

FRUIT WALLS AND NUT SHELLS AS AN INSPIRATION FOR THE DESIGN OF BIO-INSPIRED IMPACT-RESISTANT HIERARCHICALLY STRUCTURED MATERIALS

R. SEIDEL¹, M. THIELEN¹, C. SCHMITT¹, A. BÜHRIG-POLACZEK², C. FLECK³ & T. SPECK^{1,4}

¹Plant Biomechanics Group Freiburg, Botanic Garden, Faculty of Biology, University of Freiburg, Germany.

²Foundry-Institute of the RWTH Aachen, Germany.

³Materials Engineering, Berlin Institute of Technology, Germany.

⁴Competence Networks Biomimetics and BIODON, Germany.

ABSTRACT

Until today the structuring of different types of fruit walls has been used only as an inspiration for packaging when seen from a biomimetic perspective. However, by a detailed investigation of the *Macadamia* nut with its tough testa, *Citrus maxima*, possessing a large spongy mesocarp and *Cocos nucifera*, having a combination of a fibrous mesocarp and a tough endocarp, it becomes evident that those structures also provide excellent biological role models for impact- and puncture-resistant materials. Both *Citrus maxima* and *Cocos nucifera* are relatively heavy, lack any aerodynamic adaptation and share the same challenge of having to withstand the impact from heights of >10 m. Conducting high-speed camera-controlled free fall experiments of *Citrus maxima* from 6 m height, we could demonstrate a deceleration of the fruits of 3100 m/s², which corresponds to 316 g, without any visible damage of the fruit. An analysis using cyclic quasi-static compression tests of the pericarp of *Citrus maxima* revealed that the material behaves constant in good approximation after the first loading cycle. During the first cycle, almost 75% of the energy is dissipated. The pericarp of *Citrus maxima* is highly visco-elastic, which causes the samples within 1 min to recover 30% of their initial deformation caused by loading to 40% strain. The mesocarp of *Citrus maxima* is best described as an open-pore foam with a gradual increase in the pore size. Understanding the principles of as to how combining the structure and material in biological constructions yields a fully functional protection layer will allow us to construct new lightweight bio-inspired materials of high impact and puncture resistance with a combination of high energy dissipation, benign failure and almost complete recovery from large deformations.

Keywords: Biomimetics, *Citrus maxima*, *Cocos nucifera*, energy dissipation, gradual open-pore foam, *Macadamia sp.*

1 INTRODUCTION

The fruit wall, the pericarp, is composed of three layers in all angiosperms. The outermost layer is formed by the exocarp, followed by the mesocarp and the innermost layer named endocarp. The pericarp of nuts dehydrates completely and forms a highly lignified, mechanically very stable compact shell. In the case of drupes, only the endocarp lignifies and thereby forms a tough protective layer surrounding the seed. The tough outer layer of the *Macadamia* presents a special case. The *Macadamia* ‘nut’ does not belong to nuts from a botanical point of view as the tough shell is the testa, the seed coat, and not the pericarp. However, the testa of *Macadamia sp.* is also highly lignified and presents a perfect example for a puncture-resistant material [1]. It is made up of two distinct layers where the outer, thicker portion is a very hard sclerenchymatous tissue consisting of fibres and stone cells [1]. Jennings and MacMillan [2] and Wang and Mai [3, 4] analysed the biomechanical properties of *Macadamia* nuts (*Macadamia sp.*) and came to the conclusion that the structure of the testa ought to be highly optimised for toughness. Compared with ceramic and glass, the testa even outperforms these technical materials if the low density of the *Macadamia* is taken into account. The research on nuts include *Balanites aegyptiaca* [5], *Pistacia vera* [6] and roasted shells of cashew nuts, *Anacardium occidentale* [7], although the focus of these papers is mainly on the relationship between the state of hydration and mechanical behaviour in regards to processing in food industries. Mainly compression

tests were performed and the orientation of the tested nuts was varied to find the lowest energy necessary to crack the shell, which is best achieved at higher velocities (500 mm/min).

