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Research Advances on Leaf and Wood Anatomy of Woody Species of a Tamaulipan Thorn Scrub Forest and its Significance in Taxonomy and Drought Resistance

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Abstract

The present paper make a synthesis of a comparative leaf anatomy including leaf surface, leaf lamina, petiole and venation as well as wood anatomy of 30 woody species of a Tamaulipan Thorn Scrub, Northeastern Mexico. The results showed a large variability in anatomical traits of both leaf and wood anatomy. The variations of these anatomical traits could be effectively used in taxonomic delimitation of the species and adaptation of the species to xeric environments. For example the absence or low frequency of stomata on leaf surface, the presence of long palisade cells, and presence of narrow xylem vessels in the wood could be related to adaptation of the species to drought. Besides the species with dense venation and petiole with thick collenchyma and sclerenchyma and large vascular bundle could be well adapted to xeric environments. It is suggested that a comprehensive consideration of leaf anatomy (leaf surface, lamina, petiole and venation) and wood anatomy should be used as a basis of taxonomy and drought resistance.

Keywords: Variability; Leaf; Wood anatomy; Taxonomic delimitation; Adaptation; Xeric environments; Tamaulipan thorn scrub

Introduction

The trees and shrubs in Tamaulipan thorn scrub are adapted in the semiarid environments in northeastern Mexico, although they vary in its adaptability depending on the ecophysiology and potential hydric condition of the species [1,2] respectively.

The species show a large variability in leaf and other morphological characteristics which help in the co-existence and adaptation of the species in semiarid conditions in Northeastern Mexico [3-6]. It is expected that variation of leaf and wood anatomical traits may contribute to taxonomy and drought resistance. During last few years research has been undertaken on the variability of anatomical traits of leaf and wood of more than 30 woody species of a Tamaulipan Thorn Scrub in relation to taxonomic delimitation and adaptation to drought.

The present study on the leaf and wood anatomy of woody plants was carried out at the experimental station of Facultad de Ciencias Forestales, Universidad Autónoma de Nuevo Leon, located in the municipality of Linares (24°47'N. 99°32'W), at elevation of 350 cm. It represents a typical semiarid condition with hot summer and cold winter. The climate is subtropical or semiarid with warm summer, monthly mean air temperature vary from 14.7°C in January to 230°C in August, although during summer the temperature goes up to 45°C. Average annual precipitation around 805 mm with a bimodal distribution, We make here a brief synthesis of research results on leaf and wood anatomy of more than 30 woody species in Northeastern Mexico (few of them are published and or not yet published).

Leaf Anatomy

Leaves play a vital role in the productivity of plants in a forest ecosystem through photosynthesis, gas exchange (CO_2, O_2), and transpiration through stomata. Leaf surface acts as boundary between atmosphere and internal leaf tissue. The types and size of stomata vary greatly among species, used in the taxonomic determination of the species along with leaf anatomical features.

Various studies have been undertaken on the use of leaf anatomical traits in the taxonomic delimitation of the species, viz., three Brazilian species (*Peperomia dahlstedtii* CDC. *Ottonia martiana* Miq. and *Piper diospyrifolium* Kunth) showed structural similarities among them [7]; significant differences in anatomical traits among 293 trees of *Pseudotsuga* in Mexico [8], taxonomic delimitation of twelve species of *Populus* [9] and 35 species of the genus *Kalanchoë* Adans [10]; the taxonomic delimitation of different species of *Chamaecrista* (L.) Moench sect. Apoucouita (Leguminosae-Caesalpinioideae) [11] and distinction of 25 *Ficus* species in terms of multilayerd hypodermis, one to three layers palisade parenchyma [12,13] showed variations in leaf anatomical traits Chacoan forests in Argentina such as the density of epidermal cells, stomata and trichomes, mesophyll types and the type and distribution of vascular and sclerenchymatic tissues. In a study, ten species of *Crocus* that have been investigated showed that palisade cell height and spongy cell width are the best parameters to distinguish species [14].

On the other hand, few studies discuss the role of the anatomical traits in the adaptation of the species to different habitats. In a study *Solanum nigrum* collected from different habitats in Europe and in Yugoslavia showed variability in terms of stomata number, number of hairs, thickness of lamina, palisade and spongy tissue, as well as the size of mesophyll cells of the species collected from different localities [15]. A similar study on the anatomical basis of resistance on plant species

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of a typical arid Mediterranean ecosystem confirms the presence of several adaptive properties such as the presence of ergastic substances, mainly tannins and calcium oxalate in internal tissue, tolerance to the strong UV-B solar irradiance in the summer, besides the presence of trichomes, on the abaxial surfaces of leaves maintained water budget of the plants. In many species, trichomes or wax layers reduced radiation absorbance, two or three layers of palisade parenchyma presumably provide a better efficiency in utilizing the photosynthetic light. In almost every plant examined, stomata were sunken or well protected [16].

