Mechanical Behavior and High Formability of Palm Leaf Materials

Debapriya Pinaki Mohanty,* Anirudh Udupa, Anil Chandra A R, Koushik Viswanathan, James B. Mann, Kevin P. Trumble, and Srinivasan Chandrasekar

The proliferation of single-use plastics has stimulated interest in sustainable material substitutes with sufficient ductility and structural integrity. Herein, the mechanical behavior and high formability of the leaf sheath from a representative palm species—Areca catechu—and its immense potential for manufacturing of eco-friendly food packaging are reported on. Using microstructural analyses, such as X-ray micro-computed tomography (μCT), electron microscopy, and optical profilometry, under different loading conditions, it is shown that this leaf can accommodate forming strains as large as 200%, similar to ductile metals. The sheath deformation response is highly sensitive to hydration, with up to 400% increase in forming strain. The embodied energy for leaf products is four to five orders smaller than for plastic or paper products. The results establish the microstructure basis for the high formability and the contours of a forming limit diagram that delineates product shapes that can be formed in a single step from this plant material.

1. Introduction

The deleterious effects of plastics on the environment are well known, being the subject of numerous scientific reviews and popular articles. Among industrial sectors, the foodware/packaging segment is by far the largest consumer of plastics, accounting for \( \approx35\% \) of usage.[1] A disturbing feature of this sector is proliferation of single-use products, which inevitably find their way either into landfills or the ocean, adversely impacting human and animal health, and groundwater resources.[2,3] Increasing awareness and heightened "green" standards have spawned research efforts to develop environmentally sustainable alternatives for single-use applications.

Challenges for these efforts in the foodware/packaging sector are twofold: first, identifying sustainable alternative materials that mechanically, functionally, and aesthetically match plastics and second, developing scalable, energy-efficient processes for manufacturing products (e.g., plates, cutlery) from these alternative materials at a competitive cost vis-à-vis plasticware. In recent years, processing of plant-based materials has emerged as an attractive option, notable examples being plates, bowls, and cups made by molding of pulped wood fiber or bagasse. Although plants provide the primary source of these fibrous materials, this inherent advantage is offset by the highly energy-intensive pretreatment, pulping, and drying steps involved in their manufacture. These processes are also among the most water intensive of all material production processes and often entail use of fillers and chemicals (\( \approx30\% \)).

A more attractive route, both from an energy and ecological standpoint, is production of foodware, in a single step, by direct deformation processing or forming of plant materials.[4,5] This study focuses on one such opportunity with demonstrated potential—Areca catechu—a palm that has been cultivated for nearly 2000 years in India and Southeast Asia[6–8] (see also Supporting Information). Plates and bowls can be produced in a single step, directly, by forming of areca leaf sheath (or spathe), typically a few millimeters thick (Figure 1), analogous to the forming of sheet metal (see Figure S1, Supporting Information). Various macroscopic attributes of the leaf sheath and foodware products thereof are highlighted in Figure 1, which also gives an overview of the cradle-to-grave life cycle of the leaf-sheath and foodware products. The single-step processing of the sheath into foodware completely avoids the use of fillers and additives, and intermediate processes such as pulping.[9] In addition, the sheath material biodegrades in \( \approx100 \) days compared to hundreds of years for plastics.[10] As the palm is grown primarily for its nuts,
to manufacture similar products? The methodology to answer such questions is well established for metals and polymers, contributing in no small measure to their widespread use in structural applications. Unfortunately, palm leaf product manufacturers have continued to rely on empiricism and intuitive understanding of material behavior for their product design and manufacturing.

In this work, we study the structure and mechanical deformation response of areca palm sheath, a model palm leaf system.\(^\text{[14]}\) We focus on the formability of the leaf materials, most critical for product manufacturing, and establish the contours of a forming limit diagram. We elucidate the unique multiscale microstructure of the sheath, followed by detailed deformation studies using techniques commonly used to assess sheet metal formability. We also obtain independent assessments of formability based on product shapes and deformation of surface topographical features. The analyses reveal the extraordinary formability of areca sheath, with the capability to withstand strains as large as 2 prior to failure, as well as how such large strains are accommodated. The high formability, together with other intriguing aspects of the mechanical response of areca sheath, suggest wide-ranging opportunities for use of palm tree materials in eco-friendly food packaging, and for unlocking the sustainable manufacturing potential of various plant-based materials.

2. Results

The microstructure of the areca leaf sheath, its deformation response under loading modes typical of forming processes and strength testing, and effects of hydration on deformation are described in this section. Details of the test procedures are given in the Experimental Section.

