Microscopical features of six species of Phyllostachys bamboo and Arundo donax

Silvia Greco (s.greco@unibo.it)
DICAM, Alma Mater Studiorum – Università di Bologna
Luisa Molari
DICAM, Alma Mater Studiorum – Università di Bologna
Giovanni Valdrè
BIGEA, Alma Mater Studiorum – Università di Bologna
Jose Jaime Garcia
Escuela de Ingeniería Civil y Geomática - Universidad del Valle

Research Article

Keywords: Phyllostachys bambusoides, Phyllostachys edulis, Phyllostachys iridescens, Phyllostachys viridiglaucescens, Phyllostachys vivax, Phyllostachys vio-lacescens, Arundo donax

Posted Date: January 3rd, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2409572/v1

Abstract

Advancement in the application of natural materials in construction requires an understanding of their anatomical and physical characteristics and strength. Nowadays, a lack of knowledge is unfortunately present regarding some bamboo species. The aim of this paper is to provide detailed information to close this gap. *Phyllostachys bambusoides, edulis, iridescens, viridiglaucescens, vivax and violacescens* have been analysed. Such bamboo species are easily cultivated in Italy, but not all of them are the same in terms of diameter, wall thickness, and mechanical behaviour. The properties and differences of *Arundo donax* are also presented and explained to compare these very similar materials. In the first part of this study, the features of the components of these species are investigated. A detailed description and pictures of the microstructure are reported. In the second part, the distribution of the components of the plants is analysed and then cross-correlated to mechanical properties. All the bamboo species studied exhibit similar characteristics in terms of component morphology, with the exception of *Arundo donax*, which differs in terms of component distribution along the culm wall. Generally, species having a higher percentage of fibre, and larger fibres in the average vascular bundle, have higher tensile, compressive, and bending strengths.

1 Introduction

Locally sourced natural materials represent a viable alternative for the future of the construction industry because of their sustainability in terms of production, transport, and disposal. In this regard, bamboo and *Arundo donax* are able to combine a high mechanical resistance with a low specific weight and a very fast growth rate, making them suitable materials to replace high-contaminating materials in many applications. Because of their natural origin, the composition and anatomical and physical characteristics of these plants vary, which has significant effects on their durability and strength. Because of their heterogeneous composition, relating their microstructure to their mechanical behaviour is challenging.

Bamboo has been defined as a composite functionally graded material (Amada et al., 1996), because of its multi-component structure and the disposition of its components.

The cribro-vascular vessels provide water and nourishing substances to the plant. They spread out from the internal to the external part of the culm wall, increasing their number and decreasing their thickness. The number and dimension of the vessels vary significantly within the plant. The vessels are surrounded by sclerenchymatous tissue, made by longitudinally developed cells called fibres which give mechanical support and are responsible for the excellent mechanical characteristics of this plant. These cells are made of a strongly thickened secondary wall in which the microfibril percentage is higher than that of the matrix, and the structure is defined by an alternation of broad and narrow lamellae or layers with a different fibril orientation. That yields a criss-cross configuration to fulfil the combined function of withstanding internal stress and allowing longitudinal expansion (Parameswaran & Liese, 1976).

Fibres are subjected to the lignification process to become impermeable and resistant to pathogenic microorganisms, and for this reason they modify the strength and stiffness of the plant. When fibre thickness decreases, culm diameter, thickness, and internode distances increase (Dessalegn & Singh, 2019). Fibres have an almost hexagonal cross section of variable dimension and are gathered in islands around vessels in a different manner according to the species. Fibres and vessels form the vascular bundles, whose morphology and distribution change within the plant. Li and co-workers (Li et al., 2007) observed, in a five-year old bamboo, a vascular bundle concentration of 298 to 458 bundles/cm^2 for the bottom and top parts, respectively, in the external part of the culm, and a difference of 458 to 148 bundles/cm^2 for the outer and inner parts of the culm wall. Dai and co-workers (Dai, et al., 2023) investigated the morphological characteristics of *Dendrocalamus sinicus* vascular bundles along the radial direction and discovered that the distribution of length, width, length to width ratio, and area of vascular bundles can be described by quadratic functions.

Vascular bundles are embedded in a porous matrix of parenchymatic tissue that works as a store for the plant. Parenchymatic tissue is made of elongated cells, each composed of the middle lamella, primary wall, and cytoplasmic structure. This type of cell only has a thin cell wall made of microfibrils embedded in a large quantity of matrix made of water and pectins. Parenchymatic tissue is not subjected to the lignification process in bamboo.

The strength and stiffness of bamboo are strongly connected to the presence of lignin. This is one of the main constituents of this plant, and its amount varies with the age and the position of the culm (Li, et al., 2007) lending different mechanical properties to various parts of the culm. Tensile strength is mainly provided by the cellulose content, while the microfibrillar angle is proportional to the failure-strain due to irreversible deformation of the cell wall. The modulus of elasticity is proportional to the cellulose content and inversely proportional to the microfibrillar angle. The almost axially oriented cellulose fibrils in the fibre walls maximize the longitudinal elastic modulus of the fibres and their lignification increases the transverse rigidity (Wang et al., 2013). Among the various lignocellulosic fibres, bamboo has a high percentage of lignin (32%) and its microfibrillar angle is relatively small (2°–10°). These factors contribute to the extremely high tensile strength, flexural strength, and rigidity of the fibre poly-lamellate wall structure (Liu et al., 2012).

The fibre bundles consist of an exclusively tension-resistant geometry, but when associated with the matrix along their length, they also provide reinforcement in compression due to the stiffer and stronger crystalline cellulosic composition, as compared to the lignified amorphous nature of the parenchyma (Krause et al., 2016). The compression behaviour curves changed according to the amount of fibre content as fibres started cooperating to increase the compressive strength. In specimens with a major amount of fibre (medial and external layers), the matrix volume fraction decreased, forming an initially softer curve that becomes stiffer after the fibre bundles settle. Wahab and co-workers (Wahab, et al., 2012) correlated shear and tensile strengths with vascular bundles and fibres dimensions. They found that shear and tensile strengths have a positive relationship with the number of vascular bundles, while tensile and shear strengths decrease when vascular bundle size increases. Regarding fibre morphology, only the fibre wall thickness has been deemed to have a significant positive correlation with shear strength but not a clear correlation with tensile strength. The modulus of elasticity and strength were measured in many studies ((Amada, et al., 1996), (Shao et al., 2010), (Aiping et al., 2012) (Habibi et al., 2015)) with different methods like nanoindentation or the rule of mixture, and led to very different results. Akinbade and Harries (Akinbade & Harries, 2021) collected existing literature on the fibre longitudinal modulus of elasticity for *P. edulis*, ranging from 5.9 to 55 GPa, and on the matrix longitudinal modulus of elasticity, ranging from 0.2 to 5.8 GPa.

Arundo donax is made with the same bamboo components but disposed of in a different way. Spatz and co-workers (Spatz et al., 1997) described a ring of sclerenchymatous fibres with small vascular bundles surrounded by a layer of the cortical parenchyma on the external part of the culm wall, while the inner parenchymatous tissue included numerous vascular bundles with sclerenchymatous bundle sheaths. The bending stiffness was guaranteed by the mechanical properties of the fibre ring and its location, while the isolated vascular bundles embedded in lignified parenchyma further stiffened the culm. Parenchymatous cells have significantly lignified cell walls, in contrast to bamboo parenchymatous cells. In tensile tests, an elastic modulus of 10 GPa was measured for the external part of the culm wall, while an elastic modulus of around 9 GPa was calculated for the inner part. Markus and Ruggeberg (Rüggeberg et al., 2010) measured a tissue stiffness of 11 GPa for the sclerenchymatic tissue, while the tissue stiffness of the parenchyma was in the range of 0.4–1 GPa. Moreover, they focused on the characteristics of the interface between the different tissues. They found that the cellulose microfibril does not show any gradual transition, and consequently any gradual stiffness transition at the tissue interfaces, and explained this as an 'evolutionary strategy' to compromise between avoiding stress discontinuities and optimizing the bending stiffness of the entire culm.

Bamboo has been studied for many years(Fangchun, 1981) (Janssen, 1991),(Trujillo, 2016) but the current knowledge is mainly limited to some Asian and South American bamboo species. Phyllostachys is one of the most popular bamboo families in the world, especially in temperate climates (Liese & Köhl, 2015). Very little knowledge exists about these species and detailed information is very important to grade bamboo and use each species correctly. *Arundo donax* is a native plant of the Mediterranean areas, similar to bamboo, recently rediscovered as a source of inexpensive, sustainable material for construction purposes. It has been studied by many academics (Spatz et al., 1997) (Conte et al., 2018) (Hardion et al., 2014) (Molari et al., 2021) because of a great interest in using it for several purposes, such as vibrating reed for woodwind instruments or a source of biomass.

