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The variable response to the environment of plant stems as an example of natural intelligence

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Abstract: The stem of dicotyledonous plants is constituted by three approximately concentric structures, named as epidermis (or periderm), phloem, and xylem from the outside to the inside. The combination of the three different materials corresponds to various characters, namely coating, hence offering resistance to shear forces, fibrosity, hence conferring capability to withstand tension and softness, hence able to resist impact i.e., localised compression. This can be intended as a designed structure with different functions, tailored according to the plant's requirements and also modified in presence of specific conditions of environmental stress. The plant species indicates in this way a proof of natural intelligence, which can be exploited as an inspiration for the solution of various problems. This approach has been suggested initially by the development of the "biomimetic stem", which comprised a number of features to be applied to design, such as non-circularity, presence of different scale porosities, and tube-like structure. However, this study is aimed at demonstrating that this inspiration can also be taken further down to the cell level, and can extend also to other fields than mechanics, such as hydraulics, while considering additionally the function of the inner part of the stem, hence of the xylem. This has been in most cases (such as for the "biomimetic stem") so far resolved just by leaving an internal cavity, so to improve the flexural loading of the structure.

Keywords: Biomimetic - Bioinspiration - Plant stem - Multifunctionality - Transfer to design

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Introduction

It has been long recognised that the base for survival in plants that are strong yet with a limited amount of external protection, or epidermis, which we recognise as a whole from the presence of "canes", and therefore share fast-growing characteristics, is based upon an effective management of their flexural oscillation damping (Spatz *et al.*, 2004). Further development led to studies on plant vibration at all scales and with different forms (shapes, stiffness, moisture-dependant behaviour) of mechanical constraints (De Langre 2019). Even more recently, it has been recognised that the interaction of the plants with the environment does also take an acoustic component (Appel and Cocroft 2023).
Delving into more details with the stem, according to the previous considerations, the objectives of an inspiration from the tripartite stem structure (periderm, phloem, and xylem) goes well beyond what has been investigated over time on the so-called "biomimetic stem" (Speck *et al.*, 2018). Also, the combined availability of data from novel investigation techniques (X-ray computed tomography) (Duplessis and Broekhoven 2019) and the possibility for additive manufacturing of more nature-like structures (Duplessis *et al.*, 2019) do suggest an integrated study of the stem finally as a composite rather than unitary structure. A first aspect is the optimization of the stem structure leading to adaptability with environmental changes (Crivellaro and Schweingruber 2015). However, this is also coupled with more deterministic considerations, which involve the "programmed death" of cells when they appear singularly to have achieved their role and are ready to provide mechanical support with no longer hydraulic action, as sclerenchyma (Schweingruber and Börner 2018).
One of the obvious limits of the simplified structure, as proposed above, is its static behaviour, which does not imply the simulation of any form of movement, as instead proposed from nastic plants (Stahlberg and Taya 2005). In this sense, it does not appear far from reality to try to model a plant stem as a morphing yet confined structure, also for its essential character of being required to change shape over loading yet limiting the geometrical variations to the inside (Vasista and Tong 2012). In a sense, this is what also justifies the presence of three drastically different materials across its section. It is suggested that a

designed structure needs to comprise the three types of character solidly bonded among them, while additionally conferring some capability to adapt to their mutual presence. Engineering use tended to separate the three functions in order to exploit one of them regardless to the other. Most often the choice privileged the intermediate layer, normally referred to as bast, from which the so-called lignocellulosic fibres are extracted (Santulli 2008).
Basically, the three parts do constitute an ensemble formed by an outer protection, a fibrous intermediate layer and a porous core (Baley *et al*., 2018). This can be of inspiration whenever a composite structure is to be applied, which is intended to work under flexural loads (Masselter *et al*., 2012). It is noteworthy that the global design of the stem can also lead to a non-circular section, even approaching a quadrangular one, such as in the case e.g., of the *Perilla* (beefsteak plant), where in this way an increased flexural stiffness is achieved (Kurashiki *et al*., 2004). Deviations from circularity have been widely investigated as a natural expedient in order to vary the relation between the height and the volume of the tree to improve the function of its stem to required environmental characteristics (Pulkkinen 2012). This extends the field of bio-inspiration from stem's structure, which has been usually limited to the most obvious examples, such as bamboo, where circularity is obvious, nodes tend to be rather equidistant and vascular tissue is regular, which indicates a plant designed for an exposure to not very variable winds and predictable environmental actions. This does not require the three different tissues to be easily discernible, as depicted in Figure 1 (Wang and Shao 2020). For these reasons, bamboo has been excluded from our reasoning, trying to elucidate a richer and possibly more subliminal investigation of what a bio-inspired process might imply in this case, leading to clarify how natural intelligence acts in its design.

