

Leaf Midrib Anatomy of Palmyra Palm (*Borassus flabellifer* L.) - structural differentiation, adaptive features, and micro morphological insights

Esakkimuthu K¹, Ravichandran P², Manimekalai V³,

¹ & ²Lab of Developmental Biology and Plant Biotechnology, Department of Plant Science, Manonmaniam Sundaranar University, Tirunelveli – 627 012, Tamil Nadu, India.

³Department of Botany, Sri Parasakthi College for Women, Courtallam – 627 802, Tirunelveli, Tamil Nadu, India.

E-mail: kesakki1994@gmail.com; grassravi@msuniv.ac.in

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Abstract

Palmyra palm is a multipurpose tree due its wide range of economical uses to the poor and Palmyra dwellers. The biology of Palmyra palm is being studied in justifying the usage of every part of the plant. Besides leaf, the midrib of palm leaf lamina is specifically used for making certain handicrafts and toys. The craftsmen and palm dependents have identified the flexible nature of leaf midribs (*Eierkku in Tamil*) and make unique objects only with midribs like tea/coffee cup holders, garlands and many other products which have elastic nature. The present study aims at understanding the anatomy and tissue properties which are responsible for such flexible nature of the products. The investigation elaborates on description and characterization of fibro vascular bundles, fibrous sheaths and flexible collenchyma from midribs. Comparative anatomical studies are carried out on basal, middle and apical regions of leaf laminal midrib with reference to diversity and arrangement of fibro vascular bundles and other tissues. For anatomical and histochemical studies free hand sections of the Palmyra leaf laminal midrib were made and studied with florescence, light and polarized microscopic facilities. Midribs were macerated for studying occurrence of stomata, typifying of fibres and for micrometry. Parameters such as micrometrics of all type of cells, and wall thickness were made and the results were statistically analyzed. The midrib epidermis is covered by thick cuticle layer of waxes followed hypodermis. Variety of fibro vascular bundles, fibre sheaths, peculiar collenchymas and other tissue characteristics were recorded. The flexible nature of the objects made out of midrib is mainly due to the presence of highly thick walled fibro vascular bundles, patches of fibre sheaths and elastic collenchyma with their well evolved architectural design. The findings on midrib anatomy would be useful in comparative studies of other species and genera of Palmae. The midrib anatomical characteristics justify that Palmyra palms are well evolved species to adapt themselves to dynamic environmental factors like heavy wind coupled with dry and high temperatures. Thus, the findings of this investigation are unique and shed more light on the evolutionary and adaptation features of Palmyra Palm.

INTRODUCTION

The Palmyra palm (*Borassus flabellifer* L.), known locally as *Panaimaram* in Tamil, is one of the most culturally and economically significant palms in South and Southeast Asia. In India, this palm has been recorded for over 2,000 years, with references dating back to the classical Tamil text *Thirukkural*

(*Thiruvalluvar*, 300 A.D. to 600 A.D.; Markandan, R. 2021). Owing to its wide utility and cultural relevance, *B. flabellifer* was declared the state tree of Tamil Nadu in 1978 (Government of Tamil Nadu, India) G.O. No. 746, 1988).

A dioecious species (rarely showing bisexuality), *B. flabellifer* is a stately, solitary fan palm reaching heights of 25–30 m with a trunk diameter of up to 1 m at the base. The trunk is initially covered with persistent leaf bases and becomes smooth in older individuals, retaining only narrow leaf sheath scars. The base of the trunk often shows a dense aggregation of long adventitious roots. The wood of mature palms takes on a dark black or grey color (Burkill, 1966).

Palmyra palm has been intimately associated with rural livelihoods and traditional practices across the Indian subcontinent. Palm dwellers routinely prune 12–15 leaves annually or biennially, with the belief that this encourages better fruit development (Seemann, 1856). The leaves are widely used in rural fencing and are even incorporated into rice field soils for organic enrichment. Cultural uses include fashioning thin leaf strips to maintain earlobe openings for traditional jewellery (Blatter, 1926). The leaf itself is a versatile structure, providing strong, durable material for making mats, baskets, fans, and thatch.

