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Biomechanical Properties of Pinang Jawa (*Pinanga javana*): Structural Performance and Ecological Significance

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ABSTRACT

The mechanical strength of Pinang Jawa (*Pinanga javana*), an endemic palm species in Java, is essential for understanding its structural resilience and ecological role. This study characterizes its biomechanical properties by evaluating the modulus of rupture (MOR) and the modulus of elasticity (MOE) using standardized three-point bending tests. Samples were collected sustainably from mature palms on Mount Slamet, ensuring minimal ecological disruption. Results indicate that the MOR ranged from 7.78 to 14.47 MPa, with a mean of 11.24 MPa (±2.19 MPa), and MOE values spanned from 440.82 to 792.95 MPa, averaging 572.17 MPa (±89.48 MPa). Statistical analysis, including 95% confidence intervals of [9.77, 12.71] MPa for MOR and [512.06, 632.28] MPa for MOE, confirmed the reliability of these estimates. A one-way ANOVA revealed significant variability in MOE ($p < 0.05$), attributed to the anisotropic nature and heterogeneous fiber orientation, while MOR showed less pronounced variability ($p > 0.05$), suggesting consistent rupture resistance. These findings highlight the stem's moderate mechanical properties compared to other palms and provide insights into its structural adaptations. This study enhances the understanding of Pinang Jawa's biomechanical behavior, reinforcing its ecological significance as an endemic species and supporting further research on palm biomechanics and conservation strategies.

Keyword: Biodiversity, Endemic palm, Montane forest, *Pinanga javana*, Three-point bending test

1. Introduction

The mechanical strength of plants is a crucial area of study within plant biology, encompassing biomechanical properties that enable plants to withstand environmental stresses, maintain structural integrity, and interact with their surroundings [1], [2]. These properties are particularly significant in tropical ecosystems, where high plant diversity and structural complexity contribute to ecosystem resilience and functionality. This study focuses on Pinang Jawa, an endemic palm species in Java, whose biomechanical properties offer insights into its structural adaptations and ecological role [3], [4]. As a lesser-studied species, Pinang Jawa provides a unique opportunity to expand the understanding of palm biomechanics in tropical environments.

Plants' mechanical behavior is primarily determined by their tissue composition, which includes biomaterials such as cellulose, hemicellulose, and lignin, which provide rigidity and toughness essential for structural stability. Variations in cell wall composition across species and even within different tissues influence biomechanical properties like bending stiffness and toughness, which can be quantitatively assessed through standardized mechanical tests [5]–[7]. These biomechanical principles are critical for evaluating how palm species, including Pinang Jawa, adapt to mechanical stresses and contribute to ecological functions.

Extensive research has been conducted on the mechanical properties of palm species, including oil palm (*Elaeis guineensis*), coconut palm (*Cocos nucifera*), and date palm (*Phoenix dactylifera*), all of which exhibit diverse structural adaptations [8]–[10]. Some studies have examined modifying palm fibers through chemical treatments to enhance tensile and flexural properties, improving durability under varying environmental conditions [11]–[13]. These findings highlight the variability in palm biomechanics influenced by fiber structure, treatment methods, and testing conditions, providing a comparative framework for less-studied species like Pinang Jawa.

Despite these advances, the biomechanical characteristics of Pinang Jawa remain largely unexplored, with limited data on its modulus of rupture (MOR) and modulus of elasticity (MOE) under standardized testing conditions. Unlike well-studied palms, Pinang Jawa's unique fiber structure, characterized by heterogeneous vascular bundles observed in preliminary tests, and its ecological role as an endemic species in Java's conservation-sensitive regions, such as Mount Slamet, are poorly understood. This study addresses these gaps by systematically characterizing Pinang Jawa's MOR and MOE through three-point bending tests, comparing its performance to other palms, and evaluating its potential for sustainable applications. By providing novel insights into Pinang Jawa's structural adaptations and ecological significance, this research contributes to palm biomechanics and supports broader studies on species resilience and tropical ecosystem functionality [14], [15].

2. Method

2.1. Sample Selection

The sample selection process for studying the mechanical properties of Pinang Jawa stem involves careful identification and collection of mature specimens (7° 17′ 26.37″ S, 109° 12′ 33.62″ E) from Mount Slamet, an area known for its abundant populations of this species (Figure 1). Mature palms are characterized by their height, typically exceeding 10 meters, and distinctive morphological features such as reduced leaflets within the trunk. These indicators help identify palms that have reached an advanced stage of growth and development. By selecting mature palms, the study aims to capture a representative sample of Pinang Jawa that exhibits typical characteristics relevant to understanding the mechanical behavior of this species.