In the present study, six types of *Phyllostachys* have been analysed. In the first part, the features of the components of these species are investigated from a microscopical point of view, and a quantitative description is reported. In the second part, their distribution is analysed and then cross-correlated with the macroscopical mechanical properties.

2 Materials

All the specimens used in this study were obtained from untreated culms of bamboo and *Arundo donax* cultivated in different zones of Italy. Six species of the *Phyllostachys* family were evaluated: *P. edulis, P. bambusoides, P. viridiglaucescens, P. vivax, P. violascens and P. iridescens*. In particular *P. bambusoides*, *P. iridescens, and P. vivax* are from Langhe (Piemonte region, North-West of Italy), *P. edulis* is from Pordenone, (Friuli Venezia Giulia, North-East of Italy), *P. viridiglaucescens* is from Selvaiana Capezzano Pianore (Tuscany, central Italy) and *P. violacescens* is from Bologna (Emilia Romagna, central part of Italy). *Arundo donax* was cultivated in Cadriano, a small town close to Bologna. All the culms were collected in winter of 2018 and were stored in a protected warehouse at the University of Bologna. Data about dimensions of diameter, thickness and density of the culms used in this study are reported in Table 1.

For both bamboo and *Arundo donax*, two parts of each culm were studied: the A part was collected from 2.5 to 3.5 m from the ground, and the B part was collected from 0.5 to 1.5 m from the ground. Regarding bamboo, the part of the culm higher than 3.5 m was excluded because of the leaves and the consistent change in diameter that generally makes it unsuitable for construction.

3 Anatomic Analysis

Optical microscopy analysis was used to obtain the microstructure of the material. For polarized optical microscopy (POM), thin sections (about 30 ± 1 µm) of each bamboo sample were prepared, polished at least with 0.5 µm grit over areas several mm^2 in size. Both reflected and transmission polarized optical microscopy analyses were performed on thin sections, employing a Zeiss Photomicroscope III with polarized light and digitized with an Edmund Optics CMOS-sensor colour camera.

The preparation of the bamboo thin sections (about 30 ± 1 µm) required the use of embedding and surface impregnation techniques. Samples were embedded in a vacuum with resin to provide a robust supporting layer, and the specimens were cut into small blocks by means of a wheel saw. Then, the preparation of thin sections included the creation of a flat surface (± 1 µm) with abrasives. After this procedure, a glass slide was glued onto that surface and finally the specimens were thinned down to 30 µm by means of cutting, lapping and polishing (at least with 0.5 µm grit), over areas several mm^2 in size.

Different zooms were used: 2,5 X, 10X, 25X and 40 X, to analyse microstructural details at various magnifications. An image from the top and one from the bottom of each species were selected.

3.1 Vascular bundles: disposition, dimension, and shape

The disposition and distribution of bamboo and *Arundo donax* components are shown in Fig. 1a and 1b respectively. In the case of bamboo (left picture), the increase of sclerenchymatous sheaths is evident from the inner to the outer part of the culm wall, in parallel with the reduction of the area occupied by parenchyma. In the case of *Arundo Donax* (right picture), two zones are clearly distinguishable: the inner one, in which vascular bundles are rather homogeneously embedded in the ground parenchyma, and the second, in the neighbourhood of the outer culm wall, in which the ring of sclerenchymatic tissue divides the cortical parenchyma from the rest of the section.

The components of a bamboo vascular bundle are clearly visible in **Fig. 2a.** They are a group of small phloematic vessels, two big xilematic vessels, and an intercellular space that is a cavity deriving from an ancient proto-xilematic vessel, all of which are protected by four sclerenchyma sheaths, embedded in the ground parenchyma. According to (Grosser & Liese, 1971) classification, in *P. edulis, P. bambusoides, P. iridescens, P. violacescens, P. vivax and P. viridiglaucescens*, there is only one type of vascular bundle along the wall thickness, as there is for all species with leptomorph rhizomes, in which there is only a central vascular strand and the island is concentrated only in sheaths around vessels. The shape of the sheaths varies along the thickness, as reported in Table 2. The sheaths appear as four little islands around the vessels and the intercellular space, in the inner side, while they start stretching towards the external side, where only two big fibres islands surround the vessels: a bigger one for the two xilematic vessels and a smaller one for the phloematic ones. The intercellular spaces seem to disappear. No differences were found in terms of shapes between the six species, while the proportion between fibres sheaths and vessels change visibly, as will be discussed below. As a result, the inner vascular bundle has a greater width and a smaller height, while the outer vascular bundle has a greater height and a smaller width. The dimensions of an average vascular bundle are reported in Table 3. Generally, vascular bundles from the top part of the culm look smaller than those from the bottom part, both in width and height. The trend is the same for the vascular bundles in the external part compared to the inner one. Different species present similar dimensions of the vascular bundles, except for *violacescens* species, which has a lower vascular bundle dimensions, both in height and width.

A vascular bundle of *Arundo donax* is illustrated in **Fig. 2b**. Its composition is the same as that of the bamboo vascular bundle, but there is no subdivision into islands of fibres as in bamboo. A ring of sclerenchymatous tissue surrounds the vessels, and the part around the phloematic vessels is thicker. Small parenchymal cells are present between the vessels, while the ground parenchyma surrounds the entire bundle. Some other vessels are present between the outer part of the sclerenchymatous ring and the ground parenchyma. No difference in the shape of the vascular bundles was found along the thickness, as visible in Table 2. The dimensions of the vascular bundles decrease appreciably near the external part of the culm wall, as noticed in Table 3. Moreover, it was found that vascular bundles from the upper part of the culm (part A) are smaller than those of the lower part (part B).

3.2 Schlerenchymatic cells: dimensions and shape

The sclerenchymatic tissue was observed using the optical transmission technique. In this case, the lumen of the fibre behaves as a channel through which the light goes and appears as white in the reported picture. The reflection technique was not used because the image appears poorly defined.

Fibre dimensions vary both with respect to the position along the culm and location within the culm wall. Measurements for a mean fibre are reported in Table 4 for every species of the inner and outer parts of the culm. The average fibre diameter is in the range of 12–20 µm and 15–22 µm for the inner and outer positions, respectively. The average lumen diameter ranges from 2 to 6 and from 2 to 7 µm for the internal part and the external parts, respectively. Cell wall thickness goes from 4,5 to 7 µm and from 6 to 9 µm for the internal or external cells, resulting in very different results in these two cases. The ratio between the dimension of the entire cell and its wall thickness is almost constant. Fibres of the same vascular bundles can change in dimension, as shown in **Fig. 3**. The cross-sectional dimension of the bundles is generally bigger near the edge of the parenchyma and becomes smaller toward the inner part near the vessels in every species. The multilayer structure of fibres is clearly visible in the microscope observation and is shown in **Fig. 4** where the schlerenchymatic tissue for all of the six bamboo species are compared.

No differences were found for the average *Arundo donax* fibre, which follows the same trend explained for bamboo species.

3.3 Parenchymatic cells: dimensions and shape

Parenchyma cells are located mainly in the inner part of the culm wall and gradually decrease toward the external one. A little band of parenchymal cells divides the last sequence of fibre bundles from the external skin. No substantial differences were found in the parenchymatic tissue for all six species, as reported in Table 5. Cell size varies greatly: smaller cells are found between fibre bundles or in the external band. However, very different dimensions of parenchymatic cells were found in the same part of the section. The particular morphology of these cells made it difficult to observe them with the optical transmission microscope. As they are short and “cube-like” (Grosser & Liese, 1971) cells, the lower light of the microscope cannot go across the section, and the results are dark. However, they were observed with an optical reflection microscope or, in some cases, with a mixed technique to enlighten sclerenchymatic tissue too.

4 Composition

Images from the microscope were then processed to evaluate the percentage of fibres, parenchyma, and voids as shown in **Figure 5**. Firstly, a portion of the section was chosen to identify a representative and approximately rectangular section. Then, the features in this rectangle were redrawn with splines using a CAD software (Autocad 2023, from Autodesk).

The percentage of area occupied by each bamboo component is reported in **Table 6**. No great differences were found between part A and part B of the culm for both fibre and voids, although part A seems to have a slightly greater amount of fibre. Generally, the fibre content is approximately 30%. *P. bambusoides, P. viridiglaucescens, P. vivax* and *P. iridescens* species have a higher content of fibres with respect to *P. edulis* and *P. violacescens* species. *Arundo Donax* has a percentage of fibre area under 20%, which is lower than bamboo, and a higher percentage of void area. A very slight difference exists between parts A and B of the same plant.