Various parts of the palm yield unique fibres. The wiry, mature leaf fibres are converted into ropes and twine. The base of the leaf sheath bears a downy fibre traditionally used for filtering liquids or as a remedy for cuts and wounds (Royle, 1855). A tough fibre from the forked butt of the petiole is used to make brushes (Dodge, 1897), while the main fibre known as "tar" or "tar coir" is traditionally crafted into fish traps (Blatter, 1926; Dodge, 1897). Davis and Johnson (1987) documented an exhaustive list of uses of Palmyra parts and their socio-economic relevance in Tamil Nadu.

From a botanical perspective, extensive anatomical research on palms has been

carried out by P.B. Tomlinson, whose seminal work *Anatomy of the Monocotyledons: Palmae* (1961) remains foundational. Since then, a range of anatomical studies across the palm family (Arecaceae) has expanded our understanding (Glassman, 1972; Barfod, 1988; Mathew & Bhat, 1997; Seubert, 1998; Rudall et al., 2003; Dransfield et al., 2008; Horn et al., 2009). A comprehensive synthesis of palm leaf anatomy was later presented by Tomlinson, Horn, and Fisher (2011), which highlighted both resolved and unresolved aspects in palm anatomical diversity. While the root and leaf anatomy of certain subfamilies like Arecoideae have received attention (Seubert, 1998; Alvarado & Jauregui, 2011), gaps remain, especially in taxa like *Borassus*, which are anatomically underexplored (Tomlinson et al., 2011).

One such neglected structure is the **leaf midrib** or rachis of *B. flabellifer*. This structural component is not only morphologically distinct but also functionally important. It is widely used in traditional craftsmanship to create highly flexible and durable products such as coil-based tea cup holders, sun hats, and other ornamental items (Fig. 5–8). Despite their widespread use, the anatomical basis for the flexibility and mechanical strength of these midribs remains unknown. Notably, the *pinnae* midribs—central to these crafts—appear to exhibit exceptional elasticity and longevity, properties that suggest a unique anatomical architecture.

MATERIALS AND METHODS

Source of Plant Material

Palmyra (*Borassus flabellifer* L.) leaf lamina and midrib specimens were collected from the campus of

Manonmaniam Sundaranar University and its surrounding villages. The collected midrib samples were immediately fixed in a standard fixative solution of Formalin-Acetic-Alcohol (FAA), following the protocol of Berlyn and Miksche (1976), to preserve tissue integrity for long-term studies. After a fixation period of seven days, the samples were transferred to 70% ethanol for storage. However, for anatomical, histochemical, and maceration studies, fresh material was prioritized to ensure optimal tissue preservation and contrast under microscopic observation. All observations were carried out using light, polarized, and fluorescence microscopy.

Free-Hand Sectioning and Staining

Free-hand sectioning of fresh Palmyra midribs is challenging due to their rigid and fibrous nature. Therefore, FAA-fixed samples were preferred for sectioning, as the fibrous tissues become relatively softened over time. Small segments (1–2 cm in length) were excised from three different regions of the midrib: one inch above the base, middle portion, and one inch below the apex. Each segment was embedded in pith for support, and transverse sections were carefully made using a sharp blade (platinum or surgical-grade).

Thin and intact sections were floated in distilled water in a Petri dish, from which the most transparent and well-defined sections were selected for staining. The selected sections were stained with a range of histochemical and fluorescent stains, including Safranin, Toluidine Blue O (TBO), Acridine Orange, Rhodamine B, and Iodine-Potassium Iodide (I₂KI). Following staining, sections were mounted using distilled water, dilute glycerin, or 20% calcium chloride solution. Thin cover slips were placed with care to avoid air bubbles. Prepared slides were examined under a Nikon 80i

advanced compound microscope equipped with both bright-field and fluorescence optics, digital camera, and Image One software for documentation and imaging.

Maceration of Midrib Tissues

Maceration of midrib segments was performed using a modified Jeffrey's solution composed of 10% nitric acid and 10% chromic acid (prepared by dissolving 10 g of potassium dichromate in 100 ml of 30% acetic acid) following Jeffrey (1917). Equal volumes of both acids were mixed freshly before each use. Midrib slivers (1–2 cm in length) were obtained from basal, middle, and apical portions and placed in 20–100 ml glass vials containing the maceration mixture.

The samples were left undisturbed at room temperature for 24–48 hours until the tissues softened completely. In cases of incomplete maceration, mild heating over a low flame was performed. Once macerated, the tissues were thoroughly washed in distilled water to eliminate any residual acids and stored in 100% ethanol.

