THE ADAPTIVE DESIGN OF HERBACEOUS PLANTS – INSPIRATION FOR BIOMIMETIC SOLUTIONS

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Abstract

In the course of 3.8 billion years plants have evolved the amazing capacity to deal with changing environmental conditions (e.g. water availability) and/or disturbances (e.g. injuries). Adaptive design in herbaceous plants is the result of significant changes of e.g. mechanical properties and / or geometric configuration on several time scales.
Adaptive stiffness of petioles of *Caladium bicolor* 'Candyland' show distinctive dependencies on water-availability. The decrease in petiole's flexural rigidity during wilting results from (1) a water-loss-induced decrease in mechanical efficiency of the collenchyma fibres, and (2) a turgor loss of the parenchyma cells.
Comparative studies on artificially injured plant organs show a huge variety of different self-sealing and self-healing mechanisms. Besides specific wound reactions, they have three traits in common: (1) wound reactions are highly dependent on the type of incision (longitudinal or transversal along the plant organ), (2) damaged fibres themselves cannot be healed, and (3) local reinforcement during self-repair takes place in fibres and parenchyma (e.g. lignification).

1. Introduction

During evolution living beings have evolved structures and mechanisms, ensuring their survival according to markedly different selective pressures. Especially for immobile plants, which cannot quickly escape from unfavourable environmental conditions and cannot rapidly hide themselves behind protective structures, adaptivity plays a major role. Adaptive design of plants means the capability of dealing with changing environmental conditions (e.g. water availability) or disturbances (e.g. injuries) by a significant change of one or more features (e.g. mechanical properties, geometric configuration, internal structure) on several time scales [1,2]. Herbaceous plants are characterized by non-woody stems above ground. From a material scientist's point of view herbaceous plant organs are built up of fibre-reinforced composites which consist of unlignified (collenchyma) or lignified fibres

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(sclerenchyma) and vascular bundles embedded in a matrix of lignified or unlignified parenchyma. The adaptive turgor-dependent mechanical and self-sealing functional designs of herbaceous plant organs are based on the interaction of different tissues and their varying mechanical properties. In this context, plant's amazing self-X-properties (e.g. wound sealing and adaptive stiffness) have to be mentioned as an important source of inspiration for biomimetic self-X materials and structures. Prerequisites for a successful development of biomimetic materials are quantitative analyzes of the biological concept generators and an abstraction process including the development of analytical, numerical or hands-on-models [3,4].

2. Materials and Methods

2.1 Water-dependent adaptive stiffness

Adaptive mechanical behaviour of petioles of *Caladium bicolor* (AITON) VENT. 'Candyland' (Araceae) have been investigated by using two point bending tests for calculating the bending elastic modulus taking into account the tapering mode, and using the pressure probe technique for determining the corresponding turgor of parenchyma cells. In addition, thin sections of fully turgescent petioles, and handcut sections of wilting and wilted petioles were analyzed after staining with Fuchsin Chrysoidine Astra Blue (FCA). [5,6]

2.2 Wound-reaction in succulent plants

Comparative studies of wound reaction were carried out on plants with succulent cylindrical plant organs: *Rhipsalis baccifera* ssp. *mauritiana* (DC.) BARTHLOTT (Cacatceae), *Sansevieria cylindrica* BOJER EX. HOOK. (Asparagaceae) and *Euphorbia tirucalli* L. (Euphorbiaceae). After artificial damages in longitudinal and transveral direction, the wound regions were observed for a period of 21 days by hand cuts of fresh plant material – on a daily basis for the first 3 days and later each second or third day – in order to characterize and to analyze the structural changes occurring during the self-repair processes. Thin sections were stained with the overview staining Fuchsin Chrysoidine Astra Blue (FCA) and a special staining for lignified tissues (Acridine Orange). Alcian Blue Staining was used for localization of the mucilage cells and discharged plant mucilage. [7]