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Figure 1. Distribution of Pinang Jawa in the natural habitats of Mount Slamet, Central Java.

Selective harvesting methods ensure minimal disruption to the natural regeneration and ongoing development of Pinang Jawa populations on Mount Slamet. This approach prioritizes biodiversity conservation by preserving the integrity of the local ecosystem. The study emphasizes sustainable sampling practices to contribute valuable insights into Pinang Jawa properties while supporting the long-term conservation and management of this species within its natural habitat. Through sample selection and thoughtful consideration of ecological impacts, the research endeavors to advance scientific knowledge while promoting the sustainable utilization and conservation of Pinang Jawa resources.

2.2. *Sample Preparation and Data Analysis*

The research was conducted in the Integrated Laboratory of Bioproduct (ILAB), Research Center for Biomass and Bioproduct, Cibinong, West Java. Samples were cut to 28 cm x 2 cm x 2 cm. Sampling and flexural tests refer to modified ASTM D-143. Static bending tests were carried out in oven-dried. Measurements were carried out to obtain mechanical strength through MOR (Modulus of Rupture) and MOE (Modulus of Elasticity) using a Shimadzu 50KN Universal Testing Machine (UTM) with a three-point loading system and test speed of 5 mm/min. The MOR and MOE values were calculated using the formula:

$$MOR\ (kg/cm^2) = \left[\frac{3PL}{2bh^2}\right] \quad (1)$$

$$MOE\ (kg/cm^2) = \left[\frac{\Delta P L^3}{4 \Delta y b h^3}\right] \quad (2)$$

Where :

P = load (kg)
ΔP = load difference (kg)
L = span (cm)
Δy = deflection (cm)
b = sample width (cm)
h = sample thickness (cm)

A conversion factor of 0.0980665 was applied (1 kgf/cm² = 0.0980665 MPa) to convert MOR and MOE values to MPa. The data were analyzed to determine the mean values and standard deviations. Additionally, a one-way analysis of variance (ANOVA) was performed using R software (version 4.5.0) to assess the variability in MOR and MOE across the 11 samples, testing the null hypothesis that all samples have equal means. The analysis was conducted with the aov function, treating each sample as a factor level to evaluate inter-sample variability. Furthermore, 95% confidence intervals for the mean MOR and MOE were calculated using the t.test function in R with a confidence level of 0.95, providing a range within which the accurate population means are likely to lie.

3. Result and Discussion

3.1. *The Mechanical Strength of Pinang Jawa*

The mechanical strength of Pinang Jawa was evaluated through standardized three-point bending tests, yielding Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) as key indicators of its structural performance. The results are summarized in Table 1, where MOR values ranged from 7.78 to 14.47 MPa, with a mean of 11.24 MPa (±2.19 MPa), and MOE values spanned from 440.82 to 792.95 MPa, averaging 572.17 MPa (±89.48 MPa). Statistical analysis revealed 95% confidence intervals of [9.77, 12.71] MPa for MOR and [512.06, 632.28] MPa for MOE, indicating the likely range of the true population means. A one-way ANOVA suggested significant variability in MOE ($p < 0.05$), likely due to the anisotropic nature and heterogeneous fiber orientation, while MOR variability was less pronounced ($p > 0.05$). These values highlight the anisotropic nature of the stem, influenced by fiber orientation and internal variability, which affect its structural performance (Table 1). These results classify Pinang Jawa as having moderate mechanical strength, providing insights into its structural adaptations compared to other palm species [16].

Comparative analysis with other palm species highlights Pinang Jawa's moderate biomechanical properties (see clearly in Table 2). For instance, oil palm (*Elaeis guineensis*) exhibits significantly higher mechanical strength, with reported MOR values of approximately 39.83 MPa and MOE values of 5,913.58 MPa [17]. Coconut palm (*Cocos nucifera*) fibers show tensile strengths ranging from 27.30 to 30.44 MPa and MOE between approximately 2,374 to 2,633 MPa, depending on treatment and fiber orientation [8]. Date palm (*Phoenix dactylifera*) displays variable MOR and MOE values, often enhanced through fiber reinforcement in composites, with MOR 35.04 MPa and MOE to 6674.04 in treated samples [10]. Sugar palm (*Arenga pinnata*) fibers, when untreated, exhibit a tensile strength of approximately 15.49 MPa and a tensile modulus of 4,200 MPa, but alkaline-treated sugar palm fiber in hybrid composites with poly(lactic acid) and glass fiber demonstrates improved flexural properties due to enhanced fiber-matrix adhesion [40]. While specific MOR and MOE values for alkaline-treated sugar palm composites are not reported, their enhanced flexural performance suggests potential MOR values in the range of 14.71–24.52 MPa, though lower than other palms like oil palm [40]. Pinang Jawa's lower MOR and MOE values reflect its anisotropic nature, characterized by heterogeneous fiber orientation and structural variability, as observed during three-point bending tests (Figure 2). This anisotropy contributes to its moderate stiffness and resistance to deformation, distinguishing it from more robust species, such as oil palm or sugar palm.