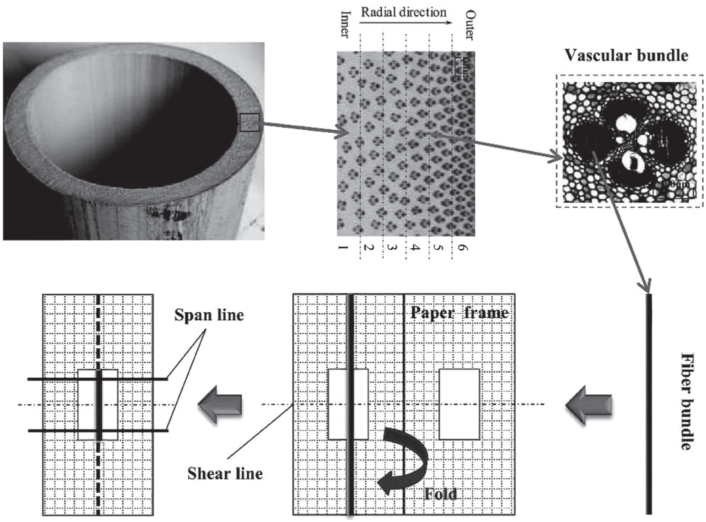

Figure 1. Schematic of samples generally taken from the stem of a Bamboo plant.

Natural design can play differently with the three parts in order to better manage the balance between the three functions, protection (epidermis), tension (phloem), and compression/impact (xylem) in the design structure. Going beyond the mechanical aspect, xylem has not only a passive action given by already dead tissue, yet also an active one. This offered by the living one (parenchyma), which allows the distribution of the hydraulic fluids across the plant and at the same time does enable the recovery from a significant water stress, with its rather spongy structure (Secchi *et al.*, 2017). This has been particularly studied lately, leading to the conclusion of the relation between the dimensions of vessels and the external packing of a higher fraction of axial parenchyma tissue (Slupianek *et al.*, 2021). It is furthermore suggested elsewhere that in case of scarcity of water and nutrients plants are able to optimize the conductivity characteristics required from the xylem living cells (Franklin *et al.*, 2022). In structural terms, an outstanding resistance to impact was observed in the case of cornstalk where a particularly extended medullary foam core formed the xylem structure (Siddique *et al.*, 2023). This possibility to rearrange as most suitable to the species' needs with the structure of the three parts and their relevant functions is one of the countless demonstrations of plants' intelligence. As suggested by Trewavas 2005, the intelligent behavior "arises as a property of the whole integrated cell and tissue system", therefore its organization at full development responds to specific exigencies of the species.

Examples of tripartite arrangements in various species and case studies

Periderm, phloem and xylem have been recognized from long time as mutually enhancing sub-structures, which serve to each other to complete the lignocellulosic complex. The periderm is strictly speaking the frontier of the plant towards the environment (biotic and abiotic stress) and is intended as being responsive to it only limitedly, rather exerting a protection function, while delegating to the more internal parts the adjustment of life-enhancing parameters for the plant (Campilho *et al.*, 2020). However, the strategy applied by the periderm is also different from the one operating in different tissues, as it is based on self-repair rather than on distribution of primary and secondary cells and of living and sclerenchyma material (Serra *et al.*, 2022).

