhesion and energy absorption. At 40% starch, more brittle failure likely occurred due to weaker bonding and phase separation [21, 24]. The increase in flexural modulus up to 30% starch suggests that the structural stiffness of the composite was enhanced, leading to improved load-bearing capacity [12]. However, as the starch content increased beyond this level, the excess matrix likely reduced fiber interaction, leading to lower structural integrity and decreased resistance to flexural loads [23]. The rigidity induced by 40% starch made the composite more brittle, causing an abrupt failure under bending stress, as reflected by the decline in both flexural strength and modulus. This indicates that while moderate starch content improves mechanical performance, excessive matrix content compromises the balance between flexibility and strength [10, 12, 16, 23].

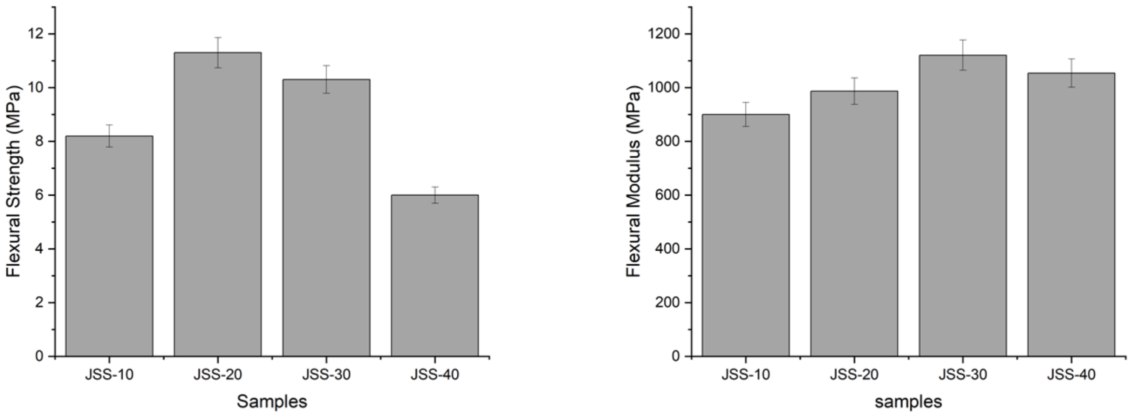

Figure 3 Flexural strength and modulus

3.3 Impact strength

The impact strength results show a steady increase from JSS-10 (4.5 kJ/m²) to JSS-30 (6.3 kJ/m²), followed by a slight decline at JSS-40 (6 kJ/m²). The rising impact strength up to 30% starch content suggests that the matrix effectively absorbed and distributed the impact energy, preventing sudden fracture (Figure 4). However, at 40% starch, the increased brittleness reduced the material's ability to absorb energy efficiently, leading to a minor reduction in impact resistance. This trend aligns with the tensile and flexural results, highlighting that an optimal balance of matrix and fiber content is crucial for maximizing mechanical performance [11, 13].

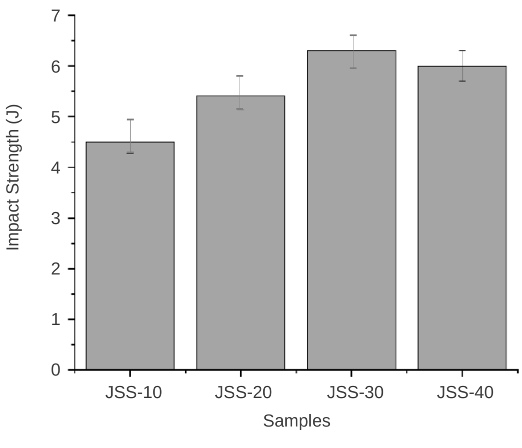

Figure 4 Impact strength of all 4 samples

3.4 Hardness test

Based on the hardness test results for the composite materials with varying starch content, the trend shows that as the starch content increases, the hardness of the material also increases. The sample with 40% starch content (JSS-40) exhibited the highest hardness value, indicating that the increased starch matrix has contributed to a more rigid and durable surface (Figure 5). This can be attributed to the stronger bonding and densification of the matrix, which reduces the material's susceptibility to indentation. On the other hand, samples with lower starch content (JSS-10, JSS-20, and JSS-30) demonstrated lower hardness values, suggesting that the lower starch levels result in a less compact and more flexible material. This supports the notion that a higher starch matrix imparts greater surface resistance, making the composite tiles more resilient to mechanical stress and wear [1, 25].