The coconut, *Cocos nucifera*, is well known for the potential of its drupes to withstand long exposure to salt water. The drupes are reported to be able to germinate even after a journey of more than 4500 km in salt water [8]. The fibrous mesocarp of the drupe has mainly been analysed in its dry state for its mechanical properties, as coir fibres are used in carpets, ropes [9], and cushions and seat covers in the automotive industry [10]. The Young's modulus of single dried fibre bundles lies in the range of 3–6 GPa, and the strains lies in the range of 15–47% when tested in tension [10, 11]. The importance of the entire hydrated mesocarp as a potential material to withstand impact has so far not been addressed, although it is known that the coconut palm reaches up to 30 m [7], which equals a potential energy of a 5 kg fruit of almost 1.5 kJ. Of the genus *Citrus* only, oranges and grapefruits have been studied mechanically to some extent. Fluck and Ahmed [12] examined the degree of internal damage as inflicted on the fruits by single and repeated dropping from various heights of up to 1 m. Conducting a compression test later revealed whether a fruit had experienced impact before. Underhill *et al.* [13] analysed the dynamic and static compressive behaviour of 'Eureka' lemons. Their morphological analyses showed that the albedo is compacted during dynamic testing and ruptures during static testing. In the first report Seidel *et al.* [14] analysed the mechanical properties of *Citrus maxima*. According to their study, the fruits can withstand free falls from up to 15 m onto wet grass without major damage. Free fall experiments onto a polymethylmethacrylate plate from 6 m yielded impact durations from ~7 ms, forces of 1 kN and a total dissipation of 90% of the initial potential energy. Their morphological analysis indicated a gradual increase in intercellular space from the exocarp to the endocarp, although the anatomy was examined with only a stereo microscope.

In summary, it may be said that research on fruit walls so far has mostly focused on the mechanical properties important to the food and fibre industries and little has been done on the form–structure–function–relationship, which has been hardly studied at all in *Citrus maxima*, and only to some extent in *Cocos nucifera* and *Macadamia* sp. although all of these fruit walls reveal quite extraordinary mechanical properties. Further, no related studies on impact and energy dissipation during impact, which will be mostly achieved by the deformation of the mesocarp structure in drupes and *Citrus*, are available.

As shown in Fig. 1 the hierarchically organised fruit walls of our role models compose either (Ia) a highly damping spongy gradient structure (*Citrus maxima*), (Ib) a combination of a fibrous damping structure with a tough shell (*Cocos nucifera*) or (Ic) an entire tough shell (*Macadamia* sp.). These structural elements will be transferred into hierarchically organised technical materials (II) consisting of a solid layer in combination with a spongy fibre-reinforced structure ensuring high toughness and high energy dissipation. The following sections of this paper will focus on our results as to functional morphological and biomechanics of *Citrus maxima*.

2 MATERIALS AND METHODS

2.1 Dynamic testing

To analyse the potential of the whole *Citrus maxima* fruit to absorb energy during impact, free fall experiments were conducted. Single fruits were dropped from 6 m onto a polymethylmethacrylate plate, which was allowed to rotate on one side and was freely positioned on a force sensor on the opposite side (Fig. 2, left-hand side). The fruits' impact behaviour was filmed using two high-speed cameras capturing at 240 and 1000 frames per second, respectively. The analysis of the frames from the side view camera allowed an estimation of the deceleration of the fruit at impact.

