Morphological Structure Analysis of Taxus Based on Plant Biomechanics

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ABSTRACT: Although biomechanics has been developing for years, the research breakthrough of biomechanics at this stage is mainly to solve life and health problems (e.g., vascular mechanics, molecular cell biomechanics, as well as tissue repair biomechanics). There is not much research on plants. This study mainly considers some cutting-edge biomechanical studies in plants in recent years, focusing on Taxus Linn, combined with the observed morphological characteristics of Taxus, and analyzes the physiological structure of Taxus from three aspects of roots, stems and leaves. The morphological development of Taxus root is correlated with the mechanical action of wind and soil, and adapts and evolves with the environment. The stress and strain of stem cells have an effect on the cell morphology and then the appearance and function of stem. The transportation of leaf can be simulated by hydrodynamic model, and relevant calculations are used to explain the length and structure of Taxus leaf. Understanding Taxus from the perspective of plant biomechanics takes on a critical significance in studying the growth mode of Taxus, its relationship with the environment and biological metabolism. According to the above analyses and results, there will also be traces of how to protect wild populations, how to breed scientifically, and how to maximize the extraction of plant metabolites.

1. INTRODUCTION

Taxus Linn contains nearly 11 species distributed in the northern hemisphere, and there are four species and one variety in China. Since it is a prominent wood resource, as well as a vital source plant of anti-cancer drug paclitaxel, it has aroused wide attention and research over the past few years. However, due to its slow growth, scattered distribution and illegal logging, the wild trees are decreasing day by day. According to the red list of endangered species released by the International Union for Conservation of Nature (IUCN),1 species is considered critically endangered (CR),1 species is classified as endangered (EN) and 4 species being Vulnerable (VU).[1]

Combined with biological and physical sciences, plant biomechanics has been recognized as a relatively new field of research. While typical multidisciplinary study field of Taxus are genetics and genomics, pharmacology and drugs science, microbiology and toxicology, etc., the introducing of plant biomechanics in analyzing morphological structure will bring new ideas to the study field of Taxus Linn. As microscopic technology leaps forward, computer modeling and mapping instruments, the communication between mechanics and botany is becoming increasingly closer, and the research of botany has entered a more microscopic and computational stage.

The morphogenesis of plants is achieved primarily based on the three cellular processes, including cell differentiation, cell division, as well as cell elongation. From the perspective of architecture, plants form a variety of complicated three-dimensional (3D) shapes through the combination of thin (i.e., one- or two-dimensional) objects, including flower petals, leaves, stems, as well as roots. The above thin structures are likely to be formed due to the significantly directional tissue growth and are suitably expressed by geometric quantities (e.g., curvatures).[2]

This paper mainly considers some cutting-edge biomechanical studies in plants in recent years, focusing on Taxus Linn, combined with the observed morphological characteristics of Taxus, and analyzes the physiological structure of Taxus from three aspects of roots, stems and leaves. Plant biomechanics is a unique and prosperous field, benefiting from the synergy of interdisciplinary methods and the technological development that enables unprecedented research on biological structures and processes. Understanding Taxus from the perspective of plant biomechanics is of great significance to study the growth mode of Taxus, its relationship with the environment and biological metabolism.

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2. APPLICATION OF PLANT BIOMECHANICS ON THE MORPHOLOGICAL STRUCTURE OF TAXUS

2.1. Analysis of Root

The root is the vegetative organ of a plant and its main function is to absorb water as well as inorganic nutrients, anchoring the plant to the ground. [3] Root formation and development are related to many factors, such as soil conditions, overall plant size, distribution of adjacent plants, climate change and so on.

Aerial roots refers to the adventitious root that occurs on the plant stem, grows above the ground and is exposed to the air. It can absorb gas or support the upward growth of the plant and maintain water.

It is found that there were aerial adventitious roots in Taxus chinensis. With Taxus China var. mairei as the sample, Fengying Li, Shaoqing Tang et al. [4] observed and analyzed the aerial adventitious roots sprouting downward from the stem to reveal its internal structure and development characteristics.