The graphs of the distribution of fibres and voids along the thickness are reported respectively in Appendix A and in Appendix B for all of the six bamboo species and *Arundo donax*. Results regarding the distribution of fibres and voids along the thickness and width are reported for *P. bambusoides* from the part A of the culm in **Fig. 6**, **Fig. 7** and **Table 7**. Linear, quadratic and cubic distribution curves are compared. No significant differences were found in terms of residuals regarding the distribution of fibres along the thickness. Fibre content grows from the internal part towards the external part of the culm wall. The distribution of voids was better fitted with quadratic or cubic curves, while the number of voids decreases in the last part of the section. The distribution of the components along the width is constant.

Distribution curves of fibres and voids along the thickness of the culm wall of *Arundo donax* are reported in **Fig. 8**. An almost constant trend is shown for fibres, except at the end of the curve, in which the presence of the ring near the external skin is highlighted by a high peak. The distribution of voids shows a regular trend. Results along the width are illustrated in **Fig. 9**. Also in the case of *Arundo donax* the distribution of the components along the width is almost constant.

5 Correlation With Macroscopic Mechanical Properties

The six bamboo species and *Arundo donax* were tested in tension, compression, circumferential tension, and bending tests, as reported in previous studies (Molari et al., 2020) (Greco & Molari, 2022) (Greco et al., 2019) (Molari & García, 2021) and (Molari et al., 2021). The results are reported and compared in **Table 8-9.**

P. bambusoides and *iridescens* species have higher tensile and compressive strengths and moduli of elasticity while having a relatively smaller circumferential inner strength and a medium bending strength in both configurations. Both of these two species have a large percentage of fibre area and a large average fibre diameter and thickness.

P. *edulis* shows good tensile and compressive strength while having a higher circumferential inner strength. A slightly lower bending strength is observed when fibres are in compression. Compared to other bamboo species, *P. edulis*'s modulus of elasticity is lower in tension, compression. and bending, while it is twice that of the others in the circumferential tensile direction. This species has a lower percentage of fibre area compared to the others, while the average diameter of its fibres is smaller.

P. violacescens has a substantially lower tensile strength and a slightly lower compressive strength compared to the other species. It also shows a higher circumferential inner strength. In bending, it has the lowest strength in both configurations. This species has the lowest values of fibre and vascular bundle dimensions and percentage fibre area.

P. viridiglaucescens has a medium tensile and compressive strength but shows the best bending strength in both configurations. The percentage of fibre area is higher in part B of the culm, and it has medium values in part A. The average fibre size is higher near the external side of the culm wall, while it has medium values near the inner side of the culm wall.

P. vivax has a slightly lower tensile and compressive strength but a higher circumferential inner strength, similar to *P. violacescens* and *P. edulis*. It also shows good behaviour in bending tests, especially under fibre tension. This species has a high percentage of fibre area, especially in the upper part of the culm, and a thicker wall in both parts of the culm.

Arundo donax has, generally, strengths between 45 and 75% of those of bamboo, depending on the species considered. Compression strength ranges from 70 to 100% of the strength of the bamboo species considered. The modulus of elasticity is slightly lower compared to almost all bamboo species.

No differences between species regarding the circumferential outer strength were found.

When comparing the transversal and longitudinal directions, the mechanical behaviour of all species is significantly higher in the longitudinal axis. Both the inner and outer parts have a lower compressive strength in both directions. For the outer part, which is mainly composed of fibres, the longitudinal modulus is almost 10 times higher than the transversal, both in tension and compression. For the inner part, mainly composed of parenchyma, the longitudinal modulus of elasticity in compression is almost five times higher than the transversal one, except for *edulis* and *violacescens* species having smaller fibres, for which it is 2.5 times higher.

The average values from mechanical tests were correlated to the fibre content and dimensions of the average fibre for each species. Axial tension and circumferential bending versus percentage of fibre are represented in **Fig. 10**. Tension and external circumferential tension are strongly correlated to fibre content, consistent with (Shao et al., 2010). In contrast, the inner circumferential tension is inversely proportional to fibre content, and so is the decrease of parenchyma content. The same result was found regarding the correlation between the Young modulus and the content of fibre, shown in **Fig. 11**. A good correlation was also found between the axial tensile strength and the average fibre dimension. while a less correlation exists with the circumferential bending strength, as shown in **Fig. 12**. The Young modulus results were not correlated to fibre dimensions, as reported in **Fig. 13.**

6 Conclusions

This paper provides detailed information on six species of *Phyllostachys* and on *Arundo dona*x grown in Italy that were previously unknown. Firstly, a microscopical analysis has been done, and measurements and pictures of the microscopical features of bamboo components are reported. Then, an analysis was done to describe the trend of their distribution. Finally, results from a complete mechanical characterization of these species have been reported.

All the analysed bamboo species present similar characteristics in terms of the morphology of their components, while *Arundo donax* differs in terms of the distribution along the culm wall. Generally, species having a higher percentage of fibre, and larger fibres in the average vascular bundle have higher tensile, compressive, and bending strengths. The species with a smaller average fibre diameter in the inner part of the culm wall have a higher circumferential inner strength. In all cases, *Arundo donax* presents lower strength, which is around 50% of the best performing bamboo species, and 75% of the worst performing one, except for compression strength, which is higher. The stiffness is very similar to that of bamboo.

It is well-known that bamboo behaviour can change significantly according to the species, and this is a strong limit to the spread of this material, which is now restricted to the already known species. Concerns and considerations about the usage of these bamboo species grown in Europe can now take advantage of these data, which describe the features and behaviour of this composite material.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would thank Prof. Annalisa Tassoni for sharing her knowledge in vegetal biology and Dr. Daniele Moro for the support in using the microscope.

References

1. Aiping, Z., Dongsheng, H., Haitao, L., & Yi, S. (2012). Hybrid approach to determine the mechanical parameters of fibers and matrixes. *Construction and Building Materials, 35*, 191-196. doi:http://dx.doi.org/10.1016/j.conbuildmat.2012.03.011
2. Akinbade, Y., & Harries, K. (2021). Is the rule of mixture appropriate for assessing bamboo material properties? *Construction and Building Materials, 267*.
3. Amada, S., Munekata, T., Nagase, Y., Ichikawa, Y., Kirigai, A., & Zhifei, Y. (1996). The Mechanical Structures of Bamboos in Viewpoint of Functionally Graded and Composite Material. *Journal of Composite Materials, 30*(7), 800-819. doi:0021-9983/96/07 800-20
4. Conte, P., Fiore, V., & Valenza, A. (2018). Structural and Mechanical Modification Induced by Water Content in Giant Wild Reed (A. donax L.). *ACS Omega, 3*(12), 18510–18517. doi:https://doi.org/10.1021/acsomega.8b02649
5. Dai, F., Wang, Z., Wang, H., Zhang, W., Zhong, T., & Tian, G. (2023). Vascular bundle characteristics and mechanical properties of Dendrocalamus sinicus. *Construction and Building Materials, 363*. doi:https://doi.org/10.1016/j.conbuildmat.2022.129858
6. Dessalegn, Y., & Singh, B. (2019). Effect of analysis on morphology of bamboo fibre: a review. *International Journal of Engineering Sciences & Research Technology, 8*(3). Retrieved from ISSN:2277-9655
7. Fangchun, Z. (1981). Studies on Physical and Mecanical Properties of Bamboo wood. *Journal of Nanjing Techn.* .