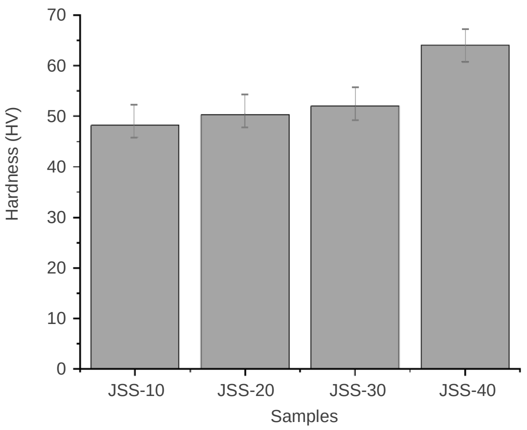

Figure 5 Hardness test result

3.5 Water absorption

The results of the water absorption test show that as the percentage of jackfruit-seed starch (JSS) increases in the composite, there is a slight increase in the water absorption tendency, which can be attributed to the inherent hydrophilic nature of starch, as presented in Table 2. The water absorption values range from 7.35% for the 10% JSS composite (JSS-10) to 8.05% for the 40% JSS composite (JSS-40), indicating that composites with higher starch content exhibit a higher tendency to absorb water. This trend is expected since starch is known for its ability to absorb moisture, and a higher concentration of starch would naturally lead to a greater amount of water uptake. Additionally, the increase in water absorption could also be due to the presence of more accessible hydrophilic sites in the matrix as the starch content increases. Despite this, all composites remain within a reasonable range of water absorption, suggesting that the developed composites still possess adequate moisture resistance for potential applications, although further modification might be necessary to reduce the water absorption tendency for more moisture-sensitive applications. To evaluate the influence of water absorption on thermal insulation performance, the JSS-30 composite was tested after full moisture uptake. Thermal conductivity measurements were conducted three times, yielding values of 0.178 W/m·K, 0.173 W/m·K, and 0.169 W/m·K, with an average of 0.173 W/m·K. Compared to the dry-state conductivity, this indicates an approximate 19.54% reduction in insulation efficiency, confirming that water absorption has a considerable adverse effect on thermal performance. This outcome is consistent with established thermal transport behavior in hydrophilic biocomposites, where absorbed moisture replaces air within the porous structure, leading to increased heat conduction. In the context of long-term exposure, sustained moisture retention is expected to further degrade thermal resistance over time [26, 27]. As water gradually accumulates within the fiber-matrix network, it not only increases the effective thermal conductivity by displacing air but may also induce swelling of the starch matrix and lignocellulosic fibers. Repeated moisture cycles can weaken interfacial bonding, create microcracks, or lead to partial delamination, all of which compromise both thermal insulation and structural integrity. This highlights the importance of moisture management in applications where environmental humidity is a concern. For long-term durability, future development should consider strategies such as hydrophobic surface treatments or barrier coatings to limit moisture ingress and preserve insulation efficiency.

Table 2 Water absorption tendency of all developed composite samples

Sample ID	Initial Weight (g)	Final Weight (g)	Water Absorption (%)
JSS-10	4.08	4.38	7.35%
JSS-20	4.12	4.43	7.52%
JSS-30	3.97	4.27	7.56%
JSS-40	4.10	4.43	8.05%

3.6 Thermal conductivity

The thermal conductivity results show a gradual decrease from JSS-10 (0.215 W/m·K) to JSS-30 (0.145 W/m·K), followed by a slight increase at JSS-40 (0.156 W/m·K) depicted in Figure 6. The reduction up to 30% starch content suggests improved insulation due to the starch matrix effectively encapsulating the fibers and limiting heat transfer. Similar reports are observed by other researchers where inclusion of WHF has reduced the thermal conductivity due to increased voids [28, 29]. Thermal conductivity found in another study reported a mix of coir fiber with WHF has reduced the conductivity tendency by more than 20% and the value circulates around 0.15-0.18 W/m·K [5]. However, the slight rise at 40% may be due to increased matrix rigidity and reduced porosity, allowing better heat conduction. JSS-30 exhibits the lowest thermal conductivity, making it the most effective for insulation applications [10, 11, 14].