A comparative study made in Venezuela on leaf epidermis of an orchid, *Cattleya jenmani in vitro* conditions demonstrated that compared to normal ones, the epidermal cells showed larger in size, lower anticlinal cell wall, lower size of stomata for adaptation of orchid, the leaves suffered changes in cells with an increase of mechanical resistance and rigidity [17].

An ecophysiological study undertaken on two urban forestry species (*Azadirachta indica* and *Millettia thonningii*) demonstrated that the pattern of transpiration in *M. thonningii* was low in the morning, high in the noon and low in the afternoon. Leaf anatomical study revealed the presence of thick cuticle and high stomatal frequency in *A. indica* and a low stomatal frequency in *M. thonningii* [18]. Significant inter-cultivar differences among *Hibiscus* cultivars in leaf anatomical characteristics were demonstrated [19]. A study undertaken on the leaf anatomy of 15 species of vascular plants occurring in coastal zones of the Falcon State (Venezuela) showed that the development of water storing tissue in the mesophyll and/or epidermal cells is the main characteristic associated with the saline habitat in those species. Besides, other characteristics of potential adaptive value were: presence of trichomes, stomata protected by papillae, crystals in mesophyll cells, secretory tissues, and Kranz anatomy [20].

Subsequently, a study undertaken on morpho-anatomical characteristics of *Celtis ehrenbergiana* revealed that its shade leaf structure was bifacial, epidermis was with wavy-sinuous anticlinal cell walls, mesophyll formed by palisade and spongy parenchyma, and angular-lacunar collenchyma. The sun leaf type had a thick leaf-limb which was leathery and dark green and its anatomical structure was equifacial, epidermis with straight anticlinal cell walls, mesophyll formed by homogeneous palisade parenchyma, and angular-massive collenchyma. There was nothing to scarcely stomata on adaxial surface in shade type leaf, however there were numerous in the sun type leaf. *Celtis ehrenbergiana* exhibited phenotypic plasticity indicating that it might be able to survive the climatic changes because of its adaptability and has an advantage over other species [21].

Anatomy of leaf lamina

A leaf in a transverse section consists of the upper and lower epidermis and mesophyll tissue consisting of palisade cells below the upper epidermis followed by loose spongy tissue containing air species. The epidermis may possess trichomes or glands of varying shapes or forms depending on species. Thick cuticle prevents loss of water by transpiration. The epidermal cells vary in sizes, shapes, layers. Below the upper epidermis is present a layer of palisade cells containing dense chloroplasts varying in length and compactness. The presence of compact palisade cells and its length is expected to prevent loss of water by transpiration which could impart drought resistance under arid environments. The species vary in thickness of spongy tissue and leaf thickness.

Petiole anatomy

Petiole plays a vital role in the transport of nutrients and water to the leaves and provides support to the leaf lamina as well as protruding leaves to solar radiation for photosynthesis. Leaf anatomical traits have been used in the taxonomic delimitation (and adaptation of the species to environments. The use of petiole anatomy in taxonomy and adaptation is rarely documented. A study has been undertaken on the petiole anatomy of 24 species of *Astragalus* Sect. with respect to the characters *viz.*, numbers of parenchymatous cell layers in pith, number of bundles, length of ventral axis, length of dorsi-ventral axis, diameter of ventral latéral vascular bundle (VLB) and diameter of dorsal médian bundle (DMB). The results revealed that anatomical characters were not useful for circumscribing section but were suitable evidences for taxonomical differentiation in species, in that section. Further, these traits were found to be useful in delimitation small natural groups and were helpful characters for determining some complexes in the section of the study [22].

A comparative systematic study made by [23] on leaf and petiole anatomical studies of the genus *Stachytarpheta* found in Awka Nigeria demonstrated significant variations in anatomical features in the leaf and petiole. The epidermis was conspicuous but one cell thick. The epidermal cells in the leaves were not of uniform size in both surfaces. Chlorenchyma was present as a very narrow portion of the leaves and petiole tissue while the palisade layer was one to three cells thick. These features however, could not confer any taxonomic relevance to the delimitation of any of the species in that genus.

Venation pattern and venation density

Leaf venation in a plant can be defined as a typical architectural system of vascular bundle traversing through leaf lamina starting from a petiole. It performs two important functions *viz.*, offering mechanical strength and transport of water, nutrients and assimilates, besides hormones.

Sufficient research inputs have been undertaken on venation pattern in Angiosperms on various aspects such as evolution [24,25]; interspecific variability [26]. Various authors described systematic classification and the architectural patterns of leaf venation [27] and several authors classified venation pattern differently of angiosperms [28-30] in different manners [31-33]. Few authors reported the importance of venation for offering mechanical strength [34], while a few discussed about the functional properties of the leaf venation system [35]. The role of venation from the point of view of water flow was discussed by Ref. [36]. On the other hand, Ref. [37], explains that xylem conduits are leaky due to lateral outflow taking place via the pits [36,37]. In a study Ref. [37], interpreted that biological transport phenomena occurring in branching systems influences internal fluid flows necessary to maintain the metabolic functions. The integrity and density of leaf venation is considered not only important for water influx, but also for carbohydrate [38].