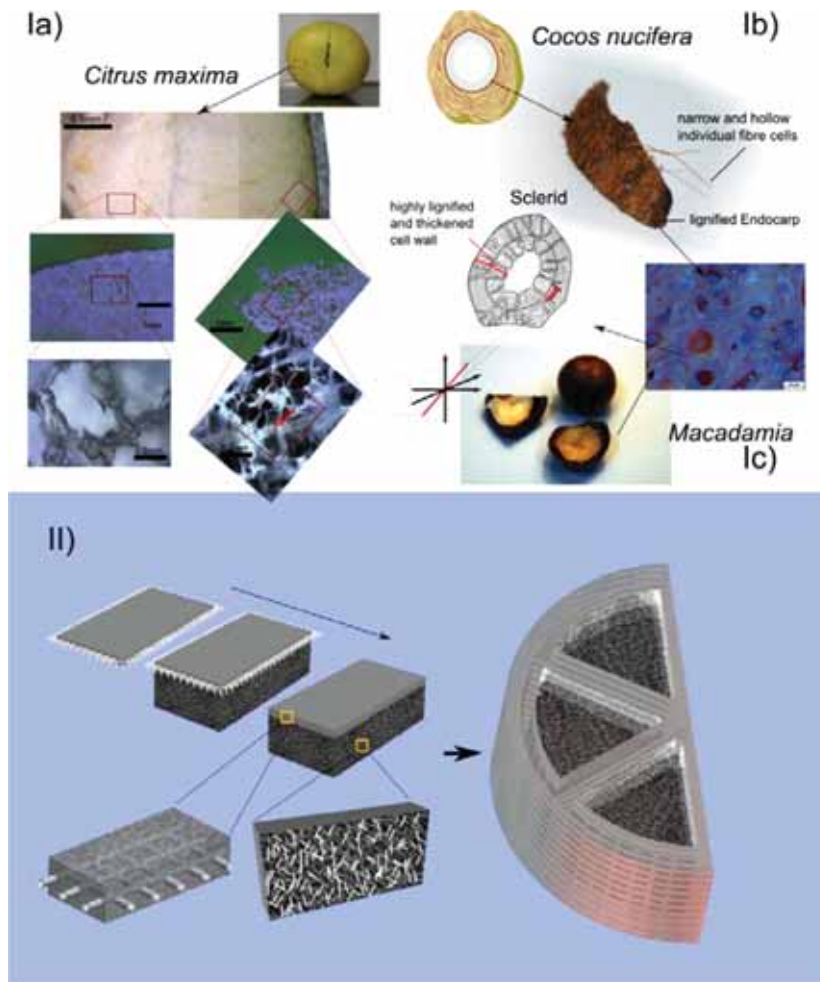


Figure 1: The biological role models and technical implementation.

2.2 Static testing

The samples of the pericarp of *Citrus maxima* were cut with a cylindrical cork knife and tested in compression using an Instron testing machine (at a testing speed of 5 mm/min). All the samples were cut along the radial axes of the fruit. To examine the energy absorption and the potential to absorb energy in consecutive cycles, four compression cycles to 40, 40, 40 and 75% compression, respectively, were conducted. Between the cycles the sample was allowed to relax for 60 s.

2.3 Morphology

The pericarp of *Citrus maxima* was cut into semi-thin sections of ~2 mm thickness each at different positions on the fruit. The sections were immediately analysed using advanced light microscopy to

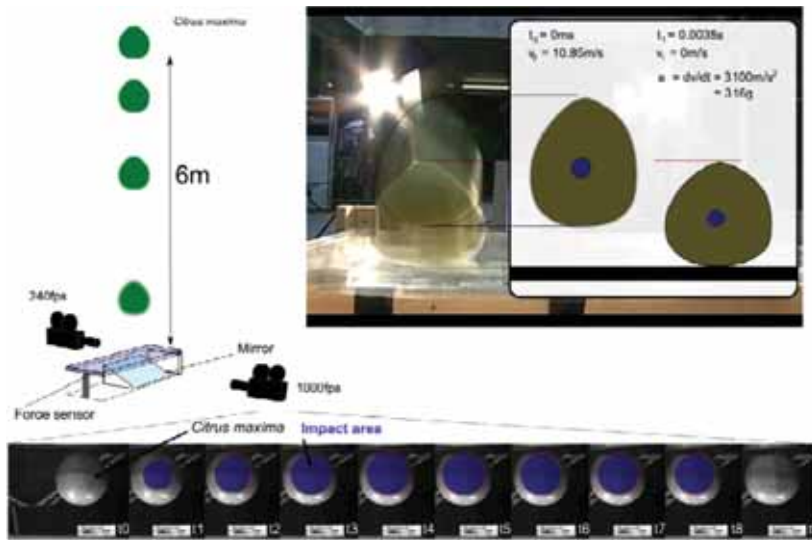


Figure 2: The free fall experiment of *Citrus maxima*.