The macerated samples yielded various anatomical elements, including epidermal peels, stomatal complexes, fibers, vessels, tracheids, and crystal inclusions. Stomatal index values were calculated using the formula described by Chisom et al. (2015). For microscopy, macerated fibers were stained using Safranin and Toluidine Blue O. Excess stain was removed through gentle washing with distilled water to achieve optimal contrast for visualization and microphotography.

Results and Discussion

The present study provides a detailed anatomical investigation of the midrib and laminal regions of the Palmyra palm (*Borassus flabellifer* L.), aiming to

elucidate the tissue characters underlying its notable flexibility and mechanical strength. Palm anatomy, particularly midrib structure, has received limited attention in botanical literature, and this study addresses an important knowledge gap with novel observations and interpretations.

Palm anatomy has historically contributed to taxonomic resolutions and evolutionary insights at the family, genus, and species levels (Tomlinson, 1961; Dransfield et al., 2008). The present study follows that tradition but adds new evidence by investigating the expansive, elastic tissues of *B. flabellifer* midribs. Palmyra leaves span 3–6 feet in length and 2–5 inches in width, with a midrib thickness of 2–5 mm. This midrib provides vital structural integrity and is utilised in handicraft industries to make flexible and durable items, underscoring the relevance of understanding its anatomical architecture.

Anatomy of Leaf Laminal Midrib

The laminal midrib of *Borassus flabellifer* was examined in transverse section at three distinct regions: basal, middle, and apical. Notable variations were observed in the organization and dimensions of tissues across these regions. The size and number of fibrovascular bundles and isolated fibrous sheaths decreased progressively from the basal to the apical region. This gradient is directly associated with the midrib's flexibility, which is primarily attributed to the density and distribution of fibrous sheaths, fibrovascular bundles, and specialized collenchymatous tissues.

The outline of the midrib also varies anatomically along its length. In the basal region, the midrib is horizontally broad (3–5 mm) and appears columnar in cross-section. The middle region is relatively thick (2–4 mm), generally rectangular in profile, while the apical region tapers into a thinner, triangular outline (1–3 mm), reflecting the gradation in structural complexity.



Figure 1–8. Morphology and Application of Palmyra Leaf Laminal Midrib (*Borassus flabellifer* L.) 1. Basal region of the palm leaf showing densely packed, wiry midribs emerging from the petiole. 2. Middle portion of the leaf displaying broader, flattened midrib structures interspersed between the lamina. 3. Apical region of the leaf exhibiting tapering midribs with gradually reduced thickness. 4. Full view of manually stripped midribs laid parallel for size comparison (scale bar: 30 cm ruler). 5. Close-up of the basal portion of midribs showing coarse, rigid bases. 6. Enlarged view of the middle region of midribs highlighting gradual tapering and increased flexibility. 7. Apical segment of midribs displaying narrow, elastic tips ideal for fine weaving. 8. Range of handcrafted products made from midribs, including coffee cup holders, baskets, trays, and coiled fiber ornaments—demonstrating elasticity and mechanical strength.

Cuticle

The outermost protective layer of the midrib is the cuticle, composed of epicuticular wax. This waxy covering plays a crucial role in minimizing water loss and defending against environmental stress. The space between the cuticle and the epidermal cells varies from 1 μm to 7.6 μm . The cuticle is an extracellular matrix largely comprised (40–80% by weight) of cutin, a polymer of oxygenated C16 or C18 fatty acids cross-linked via ester bonds (Freymy, 1859). The cuticle's thickness ranges from submicron levels to over 10 μm , depending on species (Walton, 1990; Heredia, 2003). Epicuticular wax may appear as a uniform amorphous layer or discontinuous crystalline structures (Trevor et al., 2013).

Epidermis

Beneath the cuticle lies the epidermis, consisting of a single layer of oval to polygonal cells. These cells are covered by the thin cuticular layer mentioned above and provide essential protection and mechanical support. The length of epidermal cells ranges from 5 μm to 17 μm across different midrib regions. This variability suggests functional specialization in response to mechanical stresses or transpiration rates. The presence of a well-developed cuticle over the epidermis reflects its role in reducing water loss and shielding internal tissues from desiccation and environmental insults.