The aerial adventitious roots sampling part and anatomical structure are presented in Fig. 1. The aerial adventitious roots of Taxus chinensis var. mairei with different sizes were observed by cross-sectional anatomy. The cross-sectional plane was round and could be clearly divided into epidermis, cortex and vascular column from outside to inside. The structure of primary xylem is simple. It only comprises tracheids and develops into exophytic type. The secondary structure largely comprises periderm and secondary vascular tissue.

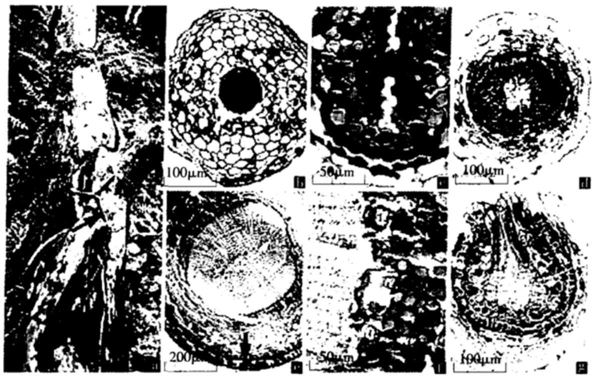

Figure 1 Anatomical structure of aerial adventitious roots of Taxus chinensis

Buttresses refer to a typical form of aerial adventitious root. Engineer Claus Mattheck and his team analyzed the structure of the force distribution close to the tree bases. On that basis, a plausible mechanical role for buttresses was found, and the development pattern of buttresses was explained. Moreover, the model could be conducive to explaining the correlation between the development degree of aerial adventitious roots and the mechanical environment, age and morphology of a tree. [5]

There is considerable evidence that the cambium of trees grows most rapidly within areas that are under the largest mechanical stress, thus strengthening areas of weakness. After the tree has been growing for several years, the pressure close to it will even out. Based on the assumption of the correct "constant stress hypothesis", Marchek's team could model how buttons develop in nature. First, they calculated local stresses close to the base of the sapling under horizontal winds using a finite element analysis software package. As revealed by the result, stress was higher at the top of the lateral root, in particular where it joined the trunk, whereas it was lower at the sides of the lateral root and close to the base of the trunk. Furthermore, materials were added to high-stress regions of the model tree, and the stress analysis was repeated. After the above process is repeated several times, the buttress grows fast between the trunk and the lateral root (Fig. 2b). Moreover, the radial growth of the lower trunk stops and the inverted conical character of the buttress tree is acquired.

Accordingly, the apparently abnormal growth patterns of buttress trees can be modeled in accordance with a simple rule of growth. As depicted in Fig. 2, if a tree is pushed by the wind, the bending force will be smoothly transmitted to the lateral sinker root through the buttress. The windward sinker resists the upward force and the buttress is in tension. However, the leeward sinker resists the downward force, and the buttress is compressed. (Fig. 2b). (Fig. 2c) and (Fig. 2d) depict the continuous stages of Mattheck's simulated support development. When the trunk is pulled over, the stress is concentrated on the top of the junction between the lateral root and the trunk (stippling). With the growth in the heavy stress region, the buttress is formed (Fig. 2d), and the stress concentration decreases significantly.

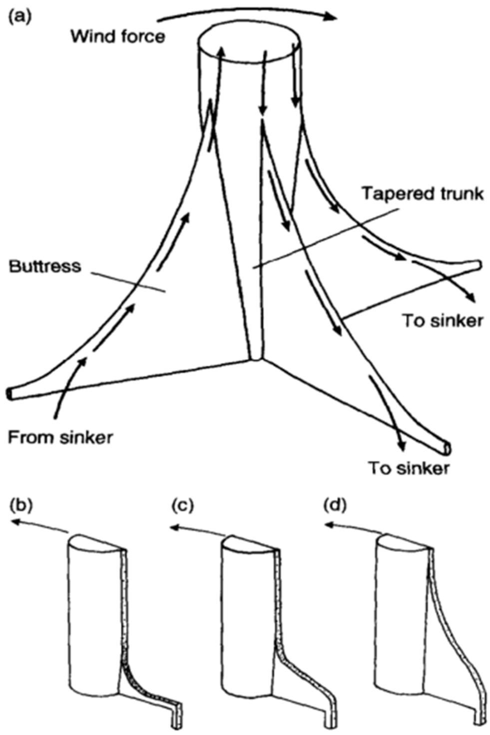

Figure 2 The function and development of buttresses

Although there are no obvious large buttresses in Taxus like tropical rainforest plants, the aerial adventitious roots of Taxus go deep into the soil through germination. They serve as vital organs in the propagation of Taxus unique initiation ramet and occupy a certain volume. Accordingly, the buttresses hypothesis model takes on a critical significance in the study of aerial roots of Taxus.