prevent any artefacts due to dehydration of the tissue. A second set of sections was embedded in a PEG 2000, water solution (1/1) and left for 4 days at 55°C for the water to evaporate. The sections were then cut with a freezing microtome to 10 μm thick subsections and stained with Toluidin blue (Fig. 3). To analyse the distribution of the cell wall, cell lumen and intercellular space, the slice was photographed and the digital image processed with GIMP (version 2.6) to separate the materials and set to a single colour value, blue, green red, respectively.

3 RESULTS AND DISCUSSION

To estimate the deceleration of the whole fruit during impact, the side view camera of the free fall experiments presented by Seidel *et al.* [14] were analysed frame by frame. The capture rate of the camera with 240 fps was too slow to yield sharp images of the fruit at each time-point; although due to the blurred position an estimate was possible about the action within each frame of 3.5 ms time duration when approximating the time for the shutter to open and close with ~ 0.66 ms. Figure 2 presents the case of the fruit immediately before impact and during impact just before initiating the bouncing off the plate again. The initial speed equals the full conversion of potential energy into kinetic energy and calculates to 10.85 m/s. Before it bounces off, the speed will be 0 m/s. The division of the change in speed by the time duration of the frame yields a deceleration of 3100 m/s^2 , which corresponds to 316 g. Multiplication of this by an average fruit weight of ~ 1.5 kg results in forces of ~ 4.6 kN acting on the fruit. The calculated forces are ~ 4.5 times higher than those reported [14], which is most likely due to the sample rate of the force sensor in combination with the amplifier used in their setup. As at the beginning of the 3.5 ms of the frame duration the fruit is not in contact with the plate, the time duration of the impact may be even lower, resulting in higher decelerations. Seidel *et al.* [14] reported the impact durations of the same setup as 7.2 ms. Assuming that this time is split evenly between deceleration and acceleration results in 3.6 ms per event, which is very close to the approximated 3.5 ms in the calculation presented above.

Consecutive static compression tests of the pericarp of *Citrus maxima* to 40% compression confirmed a loss of maximum 75% energy within one hysteretic cycle [14]. Further from the second