Various research inputs have been undertaken on the carbohydrate transport in the venation system. The site of phloem loading is the minor venation is dependent on the type of loading involved [39-41] and the mode of carbohydrate transporters is well demonstrated [42] flow of carbohydrates is subsequently transported towards the major veins.

Some authors demonstrated that the site of phloem loading with carbohydrate is the minor venation with fine structure which is dependent on the type of loading involved [39-41] and the expression of corresponding carbohydrate transporters has been observed demonstrating the flow of carbohydrates is subsequently conducted towards the major veins [42]. A comprehensive review on evolution and function of leaf venation architecture was made by Ref. [43,44].

Wood anatomy

Wood is the product of the cambial activity and is of high commercial and domestic importance to the forest dwellers. Significant research advances have been undertaken on wood anatomy and its significance in dendrology and application. Few studies have been undertaken on ultrastructural and biochemical changes in the development of wood elements, *viz.*, vessel and fibre orientations in *Acacia mangium* Wild. Both vessel and fiber orientations had a similar radial characteristics and distinct inversion of the grain but the vessel orientation showed larger amplitude of change than fiber orientation [45]. The secondary wall structure of tension wood of *Laetia procera* Poepp. (Flourtiaceae), revealed alternate arrangement of thick and thin layers with S1+S2+S3 revealing that in the thick secondary wall, cellulose microfibril angle is very low (very close to fibre axis) and cellulose microfibrils are well organized but in thin layer the cellulose microfibrils are less organized and oriented with a large angle in the axis of the cell. Thick layers are highly lignified [46].

In a study that was undertaken on the structural heartwood characteristics for *Prosopis laevigata* (Humb. & Bonpl. *Ex* Wild.) M.C. Johnst., using light microscopy coupled with a digitised image analysis system showed that the Holocellulose content ranged between 61.5 and 64.7% and Klason lignin content between 29.8 and 31.4%. Major compounds in acetone/water extracts were identified as (-)-epicatechin, (+)-catechin and taxifolin, and were quantitatively determined by liquid chromatography [47]. Later, a study on wood anatomy and ultra-structure of the three species of wood of *Prosopis* (*Prosopis vinalillo*, *Prosopis alba* and *Prosopis nigra*) growing in heterogeneous forest dry Chaqueño Park revealed that the three species showed similarity in the structural features of the subfamily Mimosoideae. However, the number of vessels/mm^2 showed large variations among species and between individuals of the same species. The variations in striations were shown to be characteristics of the three *Prosopis* species [48].

Environments play a great role on wood anatomical characters. A study was undertaken on wood anatomical features measured in tree-rings in the East-Ore Mountains, Germany in rings of trees grown under severe stresses. It is observed that environmental changes have caused modifications or adaptations of structural features in dated tree-rings, revealing that growth and development of trees reflects dynamic processes [49]. Another study on wood anatomy and annual rings of *Prosopis pallida* in the arid and semi-arid lands of the American continent revealed that *Prosopis pallida* has well-differentiated annual growth rings, which is related well with precipitation events associated to El Niño Southern Oscillation phases [50].

A comparative study undertaken on anatomical characteristics of five species of the family Rosaceae, *Crateagus mexican*, *Pyrus cummunis*, *Pyrus malus*, *Prunus americana* and *Prunus domestica, s*howed similar macro and microscopic characteristics [51]. There exists a large variability in size, cell wall thickness and lumen breadth which may predict the quality and utility of the particular species [52].

Wood anatomical traits are found to be related to the adaptation of woody plants to environmental stresses. A study undertaken on the anatomical characteristics of heartwood at Linares, Nuevo Leon, Mexico has shown that wood in the locality of Linares, with higher precipitation and lower temperature showed higher fibre length and higher diameter of the vessels than a wood at the drier site of high temperature [53]. Wood anatomical features play important role in the phylogeny of the species and also the adaptive capacity of the species to environmental stresses [54,55]. It is well documented that the hydraulic architecture of woody plants determines the adaptative strategies of these woody plants to adverse climatic conditions [56-63]. From a functional viewpoint, few vessel attributes such as narrow pores and pores multiples acts against cavitation and embolism under hot summer and freezing stress, thereby offering mechanical strength [58,64,65].