8. Greco, S., & Molari, L. (2022, January). Flexural Behaviour of Five Species of Italian Bamboo. *Construction Technologies and Architecture. Trans Tech Publications Ltd, 1*, 723-729. doi:https://doi.org/10.4028/www.scientific.net/cta.1.723.
9. Greco, S., Molari, L., & Maraldi, M. (2019). Assessing the mechanical properties of bamboo cultivated in Italy. *IC-NOCMAT 2019.* Nairoby, Kenya.
10. Grosser, D., & Liese, W. (1971). On the Anatomy of Asian Bamboos, with Special Reference to their Vascular Bundles. *Wood Science and Technology, 5*, 290-312.
11. Hardion, L., Verlaque, R., Saltonstall, K., Leriche, A., & Vila, B. (2014, September). Origin of the invasive Arundo donax (Poaceae): a trans-Asian expedition in herbaria. *Annals of Botany, 114*(3), 455-462. doi:https://doi.org/10.1093/aob/mcu143
12. Janssen, J. (1991). *Mechanical Properties of Bamboo.* Dordecht, Nederlands: Kluwer Academic Publishers.
13. K.Habibi, M., T.Samaei, A., Gheshlaghi, B., Lu, J., & Lu, Y. (2015). Asymmetric flexural behavior from bamboo's functionally graded hierarchical structure: Underlying mechanisms. *Acta Biomateralia, 16*, 178-186. Retrieved from https://doi.org/10.1016/j.actbio.2015.01.038
14. Krause, J. Q., Silva, F. d., Ghavami, K., Gomes, O. d., & Filho, R. D. (2016). On the influence of Dendrocalamus giganteus bamboo microstructure on its mechanical behavior. *Construction and Building Materials*(127), 199-209. Retrieved from http://dx.doi.org/10.1016/j.conbuildmat.2016.09.104
15. Li, X., Shupe, T. F., Peter, G., Hse, C.-Y., & Eberhardt, T. (2007). Chemical changes with maturation of the bamboo species phyllostachys pubescens. *Journal of Tropical Forest Science, 19*(1), 6-12. Retrieved from https://www.fs.usda.gov/treesearch/pubs/29071
16. Liese, W., & Köhl, M. (2015). *Bamboo, the Plant and its Uses.* Hamburg: Tropical Forestry.
17. Liu, D., Song, J., Anderson, D. P., Chang, P. R., & Hua, Y. (2012). Bamboo fiber and its reinforced composites:structure and properties. *Cellulose, 19*, 1449–1480. doi:10.1007/s10570-012-9741-1
18. Molari, L., & García, J. J. (2021). On the radial variation of the transverse mechanical properties of bamboo. *Journal of Building Engineering, 33*. doi:https://doi.org/10.1016/j.jobe.2020.101557
19. Molari, L., Coppolino, F. S., & Garcìa, J. J. (2021). Arundo donax: A widespread plant with great potential as sustainable structural material. *Construction and Building Materials, 268*(121143). doi:https://doi.org/10.1016/j.conbuildmat.2020.121143
20. Molari, L., Mentrasti, L., & Fabiani, M. (2020). Mechanical characterization of five species of Italian bamboo. *Structures*, 59-72. doi:https://doi.org/10.1016/j.istruc.2019.12.022
21. Parameswaran, & Liese. (1976). On the Fine Structure of Bamboo Fibres. *Wood Science and Technology, 10*, 231-246. doi:https://doi.org/10.1007/BF00350830
22. Rüggeberg, M., Burgert, I., & Speck, T. (2010). Structural and mechanical design of tissue interfaces in the giant reed Arundo donax. *Journal of the Royal Society Interface, 7*, 499–506. doi:http://doi.org/10.1098/rsif.2009.0273

23. Shao, Z.-P., Fang, C.-H., Huang, S.-X., & Tian, G.-L. (2010). Tensile properties of Moso bamboo (Phyllostachys pubescens) and its components with respect to its fiber-reinforced composite structure. *Wood Science and Technology, 44*, 655-666. doi:https://doi.org/10.1007/s00226-009-0290-1
24. Spatz, H.-C., Beismann, H., Bruchert, F., Emanns, A., & Speck, T. (1997). Biomechanics of the giant reed Arundo donax. *Philosophical Transactions of the Royal Society of London, 357*, 1-10. doi:doi: 10.1098/rstb.1997.0001
25. Trujillo, L. (2016). Bamboo material characterisation. In *Nonconventional and Vernacular Construction Materials* (pp. 365-392). Kent Harries; Bhavna Sharma.
26. Wahab, R., Mustafa, M. T., Rahman, S., Salam, M. A., Sulaiman, O., Sudin, M., & Rasat, M. S. (2012). Relationship between physical, anatomical and strength properties of 3-year-old cultivated tropical bamboo. *ARPN Journal of Agricultural and Biological Science, 7*(10), 782-791. doi:ISSN 1990-6145
27. Wang, F., Shao, Z., & Wu, Y. (2013). Mode II interlaminar fracture properties of Moso bamboo. *Composites Part B: Engineering, 44*(1), 242-247. doi:https://doi.org/10.1016/j.compositesb.2012.05.035.

Tables

Table 1
Mean value and standard deviation of diameter (D), thickness (δ) and density (ρ) of the culms used in this study.

		D [mm]		δ [mm]		ρ [kg m^3]	
		Mean	St.Dev	Mean	St.Dev	Mean	St.Dev
BAMBUSOIDES	A	58.06	3.25	4.70	0.55	875	6
	B	58.67	2.96	5.95	0.41	891	43
	AVG	58.36	2.98	5.33	0.80	883	29
EDULIS	A	62.42	3.88	5.81	0.59	918	67
	B	71.78	0.84	8.69	0.79	898	55
	AVG	67.10	5.57	7.25	1.65	908	56
IRIDESCENS	A	62.07	2.30	5.74	0.31	887	36
	B	61.73	3.18	7.83	1.10	832	29
	AVG	61.90	2.65	6.78	1.34	860	42
VIOLACESCENS	A	46.18	4.15	3.94	0.19	762	9
	B	56.08	3.31	5.11	0.33	724	52
	AVG	51.13	6.29	4.53	0.67	743	39
VIVAX	A	77.67	8.88	5.49	0.81	790	19
	B	81.19	6.70	7.10	0.44	751	22
	AVG	79.43	7.72	6.29	1.05	770	28
VIRIDIGLAUCESCENS	A	59.45	3.44	5.28	0.34	829	45
	B	64.48	6.68	7.14	1.11	798	56
	AVG	61.96	5.11	6.205	0.63	813	47
ARUNDO DONAX	A	10,27	0,05	1,50	0,07	653	0,06
	B	23,97	0,01	3.28	0.09	619	0,03

Tables 2 is available in the Supplementary Files section.

Table 3
Dimensions of an average vascular bundle from the inner, middle, and outer parts of the culm wall. W stands for the width (measured along the circumferential direction), H for the height (measured along the radial direction) of the vascular bundle, while A and B indicate the position along the culm.

.		INNER			MIDDLE			OUTER		
		W_{max} (mm)	H_{max} (mm)	W/H	W_{max} (mm)	H_{max} (mm)	W/H	W_{max} (mm)	H_{max} (mm)	W/H
Bambusoides	A	0,68	0,41	1,33	0,46	0,63	0,73	0,25	0,42	0,60
	B	0,72	0,48	1,76	0,49	0,58	0,86	0,25	0,49	0,51
Edulis	A	0,66	0,40	1,69	0,49	0,47	1,06	0,31	0,51	0,61
	B	0,72	0,45	1,60	0,59	0,57	1,03	0,35	0,49	0,71
Iridescens	A	0,42	0,36	1,25	0,37	0,41	0,90	0,24	0,40	0,60
	B	0,45	0,37	1,22	0,41	0,45	0,91	0,28	0,40	0,68
Violacescens	A	0,66	0,47	1,40	0,56	0,56	1,05	0,32	0,59	0,54
	B	0,75	0,51	1,47	0,58	0,65	0,86	0,40	0,66	0,61
Vivax	A	0,70	0,40	1,78	0,54	0,59	1,04	0,36	0,56	0,64
	B	0,75	0,44	1,57	0,60	0,72	0,77	0,34	0,49	0,69
Viridiglaucescens	A	0,76	0,50	1,52	0,58	0,61	0,95	0,34	0,60	0,57
	B	0,76	0,53	1,43	0,51	0,69	0,74	0,30	0,57	0,53
Arundo donax	A	0,27	0,30	0,90	0,24	0,19	1,26	0,19	0,15	1,27
	B	0,20	0,33	0,61	0,21	0,21	0,98	0,18	0,18	1,00

Table 4

Fibre morphology. Fibre diameters, lumen diameters, and wall thickness are here reported for parts A (2,5 to 3,5 m from the ground) and B (0.5 to 1,5 m from the ground) of all six bamboo species. The data refer to the average dimension of the fibres.

		INNER			OUTER		
		Fibre diameter (μm)	Lumen diameter (μm)	Wall thickness (μm)	Fibre diameter (μm)	Lumen diameter (μm)	Wall thickness (μm)
Bambusoides	A	18	4	7	20	4	8
	B	16	2,8	6,6	22	7	7,5
Edulis	A	14	2	6	17	3,5	6,75
	B	14	3	5,5	15	2	6,5
Violacescens	A	12	3	4,5	17	3,8	6,6
	B	13	4	4,5	15	3	6
Viridiglaucescens	A	15	3	6	21	4	8,5
	B	14	4	5	19	4	7,5
Iridescens	A	16	2	7	21	3	9
	B	18	6	6	17	2,5	7,25
Vivax	A	20	6	7	19	2	8,5
	B	13	2	5,5	21	5,8	7,6
Arundo Donax	A	14	2	6	16	1,5	6,5
	B	18	1	8,5	20	3	8,5

Tables 5 is available in the Supplementary Files section.