In this sense, the design approach is aimed at offering distinct value to each of the three parts, mimicking their characteristics into various functions. This is clearly different from what is suggested into chemical and engineering practices, which explore various approaches, yet hardly even valuing the differences among these. In practice, the principal routes appear to be: a. The digestion of the whole lignocellulosic complex as a source of fine chemicals, in which case the mechanical structure is at all led to exhaustion (Scelsi *et al.*, 2021); b. The separation of the two larger value components, namely the structural polysaccharidic one (cellulose) and the alcoholic one (lignin), leading possibly to the production of biopolymers (Banu *et al.*, 2019); c. The extraction of the nanocrystalline cellulose content, via disassembly of the hierarchical lignocellulosic building (Bünder *et al.*, 2021). All of these approaches have different merits and are currently practiced to different extents and success, despite their relatively low production yield. Their principal drawbacks are nonetheless that they annihilate the natural intelligence in the process of stem building via the different components, and they do not account for inter-species differences, which also contribute to a substantial understanding of the concepts through which nature operates for structural design. However, deepening our knowledge about the functional characteristics of different species in the same "task" to be accomplished would definitely optimize the application of biomimetic approaches in field such as design and architecture. For example, it was proven that a careful selection of the species would increase and differentiate the absorption of volatile organic compounds (VOC) in "green walls" for buildings (Irqa *et al*., 2019).

However, some more refined data on the whole stem structure and potential are gradually obtained e.g., availability of database of microscopic tissue information did allow comparative studies down to the cell's level, as for example in Singhakaew *et al*., 2023. Microscopic observations do provide unfortunately only a static observation of the plant behavior, mostly through samples extracted post-mortem, not offering information about micro-movements that are recognized by the natural structure to be allowed (Perricone *et al*., 2022). These do typically respond to some specific exigencies, most frequently nutrition, and that do not appear externally, therefore not modifying the perception of the plant as a sessile organism (Charpentier *et al*., 2017).

Some plants are here proposed in more detail, as concerns their tripartite structure, whose variation indicates the presence of intelligence in them in relating with the context they are likely to thrive in. They have been selected for their larger availability, especially in the so-called "green waste", which makes their investigation and proposition as models for phyto-mimicking into various design applications also desirable in terms of circular economy. It is no surprise that more literature is available on these plants' structure. They are all cane-based stems, where the extent of the epidermis is limited, though effective for protection. In particular, the four plants selected for study are: sunflower (*Helianthus annuus*), river cane (*Arundo donax*), sugar cane (*Saccharum officinarum*), and hemp (*Cannabis sativa*).

Sunflower has been one of the first plants investigated for their morphological irregularities, which in reality represent a suitable adaptation to the environment for the plant. This obviously started from the sun tracking troping abilities of the flower, which is not disconnected, or else enhanced, from the structure of its stem with a significant development of its xylem (Atamian *et al*., 2016). An early study by Thoday (1922) suggested already the cumbersome and unusual presence of irregularities in its stem structure, which was not immediately correlated to any need for adaptation to the environment. This irregularity was following this explained in a more detailed way by comprising a number of different components variously arranged among them. More specifically, sunflower stem rind included other than phloem and xylem fibers, vessel elements, various parenchyma cells in different locations, including ground, axial, xylem ray, and pith ray (Wang *et al*., 2021). In other terms, and also for the sake of educational botanical studies, it is indicated as sunflower comprises all possible types of tissues, namely periderm, parenchyma, collenchyma, phloem (fiber and primary) xylem (primary and secondary), and vascular cambium (Yeung 1998). It is very likely that tropism and relation with the environment led this plant