Hypodermis

Located directly beneath the epidermis, the hypodermis serves as a key mechanical layer. Its composition differs along the midrib length: a single layer of hypodermal cells is observed in the apical region, while the middle and basal regions typically exhibit two distinct layers. These cells are thick-walled and

often lignified, adding rigidity and tensile strength to the midrib. The length of hypodermal cells varies from 27.01 μm to 65.58 μm , and the width ranges from 14.13 μm to 41.6 μm . This structural reinforcement is critical in withstanding mechanical forces, particularly in wind-exposed environments, and reflects the ecological adaptation of *B. flabellifer*.

Specialized Collenchyma Tissue

Collenchyma cells are known for their flexibility and elasticity, playing a vital role in supporting young and growing tissues. In the *B. flabellifer* leaf midrib, collenchyma cells show notable variation in size across different regions (Fig. 11-13). In the apical region, cell lengths range from 10.54 μm to 46.11 μm ; in the middle region, they span from 93.65 μm to 288.67 μm ; and in the basal region, between 57.48 μm and 73.01 μm . This gradation corresponds to the increasing mechanical load-bearing function from apex to base.

These cells are living, elongated, and unevenly thickened, with non-lignified walls composed primarily of hemicellulose, cellulose, and pectin. Lamellations on the inner wall are characteristic features that provide structural reinforcement (López & Yahia, 2018). The combination of strength and flexibility allows collenchyma to support the leaf without hindering its movement or growth. Additionally, some collenchyma cells in the midrib are observed to contain oil bodies, further contributing to their functional complexity.

Fluorescence microscopy reveals highly autofluorescent collenchyma cells, especially in the mid and apical midrib regions, indicating an abundance of hemicellulose and pectins. These contribute to the elasticity and torsional

resilience of the leaf, allowing controlled deformation under wind pressure without fracture. Similar biomechanical strategies have been documented in *Phoenix dactylifera* and monocot leaves with wind-adaptive morphologies (Niklas, 1999; Lugas et al., 1991). This specialization also explains the popularity of palmyra midribs in making coiled, flexible handicrafts. Previous anatomical investigations in *Corypha umbraculifera* have reported similar structural strategies to those seen in *B. flabellifer*, particularly in the arrangement of large vascular bundles and the presence of hypodermal fiber or collenchyma layers. In *Corypha* seedlings, a sub epidermal layer was notably replaced by fiber strands in bundles at regular intervals, akin to what we observe in Palmyra midribs (Henderson, 2006). While both palms exhibit prominent mechanical reinforcement and stress tolerance via these structures, *Borassus* midribs surpass *Corypha* in the abundance of silica bodies and oil cells likely adaptations for xeric, marine-edge environments. The anatomical evidence provides structural justifications for the traditional use of midribs in flexible woven crafts, such as hats and holders. This strengthens the call for biomimetic and sustainable materials research drawing inspiration from palm leaf architecture.

Lignified Isolated Fiber Sheaths

The lignified isolated fiber sheath is another key anatomical component providing mechanical support (Figs. 14 & 16). In the basal region, these sheaths are abundant and densely packed, contributing to the structural robustness necessary for load-bearing. Toward the apex, the number of isolated fiber sheaths diminishes, corresponding with reduced mechanical stress in younger tissue. This spatial variation is indicative of structural adaptation, ensuring optimal reinforcement where needed while maintaining overall flexibility and efficiency in the plant's architecture.

Macerated fibers show multilamellate thickening and varied end morphology—features indicative of high tensile strength and resilience. The fibrous sheaths resemble miniature I-beams, mechanically supporting the midrib lamina by integrating vascular and supportive tissues (Read & Stokes, 2006; Meicenheimer et al., 2008). Such reinforcement allows the leaf to maintain flatness over long spans while resisting torsion—a trait especially useful in high-wind coastal habitats where *B. flabellifer* thrives.

Table 1. Detailed micrometrics of *Borassus flabellifer* leaf laminal midrib.