Various authors stated that the presence of narrow vessels and multiple vessels acts against cavitation during summer stress and winter freezing. A study was undertaken [66], on the patterns in hydraulic architecture and their implications for transport efficiency. In another study undertaken on the stem and root wood anatomy of the shrub-*Phlomis fruticosa* (Labiatae) a malacophyllous Mediterranean drought semi-deciduous species [67] has revealed that though narrow vessels offered high conducting resistance, they were less vulnerable to cavitations, thus providing safety during summer drought and winter freezing. Vessel grouping is a widespread phenomenon in most woody species, especially those from the arid desert flora and Mediterranean species [68]. The wood anatomy and hydraulic architecture of stems and twigs of some Mediterranean trees and shrubs along a mesic-xeric gradient [69]. Similarly Ref. [69] conducted a study focussing on the anatomy of juvenile and mature wood of some species representative of continuous sequences of Mediterranean vegetation formations according to gradients of water availability, from xeric to relatively mesic. The difference between juvenile and mature structures was large in the species of the mesic end of the gradient while it was relatively small in those more xeric, vessels were narrow resistant to cavitation during drought and freezing conditions. A study was undertaken on the seasonal dimorphism in wood anatomy [69] in Mediterranean sub sp. *Cistus incanus* revealed that brachyblast wood was safer than dolichoblast and has narrower and more frequent vessels. Based on the measurement of other specific anatomical traits, such as vessel wall thickness, it was suggested that brachy blast wood has a higher resistance to implosion due to drought-induced embolism.

Methodology

Standard techniques and methodologies are used to study leaf anatomy including leaf surface, petiole anatomy and woody anatomy of 30 woody species of Tamaulipan Thorn Scrub. Methodologies are published in few journals.

Results and Discussion

Leaf surface anatomy

In the context of above literatures we investigated the variability in leaf dermal characteristics of thirty woody species in Northeastern Mexico and its possible relation to taxonomic delimitation and adaptation of the species in xeric conditions. The results show the presence of large variability in several leaf anatomical traits *viz.* waxy leaf surface, type of stomata, its size, and distribution. The species have been classified on the basis of various traits which can be used in species delimitation and adaptation to the semiarid condition such as waxy leaf surface, absence or sparse stomata on the leaf surface, sunken stomata which could have direct impact in reducing transpiration.

On the basis of the presence and abundance of stomata on both adaxial and abaxial surface we can classify species into three classes.

In the present study, most of the species possessed very few or absence of stomata on the adaxial surface.

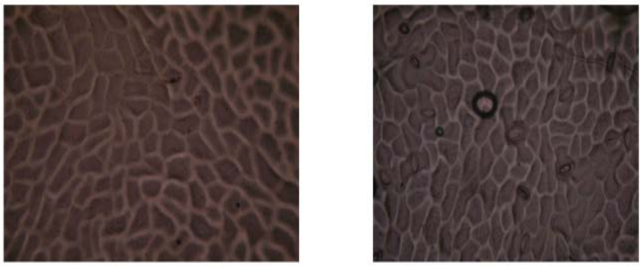
Class 1: Species with rare or absence of stomata on the adaxial leaf surface and very few stomata on the abaxial leaf surface (14 species): *Berberis chococo, Celtis laevigata, Condalia hookeri, Diospyros palmeri, Diospyros texana, Ebenopsis ebano, Ehretia anacua, Forestieria angustifolia, Havardia pallens, Helieta parviflora, Karwinskia humboldtiana, Sargentia gregii, Sideroxylon celastriana, Zanthoxylum fagara.* Most of these species possess sunken stomata to maintain microclimate for adaptation to semiarid habitats. These species are expected to exhibit high stomatal control to prevent loss of water by transpiration.

Class 2: Very few stomata on both adaxial and abaxial surface (11 species): *Acacia farnesciana, Acacia gregii, Acacia shaffneri, Caesalpinia mexicana, Celtis pallida, Eysenhardtia texana, Leucaena leucocephala, Parkinsonia aculeate, Parkinsonia texana, Prosopis laevigata.* It is expected that these species are moderately susceptible to drought but could be resistant for other traits such as waxy leaf surface or deep root system.

Class 3: Very few stomata on adaxial surface and many stomata on abaxial surface (5 species): *Acacia berlandieri, Acacia rigidula, Amyris texana, Guaiacum angustifolia, Gymnospermum glutinosum.* The species having many stomata are expected to be susceptible to drought, but these species might have deep root system for adaptation to drought situations. Different classes are depicted in Figures 1-4.