to develop that wealth of different botanical tissues. This led to suggesting the application of sunflower, together with water lilies (Nymphaeaceae), to the development to more efficient photovoltaic panels (Regassa *et al.*, 2023). However, simplification is likely to be needed to lead to possible use of concepts elicited from this complex structure. As a matter of fact, the whole of the stem structure for the sunflower is usually defined as constituted by an external bark and an internal pith, corresponding to the xylem (possibly suggesting that the limited phloem extension does suggest its negligibility). From hygro-mechanical evaluation of the stem, some evidences were obtained: while, the bark was stiffer than the pith, the former showed a lower moisture diffusion than the latter. More refined study was needed nonetheless, due to the large variation of mechanical and hygroscopic properties of plant tissue depending on their location along the stem (Sun *et al.*, 2013).
In the case of the giant reed (*Arundo donax*) it can be noticed as the level of lignification of the xylem parenchyma is designed to offer different stiffness by an order of magnitude between the longitudinal and the tangential direction. The variability of properties among the node and the internode zones was distinctly revealed and measured in Molari *et al.*, 2021, by also introducing C-shaped samples characterization to have a closer approach to the real conditions in which the biological structure is working. This is intended to promote plant growth and development. Moreover, a reinforcement able to offer sufficient resistance to the plant in the exposure to heavy winds is also offered via the presence of vascular bundles, which are considerably sclerenchymatized (Spatz *et al.*, 1997). Such as in the case of sunflower, where the contamination with cadmium creates a sub-periderm layer (Lux *et al.*, 2011), for giant reed a soil polluted with presence of cadmium, arsenic and lead evident tissue changes are revealed (Guo *et al.*, 2010): in both cases, these suggest the possible strategies for phytoremediation of soils.
In sugar cane (*Saccharum officinalis*), early studies clarified the presence under the epidermis of the two structures easily separated, which are usually defined as the rind and the core. The former is constituted by vascular bundles of various sizes, embedded in a parenchymatous matrix with various levels of lignification, whereas the latter, which is particularly intended for crushing resistance, has been always researched as to have storage cells as large as possible with very thin walls (Khanna and Sharma 1949). The reason for this is that for sugar cane, the interest is mainly concentrated on the xylem (core) and more specifically on the sap that can be extracted from it. It is suggested that the amount of nitrogen and potassium do lead to modifications of the xylem structure, since in sugar cane the materials are recycled between the phloem and the xylem (Subasinghe 2008). Structures such as sugarcane xylem do particularly indicate having a notable concave polygonal cellular (mainly re-entrant) geometry, which implies the possible presence of auxetic (negative Poisson's ratio) behavior (Haas *et al.*, 2022). Externally the distance between the nodes (internode) appears as an essential element for design in view of the fact that flexural and shear stress need to be tailored as opposite characteristics according to the moisture content present in the plant (Abdelhady *et al.*, 2023).
In hemp (*Cannabis sativa*), different characteristics can be explored, and the microfibrillar angle assumes much larger importance in this case, as a regulating factor for the flexure/shear resistance ratio, offering the distinct advantage to adapt the plant also to torsion via microfibrils mutual rubbing (Le Duigou *et al.*, 2017). Though a quite complex tripartite

structure is observed also in the case of hemp, cellulose does appear to be concentrated in secondary phloem fibers (Blake *et al*., 2008). As the consequence, in practice, most studies concerned phloem fibers from hemp and their extraction (Manaia *et al*., 2019) or the study of the epidermal cane, normally fragmented as "shives", which have increasing success in the construction industry also for thermal energy accumulator (Nowakowski-Pałka & Roman 2023). In contrast, studies on hemp xylem as a compressible and resistant structure are very limited (Khan *et al*., 2010), though recognizing that it takes most of the hydraulic conduction and has particular conditions of variability under water stress (Yuksel *et al*., 2023).

Design applications

The biomimetic stem and beyond, going into the species observation of the relevant design features of the three parts, can be applied whenever in design an elongated, therefore tensioned, structure needs at the same time to be externally protected and internally resistant to impact or compression. In addition, the node-enhanced structure would provide in the majority of cases hindrance to the propagation of cracks, which are deviated across the stem, and consequently a very high toughness, which justifies further the biomimetic interest (Knippers and Speck, 2012). The flexible relation of the periderm with the other parts of the plant is very appropriate to serve as an adaptive architectural envelope, of which some examples are offered in *Figure 2* (Lopez *et al*., 2017). Though these examples are definitely of interest, bio-inspiration from stem structure would allow adapting these characteristics to a scale more relevant for industrial design. The problem of scale transfer has been recognised to be essential for the possible success of the bio-inspiration process (Perricone *et al*., 2021). The relationship between the three parts of the stem does appear particularly inspiring when, as in examples shown above, they result as a whole in biological structures of comparable dimensions. However, the internal arrangement, starting from relative extensions of the different tissues and porosity, may considerably vary, according to the specific purposes, first and foremost the adaptation to the actual environment in which the plants are supposed to thrive. The relation structure-environment does not appear obvious and easy to be modelled in the case of the stem though, most studies being still centred on the potential offered by the wood material, such as measuring growth rings (Schweingruber *et al*., 2007). Considerations taken from the origin and climate of the plants can be considered though, according to situations such as those suggested in *Figure 3*.