Parameters	Mean of 100 cells \pm SD (μm)
Epidermis length	9.3 \pm 2.75
Collenchyma cell length (apical)	25.51 \pm 7.05
Collenchyma cell length (middle)	187.34 \pm 40.76
Collenchyma cell length (basal)	35.03 \pm 7.91
Fiber sheath length	15.12 \pm 3.71
No of vascular bundle midrib (apical)	4.12 \pm 1.05
No of vascular bundle midrib (middle)	10.92 \pm 1.89
No of vascular bundle midrib (basal)	31.84 \pm 5.52
No of isolated fibrous sheath (apical)	8.36 \pm 2.69
No of isolated fibrous sheath (middle)	14.76 \pm 3.33
No of isolated fibrous sheath (basal)	20.84 \pm 3.56
Sclerenchyma single cell length	15.77 \pm 2.8
Cuticle length	3.05 \pm 1.03
Phloem length	12.28 \pm 3.46
Xylem length	121.75 \pm 46.02
Stomata length	8.22 \pm 1.36
Stomata width	14.32 \pm 2.37
midrib circumference (apical)	0.125 \pm 0.38
midrib circumference (middle)	0.808 \pm 0.199
midrib circumference (basal)	1.276 \pm 0.192

Fibrovascular Bundles

Fibrovascular bundles—vascular tissues ensheathed by thick sclerenchymatous fibers—form the structural core of the midrib. In *B. flabellifer*, these bundles are centrally located, with occasional smaller bundles near the periphery. Quantitatively, the apical region contains 3–6 fibrovascular bundles, the middle region 8–13, and the basal region 23–45. In the middle region, they appear in collateral arrangement, while in the basal region, they are scattered, offering additional strength and support.

Each fibrovascular bundle includes metaxylem, protoxylem, and phloem tissues enveloped by sclerenchymatous fiber caps. Tomlinson (1964) classified vascular bundles in coconut leaf bases into three types based on size and position. Type I (largest) occur abaxially,

Type II (intermediate) lie between ridges or adaxial rows, and Type III (smallest) are irregularly distributed. A similar classification was proposed for *Trachycarpus* by Zhai et al. (2012), emphasizing the structural significance of these bundles in monocot leaf mechanics.

The sectional anatomy of the palmyra midrib from base to apex reveals a striking gradient in vascular differentiation. The basal region (Fig. 9) exhibits a dense arrangement of large fibrovascular bundles (Fvb) encased in robust fibrous sheaths (Fs), providing structural reinforcement to withstand mechanical load and wind stress. In contrast, the apical region (Fig. 11) shows fewer and smaller vascular bundles embedded in flexible collenchyma, highlighting a functional transition toward flexibility. Such structural zonation is a hallmark of

biomechanical adaptation in tall palms, aligning with reports in *Phoenix* and *Trachycarpus* species (Horn et al., 2009; Zhai et al., 2012). This anatomical modularity ensures that palmyra leaves can support their own weight while remaining pliable under dynamic stress.

Oil Cells and Thermal Pliability

The midrib of *B. flabellifer* exhibits aromatic properties due to the abundance of oil cells and glands. Sudan III staining confirmed the presence of oil bodies in transverse sections. Oil cells range in length from 229 to 446 μm , with widths between 59 and 391 μm (mean length: 159 μm ; mean width: 328 μm). These oil bodies are commonly embedded within collenchyma cells, contributing to the midrib's flexibility and possibly to anti-herbivory or antimicrobial defence (Fig. 15). The presence of oil bodies (Oi) in association with sclerenchyma and collenchyma layers may indicate a dual adaptive function: deterrence against herbivory and facilitation of tissue plasticity under thermal fluctuations. Such roles have been noted in other arid-zone palms like *Sabal palmetto* and *Livistona chinensis*. The oil's viscoelastic properties could enable better mechanical dampening of wind-induced oscillations, offering further ecological advantage in xeric environments.

Stomata

The leaf midrib bears brachyparahexacytic stomata—characterized by two guard cells flanked by four subsidiary cells, two parallel and two terminal (Mitra et al., 2015). Guard cells house distinct nuclei, starch grains, and presumably chloroplasts. The calculated stomatal index for the midrib is 68.35, with stomatal lengths ranging between 5.98 μm and 11.47 μm .