The aerial adventitious roots of Taxus entered secondary growth after primary growth and the lateral roots of Taxus originated from the pericycle (Fig. 1). When the lateral roots began to occur, the pericycle cells at one end of the primary xylem ridge were subjected to pericycle division to increase the number of cell layers and produce outward protrusions. Subsequently, the pericycle and vertical divisions were performed to make the protrusions continue to grow to form the root primordium of the lateral roots. Next, the tissue root primordium was divided and grown, which was progressively differentiated into the growth point and root cap, and the cells in the growth point continued to divide, increase and differentiate, and move forward with the root cap as the guide. The mechanical pressure generated by the continuous growth of lateral roots in the south, coupled with the substances secreted by the root cap, is capable of dissolving the pericarp, cortex and epidermal cells, so the lateral roots can pass through the pericarp, endothelial layer, cortex and epidermis in turn and exposing outside the mother root. As a result, new adventitious roots are formed.

From the perspective of environment, the sample is grown in subtropical Alpine woodland, with low temperature and humidity, fog, more rain, less sunshine, more humus, as well as limited rooting depth. As a result, lateral roots will be stressed further down their length, causing buttresses to be developed. Moreover, the survey reveals that the distribution area of yew is largely found in the shallow and flooded soil on both sides of the valley, and rarely seen on the hillside, in particular the sunny slope and semi sunny slope, which can well explain the above result. The distribution of stone cells in the secondary phloem of Taxus can increase the strength and support of roots, which takes on a far-reaching significance in plant anchorage and wind load.

2.2. Analysis of Stem

Stem refers to a vital vegetative organ of plant and plays a certain role in the transport and the support between root and leaf. For Taxus, the stem is not only the enrichment area of various drugs and derivatives, but also an important part of wood source.

Below is a Fig. (Fig3) illustrating some fundamental principles of mechanics and how it can affect plant growth. [6]. (Fig3a) applied the basic properties of solid, elastic and plastic, to the plant cell wall. Suppose the length of the cell wall is L with a cross-section of area S. When it is subjected to a force of magnitude F, by definition, stress σ denotes the force per unit area exerted on area S, strain ε is calculated by $(L - L0)/L0$, proportional to stress. If stress σ is lower than the yield threshold Y, the wall remains elastic and recovers its initial shape after the stress is relieved. If the stress is higher than the yield threshold, the wall creep is irreversible. E is tensile modulus that characterizes the stiffness of the material, whose value is the ratio of the force required to stretch the material per unit length along the central axis to its cross-sectional area. Moreover, μ as the shear modulus or modulus of rigidity is also denoted as G or S, which is determined as the ratio of shear stress to the shear strain. Growth is the combination of wall yielding and incorporation of new materials in the wall. Although this model deals only with shape changes in one direction and is not specific enough, the concepts of strain and stress can be extended to 3D shape changes and are the basis for linking mechanics and plant development.

For anisotropic growth of a cell, as depicted in Fig3b, modifications in its mechanical properties are the major determinant of shape changes. When turgor pressure P is exerted to a cylindrical cell which is highly common in stem cells, the nonequivalence between the stress of circumferential direction and longitudinal stress will lead to directional deformation. If the cellulose microfiber is circumferential, the axial ductility is significantly higher. Accordingly, the growth is mainly longitudinal.

The shoot of higher plants has a simple conserved body plan based on three major tissue systems: the epidermal (L1), sub-epidermal (L2) and inner ground and vascular (L3) tissues.[7] In Fig3c, tension in the epidermis has impact on morphogenesis. If the extension of the epidermis is less than that of the internal tissue, the isolated epidermis will retract, thus revealing that the epidermis is tensioned. The more malleable areas of the epidermis tend to form lumps. Cells in the epidermis both promote and restrict growth of the entire shoot by sending growth signals — either physical or chemical — to the

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inner layers. [8] However, if and how mechano-transduction functions during growth should be further investigated.