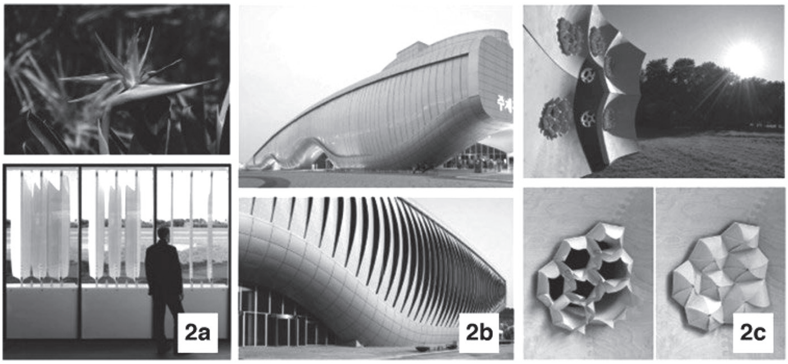

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Figure 2. Some biomimetic projects for adaptive architectural envelopes: (a) Flectofin® (b) One Ocean Thematic Pavilion (c) HygroSkin (Lopez *et al.*, 2017). **Figure 3.** Some ecosystems typical for various climatic zones (Sandak & Butina Ogorelek 2023). Another aspect that was recently emphasized in the case of the design of coniferous is their ability to self-centre their bending displacement, which is the result of the internal presence of softer materials, therefore avoiding buckling with respect to reinforced concrete columns (Toader *et al.*, 2024).

The cases for these structures can concern design of products for interior application, such as lamps or pieces of furniture. More recently, it is also suggested that the responsivity of plant structures to light, moisture, and heat might constitute a possibility of applying phyto-mimetics, which is here referred to the possibility to take inspiration from plants beyond shape morphing, as from Bar-Cohen 2006. The development of 4D printing materials offered more possibilities to this, in that one physical parameter can be introduced to vary independently from plant geometry. This is in principle based on discrete shapes of thin plates and shells, yet can in future take any form, adapting especially to natural achievements in the design of plant structures (Kanu *et al.*, 2019). Studying the different shapes of cells, such as tracheid in xylem as multifunctional structures can lead through additive manufacturing to the closer reproduction of their features then functions dynamic biological envelopes for any design purpose (Xing *et al.*, 2018).

Yet, they can also be applied to some specific items, such as benches for exterior applications, which constitute paradigmatically an example for the combination of the three functions of the biomimetic stem outwards to inwards, protection, tension, and impact/compression. Natural fibre composites prove particularly suitable for this kind of proofs of concepts, such as demonstrated by the FlexFlax stool (Costalonga Martins *et al.*, 2020) *(See Figure 4)*. The fulfilment of these three needs can be rearranged across the seat through the use e.g., of additive manufacturing into offering other properties, not directly connected to mechanical performance. This has been e.g., recently proven by the design of a biomimetic stool where the optimization of natural fibre structure has been combined with inspiration from flea exoskeleton, as for protection (Rihaczek *et al.*, 2020) adding foldability. This characteristic is, other than animals, such as flea, typical of structures such as leaves, once again with patterns specific of the single plant (Yasuda *et al.*, 2022), yet another element of their intelligence as adaptation to specific life conditions. While origami still serves as a useful metaphor for folding, its development along the thickness with elements with different hydromechanical characteristics would result in an improved yield for renewable energy accumulation, such as for solar one (Johnson *et al.*, 2023).