Table 1. Biomechanical Properties of Pinang Jawa

Sample	MOR	95% CI	MOE	95% CI
	(Mpa)			
1	10.68	[9.77. 12.71]	548.15	[512.06. 632.28]
2	7.78		542.49	
3	9.79		637.77	
4	11.48		596.14	
5	14.47		792.95	
6	14.22		581.87	
7	13.62		512.22	
8	11.42		545.59	
9	11.47		580.41	
10	10.06		440.82	
11	8.61		515.49	
Mean	11.24		572.17	
Sd	2.19		89.48	

Note: Mean values, standard deviations (Sd), and 95% confidence intervals (CI) of Modulus of Rupture (MOR) and Modulus of Elasticity (MOE)

Table 2. Comparison of Biomechanical Properties of Pinang Jawa with Other Palm Species

Species	MOR	MOE	Literature
	(Mpa)		
Pinang Jawa	7.78–14.47	440.82–792.95	This study
Oil palm	~39.83	~5,913.58	[17]
Coconut	27.30 – 30.44	2,374 – 2,633	[8]
Date palm	35.04	6647.04	[10]
Sugar palm	~15–25	~4,200	[40]

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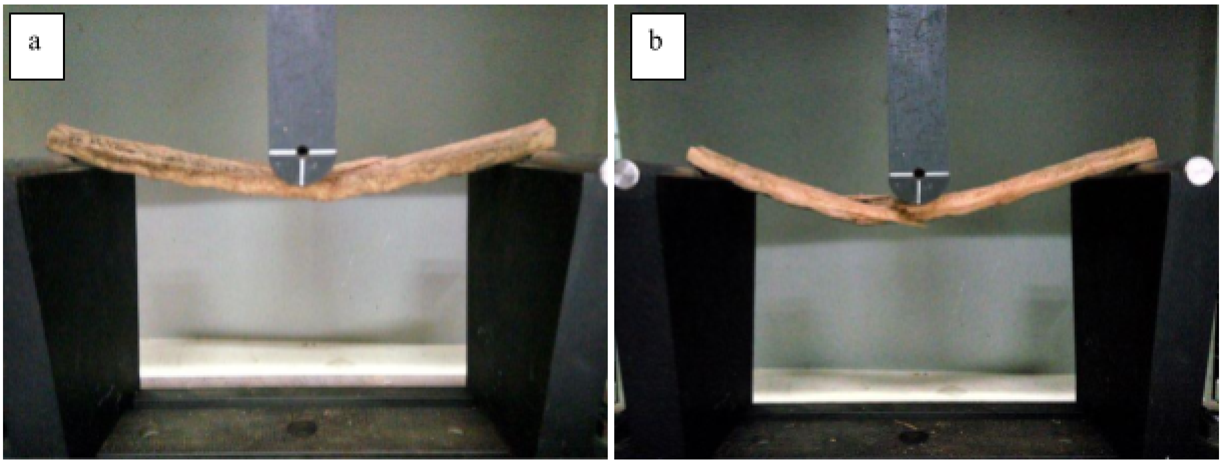

Figure 2. (a) Three-point bending test with a span length of 28 cm, loading at the center of the sample, and fiber orientation parallel to the longitudinal axis; (b) Cracks observed in the sample upon receiving maximum compressive force

3.2. Force-Stroke Relationship and Structural Behavior

The force-stroke curve (Figure 3) revealed key aspects of Pinang Jawa's mechanical behaviour under stress. Derived from static bending tests, the curve illustrates the relationship between applied force and resulting displacement. Three distinct phases were observed: the elastic region, where the material resists deformation proportionally; the plastic deformation phase, marking the onset of permanent structural changes and the failure point, where the material's load-bearing capacity is exceeded.

The force-stroke curve exhibited a linear relationship in the elastic stage, indicating proportional resistance to the applied load. This behaviour aligns with the principles of elasticity, where the material returns to its original shape upon load removal [21], [22]. The elastic properties of stem, including Pinang Jawa, are influenced by the microstructural characteristics of its cell walls, which are composed of cellulose, hemicellulose, and lignin. These components contribute to the material's stiffness and resilience [23], [24].