2.1. Sheath Microstructure

Figure 1(middle and bottom) shows overall views of external surfaces of the areca sheath both in raw form and after processing into products, obtained with a high-resolution camera. The inner surface of the sheath is brighter (lighter), whereas the outer side has a duller (brown) appearance. After processing, the former becomes the inside surface of the plate/bowl. A characteristic feature of the sheaths is the presence of striations, best visible on the inner surface and much less prominent on the outer surface, that run along the length of the sheath. Herein, the length direction is referred to as the “longitudinal direction” (LD), and its perpendicular as the “transverse direction” (TD); the out-of-plane normal to the surface is the depth direction (DD) (see Figure 1, bottom row). In the raw sheath, the striations have a peak-to-valley height of $\approx 400 \, \mu\text{m}$, and a lateral spacing of $\approx 3 \, \text{mm}$. The striations are also useful as intrinsic markers for analyzing the deformation.

Examination of the areca sheath using micro-computed tomography ($\mu\text{CT}$) and scanning electron microscopy (SEM) (see the Experimental Section) showed a hierarchical microstructure, common in herbaceous materials and plants\(^\text{[14–19]}\) (see Figure 2). Figure 2a is a $\mu\text{CT}$ scan reconstruction of the sheath internal structure (2.3 $\mu\text{m}$, voxel resolution) showing a combination of vascular bundles (fibers), parenchyma (matrix), and air

Figure 1. Areca palm leaf sheath and products: (top row) areca product life cycle from cradle to grave (left) and palm tree with leaf sheath (right); (middle row) typical areca sheath and foodware products; (bottom row) inner and outer surfaces of a sheath (or plate/bowl) with striation features.
spaces. This structure can be described as being of porous fiber-matrix type. The vascular bundles (fibers) are distributed throughout the sheath cross-section and are oriented along the LD. The bundle distribution and shapes (circular/elliptical) are clearer in the SEM cross-sections, in transverse and longitudinal planes (Figure 2b,c). The fiber cross-sections are nearly circular close to the inner surface of the sheath and elliptical toward the outer surface. A thin, more dense layer—"the epidermis"—of thickness <50 μm adjoins the inner and outer surfaces of the sheath. This epidermis is composed of thick-walled, lignified cells of low porosity, resulting in a rigid and scarified layer. In addition, small fibrous tissue (diameter ≈50 μm) adjoining the outer surface provides higher stiffness/strength to the material in this region.14 The epidermis overall provides strength and stiffness to the entire sheath, analogous to a composite sandwich panel.16

Figure 2. Structure of areca sheath: a) μCT scan image showing the 3D structure. The humps on the top surface correspond to the striations; "LD," "TD," and "DD" denote the longitudinal, transverse, and depth directions, respectively. SEM images of the sheath cross-section in the b) transverse and c) longitudinal planes showing the vascular bundle (fiber) and matrix. Details of the hierarchical structure: d) individual fiber; e,f) cross-sections of circular and elliptical fibers in the transverse plane, with the xylem and phloem the conducting elements of the vascular bundle; g) enlarged view of region inside the red square in (e) showing the xylem and phloem; h) cross-section of an individual fiber in the longitudinal plane; i) arrayed Si-rich particles on the surface of fibers revealed by EDX analysis (inset).

Higher magnification SEM images of sheath cross-sections (Figure 2d–i) reveal more details of the microstructure. A single fiber having a vascular bundle is shown in Figure 2d (longitudinal plane), with a typically circular or oval cross-section; see Figure 2e,f (note that these fibers are different from the fibrous tissue adjoining the outer surface, which does not contain any vascular bundles). The vascular bundle itself consists of two tissues: the xylem for transporting water and minerals and the phloem for transporting soluble organic substances, including sugars and nutrients. The larger pores located at the center of a fiber are the vessel elements, which are components of the xylem, while the phloem cells can be seen as the smaller pores surrounding the xylem. The micrographs in Figure 2e–h show the structure of the xylem and phloem in the transverse and longitudinal planes, respectively. The xylem is long (>50 mm) tubes of ≈70 μm diameter, and without a cross-wall, which allows for continuous and rapid flow of water and minerals. The number of xylem in a fiber is typically one to five. The phloem is shorter tubes of length ≈150 μm and diameter ≈10–30 μm, and has a cross-wall with pores. The overall (macroscopic) porosity of the sheath as measured from the SEM images (c.g., Figure 2b) is 50–60%. Of this porosity, a somewhat larger fraction (≈60%) is found to reside in the parenchyma (matrix). When the fibers are examined at high magnification, arrays of particles (size ≈10 μm) are seen distributed along the length of their surfaces (Figure 2i).
energy dispersive X-ray spectroscopy (EDX) elemental analysis showed these particles to be Si-rich; see inset of Figure 2i. These particles serve varied roles, including enhancing the mechanical strength of cells; increasing the abrasiveness of cell walls and reducing attack by various herbivores; and even enhancing the drought resistance of plants (e.g., tomato leaves) by increasing the cell wall thickness.\[20–22\] This hierarchical structure of the areca sheath that we have described is broadly similar to that of the leaf sheath of other palm trees, with the principal differences being in the extent of the porosity.\[14\]