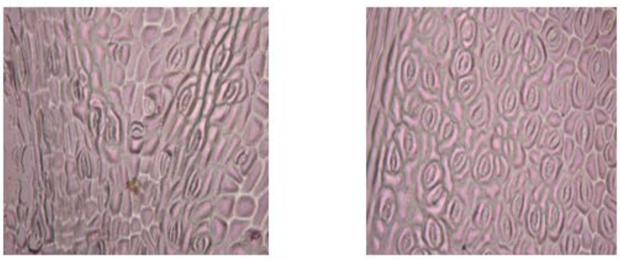
Leaf lamina anatomy

A comparative study undertaken on anatomy of leaf lamina of 26 woody species in Northeastern Mexico has shown that there exists a large variability in anatomical traits of leaf lamina with respect to presence of trichomes, thickness of cuticle, epidermal cells, length of palisade cells, spongy parenchyma. The abundance of trichomes and thick cuticle could reduce transp transpiration. Each species has specific characteristics of leaf anatomy, which will help in the taxonomic delimitation of the species. Few species possess two layers of compact palisade cell *viz.*, *Karwinskia humboldtiana, Lantana macrum, Celtis laevigata, Havardia parviflora, Prosopis laevigata. Acacia gregii* has palisade cells both below adaxial and abaxial surface. Several species possessed hypostomatic cavity to maintain microclimate and reduce loss in transpiration.



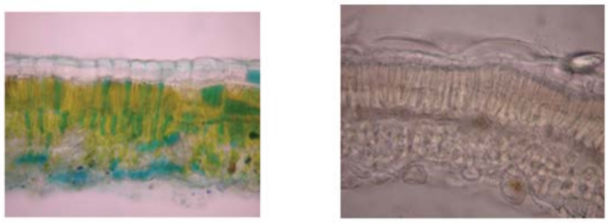
Adaxial Abaxial

Figure 1: Showing the absence and low frequency of stomata in *Condalia hoockeri.*



Adaxial Abaxial

Figure 2: Showing more stomata both on the adaxial and abaxial leaf surface of *Acacia berlandieri.*



Karwinskia humboldtiana (Schult.) Zucc. (40x) Lantana macropoda Torrey

Figure 3: Showing long and compact palisade cell in *Karwinskia humboldtiana* and *Lantana macropoda.*

Caesalpinia mexicana A. Gray (40x) Cordia boissieri A. DC. (40x)

Figure 4: Showing loose palisade cell in *Caesalpinia mexicana* and *Cordia boisiieri.*

The intensity and length of palisade tissue reflects the photosynthetic capacity of the species. On the other hand, compact palisade tissue function as impervious layer impeding the loss of water by transpiration (Figures 5-9).

On the basis of palisade cell length and compactness the woody species are classified into four categories.

Class 1: Small and compact palisade cell [8]: *Leucophyllum frutescens, Condalia hookeri, Celtis laevigata, Ebenopsis ebano, Sideroxylon celastrinum, Cercidium macrum, Diospyros palmeri, Fraxinus gregii.*

Class 2: Medium and compact palisade cell [6]: *Sargentia greggii, Diospyros texana, Forestiera angustifolia, Guaiacum angustifolium, Havardia pallens, Berberis chococo.*

Class 3: Long and compact palisade cell [7]: *Karwinskia humboldtiana, Lantana macropoda, Prosopis laevigata, Zanthoxylum fagara, Helietta parvifolia, Acacia berlandieri* and *Acacia greggii.*

Class 4: Loose Palisade cell [5]: *Caesalpinia mexicana, Cordia boissieri, Celtis pallida, Amyris texana* and *Bernardia myricifolia.*

It may be concluded that the species belong to class 4 having long and compact palidase cells have direct impact in reducing transpiration and at the same time could be efficient in photosynthesis.

Petiole anatomy

Similarly, in a study that was undertaken on the petiole anatomy of 36 woody shrubs and trees in a Thornscrub ecosystem in Linares, Northeastern Mexico and to understand its possible relation to the taxonomic delimitation and adaptation of the species to the semi-arid environments has shown that in a transverse section of a petiole, it consisted of three layers of tissue epidermis, cortex, vascular bundle and pith. Cuticle may be thick or thin over epidermis. Besides, trichomes may be present or absent. The collenchyma present below the epidermis may be multi-layered or few layered. Cortex consists of several layers of parenchyma. Sclerenchyma may be present outside vascular bundle area. Vascular bundles may be collateral and may be in several split patches. Vascular bundle may be strong or weak or elaborate. Pith consists of few layers of parenchyma, may or may not be distinct.

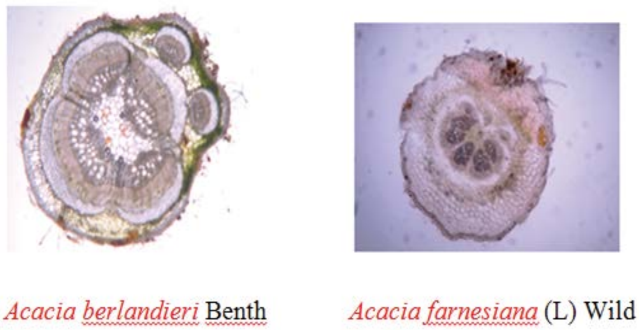


Figure 5: Showing strong petiole with thick collenchyma and sclerenchyma in *Acacia berlandieri* and weak petiole with thin collenchyma and sclerenchyma in *Acacia farnesciana* respectively.