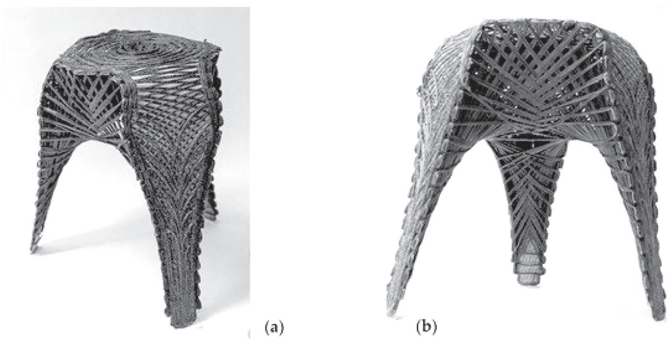

Figure 4.
Two different views of the FlexFlax stool (Costalonga Martins *et al.*, 2020).

In this work, synergic arrangements of the three parts are reported in different dicotyledonous plants to try to elucidate what is the prevalent role attributed to it and to suggest comparisons with possible design structures. With the assistance of microscopic observations, it will be possible to clarify the sense of a possible inspirational parallel of the plant stem with typical situations and issues encountered in design practice. The combination of the three mechanical functions can in fact being added with other possible skills of the plant, such as self-repair, stress sensing and variable relation with water (Santulli 2021). Also, the morphological characteristics of the stem can also be applied to enhance just one

function of it, namely protection, tension and impact/compression. The desired function can be therefore extrapolated from the stem to concentrate on it. This would be e.g., the case for example when using bioluminescent fungi already exploited for lighting devices (biomimetic lamp) (Provost *et al*., 2020), yet inserting it in an easily compressible yet resistant foam, designed according to a species, used as biomass for mycelial development. It is suggested that the imitation refers as an active learning process, where the natural intelligence process is elicited and applied to the solution of different, yet paralleled, issues (La Shun 2017).
Another possibility did concern the application of bark features for plant protection to the design of adaptive structural skins, able to go beyond shielding, also providing the required amount of heat and transpiration to the internal compartment, as suggested by Loonen 2014. The characteristics of tree bark have also been exploited by proposing a biomimetic building skin, in trying to go beyond the use of it simply as a biological paradigm, instead directly applying some of the bark's features to building design, one of the essential ones being breathing characteristics (Yowell 2011). One of the possible routes towards that can be defined as an explicit one, by developing bark-inspired materials (Durai Prabhakaran *et al*. 2019), which can enter the very wide field of phytomimetics, where the skin would be able to look like the aspect one of the countless plants that have been investigated for the purpose. However, most examples of phytomimetics relations can be considered implicit, such as it has been cited two junction systems, namely barbed wire and extendable cables, which are respectively perceived as copies of thorny branches of the Osage orange *Maclura pomifera* and tendrils of climbing passion flower (*Passiflora incarnata*) plants *(See Figure 5)*.

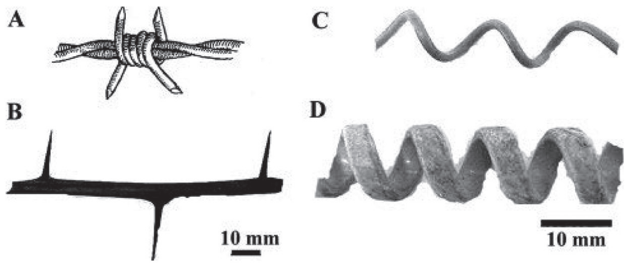

Figure 5. Different examples of early phytomimetic structures from obvious plant patterns: (A) Barbed wire as inspired to (B) thorny branches; (C) Extendable cables as inspired to (D) tendrils (Stahlberg 2009).

Considering the possibility to enhance the material by removing it from bare static appreciation, moisture-sensitive structures have also been studied, such as the variable helical morphing of Pelargonium seed awns (Ha *et al*., 2018). This has brought, always by the accurate balance of the tripartite structure, to a dehydration induced curling, such as with resurrection plant *Selaginella lepidophylla* (Rafsanjani *et al*., 2015).
In that respect, also colour nuances of the different epidermises would also be interpreted, other than with the usual relation with animal camouflage (Clegg 2023), also in terms of energy absorption/release for structures such as furniture. This specific relation based on colour can also be specifically designed and biomimicked by the use of adapted and tailored filaments for fused deposition mode (FDM) 4D printing (Wang *et al*., 2019) with colour changing, as in some plants, according to sunlight and moisture conditions (Baar *et al*., 2019).