According to Metcalfe et al. (1960) and Beerling & Woodward (1997), smaller stomata correlate with higher stomatal densities, a pattern further validated in vegetable species by Abdul Rahaman & Oladele (2003). Stomatal density is a critical factor in plant water-use efficiency, especially under arid conditions (Wang et al., 2007). Small stomata are also mechanically advantageous, maintaining aperture with reduced guard cell turgor (Spence et al., 1986; Spence, 1987; Royer, 2001). This structural efficiency likely contributes to the palmyra palm's ability to minimize water loss under intense summer heat.

Fiber Macerates: Microscopic and Dimensional Features

The remarkable flexibility and strength of the midrib are primarily attributed to its fibrous elements—isolated fiber sheaths and fibrovascular bundles. Upon maceration, four types of fibers were observed based on wall thickness: very thick-walled (Vtkf), thick-walled (Tkf), thin-walled (Tnf), and very thin-walled (Vtnf), consistent with fiber classifications in *Sorghum bicolor* (Manimekalai, 2002) and *Cyperus pangorei* (Ravichandran et al., 2005). Fibers exhibit tapering, blunt, and cleft ends, and associated xylem vessels display scalariform thickening.

Palm leaf mechanical resilience is partly due to the co-evolution of epidermal and hypodermal layers, forming a protective "rind" or mechanical skin (Gibson et al., 1988; Niklas, 1999; Meicenheimer et al., 2008). Internal structural support is further reinforced by a network of lignified fibers and sclereids (Lucas et al., 1991; Choong et al., 1992; Roth-Nebelsick et al., 2001). These are often embedded in or attached to the vascular network, functioning analogously to I- or T-beams (Schwendener, 1874; Read & Stokes, 2006).

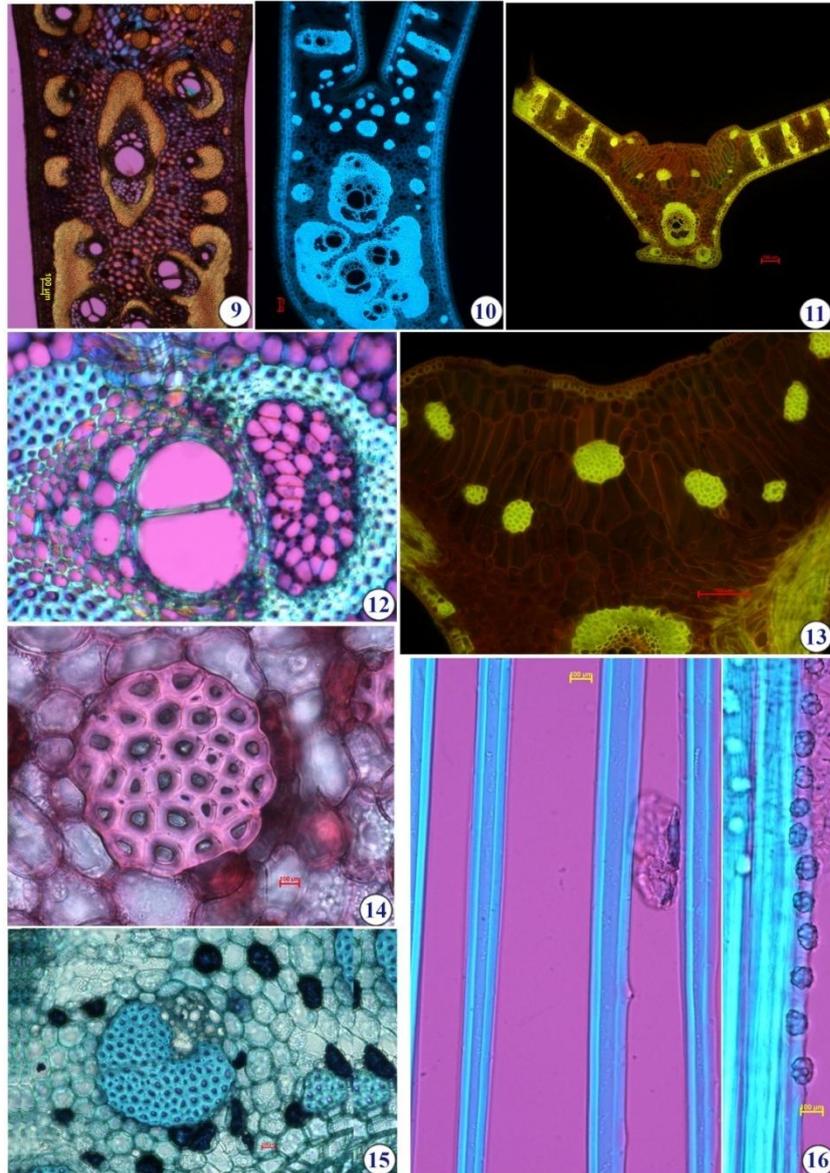
Silica Bodies (Phytoliths) as Taxonomic and Paleoecological Tools