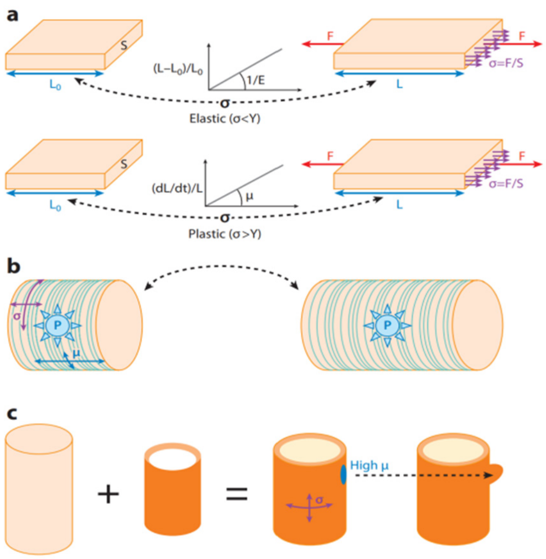

Figure 3 The mechanics of growth

In gymnosperms like Taxus, tracheids have been found as the major cell type, providing transportation and strength. Parenchyma cells store gums, starch, resin, tannins, latex and other substances in radiation. The mechanical properties of wood fibers or tracheids are mainly determined by the structure of secondary cell walls. Understanding the structure of cell walls and their properties is key not only to supporting wood or plant materials themselves, but also to the way the above materials are used in modern materials applications and how they can be dismantled to take advantage of individual polymer components.[9]

As depicted in Fig. 4, the cell wall of wood is composed of several layers and sublayers, namely, the middle lamella (ML), the primary wall (P), several sublayers of the secondary wall (S1, S2 and S3) and an additional verrucous layer (W). [10] Since ML is difficult to distinguish from P, ML and two adjacent Ps are commonly referred to as composite intermediate layer (CML). However, the real structure of cell wall is still controversial. The direction and distribution of cell wall materials in trees are significantly different, whereas this is rarely considered in the model. The delamination of wood cell wall can be observed by conventional optical microscope, whereas obvious structural differences can be identified only under an electron microscope.

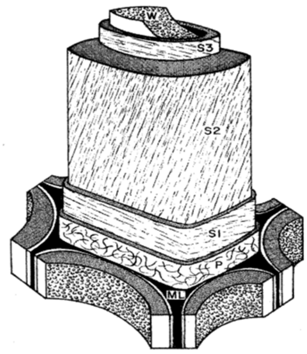

Figure 4 Schematic design of the cell wall of wood cells

For Taxus stem specifically, Fig. 5 presents the transverse section of Taxus wallichiana var.mairei stem under microscope.[11] The cross section of the young stem (branches with leaves) of Taxus chinensis var. mairei in Yuanbaoshan has a shape of "plum blossom", the cortex is petal shaped and uplifted outward, the epidermis is distributed in ridge groove shape, and there is no pericarp structure. From outside to inside, it is composed of epidermis, cortex and vascular column without resin channel. The secondary structure of the stem is mainly composed of pericarp and secondary vascular tissue, and the primary xylem and pith remain in the center of the stem (Fig. 5). The characteristics of different cells can be observed at different levels though there are no high-resolution transmission electron microscopy imaging conditions for clearer observation of subcellular structure. For instance, the cells next to the epidermis are small, the cell wall is thick, and arranged neatly and closely, while the pith in the center of the stem is composed of large parenchyma cells with equal diameter polyhedron, nearly circular or oval shape, and the cells are large.