Table 6. Percentage of each bamboo component for each species analysed, from the part A and B of the culm

	PART A			PART B		
	Fibre (%)	Vessels (%)	Parenchyma (%)	Fibre (%)	Vessels (%)	Parenchyma (%)
BAMBUSOIDES	38,8	4,5	56,7	38,5	4,7	56,8
EDULIS	29,4	5,0	65,7	27,0	3,9	69,1
IRIDESCENS	37,6	6,9	55,5	31,2	5,0	63,8
VIOLACESCENS	27,9	5,8	66,2	26,3	6,5	67,2
VIVAX	38,8	6,1	55,1	33,3	4,7	62,0
VIRIDIGLAUCESCENS	33,3	4,6	62,1	38,1	4,9	57,0
ARUNDO DONAX	17,02	8,66	74,32	15,56	5,99	78,45

Table 7. Linear fittings of fibre distribution along the wall thickness, where x is the position measured from the inner wall

	Fibres along the thickness	
	A	B
BAMBUSOIDES	0.5721x+0.1013	0.6545x+0.05725
EDULIS	0.5915x-0.00282	0.556x-0.008175
IRIDESCENS	0.7012x+0.02478	0.622x+0.00038
VIRIDIGLAUCESCENS	0.6158x+0.02496	0.6694x+0.04612
VIOLACESCENS	0.5536x-0.001959	0.5626x-0.01867
VIVAX	0.541x+0.1167	0.6411x+0.01206

Table 8. Compared results from mechanical tests executed on *P. bambusoides, edulis, violacescens, viridiglaucescens, iridescens, vivax* and *A. donax*. Axial tension and compression results are from Molari et al. (2020), except for the *viridiglaucescens* species, which are from Greco et al. (2019). Circumferential bending values are from Molari & García (2021) calculated as the average of two different tests. Axial bending test values are from Greco & Molari (2022). Results for *A. donax* are from Molari et al. (2021).

Species		AXIAL TENSION		AXIAL COMPRESSION		CIRCUMFERENTIAL BENDING				AXIAL BENDING	
		σ_{max} (Mpa)	E_L (Gpa)	σ_{max} (Mpa)	E_L (Gpa)	$\sigma_{inner,MAX}$ (Mpa)	E_{inner} (Gpa)	$\sigma_{outer,MAX}$ (Mpa)	E_{outer} (Gpa)	$\sigma_{,MAX}$ (Mpa)	E_h (Gpa)
Bambusoides	A	234	21	82	21	13,3	1,3	30,6	3,5	147,5	20,25
	B	204	17	79	19	18,6	1,4	43	4,8		
Edulis	A	210,3	17	75,6	16,5	36,4	3,9	26,3	2,8	143,7	15,9
	B	188,4	14,2	61,8	12,9	35,2	3,5	24,4	2,5		
Violacescens	A	151	17,4	62,1	15,3	27,5	0,9	32,3	2,4	98,2	12,2
	B	138,2	19,1	56,8	15,9	16,3	1,2	23,8	1,7		
Viridiglaucescens	A	216,5	18,8	71,3	18,1	-				155,9	17,8
	B										
Iridescens	A	240,5	19,8	83,6	20,8	19,4	1,6	32,9	3,0	151	16,6
	B	220,7	16,2	76,6	21,1	16,9	1,4	31,8	3,6		
Vivax	A	193,8	16,6	65,2	18,3	28,2	1,1	31,7	1,7	159,6	17,8
	B	176,3	15,3	64,5	16,2	12,1	0,7	40,3	2,1		
Arundo Donax		111,7	15,2	57,0	13,4	-		17,8	1,5	74,4	10

Tables 9 is available in the Supplementary Files section.

Figures

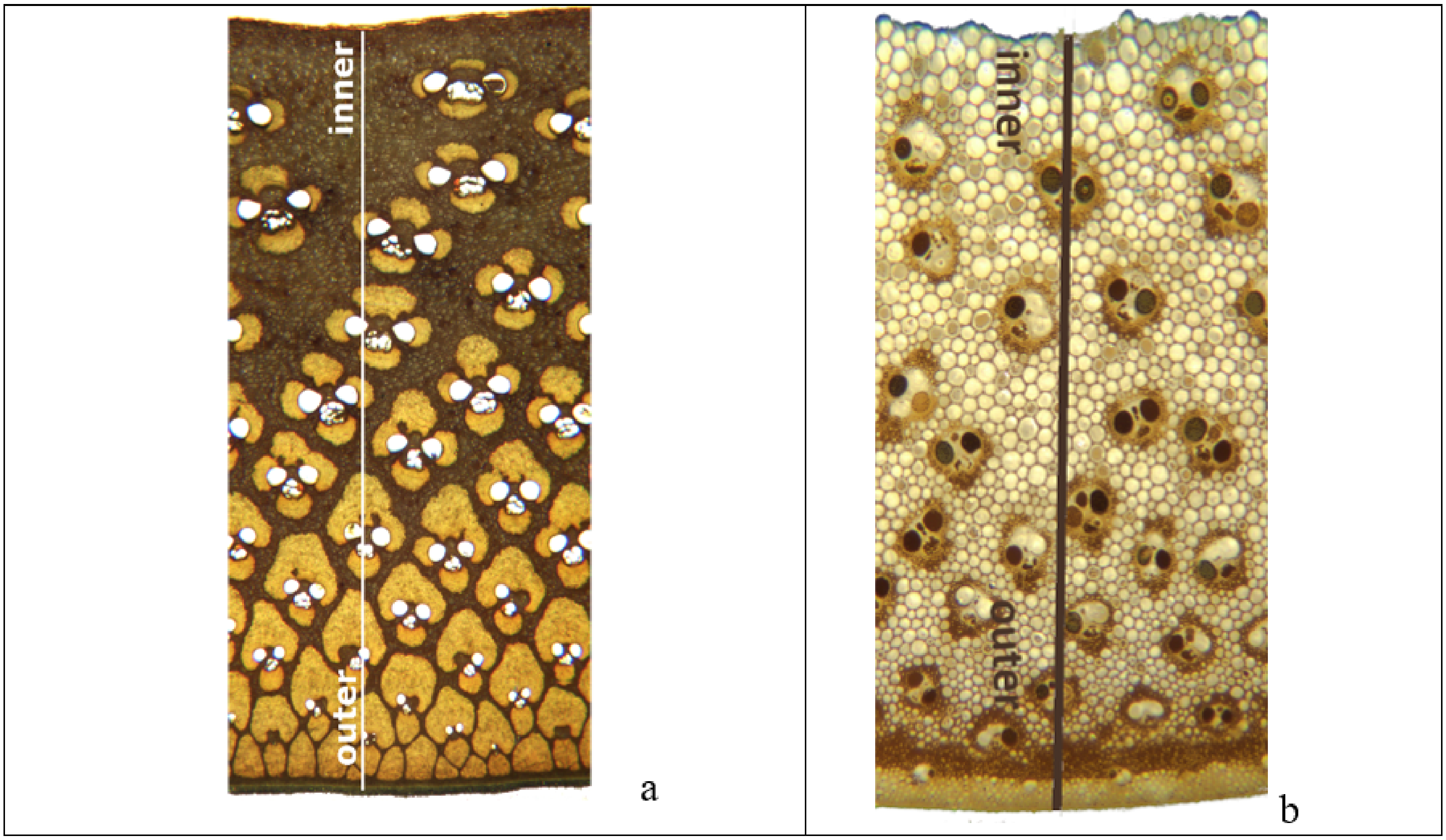

Figure 1

Cross-section of a culm wall of a *P. Iridescens* (a) and of an *Arundo Donax*(b), with the inner side on the top part of the pictures, and the external side on the bottom part of the pictures. Transmission optical microscope, enlargement 2.5x