Conclusions

The different articulation of the triparted structure, which constitutes dicotyledonous plant stems, namely represented by the triad periderm-phloem-xylem, does constitute one of the examples of natural intelligence. The design of this structure is connected with the various exigencies of the species, namely the relation between mechanical loading from the environment, the hydraulic flux through the stem and the presence of tropism, which might require effective and reversible rotation of the structure. The research so far has concentrated nonetheless especially on the separation of the structure into its three conceptual components, which also conceals the complexity resulting from the presence of further tissues with specific functions. This appears rather ineffective for a possible bio-inspiration, which should depart from the considerations of the different parts and on the balance among them in the plant.
This could be achieved by disposing of more comparative studies among the tripartite arrangement of different plants, of comparable dimensions. This should neglect a simple shape morphing, rather concentrating on the various physical properties that are tailored by a judicious balance of the relevant weight, extension and structure down to the cell level of periderm, phloem and xylem.

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Resumen: El tallo de las plantas dicotiledóneas está constituido por tres estructuras aproximadamente concéntricas, denominadas epidermis (o peridermo), floema y xilema de afuera hacia adentro. La combinación de los tres materiales diferentes corresponde a varias características, a saber, recubrimiento, que ofrece por lo tanto resistencia a las fuerzas de cizallamiento, fibrosidad, que confiere por lo tanto capacidad para soportar la tensión y suavidad, y por lo tanto es capaz de resistir el impacto, es decir, la compresión localizada. Esto puede concebirse como una estructura diseñada con diferentes funciones, adaptada a los requisitos de la planta y también modificada en presencia de condiciones específicas de estrés ambiental. La especie vegetal indica de esta manera una prueba de inteligencia natural, que puede aprovecharse como inspiración para la solución de diversos problemas. Este enfoque fue sugerido inicialmente por el desarrollo del "vástago biomimético", que comprendía una serie de características que se aplicarían al diseño, como la no circularidad, la presencia de porosidades de diferentes escalas y una estructura en forma de tubo. Sin embargo, este estudio tiene como objetivo demostrar que esta inspiración también puede llevarse más abajo al nivel celular, y puede extenderse también a otros campos además de la mecánica, como la hidráulica, considerando además la función de la parte interna del vástago, por lo tanto del xilema. En la mayoría de los casos (como en el caso del "vástago biomimético"), hasta ahora esto se ha resuelto simplemente dejando una cavidad interna, para mejorar la carga de flexión de la estructura.

Palabras clave: Biomimético - Bioinspiración - Tallo vegetal - Multifuncionalidad - Transferencia al diseño

Resumo: O caule das plantas dicotiledôneas é constituído por três estruturas aproximadamente concêntricas, denominadas epiderme (ou periderme), floema e xilema de fora para dentro. A combinação dos três materiais diferentes corresponde a várias características, nomeadamente revestimento, oferecendo assim resistência a forças de cisalhamento, fibrosidade, conferindo assim capacidade de suportar tensão e suavidade, portanto capaz de resistir ao impacto, isto é, compressão localizada. Esta pode ser entendida como uma estrutura projetada com diferentes funções, adaptada de acordo com as necessidades da planta e também modificada na presença de condições específicas de estresse ambiental. A espécie vegetal indica desta forma uma prova de inteligência natural, que pode ser explorada como inspiração para a solução de diversos problemas. Essa abordagem foi sugerida inicialmente pelo desenvolvimento da "haste biomimética", que compreendia uma série de características a serem aplicadas ao design, como não circularidade, presença de diferentes porosidades em escala e estrutura semelhante a um tubo. No entanto, este estudo pretende demonstrar que esta inspiração também pode ser levada mais abaixo ao nível celular, e pode estender-se também a outros campos além da mecânica, como a hidráulica, ao mesmo tempo que considera adicionalmente a função da parte interna da haste, portanto do xilema. Isto tem sido na maioria dos casos (como para a "haste biomimética") até agora resolvido apenas deixando uma cavidade interna, para melhorar a carga de flexão da estrutura.

Palavras-chave: Biomimética - Bioinspiração - Caule vegetal - Multifuncionalidade - Transferência para o design