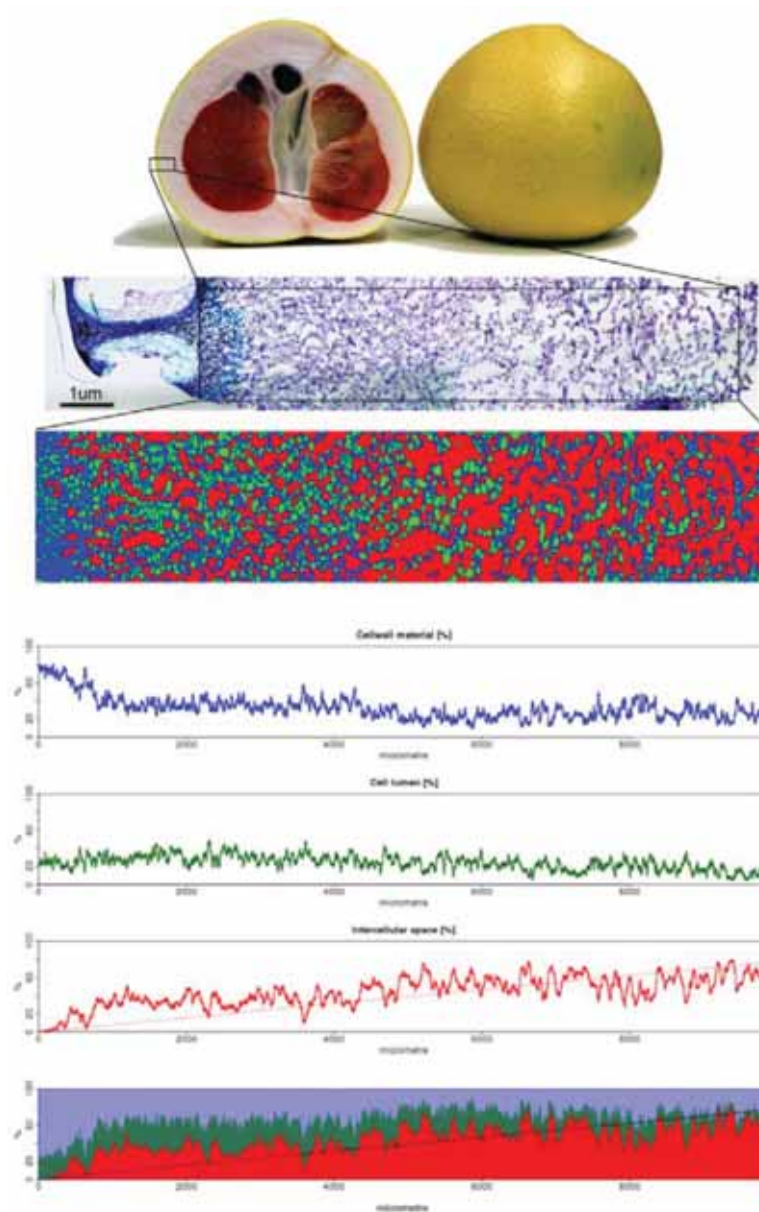


Figure 3: The analysis of the distribution of a material within the fruit wall of *Citrus maxima*.

cycle onwards, the material behaviour remains in good approximation constant as shown in Fig. 4 (upper diagram). As there was a 1 min pause between the cycles, one can distinguish at least partly between the plastic and visco-elastic deformation. During this minute, the material recovers its shape from circa 22% compression, the compression at which the unloading curve yields 0 force, to about 15% compression, the compression at which the force rises above zero in the next loading

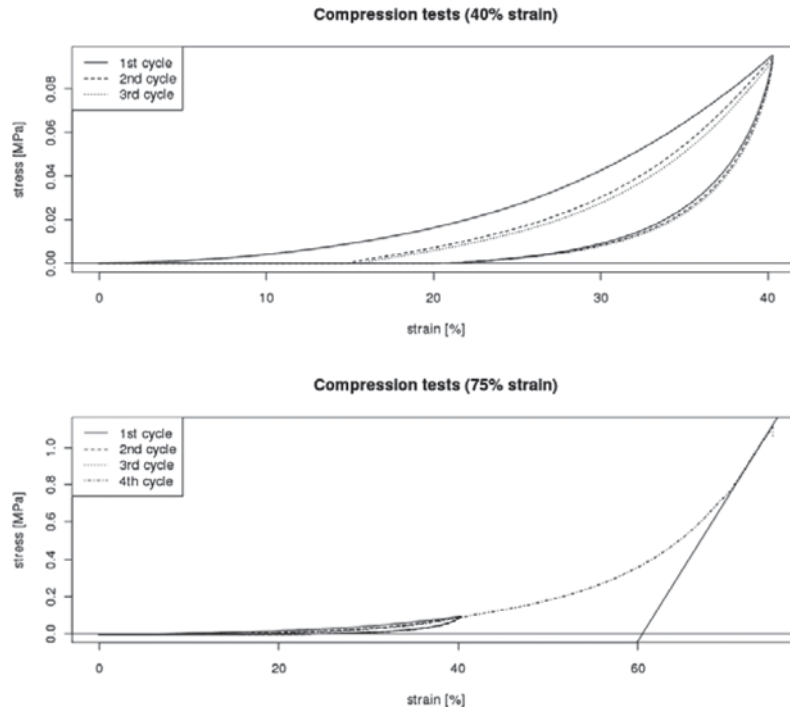


Figure 4: The static compression tests of *Citrus maxima*.

curve. These 7% gain in shape can be fully accounted to the visco-elastic properties of the material. In the final compressive loading, the material is loaded beyond the onset strain of material densification. The onset strain of densification is approximately at the strain where the tangent to the compression curve intersects the abscissa (Fig. 4, lower diagram). In the case of *Citrus maxima*, the onset strain of densification varies between 55 and 65% strain.