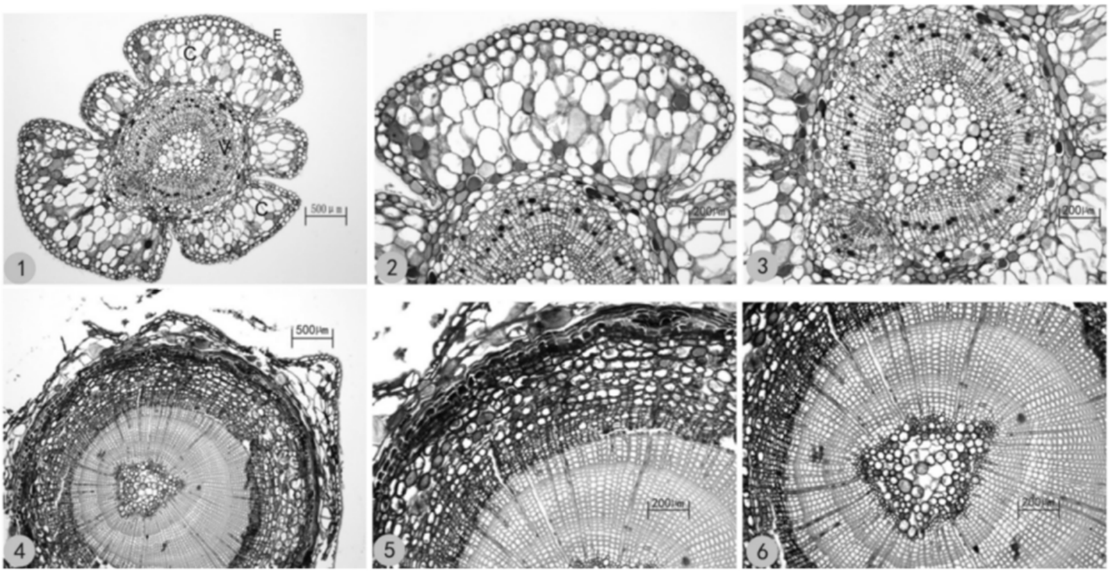

Figure 5 Anatomical structure cross section of stems of Taxus wallichiana var.mairei

2.3. Analysis of Leaf

As described in the analysis of stem, when the tissue generated by individual expansion of multiple cells is treated as a whole, leaf will be more effectively analyzed from geometric and mechanical perspective. It is generally known that the shape of leaves is closely connected with the growth process. Uniform growth will make a rod become longer or a flat circular disc become a bigger circle. Nonuniform growth may make the material bend in varying degrees, and the shape development is more difficult to predict.[12]

Fig. 6 illustrates the simple relationship between the growth tensor and Euclidean configuration. Whether disc is flat or curved, or occur elastic friction as presented in Fig. 6c is consistent with the "target metric" given by the growth pattern. Moreover, the thickness of the material will affect the leaf shape. Under the same growth pattern, if the disc is significantly thick, it will expand while keeping flat, thus resulting in nonzero stretching energy; a thinner disc will buckle, thus triggering nonzero bending energy. No stress-free configuration is found.

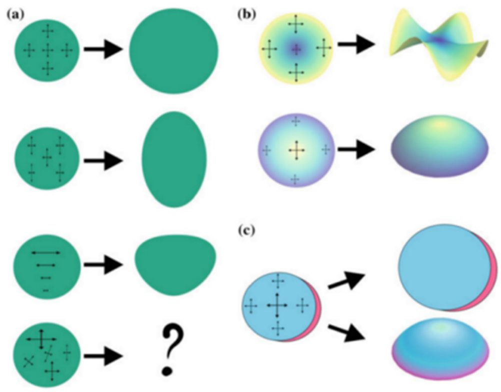

Figure 6 Growth tensor and Euclidean configuration

The structure of leaf is similar to that of stem. It is the end point of long-distance water transport in xylem, as well as the starting point of long-distance transport of sugars from the location of production in mesophyll to the location of consumption and storage in plant sink organs (e.g., reproductive organs, immature leaves and roots). [13] In general, the leaves of conifers do not show the complicated hierarchical structure of broad-leaved trees, as presented in Fig. 7 from the cross-sectional observation of wild Taxus chinensis Leaves in Taihang Mountain, Huixian County, Henan Province [14]. There are vascular bundles in the center of the cross-section of conifers, which extend from the tip of the needle to the petiole.