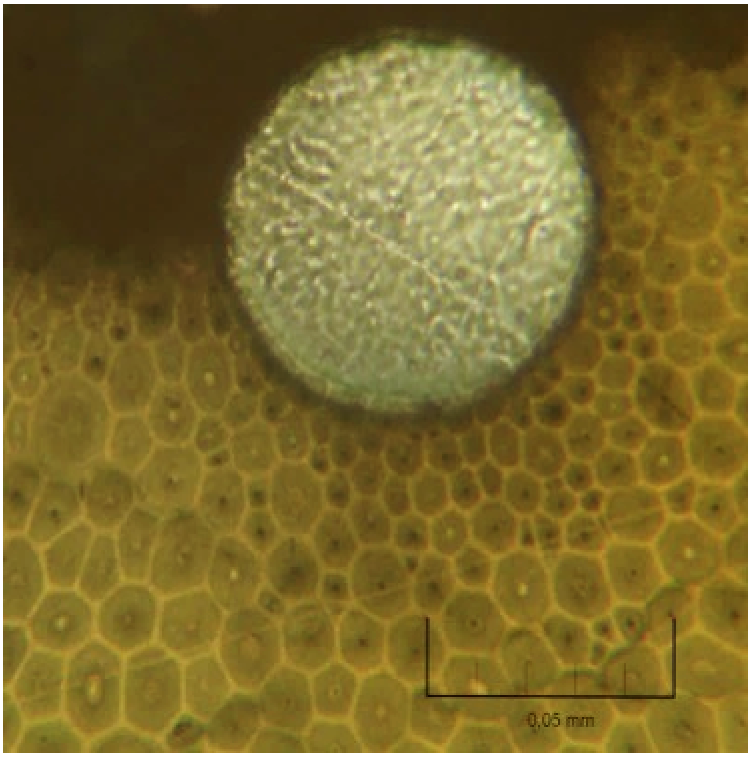

Figure 3

Progressive increase of fibre dimension from the vessel’s edge to the parenchymatic matrix. An image of a *P. edulis* from the upper part of the culm. Transmission optical microscope, 25X enlargement.

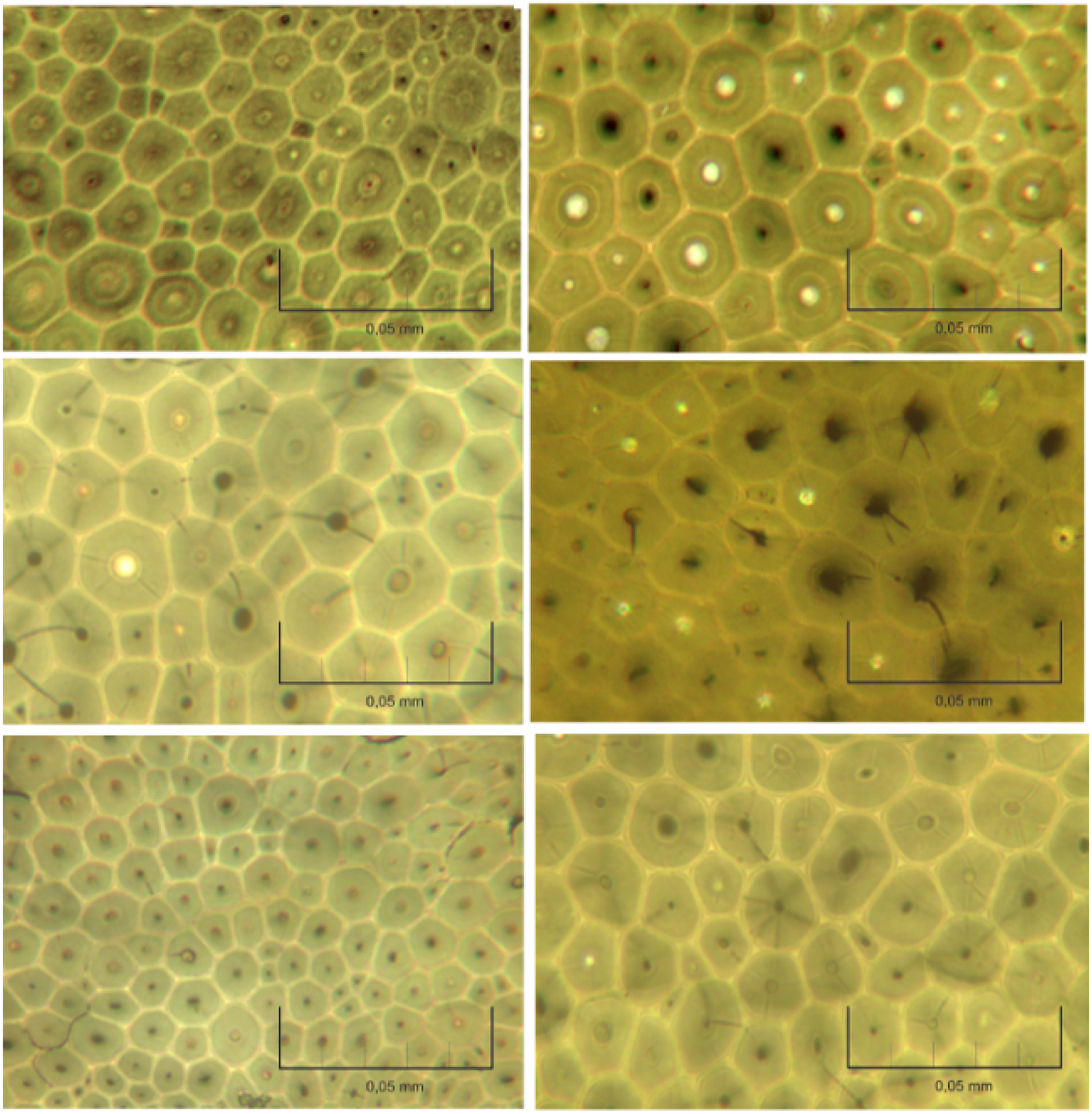

Figure 4

Sclerenchymatic tissue from the external side of the culm wall of P. a) *edulis*, b) *bambusoides*, c) *viridiglaucescens*, d) *vivax*, e) *violacescens*, f) *iridescens*. Transmission optical microscope, 25X enlargement.

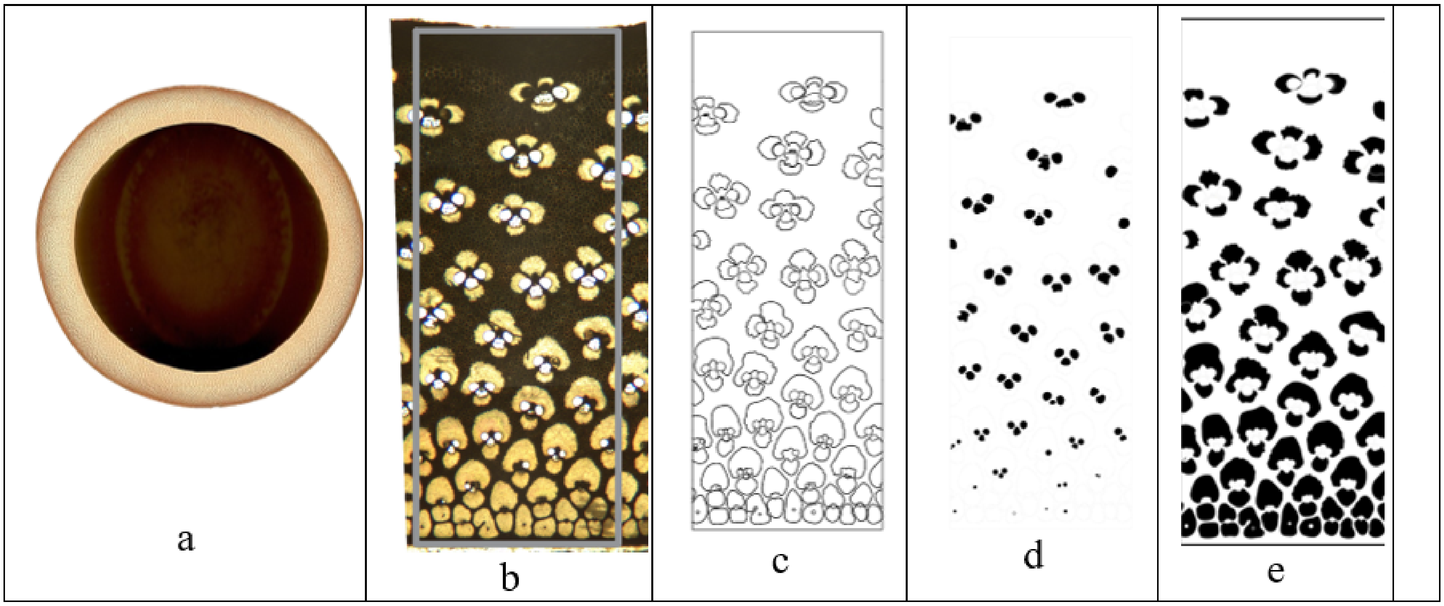

Figure 5

Image processing for *P. edulis* from the top part: the portion was selected from the culm section (a) and then an image was obtained with transmission microscope (b). A vectorial image (c) was then obteined with Autocad and divided into fibres component (d) and voids components (e) with the use of Gimp.