As reported by Seidel *et al.* [14] the fruit wall of *Citrus maxima* comprises three distinguishable parts, the exocarp containing multiple compact layers of cells, the mesocarp, showing a spongy appearance, and the endocarp consisting of a small dense layer adjacent to the pulp. The analysis of thin sections allowed to quantify the material distribution of the cell wall material, cell lumen, and intercellular space. The two lower graphs in Fig. 3 show a continuous increase in the intercellular space from the innermost part of the exocarp towards the middle of the mesocarp. This is in accordance with the reported reduction in cell density and the beginning of cavity formation composing a three-dimensional porous spongy tissue [14]. The cell wall material continuously decreases from 80 to 40% contribution to the cross-sectional area within the first millimeter, which presents the overlap between exo- and mesocarp. It remains at 40% contribution to the cross-sectional area until ~4 mm before it starts to oscillate between 25 and 35% area fraction. The lumen almost constantly varies between 15 and 30% contribution to the cross-sectional area but decreases from the eighth millimeter onwards to <20%. The most prominent result of this analysis is the proof of the predicted increase in intercellular space [14]. Within the first 300 μm of within the exocarp, no intercellular space is found; thereafter its contribution to the cross-sectional area rises quickly and reaches 30% at the first millimeter. Later, the portion of the intercellular space remains rather constant until ~4 millimeter before it rises again to values up to 80% area fraction.

The most important features of *Cocos nucifera* with regard to its potential as a biological role model for an impact and puncture-resistant bio-inspired material are, from a morphological point of view, the sandwich structure of a high energy absorption layer, its mesocarp, and a tough puncture-resistant layer, its highly lignified endocarp. The fibres and fibre bundles embedded in the mesocarp show benign failure only at 30–40% strain [14], which is a very desirable property for a technical material. As reported by Wang and Mai [4] the *Macadamia* testa is highly optimised for toughness. The properties very similar to those of the *Macadamia* can be predicted for the tough endocarp of the coconut as well, as it has a very similar structure being composed of a very similar type of highly lignified cells.

Combining these extraordinary protective properties of high- energy dissipation, benign failure behaviour and almost full recovery from large deformations as it is seen in *Citrus maxima* after the first loading cycle will lead to new bio-inspired lightweight technical materials. A bio-inspired sandwich material consisting of a high energy absorption outer layer in combination with a very tough puncture-resistant inner layer is one of our first objectives. *Cocos nucifera* is often regarded as one of the best natural role models for man-made impact-resistant structures as the fruits have to withstand impacts from more than 25 m. Although as impressively shown by *Citrus maxima*, multiple pathways can be used to achieve high energy dissipation. In their hierarchical structures, biological materials make use of cellular foams, spongy structures, laminates, fibres and various combinations of these structures on different structural levels. Investment casting allows one to model open-pore sponge structures, as well as the integration of fibres. The transfer of the properties of the biological, organic materials into technical materials such as metallic cast alloy and fibre-reinforced composite materials with a matrix made of metal, glass, ceramics or various polymers will be one of the major challenges in the technical transfer.

Potential applications for biomimetic impact-resistant fibre-reinforced foams are vessels for transportation of dangerous goods, e.g. explosives or hydrofluoric acid, helmets and other protection wear, impact protection of vehicles and space station protection against meteoroid impact.

ACKNOWLEDGEMENTS

The authors would like to thank the German Research Foundation for the funding of this project as part of the Priority Program 1420 “Biomimetic Materials Research: Functionality by Hierarchical Structuring of Materials” (SP 534/10-1).