### 2.2. Deformation Response

The deformation response of the sheath at room temperature, under the various loading modes, provided a characterization of the large strains (shape changes) that the sheath can accommodate and the underlying pathways.

#### 2.2.1. Uniaxial Tension

The uniaxial tensile stress–strain response of the sheath in LD and TD orientations is shown in Figure 3, in both dry and wet conditions. In the dry condition, the tensile strength of the sheath (maximum stress) is \(\approx 32\) MPa, and the Young’s modulus is \(\approx 780\) MPa, in the LD orientation. The corresponding values for the TD are considerably smaller, only 2 and 30 MPa, respectively. The uniform elongation strain (strain at peak stress) is \(\approx 0.04\) for the LD and \(\approx 0.07\) for the TD; although not all of this strain is plastic strain, it nevertheless provides a useful measure of ductility/formability. This strain is greatly increased in the wet condition, with LD strain doubling to 0.08 and TD strain increasing by more than fourfold to 0.3. Although the sheath strength in both the LD and TD directions is reduced by the hydration, this is more than offset from a deformation processing standpoint by the corresponding gain in ductility (see Figure 3). The TD ductility is much greater than the LD ductility in both dry and wet conditions. The mechanical properties are thus strongly anisotropic and quite sensitive to the hydration condition, akin to many woods.\[23,24\]

From a forming perspective, the strain response is a more critical parameter as it directly encodes dimensional changes. The TD tensile ductility of \(\approx 0.3\) in the wet condition is very similar to that of metals such as Al and Cu.\[25,26\] Although the material strength plays a key role in determining the forming process requirements, in the current case, even the higher LD strength values of \(\approx 32\) MPa are quite small, as to be of little consequence for the forming in terms of both energy consumption and equipment design specifications. The stress–strain data thus strongly suggest that larger shape changes can be achieved in the wet condition, and that a 2 h exposure is more than sufficient to obtain the requisite formability gain. This is consistent with what is done in practice, where the sheath material is submerged in water, albeit for a longer period of 12 h, prior to the forming. During the 2 and 12 h exposure, the moisture content in the sheath increased to \(\approx 144\%\) and \(\approx 240\%\), respectively, relative to the dry-sheath mass as estimated using mass gain measurements.

#### 2.2.2. Uniaxial Compression

The sheath material, in the dry condition, was found to withstand much greater strain prior to failure (formability) when loaded in compression than in the corresponding uniaxial tension case. This compression was applied parallel to the DD. The samples typically failed at a thickness reduction of \(\approx 70\%\), corresponding to an axial strain \(\varepsilon = -\ln(1/0.3) = 1.2\).

Figure 4a–c shows SEM images of typical sheath cross-sections in the DD–TD plane after various thickness reductions in the range of 0–50\% (\(\varepsilon = 0–0.7\)). By tracking both the deformation of individual (specific) fibers and changes in porosity (matrix/fiber), using the cross-section images, it was possible to reconstruct a picture of how the compression strain was accommodated.

First, we tracked the deformation of specific fibers at various stages of the deformation; two of these fibers are outlined in red and yellow in Figure 4. A change in shape and cross-section of the fibers is evident, especially beyond 25\% reduction. With increasing deformation, the fiber cross-sections are reduced, and the “minor axes” of the deformed fibers tend to align parallel to the DD. This type of fiber deformation is also observed in compression tests with structural composites.\[127\]

Second, the porosity decreases significantly with increasing thickness reduction. The table in Figure 4 gives the fraction of porosity and solid material after 25\% and 50\% reduction, as measured by analysis of the SEM cross-section images.

![Figure 3. Stress–strain curves for areca sheath loaded in uniaxial tension in a) LD and b) TD. Results are shown for both dry and hydrated conditions. The peak stress is taken as the strength, and the strain corresponding to this peak as a measure of uniform elongation (ductility/formability).](image-url)
Up to this 50% reduction, there was negligible change in the in-plane dimensions of the sample. It is clear from the table that the initial 25% reduction is accommodated mostly by pore size (and volume) reduction, mainly in the matrix. The fiber porosity shows negligible change, consistent with the very small level of deformation seen in individual fibers (Figure 4). However, subsequent reduction to 50% thickness lowers the area (volume) of both the pores and the solid region, accompanied by a reduction in porosity in both the matrix and the fibers. Third, at 70% reduction (compression $\varepsilon = 1.2$), all the pores in the matrix and fibers have mostly collapsed; compression beyond 70% typically resulted in sample failure in the matrix, with the fibers separating in the TD orientation perpendicular to the loading axis.