The comparison presented in Table 3 reports various composites or materials used for thermal insulation, particularly in domestic or industrial applications. Some of these insulators, such as polyurethane foam and polystyrene, are commercially produced and exhibit the highest insulation performance, primarily due to their low structural defects and uniform polymer molecular structures. However, several studies have investigated fiber-based composites for thermal insulation, including rice husk composite (0.076 W/m·K), coir fiber composite (0.112 W/m·K), and water hyacinth fiber (WHF) gypsum board (0.166 W/m·K), all showing promising results suitable for applications in buildings and automation sectors. The composites developed in this study also demonstrate competitive thermal conductivity values ranging from 0.140 to 0.150 W/m·K in the best-performing two out of four variants. The uniqueness of this project lies in the use of agricultural waste materials, complete avoidance of chemical additives, and the achievement of sufficiently good thermal insulation properties comparable to previous studies. Therefore, the JSS-30 composite is recommended for further research focused on enhancing water resistance and improving mechanical performance.

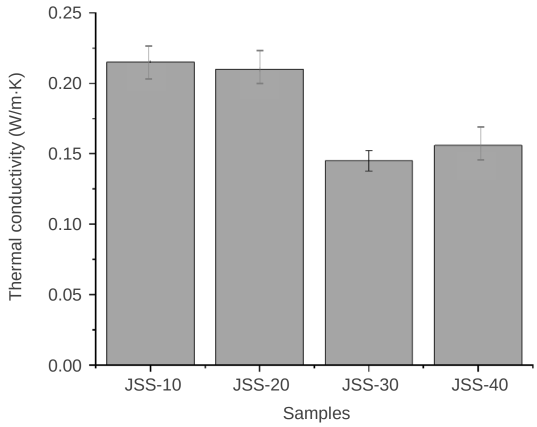

Figure 6 Thermal conductivity test result

Table 3 Comparison of different materials used for thermal insulation

Materials for thermal insulator	Thermal conductivity (W/m·K)	Density(g/cm³)	Reference
Urethane foam	0.020	0.02 – 0.05	[30]
Polystyrene	0.025	0.015 – 0.04	[30]
Stone wool	0.033	0.03 – 0.20	[31]
Cork	0.05	0.12 – 0.24	[31]
Rice husk	0.076	-	[31]
Coir fiber composite	0.112	-	[24]
WHF/Jackfruit seed (30%)	0.145	0.92	This study
Glass-carbon/ aerogel	0.133	0.003 – 0.1	[32]
WHF/Jackfruit seed (40%)	0.156	0.94	This study
WHF gypsum board	0.166	0.89 - 1.09	[5]
Bricks	0.911	1.60 – 2.00	[30]

4. Conclusion

In conclusion, the study demonstrated that water hyacinth fibers reinforced with jackfruit seed starch matrices have promising mechanical and thermal properties, particularly for use in thermal insulation applications. The results indicate that the composite with 30% starch content (JSS-30) provided the best balance of tensile, flexural, and impact strengths, while maintaining a low thermal conductivity, which is a crucial property for insulation materials. The compression molding process facilitated effective fiber-matrix bonding, enhancing the overall strength of the composite up to the 30% starch level. However, the increase in starch content beyond 30% (JSS-40) resulted in reduced mechanical properties due to the increased rigidity and brittleness of the composite, suggesting that an optimal matrix content is essential for performance. Despite the favorable mechanical properties, the water absorption tendency of the composites remains a concern, as it can significantly impact their long-term durability and performance. Further studies should focus on improving the hydrophobicity of these composites, such as through the incorporation of water-resistant coatings or other treatments, to minimize water absorption. The composites, particularly at 30% starch content, are promising candidates for use in thermal insulation applications. The 30% jackfruit seed starch content provides the best balance of mechanical and thermal performance. Further studies are necessary to reduce water absorption and improve long-term durability. Utilizing waste materials like water hyacinth and jackfruit seed starch offers an eco-friendly, low-cost solution for thermal insulation, particularly in South Asia.

5. Acknowledgement

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