As the applied force increased, the curve deviated from linearity, signaling the onset of plastic deformation. This phase, marking the yield point, represents the material's transition from reversible to permanent deformation. Plastic deformation in stem is attributed to the rearrangement and bonding of cellulose fibres within its cellular structure [25], [26]. The yield point is a critical threshold for understanding the material's limitations under mechanical stress [27], [28].

The material reached its ultimate load-bearing capacity at peak force, followed by a sharp decline, indicating structural failure. This behaviour reflects the brittle nature of stem under high stress, as the cellular structure's integrity becomes compromised [29], [30]. The failure point provides key information about the durability and resilience of Pinang Jawa under mechanical stress. The variability in the force-stroke curves, with maximum force values ranging from approximately 12 kgf to over 27 kgf and strokes between 9 to 15 mm, is likely due to the natural heterogeneity of Pinang Jawa. Variations in fibre orientation, grain structure, and density contribute to its anisotropic nature [23], [24]. These structural differences significantly impact the Modulus of Elasticity (MOE), which reflects the material's stiffness, and the Modulus of Rupture (MOR), representing its maximum strength before failure. Specimens with steeper slopes in the elastic region showed higher MOE values, indicating greater resistance to deformation under load. Peak force values correspond to the MOR, demonstrating the material's ability to withstand significant loads before failure.

Compared to other palm species, Pinang Jawa's stem exhibits moderate mechanical properties. Its MOR and MOE values provide valuable data on its structural capabilities, though its protected status as an endemic species limits its practical application. This study focuses solely on understanding the stem's strength and mechanical behavior, contributing to the broader knowledge of Pinang Jawa's material properties without advocating for its exploitation [31], [32].

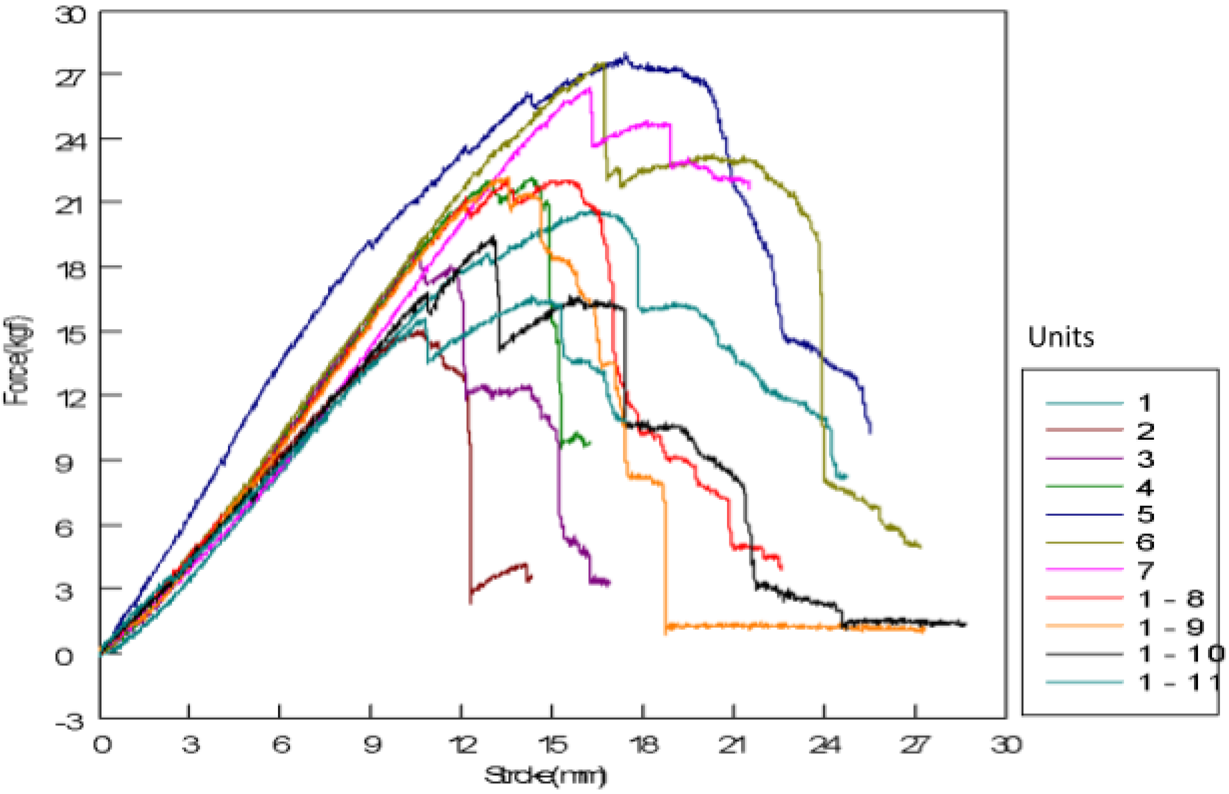

Figure 3. Force vs. Stroke graph illustrating the mechanical behavior of Pinang Jawa under three-point bending tests

