

IDENTIFYING THE STRUCTURAL ADAPTATIONS OF LEAF PETIOLES IN HERBACEOUS PLANTS FOR STRUCTURAL ENGINEERING APPLICATIONS

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Nature has long been a source of inspiration for innovative engineering solutions, particularly in structural design. Non-woody herbaceous plants are believed to have evolved from woody ancestors through nature's optimisation processes, gradually adapting their structures to withstand environmental conditions such as wind, temperature fluctuations, and sunlight exposure. One such naturally optimised structure is the petiole, a slender stalk that connects the leaf blade (lamina) to the stem, balancing flexibility, strength, and load-bearing efficiency in herbaceous plants. These features enable the petiole to withstand dynamic environmental forces, efficiently distributing mechanical loads while minimising material use and optimising performance. This study investigates the structural adaptations contributing to the mechanical performance of herbaceous leaf petioles, aiming to uncover design principles for lightweight, efficient structural systems. Two species, *Colocasia esculenta* (taro) and *Musa textilis* (abaca), were selected for their contrasting petiole morphologies and mechanical properties. Key factors analysed include cross-sectional geometry, tissue composition, material distribution, turgor pressure, and stiffness variation across layers of the petiole. Tensile testing with a universal testing machine (Instron) evaluated the elastic properties of *Colocasia esculenta* using tightened clamps with sponges to reduce moisture loss. Results showed the outer epidermis has significantly higher elastic modulus values (500 MPa) than the inner parenchyma, revealing a material gradient that enhances bending resistance while maintaining flexibility. No compliance correction was applied, so stiffness values may slightly include machine and grip effects, but results are valid for comparison across samples. Cross-sectional images processed using a custom Python script quantified geometric contributions to rigidity. A key observation was the presence of U-shaped cross-sections, which increased the twist-to-bend ratio. Compared to an I-section with similar dimensions, the U-shaped petiole exhibited a higher twist-to-bend ratio, allowing it to twist more easily than bend. This enables leaves to reorient under wind loads, reducing drag forces and minimising damage. Turgor pressure further contributes to stiffness by maintaining internal cell pressure, which supports cell rigidity and resists bending. This pressure, in combination with the material gradient, plays a critical role in structural performance. Finite element models in ABAQUS simulated stress distribution and evaluated the role of material arrangement in overall stiffness. This study highlights the interplay between geometry, material distribution, and physiological factors like turgor pressure, which together optimise the mechanical function of herbaceous petioles. The insights provide guidance for bio-inspired engineering, particularly adaptive, lightweight systems. Potential implementations include solar tree structures and other bio-inspired components, offering improved mechanical efficiency and environmental adaptability. Bridging plant biomechanics with structural engineering, this research advances sustainable and resilient design strategies for modern engineering challenges.

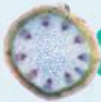
Keywords: Cross-sectional geometry, Finite Element Modelling, Mechanical properties, Twist-to-bend ratio

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Biological Inspiration

Variation in geometry



Microstructural arrangement

Twist to bend ratio = $\frac{EI}{GJ} > 1 \rightarrow$ Easier to rotate than bending

$\frac{EI}{GJ} > 1$, material related (Common)
 $\frac{EI}{GJ} > 1$, geometry related (Rare)

Mechanical & Imaging Analysis



- Type of test – Tensile test
- Testing Equipment – Universal Testing Machine (UTM) / Instron
- Elastic modulus of the epidermis of '*Colocasia esculenta*' was calculated
- Sponges were used to reduce moisture at the clamps

Image dimensions are: h = 700 x w = 700
 Centroidal distance c_x: 3.3315477
 Centroidal distance c_y: 3.5114262000000003
 Area: 2.0988
 I_xx: 5.19550
 I_yy: 4.41553
 I_z: 9.61109



Cross-sectional image Analysis using a Python code

Finite Element Analysis

SIMULIA
ABAQUS

Finite Element Model to simulate leaf petiole



SolidWorks

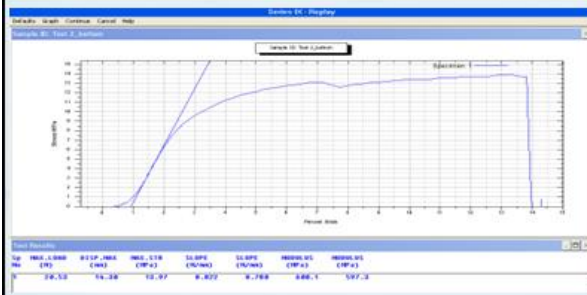


Inner Core

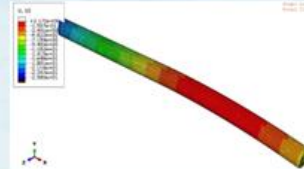


Outer Surface

Results



Width (mm)	F (N)	y (mm)	$EI_{FEH} (Nm^2)$	$EI_{lit} (Nm^2)$	Error (%)
16 (Species – <i>Musa Textilis</i>)	3	2.09	0.23	3.0	92.33
	5	3.21	0.25		91.69
	10	6.61	0.24		91.93



High errors due to **simplified modelling** that overlooked the petiole's **complex tissue structure** and **variability**

	Petiole cross-section	I section	U section
Twist-to-bend ratio	1.44	2.04	1.3