In addition to fibers, macerated midrib samples revealed abundant silica (Si) deposits—phytoliths categorized as granular echinate (Group I) with isosahedron shapes (Fig.16). These silica bodies are ecologically and archaeologically significant due to their durability and taxonomic specificity. Their resilience allows preservation in sedimentary layers, aiding in paleobotanical reconstruction (Thomas, 2013). In *Trachycarpus*, silica attaches to crater-like depressions on fiber surfaces, a pattern echoed in oil palm fibers (Law, cited in Thomas, 2013). Silica accumulation provides mechanical reinforcement, deters herbivory, and offers antimicrobial protection. This inorganic deposition in palm fiber surfaces represents a natural bioengineering marvel, improving tensile properties and longevity of the leaf. The presence of isosahedral silica bodies (Si) within the fibers is a significant taxonomic and ecological marker. These phytoliths belong to the Granular Echinate Group I (Thomas, 2013), and their shape, size, and distribution are diagnostic for *B. flabellifer*. Their resistance to decay allows them to persist in soils and archaeological deposits, making them valuable for paleobotanical reconstruction and forensic plant identification (Law, 2000).

Conclusion

The present investigation highlights the unique anatomical adaptations of the *B. flabellifer* midrib particularly its structural components such as

collenchyma, fiber sheaths, fibrovascular bundles, and silica bodies that contribute to its flexibility and mechanical endurance. These features validate the traditional use of palmyra midribs in eco-friendly handicrafts and reinforce the need for further studies to explore commercial applications rooted in traditional knowledge systems. The present study is the first to systematically investigate the anatomical and histochemical features of the Palmyra palm midrib and leaf lamina using multiple staining techniques including Safranin O, Toluidine Blue O, Sudan III, and fluorescent dyes such as Acridine Orange and Rhodamine. The work also introduces a **typification of fibrovascular bundles into four distinct types**, based on their structural arrangement with surrounding fibres reported here for the first time in *Borassus flabellifer*. Additionally, we provide **polarized light microscopy images** of leaf sections to analyze lignification patterns and discuss their adaptive ecological implications. These findings not only fill a critical gap in the anatomical knowledge of *B. flabellifer* but also provide a scientific explanation for its functional attributes, especially the biomechanical resilience of leaf-derived materials. They support the broader hypothesis that anatomical specializations in Palmyra leaves contribute to the species' success in harsh coastal environments characterized by high wind velocities, salinity, and prolonged drought—conditions under which the palm thrives abundantly.



Figures 9–16. Anatomy of *Borassus flabellifer* leaf laminal midrib in transverse section observed under light, polarized, and fluorescence microscopy 9. Transverse section of basal region of *Borassus flabellifer* midrib showing large and compactly packed fibrovascular bundles (Fvs) surrounded by sclerenchymatous fibers. (Light microscopy, Safranin O). 10. Middle region of midrib showing well-developed collateral fibrovascular bundles (Fvs) and peripheral scattered bundles. (Fluorescence microscopy, blue excitation). 11. Apical region of midrib under blue light excitation showing densely fluorescing collenchyma cells (Co) and peripheral bundles. (Acridine orange staining). 12. Enlarged view of fibrovascular bundle showing metaxylem (Mx) and phloem (Ph) surrounded by thick sclerenchyma. 13. Collenchyma (Co) cells observed under fluorescence microscopy showing uniform autofluorescence and thickened walls, indicating flexibility and mechanical strength. 14. Isolated fibrous sheath (Ifs) with distinctive ringed lignified wall layers, observed in basal region. 15. Peripheral fibrovascular bundle with distinct sclerenchyma cap (Sc) and oil cells (Oi) dispersed in parenchymatous ground tissue. 16. Macerated thick-walled fibers (tkf) showing multiple wall lamellations and silica bodies (Si) arranged along the fiber sheath.

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