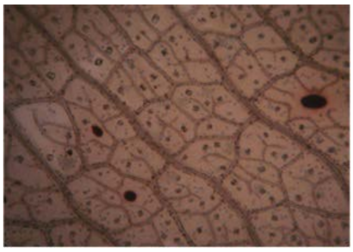


Figure 6: Showing strong and dense venation in *Karwinskia humboldtiana*.

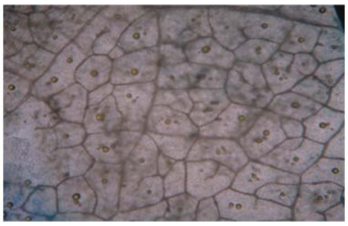


Figure 7: Showing weak and poor venation density in *Leucophylum frutescent.*

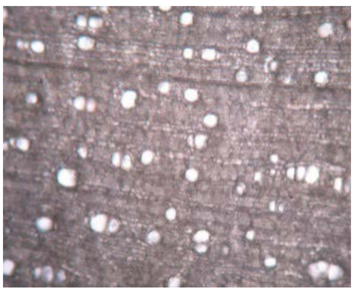


Figure 8: Showing narrow vessels in *Diospyros texana*.

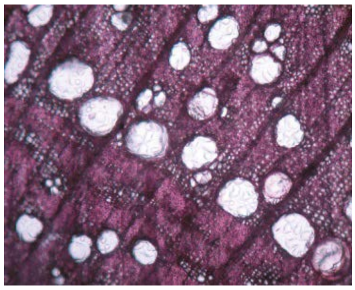


Figure 9: Showing large vessels in *Celtis laevigata*.

This comparative study on petiole anatomy of 36 woody species in Northeastern Mexico showed a large variability among species in various anatomical traits which can be used in taxonomic delimitation. Species were grouped on the basis of various petiole anatomical traits. In addition several species are selected for few desirable traits. Only five species are mentioned for each desirable trait suchas those having large vascular bundle are efficient in the transport of nutrients and water *viz., Acacia berlandieri, Acacia rigidula, Diospyros palmeri, Fraxinus greggii, Guaiacum angustifolia*, thick petiole (*Acacia berlandieri, Acacia farnesiana, Berberis chococo, Bernardia myricifolia, Eysenhardtia texana*) and mechanical tissues such as thick cuticle (*Acacia berlandieri, Celtis pallida, Condalia hookeri, Eysenhardtia texana, Gymnosperma glutinosum*), a thick collenchyma (*Acacia farnesiana, Berberis chococo, Bernardia myricifolia, Celtis pallida, Havardia pallens*) and extra sclerenchyma bands which offer mechanical strength (*Acacia berlandieri, Ebenopsis ebano, Eysenhardtia texana, Lantana macropoda, Prosopis laevigata, Xanthoxylum fagara*). The species having the combination of various desirable traits are expected to be more efficient in the physiological function and mechanical support. In this respect we can mention *Acacia berlandieri* as an ideal species.

In addition to the characters mentioned in the present study some special characteristics can distinguish some species from others owing to the presence of special anatomical features, such as vacuolar gland (*viz., Karwinskia humboldtiana, Helietta parviflora, Sideroxylon celastrina*), extra layers of vascular bundles (*Acacia rigidula, Eysenhardtia texana, Amyris texana*), extra band of thick sclerenchymatous tissue (*Acacia berlandieri, Acacia farnesiana, Acacia wrightii, Amyris texana, Caesalpinia mexicana, Leucaena leucocephala, Prosopis laevigata*). Besides the presence or absence of pigment tissue and pith are some other special characteristics in distinguishing species. Apart from taxonomic values these special features have physiological and mechanical functions in the woody plant species.

It may be interpreted that the large variability in petiole anatomy among 36 species could be efficiently utilized in taxonomic delimitation of the species. On the other hand, the tick petiole with large vascular area and intensity of mechanical tissue such as collenchyma and sclerenchyma present in few species could offer resistance to the environmental stresses and could be efficient in the translocation of nutrients and photosynthates.

Leaf venation

In the present study we classified 30 woody species according to Hickey [28] and analysed venation density of only 20 species [44].

Venation pattern

According to Hickey [28], we classified venation pattern of 30 species as shown below.

Brochidodromous: Lateral veins arising from midrib reach the leaf margin.

Craspedodromous: Lateral veins join at the margin.

Eucamptodomous: Lateral veins do not reach margin.

The venation pattern of 30 species according to Hickey [28] is shown herein.