REFERENCES

- [1] Hartung, M.E. & Storey, W.B., The development of the fruit of *Macadamia ternifolia*. *Journal of Agricultural Research*, **59**, pp. 397–406, 1939.
- [2] Jennings, J.S. & Macmillan, N.H., A tough nut to crack. *Annals of Botany*, **46**, pp. 313–321, 1980.
- [3] Wang, C. & Mai, Y., Deformation and fracture of Macadamia nuts part 2: microstructure and fracture mechanics analysis of nutshell. *International Journal of Fracture*, **69**, pp. 67–85, 1995. doi: <http://dx.doi.org/10.1007/BF00032189>
- [4] Wang, C. & Mai, Y., Deformation and fracture of Macadamia nuts part 1: deformation analysis of nut-in-shell. *International Journal of Fracture*, **69**, pp. 51–65, 1995. doi: <http://dx.doi.org/10.1007/BF00032188>
- [5] Mamman, E., Umar, B. & Aviara, N., Effect of moisture content and loading orientation on the mechanical properties of *Balanites Aegyptiaca* nuts. *Agricultural Engineering International*, The CIGR Ejournal 7, Manuscript FP 04 015, 2005.

- [6] Ozden, K. & Alayunt, F., The determination of some physical properties of *Pistachio vera* L. *Pakistan Journal of Biological Sciences*, **9**(14), pp. 2612–2617, 2006. doi: <http://dx.doi.org/10.3923/pjbs.2006.2612.2617>
- [7] Oloso, A. O. & Clarke, B., Some aspects of strength properties of Cashew nuts. *Journal of Agricultural Engineering Research*, **55**, pp. 27–43, 1993. doi: <http://dx.doi.org/10.1006/jaer.1993.1030>
- [8] Lieberei, R. & Reisdorff, C., *Nutzpflanzenkunde*, Georg Thieme Verlag: Stuttgart, 2007.
- [9] Varma, D.S., Varma, M. & Varma, I.K., Coir fibers: Part I: effect of physical and chemical treatments on properties. *Textile Research Journal*, **54**, pp. 827–832, 1984. doi: <http://dx.doi.org/10.1177/004051758405401206>
- [10] Goulart Silva, G., De Souza, D.A., Machado, J.C. & Hourston, D.J., Mechanical and thermal characterization of native brazilian coir fiber. *Journal of Applied Polymer Science*, **76**, pp. 1197–1206, 2000. doi: [http://dx.doi.org/10.1002/\(SICI\)1097-4628\(20000516\)76:7<1197::AID-APP23>3.0.CO;2-G](http://dx.doi.org/10.1002/(SICI)1097-4628(20000516)76:7<1197::AID-APP23>3.0.CO;2-G)
- [11] Kulkarni, A.G., Satyanarayana, K.G., Sukumaran, K. & Rohatgi, P.K., Mechanical behaviour of coir fibres under tensile load. *Journal of Material Science*, **16**, pp. 905–914, 1981. doi: <http://dx.doi.org/10.1007/BF00542734>
- [12] Fluck, R.C & Ahmed, E.M., Measurement by compression test of impact damage to citrus fruits. *Journal of Texture Studies*, **4**, pp. 494–500, 1974. doi: <http://dx.doi.org/10.1111/j.1745-4603.1974.tb00859.x>
- [13] Underhill, S.J.R., Mclauchlan, R.L., Dahler, J.M. & Bertram, J., Flavedo and albedo changes in ‘Eureka’ lemons caused by static compression and impact loading. *Journal of Texture Studies*, **29**, 437–452, 1998. doi: <http://dx.doi.org/10.1111/j.1745-4603.1998.tb00815.x>
- [14] Seidel, R. Bürig-Polaczek, A., Fleck, C. & Speck, T., Impact resistance of hierarchically structured fruit walls and nut shells in view of biomimetic applications, *Proceedings of the 6th Plan Biomechanics Conference*, ed. Thibaut, B., French Guyana, ECOFOG: France, pp. 406–411, 2009.

This article is a reprint of the one presented at Design & Nature V Conference, 2010 organised by the Wessex Institute of Technology.