3.3. Implications for Conservation and Potential Applications

Pinang Jawa contributes significantly to the ecological dynamics of tropical forest ecosystems, particularly in conservation-sensitive regions such as Halimun Salak National Park, Gunung Gede Pangrango National Park, Mount Slamet, Mount Ungaran, and Bromo Tengger Semeru National Park [3], [38]. Studies on its population structure indicate stable but vulnerable populations, with density estimates of 50–100 mature individuals per hectare in Mount Slamet's montane forests, threatened by habitat loss due to agricultural expansion and illegal logging [35]. Habitat preference analyses reveal Pinang Jawa thrives in shaded, humid understories at elevations of 800–1,500 m, contributing to soil stabilization and biodiversity through seed dispersal by frugivorous birds and mammals [3], [38]. Genetic diversity studies highlight moderate genetic variation within populations, with a Shannon diversity index of 0.65–0.80, but low gene flow between fragmented habitats, increasing extinction risks [34]. Ongoing seed banking efforts, including ex-situ conservation at Cibodas Botanical Gardens [37] and Baturraden Botanical Garden [41], aim to preserve genetic resources and seeds stored to support reintroduction programs. These findings underscore the need for robust conservation strategies to protect Pinang Jawa's ecological contributions.

The biomechanical properties of Pinang Jawa, with a Modulus of Rupture (MOR) ranging from 7.78 to 14.47 MPa (mean 11.24 ± 2.19 MPa) and Modulus of Elasticity (MOE) from 440.82 to 792.95 MPa (mean 572.17 ± 89.48 MPa) as detailed in Table 1, provide critical insights into its structural adaptations. These properties reflect the species' ability to withstand environmental stresses, such as wind or physical disturbances, in its native montane forest habitats. The significant variability in MOE ($p < 0.05$), attributed to the anisotropic and heterogeneous fiber structure, highlights Pinang Jawa's unique adaptations to its ecological niche. Understanding these biomechanical characteristics enhances taxonomic and ecological research, aiding in the classification of Pinang Jawa within the Arecaceae family and informing habitat management strategies. For instance, knowledge of its moderate mechanical strength can guide restoration efforts by identifying suitable planting sites that match its structural resilience, ensuring long-term survival in protected areas.

The conservation of Pinang Jawa is critical to maintaining Java's tropical ecosystem resilience, particularly in protected areas facing habitat fragmentation. Integrating its biomechanical properties into conservation strategies can promote sustainable development. Strategies such as habitat preservation through reforestation and the expansion of protected areas, as well as population monitoring using drone-based surveys to track population density, are essential for mitigating habitat loss risks [35]. Community education programs, emphasizing Pinang Jawa's ecological and biomechanical value, can foster local stewardship, as demonstrated in successful initiatives for other endemic species in Bromo Tengger Semeru National Park. Seed banking and genetic diversity enhancement, building on current efforts [34], [37], will further support long-term conservation. By linking Pinang Jawa's biomechanical properties to ecological research, this study bridges plant biomechanics and conservation science, contributing to broader studies on palm ecology and informing conservation-driven development in Java [14], [15].

4. Conclusion

This study characterized the biomechanical properties of Pinang Jawa, an endemic palm of Java, revealing moderate mechanical strength with a Modulus of Rupture (MOR) of 7.78–14.47 MPa (mean 11.24 ± 2.19 MPa) and Modulus of Elasticity (MOE) of 440.82–792.95 MPa (mean 572.17 ± 89.48 MPa) through three-point bending tests. Statistical analysis confirmed significant MOE variability ($p < 0.05$) due to the species' anisotropic fiber structure, while MOR remained consistent ($p > 0.05$), aligning with adaptations seen in other tropical palms but indicating lower strength compared to species like oil palm or coconut palm. These findings elucidate Pinang Jawa's structural adaptations, enhancing its taxonomic classification and ecological understanding within the Arecaceae family. As a vital component of conservation-sensitive regions, including Halimun Salak, Gunung Gede Pangrango, Bromo Tengger Semeru National Parks, Mount Slamet, and Mount Ungaran. This research highlights the species' ecological significance in maintaining the resilience of Java's tropical ecosystem and supports efforts to preserve its habitat and establish seed banks.

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6. Conflict of Interest

The authors declare no conflict of interest.

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