Brochidodromous (28 spp): (Lateral veins reach up to margin): *Helietta parvifolia, Karwinskia humboldtiana, Sideroxylon celastrinum, Ebenopsis ebano, Condalia hookeri, Ehretia anacua, Leucophyllum frutescens, Celtis pallida, Acacia rigidula, Diospyros palmeri, Eysenhardtia texana, Zanthoxylum fagara, Sargentia greggii, Guaiacum angustifolium, Havardia pallens, Forestiera angustifolia, Acacia berlandieri, Caesalpinia mexicana, Croton torreyanus, Leucaena leucocephala, Gymnospermae tatalencho, Celtis laevigata, Diospyros texana, Acacia farnesiana, Acacia schaffneri, Prosopis glandulosa, Parkinsonia texana, Amyris madrensis*.

Craspedodromous: None

Eucamptodomous (2 spp): *Bernardia myricifolia, Cordia boissieri*

It is observed that among 30 species, most of the species [28] belong to class Brochidodromous. None of the species belong to Craspedodromous. Only 2 species belong to Eucamptodomous. Therefore, there exists large variability in venation patterns of trees and shrubs in Tamaulipan Thorn Scrub demonstrating the variability venation architecture (vascular bundle) among species studied.

Venation density

The venation density of 20 woody species is counted on the basis of number of veinis lets per unit area through microscope [44].

On the basis of venation density we classified species as follows:

- **Medium density:** *Ebenopsis ebano, Caesalpinia mexicana, Leucophyllum frutescens, Leucaena leucocephala, Parkinsonia texana* and others.
- **Low density:** *Guaiacum angustifolium, Amyris texana, Sargentia greggii, Acacia berlandieri, Prosopis glandulosa.*

Venation architecture (network)

On the basis of size of vein islets (visually) different species may be tentatively grouped as follows.

- **Vein islet small:** *Karwinskia humboldtiana, Ebenopsis ebano, Leucophyllum frutescens, Eysenhardtia texana, Zanthoxylum fagara, Acacia berlandieri, Caesalpinia mexicana, Leucaena leucocephala, Parkinsonia texana.*
- **Medium size:** *Acacia rigidula, Diospyros palmeri, Forestiera angustifolia, Acacia farnesiana, Amyris texana, Acacia shaffneri, Prosopis glandulosa.*
- **Large size:** Sargentia greggii, Guaiacum angustifolium, Gymnospermae glutinosum, Diospyros texana.

It is expected that the large variations in venation pattern and venation density could be efficiently utilized in taxonomic delimitation of the species as well as in the efficiency of the species of the species in mechanical strength and in the transport of nutrients which needs to be confirmed in future studies. No such studies are available on the woody plants of Tamaulipan Thorn Scrub.

Wood anatomy

A study that has been undertaken on wood anatomy of 33 woody species in northeast Mexico has shown that there exists large variation among species in wood anatomical traits such as porosity, vessel diameter, its distribution, parenchyma, compactness of ground tissues and fibre cell characteristics.

Most of the species have diffuse porous wood, but very few rings to semi-ring porous *viz., Acacia rigidula, Acacia shaffneri, Bernardia myricifolia, Fraxinus gregii.* Most of the species possess narrow vessels *viz., Acacia shaffneri, Acacia wrightii, Berberis chococo, Bernardia myricifolia, Diospyros palmeri, Eysenhardtia texana, Ebenopsis ebano, Ehretia anacua, Fraxinus gregii, Guaiacum angustifolium, Helietta parviflora.* Few species have medium to narrow vessels such as *Ebenopsis ebano, Eysenhardtia texana, Acacia rigidula* while *Bernardia myricifolia* posseses bigger vessels. The species having narrow vessels mentioned have capacity of resistance to cavitation and embolism exposed to hot summer and cold winter in semiarid Northeastern Mexico, similar to those in Mediterranean climates as discussed by several authors. Therefore, the species having narrow vessels could be tolerant to xeric environment.

In the context of the results on wood anatomy of a large number of woody species it could be interpreted emphatically that the large variation in wood anatomical traits mentioned above could be utilized in the taxonomic delimitation of the species as well as in the determination of wood quality and their utility. On the other hand, few anatomical traits such intensity of narrow vessels in some species could offer resistance against cavitation and embolism in hot summer and cool winter, well documented in the literatures mentioned above. This could be confirmed by determining water potential of these species. This is a potential line of research.

Conclusion

The present study showed a large variability in leaf surface anatomical traits such as the presence and absence of stomata, leaf epidermal cell shape and size which can be used in taxonomic delimitation of the species and adaptation to xeric environments in Tamaulipan Thorn Scrub, Northeastern Mexico.

The species identified as better adapters to semi-arid environments on the basis of the presence and absence of stomata on both adaxial and abaxial surface such as *Berberis chococo, Celtis laevigata, Condalia hookeri, Diospyros palmeri, Diospyros texana, Ebenopsis ebano, Ehretia anacua, Forestieria angustifolia, Havardia pallens, Helietta parviflora, Karwinskia humboldtiana, Sargentia gregii, Sideroxylon celastriana, Zanthoxylum fagara.* Research is needed to confirm water relation and drought resistance of these selected species.