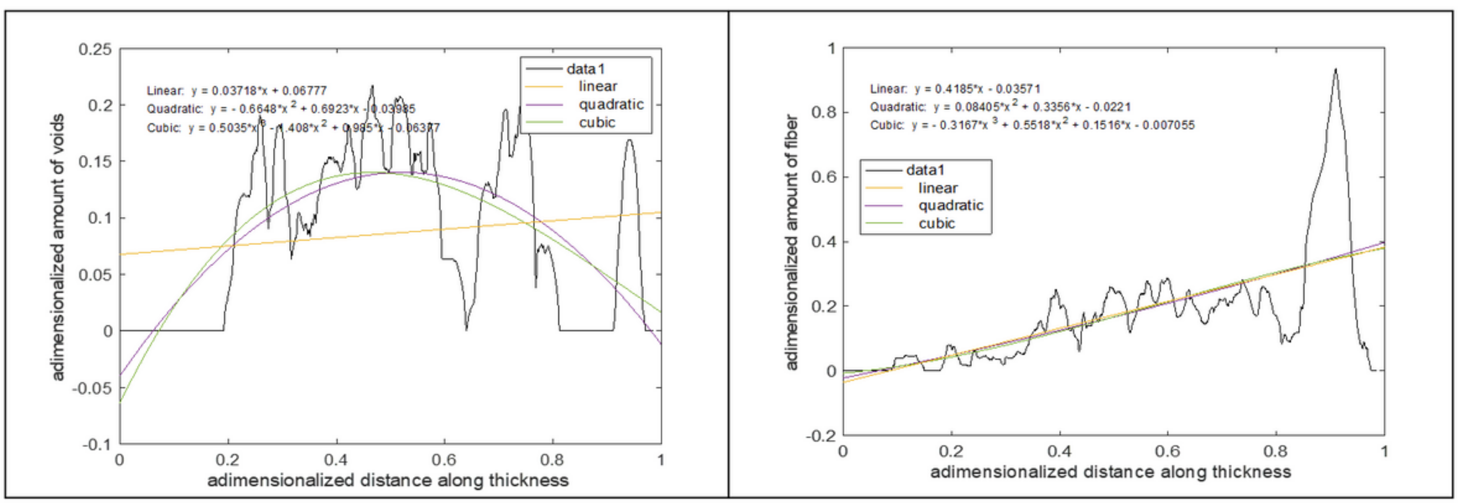

Figure 8

Distribution of voids (on the left) and fibre (on the right) along the thickness of the culm wall of *Arundo donax*, from the part A of the culm

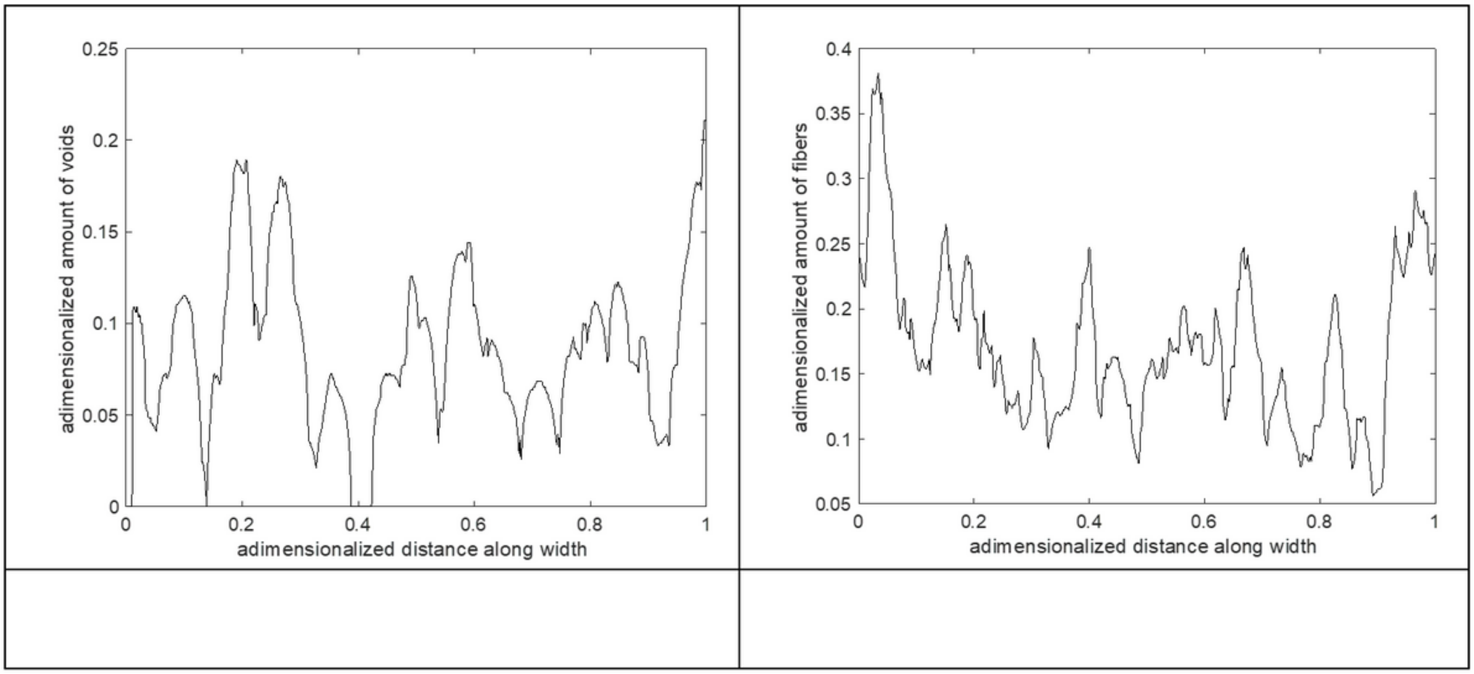

Figure 9

Distribution of voids (on the left) and fibre (on the right) along the width of the culm wall of *Arundo donax*, from the part A of the culm