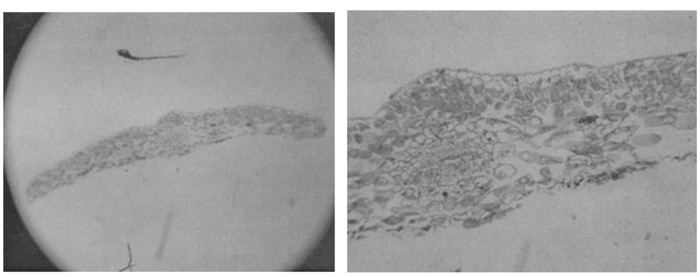

Figure 7 Cross-sectional observation of leaves of Taxus (with vascular bundle)

Focusing on the needle leaf part, assume a linear leaf like a conifer needle, researchers have modeled a conducting tube as a single, unbranched conduit of the same length as the needle. The osmotic flow in the plant needle is driven by the concentration difference of solute passing via the semi permeable membrane of the tube. Water is sucked from the surrounding environment and generates a net axial flow to maintain a constant concentration difference inside and outside the tube. An impenetrable wall is assumed as the tip of the needle, which is illustrated in Fig. 8. From x=0, the axial flow run from left to right. In a circular tube with radius a and membrane permeability L_p, the fluid flows with average axial velocity μ, average concentration c and pressure p. For stationary flows, based on the Münch-Horwitz equations, the incremental change in fluid flux Q(x) along the tube in terms of the water potential difference Δ Ψ across the membrane surface is written as:

$$dQ = L_p dA\Delta\Psi = L_p dA(RTc(x) - p(x)) \quad (1)$$

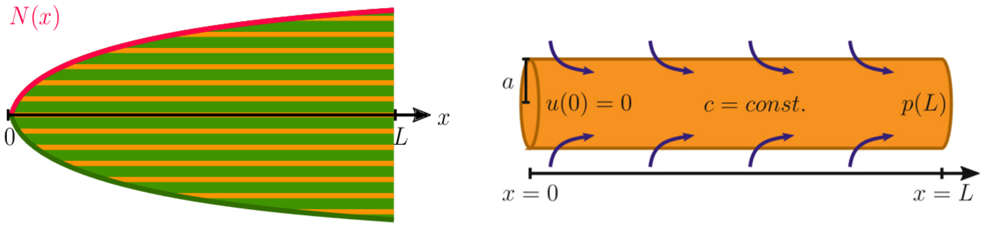

Figure 8 A system of parallel pipes as in a conifer needle and the simplest osmotic flow

In Eq. (1), c(x) denotes differences between the concentrations; p(x) represents differences between the pressures inside and outside the tube. d A, the differential surface area, is obtained by 2πadx. It is therefore revealed that the axial velocity is expressed as:

$$\frac{du}{dx} = \frac{1}{\pi a^2}\frac{dQ}{dx} = \frac{2L_p}{a}(RTc(x) - p(x)) \quad (2)$$

In accordance with Darcy's law (in terms of a Hagen–Poiseuille flow), by associating the pressure gradient with the velocity based on the viscosity η of the fluid, it yields:

$$\frac{dp}{dx} = -\frac{8\eta}{a^2}u(x) \quad (3)$$

The local loading rate ϒ(x) is defined, measuring the contribution of the respective part of the needle to the production and export of energetic sugars. Assume that the loading is capable of keeping the concentration c(x) constant = c_0 via the tube. Complemented the equation for the sugar loading with above equations, the reaction–diffusion equation is expressed as:

$$\frac{d(uc)}{dx} = D\frac{d^2c}{dx^2} + \Upsilon(x) \quad (4)$$

Differentiating (2) and inserting (3) we find

$$\frac{d^2u}{dx^2} = -\frac{2L_p}{a}\frac{dp}{dx} = \frac{16\eta L_p}{a^3}u(x) \quad (5)$$