A large variability in anatomical traits with respect to cuticle thickness, presence and absence of trichomes, length of palisade cells and thickness of spongy tissue is also observed among the species. Species have been classified on the basis of the length and compactness of palisade cells to determine its relation to the taxonomic delimitation and the adaptation of the species to drought condition. The species *viz., Karwinskia humboldtiana, Lantana macropoda*, *Prosopis laevigata, Zanthoxylum fagara, Helietta parvifolia, Acacia berlandieri* and *Acacia wrighti* having long and compact palisade cells are expected to be efficient in photosynthetic function and adaptation to drought. It is expected that thick cuticle and the long and compact palisade cells impede loss of water by transpiration. Future research needs to be directed in this direction.

Large variations exist among various petiole anatomical traits in 36 woody plant species. Species are characterized and grouped on the basis of various anatomical traits which could be used in taxonomic delimitation of the species. Besides the species were selected on the basis of various traits related to the physiological and mechanical functions of the petiole that give support to the leaves such as petiole thickness, vascular bundle size, cuticle thickness, sclerenchyma and other traits. Thus the species having the combination of various desirable traits are expected to be more efficient in the physiological function and mechanical support. These hypotheses could be confirmed in future study.

The present study has revealed the venation pattern of thirty and venation density of 20 few trees and shrubs in Northeast Mexico, according to the system of Hickey [28]. Among the 30 species studied 28 species belong to Brochidodromous, while only two species belong to Craspedodromous. The species showed variation in density of veinislets. In few species Islets are bounded by thin veins but traversed by thicker vein to give mechanical strength to the leaf lamina against stress, adaptive characteristic. Among the species studied *Eysenhardtia texana* had maximum vein islet density, *Ebenopis ebano*, *Caesalpinia mexicana*, *Karwinskia humboldtiana*, etc. possessed medium density, while *Guaiacum officinale*, *Amyris madrensis*, *Sargentia greggii* had low density. The variation in venation pattern and venation density could determine taxonomic delimitation and adaptation of the species to xeric environments which needs to be confirmed in future researches.

These characteristics could be used in taxonomic delimitation of the species as well as in the adaptation of the species in xeric habitats in summer, and cool environments in winter. Research inputs need to be directed to relate wood anatomical traits with their adaptations to hot summer and cool winter in Northeastern Mexico. Besides, the variations in wood anatomical traits could be related to the wood quality and its utilization. In this respect the trees having highly lignified cell wall could be recommended for strong furniture, similarly the species having the fibre cells with broad lumen and thin cell could be recommended for paper pulp. Research needs to be addressed in this aspect. Statistically highly significant difference in wood anatomical parameters reveals interspecific differences.

Recent advances on research on leaf anatomy (leaf surface, leaf lamina, petiole and venation) and wood anatomy of more than 300 woody species in a Tamaulipan Thorn Scrub, Northeastern Mexico were documented. The authors discussed the utility of these anatomical traits in taxonomic delimitation and adaptation of the species in xeric habitats in Northeastern Mexico [70].

General Conclusion

A comparative study on leaf anatomy (leaf surface, lamina, petiole and venation) and wood anatomy of more or less thirty woody species of Tamaulipan Thornscrub, Northeastern Mexico revealed clearly that there exist a large variability in all these anatomical traits among the species studied which can be effectively used in the taxonomic delimitation of the species. Besides some of the anatomical traits such as absence/low frequency of stomtata on both adaxial and abaxial leaf surface could reduce loss of water through transpiration. Similarly long/medium long compact palisade cell of the selected woody species could be related to efficiency in photosynthetic capacity as well as to reduce loss of water by transpirations owing to the compact arrangement of the palisade cells. Variation of sclerenchyma and vascular bundle area in the petiole could resist a number of environmental stresses and increase the translocation capacity of the species. On the other hand, dense venation could infer efficiency in translocation as well as offering resistance to the environmental stresses. It is well documented that narrow vessels and high xylem density in wood of tree species mentioned above could offer resistance against cavitation and embolism, thereby imparting resistance to drought. Therefore, the species selected on the absence/low frequency of stomata such as *Berberis chococo, Condalia hookeri, Ebenopsis ebano, Ehretia anacua, Havardia pallens* and others mentioned, species selected for compact and long palisade cells such as *Havardia pallens, Karwinskia humboltiana, Lantana macropoda, Prosopis laevigata, Xanthoxylum fagara* and others and woody species having narrow xylem vessels in wood, *Berberis chococo, Acacia shaffneri, Diospyros palmeri, Ebenopsis ebano, Ehretia anacua, Fraxinus gregii, Guiacum angustifolia, Helieta parviflora, Eysenhardtia texana, Forestieria angustifolia, Sargentia gregii, Sideroxylon celastrinum* and other could offer resistance to drought. The validity of these hypotheses could be tested in future research. All these reveal the importance of anatomical research in forest science which is ignored.

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