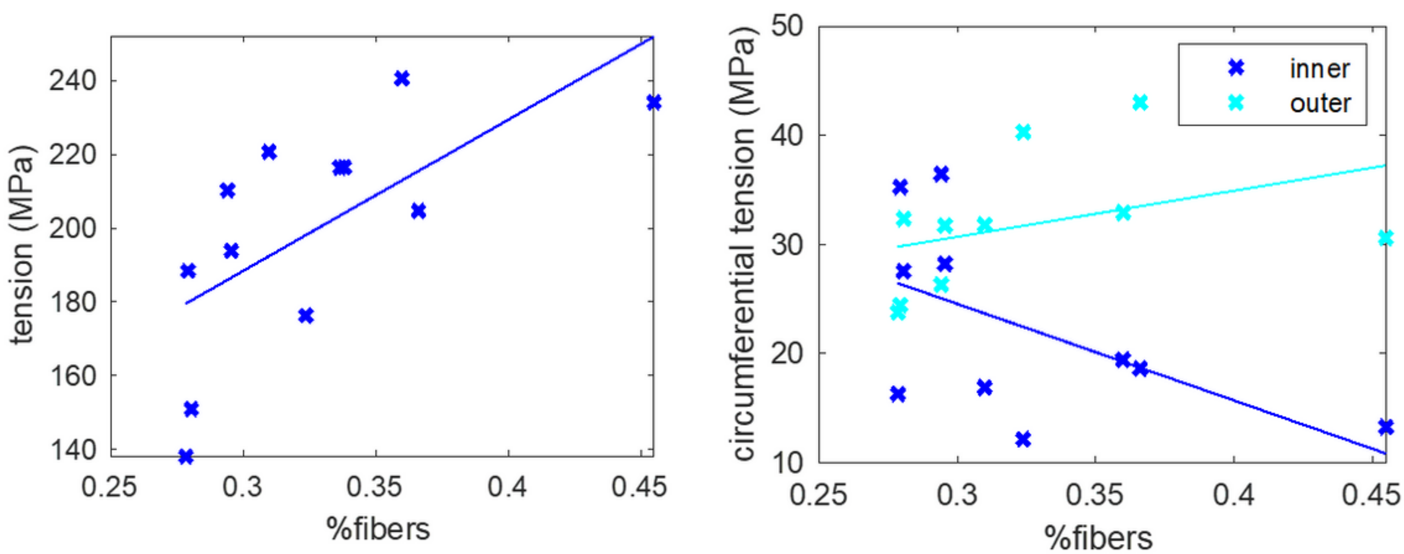

Figure 10

Strengthversus percentage of fibres

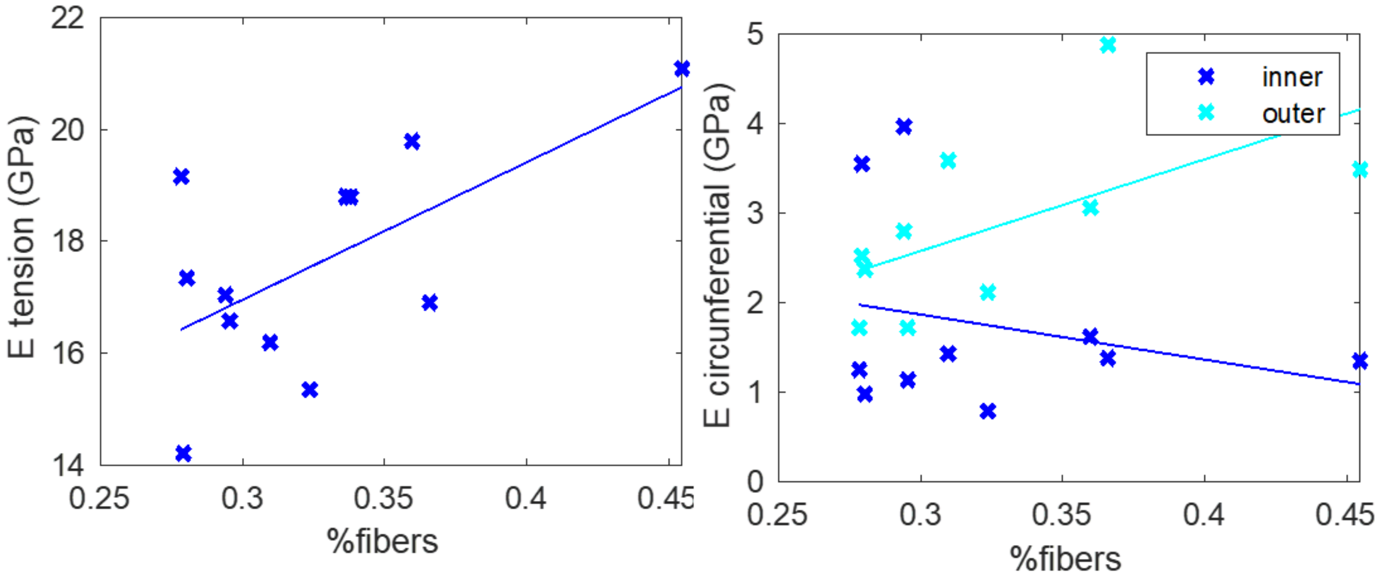

Figure 11

Young modulus versus percentage of fibres

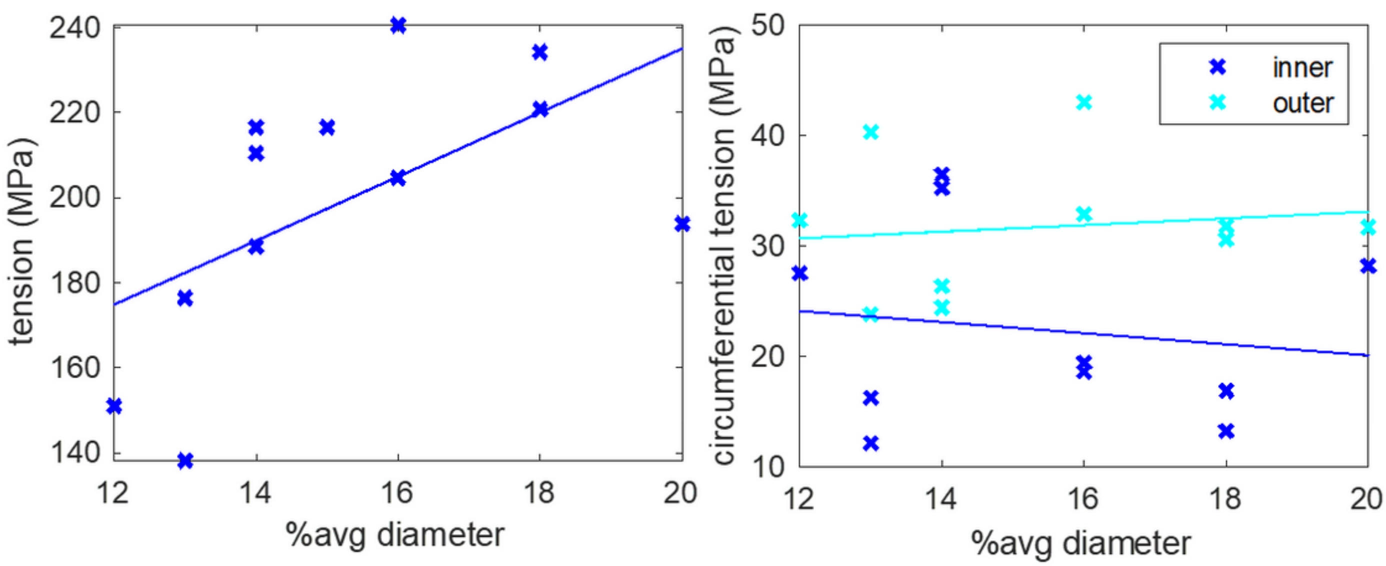

Figure 12

Strength versus fibre diameters

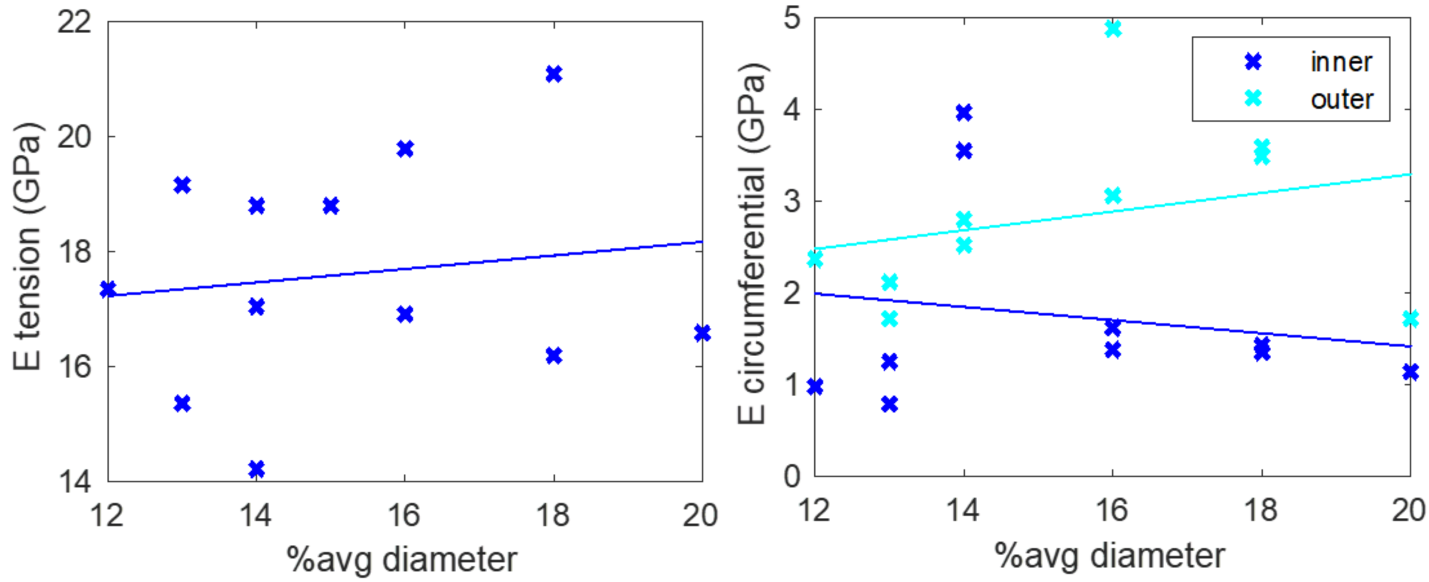

Figure 13

Young modulus versus the diameters of fibres

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table259.docx
- AppendixAB.docx