In the limit of large M, the contribution from the respective part of the needle changes significantly, and the most significant contribution originates from a region closest to the needle base. The size of the above region is expressed as the intrinsic length scale of the exponential,

$$L_{eff} = \frac{L}{\sqrt{M}} = \frac{a^{3/2}}{(16L_p\,\eta)^{1/2}} = \frac{a^{3/2}}{{l_m}^{1/2}} \quad (6)$$

where the definition of the dimensionless Münch number (the ratio of axial resistance in the tube and radial resistance on the surface) is used. Subsequently, Eq. (5) is written as:

$$\frac{d^2u}{dx^2} = \frac{1}{L_{eff}^2}u(x) \quad (7)$$

which indicates an exponential behavior as $e^{\pm x/L_{eff}}$. In fact, when u(x = 0) = 0, the solution is

$$u(x) = A\sinh(x/L_{eff}) \quad (8)$$

The length scale L_{eff} plays a special role in the assumption of the constant sugar concentration within the tube. If the limit concentration that a given species can have is denoted as C_0, it will be indicated that the largest exit velocity is generated for the situation, where c(x) = C_0 along the whole tube. A needle would not gain much in sugar transport by making its needles longer than L_{eff}. As a result, if no other concerns (competition for sun or elastic properties) have equal importance, the above length should limit needle sizes.

As a matter of fact, the diversity of leaf sizes identified is ideal to test the generality of the analysis results. As depicted in Fig. 9[15], leaf length L for 519 species (including Taxaceae) are plotted, and the distribution of needle lengths seems roughly exponential with 75% of needles no longer than 6 cm in accordance with the value of L_{eff}. Longer needles might be disadvantageous under the formation of a stagnant zone in needles greater than L_{eff}.

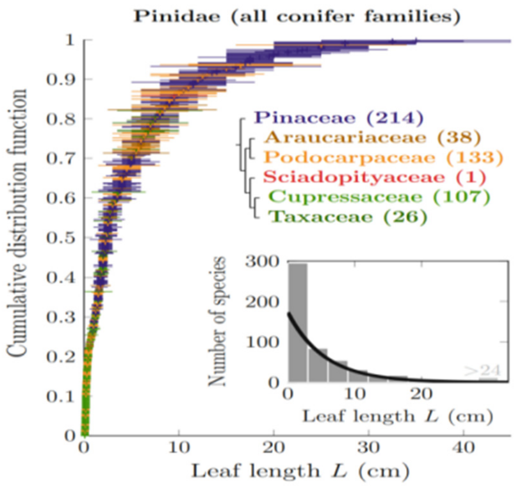

Figure 9 The distribution of needle lengths of 519 conifer species (six families)

3. CONCLUSION

Biomechanics research can provide more insights into the manner in which biological organisms cope with and use physical principles, as well as how the functional design of processes, tissues, and cells covers biochemical and mechanical concepts.[16]

The morphological structure of Taxus is significantly correlated with plant biomechanics. The formation of aerial adventitious roots partially arises from the mechanical effect of wind, soil and other environmental factors on the plant. The formation and development of stem is affected by the internal and external mechanical stimulation of cells. Furthermore, the shape, size and transport rate of leaf can be investigated and explained from a mechanical perspective.

The effect arising from biomechanics on plants is not just the effect of morphological structure. In other words, the external structure is correlated with internal functions. The analysis of biomechanics takes on a critical significance whether Taxus plays an ornamental role as wood or as a medicinal plant for drug extraction. The premise of analyzing growth, development, material secretion and transportation refers to understanding its mechanical structure and analyzing the different effects arising from different mechanical stimuli on plants. Only when plants are understood can they be cultivated, bred and protected scientifically. Lastly, the aims of improving the yield of plant derivatives and maintaining ecological balance can be achieved.

This paper places a major focus on the study of plant biomechanics for theoretical data comparison and formula modeling analysis in terms of root, stem and leaf, while reproductive organs (e.g., flowers, fruits and seeds) are not elucidated. More in-depth research and understanding still need in-depth field investigation and experiment, and there is still a long way to go from theory to application. Besides the conventional application of forestry, agriculture, medicine and ecology, the application of plant functional morphology in biomimetic materials and structures has achieved initial results. The perspective of mechanics provides a good entry point for us to gain insights into and use considerable functions and basic structures evolved by plants, so as to adapt to various autogenous and synergistic ecological constraints. Furthermore, it enables the development of novel technology products and production chains. [17] In the future, the intersection between various disciplines will be increasingly closer, and the discipline of plant biomechanics will be promising in development.

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