2.2 Wound-reaction in fiber plants

Two cultivars of *Linum usitatissimum* L. ('Eden' with stems resistant to lodging and 'Drakkar' with more flexible stems) belonging to the Linaceae family were injured along the stem in longitudinal and in transversal direction. After 25-day recovery the wound healing efficiency was analyzed in terms of morphological, anatomical and mechanical responses. Thin sections of intact and wounded stems were stained with Acridine Orange highlighting lignified tissues in bright yellow. Viscoelastic tests of injured plant stems and control plant stems were performed with Dynamic Mechanical Analysis (DMA) tension tests with strain sweep up to 0.1 % at 1 Hz (25-28 °C). [8,9]

3. Results

3.1 Water-dependent adaptive stiffness

Collenchyma fibres and parenchymatous cells of watered petioles are fully turgescent. Collenchym fibres of wilting and wilted petioles clearly show deformation by shrinking, whereas deformation of parenchymatous cells was solely found in already wilted petioles. The elastic bending modulus is highly significant higher for turgescent petioles (283.34 ± 50.74 MPa) than for wilting petioles (163.00 ± 56.92 MPa). The turgor of parenchyma cells of well-watered petioles ranges between 0.38 MPa abs.

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and 0.51 MPa abs., whereas the turgor of drought-stressed petioles ranges between 0.24 MPa abs. and 0.54 MPa abs. Comparing turgescent and wilting petioles in the overlapping turgor range of 0.38 to 0.51 MPa abs. also highly significant differences of bending elastic modulus could be found comparing well-watered and drought-stressed petioles. This result indicates, that in addition to the turgor of parenchyma cells a second water-sensitive systems must be present, which was identified as the water-dependent mechanical efficiency of collenchyma fibres. [5]

3.2 Wound-reaction in succulent plants

Various rapid self-sealing and subsequent self-healing mechanisms could be observed in all investigated plant species: (1) a rolling in and / or overlapping of the wound edges comprised of cuticula, epidermis and underlying tissues, (2) the formation of a boundary layer of lipophilic substances (lignin, suberin, cutin), and (3) the development of a wound periderm. In addition (4) *Rhipsalis baccifera* ssp. *mauritiana* showed discharge of mucilage, and (5) in *Euphorbia tirucalli* (Fig. 1) discharge and coagulation of latex could be found. [4]

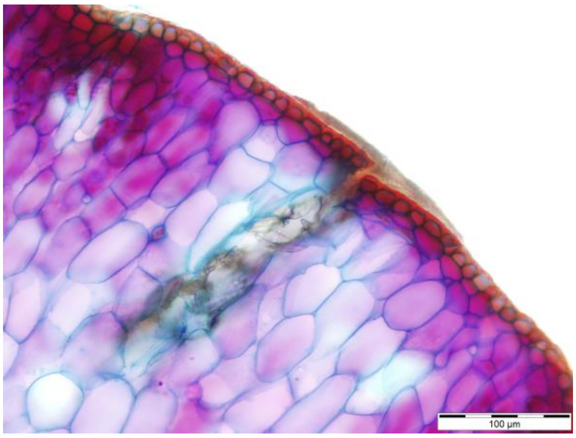

Figure 1. Cross-section of a *Euphorbia tirucalli* stem stained with FCA. The damage in longitudinal direction is rapidly sealed by the discharge and coagulation of latex (light grayish substance in the injury and at the wound surface).

3.2 Wound-reaction in fiber plants

Linum usitatissimum ‘Eden’ and ‘Drakkar’ did not fully recovery in terms of anatomical and mechanical wound healing. Longitudinal and transversal injuries caused a local lignification of the sclerenchyma bundles in the wound region. Wounding perpendicular to the fibres resulted in a marked growth of different stem tissues closing the wound completely. In the case of fibre-parallel damage a local reinforcement without wound closure results [7]. Both *Linum* cultivars showed 25 days after injury a marked recovery of viscoelastic properties with higher scores for healing after transversal damage [9].

4. Conclusions

Besides detailed new quantitative insight in fundamental processes of adaptive designs in herbaceous plants, these studies on adaptive stiffness and self-repair provide a valuable source of bio-inspiration for the transfer into innovative biomimetic materials. The development of ‘living’ materials, which are responsive, adaptive, programmable and self-healing, may contribute to solve future challenges in technology and architecture.

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