Hydro-actuation of ice plant seed capsules powered by water uptake

Abstract

Unlike well-known plant hydro-actuation systems that respond to changes in relative humidity (RH) (e.g. wheat awns), ice plant seed capsules undergo a reversible origami-like unfolding and release their seeds only in response to exposure to liquid water. The engine for ice plant actuation was found to be the water uptake and swelling of a highly swellable cellulosic inner layer (CIL) inside the cell lumen of a hygroscopic tissue responsible for the unfolding movement. CIL was found to have an open structure with porous lamellae filling the gap between denser cellulosic mats. Thermogravimetric analysis of water–CIL interaction showed that the initial enthalpy-driven adsorption of water can only account for increasing the moisture content up to about 0·4 mg/mg, which is not sufficient to initiate the actuation. By applying a combined chemo-mechanical model, we could show that the entropic gain of the system through further water uptake (40–350 wt%) is sufficient to accomplish a full opening of the seed capsules through a sophisticated design at various hierarchical levels of the system. The principles behind this actuation mechanism may inspire the development of hydro-responsive devices that, although being highly hydrophilic, only respond to liquid water and not to changes in RH.

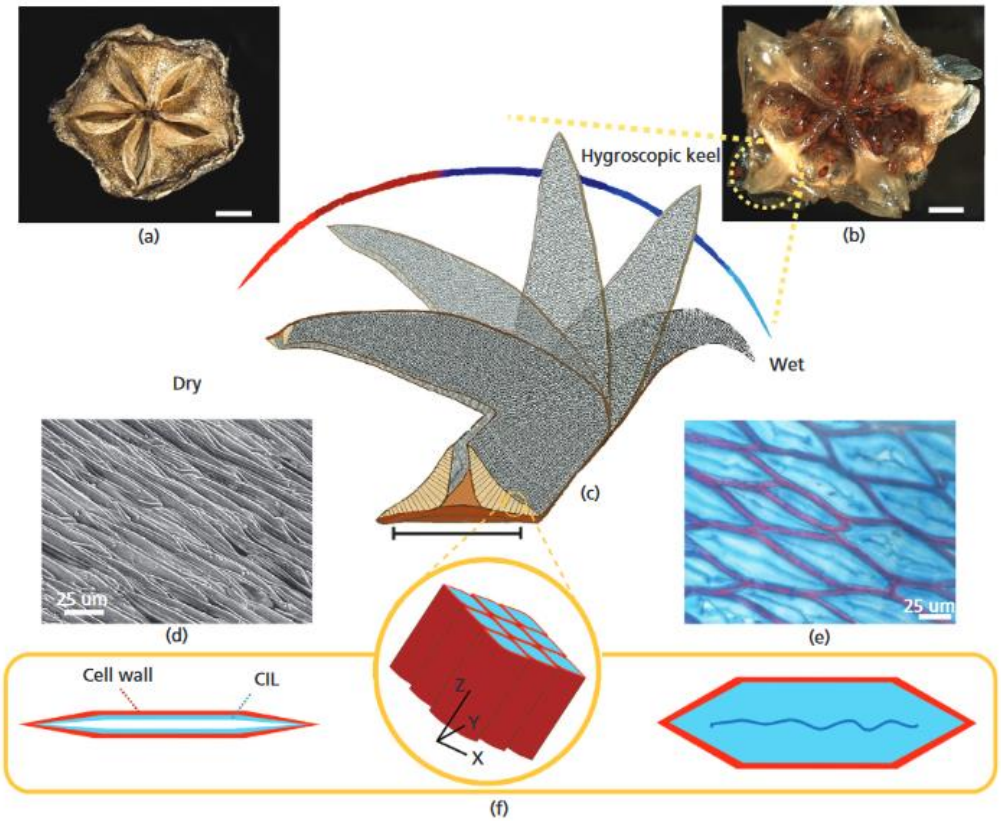

Figure 1. Hierarchical structure of the seed capsules of ice plant species *Delosperma nakurense*. Each seed capsule consists of five seed-containing compartments. The protective valves are closed in the dry state and open upon wetting (a, b). Each valve consists of two hygroscopic keels responsible for unfolding/folding of the seed capsule. The schematic illustrates the two hygroscopic keels bending upon wetting/drying (b, c). The hygroscopic keels are made up of a network of ellipsoid/hexagonal shape cells that undergo a reversible anisotropic swelling upon wetting. The short and long axes of the transverse cell cross sections are assigned as the *Y* and *X* direction, respectively, with the significant swelling occurring mainly in shorter transverse cross section of the cells (f). In the light microscopy image of FCA stained transverse cross section of the cells in the swollen state, the lignified cell wall (red) can be readily distinguished from the non-lignified cellulosic inner layer (CIL) in blue (e). The environmental scanning electron microscopy (ESEM) micrograph of cells in the dry state shows that the highly swollen CIL collapses on the cell wall upon drying (d). The cooperative unidirectional swelling of these cells is translated to the folding movement of the keels (c). Scale bars are defined as follows: a, b, c = 1 mm; d, e = 25 µm (after ref. [29]). FCA, fuchsin–chrysoidin–astrablue