### 2.2.3. Rolling

The rolling test, wherein a dry area sheath was deformed in both LD and TD orientations, further confirmed the high formability. This test provided two independent measures of the strain to failure, one based on bulk deformation (thickness reduction) of the rolled sample and the second from local deformation of striations on the sheath surface (see Figure 5). The surface deformation was inferred from profilometric traces across the striations (Figure 5a) for a 50% (bulk) sheath thickness reduction. The peak-to-valley height ($R_z$) on the sheath inner surface is seen to decrease significantly, after the reduction, from a $R_z$ of $\approx 400 \mu m$ to $\approx 80 \mu m$, for the LD rolling orientation, mainly due to flattening of the striations. This translates to a local (surface) rolling strain of $\varepsilon \approx \ln(400/80) = 1.6$. The local strain in the sample rolled in the TD direction is essentially the same as the profile height decrease is very similar to that in the LD sample (Figure 5b).

The variation of rolling strain with $r$ in the bulk of the sheath is shown by the red curve in Figure 5b. This is a plot of $\varepsilon = \ln(1/1-r)$ versus reduction ($r$) and the individual points are the mean values (error bars ±1 SD), up and until just before the final failure. When rolled parallel to the LD, the sheath typically failed at $r = 80–85\%$, that is, a strain of 1.6–1.9. The rightmost point on the rolling $\varepsilon$ curve in Figure 5b represents the strain point just before failure. An example of a failed sheath for this rolling orientation is shown in the optical micrograph in Figure 5c. The fracture is seen to run parallel to the rolling direction with very little deviation, and the fibers adjacent to the fracture surface separate in the TD. Interestingly, this bulk failure $\varepsilon$ value is similar to the local surface $\varepsilon$ of 1.9. The sheath failed at a lower $\varepsilon$ of $\approx 1.2$ (thickness reduction $\approx 70\%$) when the rolling was done parallel to the TD (Figure 5d). In this case, the failure is coincident with occurrence of a gross wrinkling instability, with fibers again separating along the TD; note also the large change in sample length in this case. These results also highlight strong anisotropy in shear deformation in the LD–TD plane, consistent with the anisotropy observed in the sheath structure (Figure 2) and uniaxial tension test. The topography of the sheath inner surface was negligibly affected by the rolling (hence only the initial profile shown in Figure 5a), indicating minimal local straining of material on this surface.

### 2.3. Biaxial Stretching (Limiting Dome Height (LDH) Test)

One of the most widely used methods for analyzing the formability of sheet materials, for example, sheet metals, is the LDH test.[28] In this test, a thin sheet of the material in the form of a disk is clamped at its periphery and then stretched (expanded) into cup (or dome) form (see Figure 6a) by application of a punch pressed onto the unclamped central region of the disk. With isotropic materials, this LDH loading is commonly described as one of biaxial stretching. This cup-forming LDH test configuration very closely resembles the forming process used to make...
foodware (Figure 2), except that there is no bottom die. In the LDH testing, areca sheath of thickness \( C_25 \) mm, and with an unclamped (central) region of 30 mm diameter, was first hydrated for 2 h and then stretched to failure by load application via a hemispherical punch of diameter 20 mm moving downward at a speed of 1 mm min\(^{-1}\). The resulting cup and its underside are shown in Figure 6a,b. The depth of penetration of the punch and the load were concurrently monitored, giving the load–displacement curve shown to the depth of 10 mm (Figure 6c). Spring back in the formed cup is prevented by removing the moisture by flowing hot air at 150 \( ^\circ\)C for 3 min.

Failure occurred at a punch penetration depth of \( C_25 \) mm, corresponding to a cup aspect ratio (depth/diameter) of 1:3. It is this failure penetration depth that is referred to as the “LDH.” Based on assumption of zero friction between the punch and sheath during this cup forming, and that the material properties in the plane are isotropic, we can estimate the maximum tensile strain, which will occur at the center of the sheath outer surface (pole) for the frictionless indentation. Hill’s solution,\(^{29}\) for bulging of a circular sheet (sheath, in current case) under pressure, gives this maximum strain as 
\[
\varepsilon = \ln(1 + (\delta/a)^2),
\]
where \( \delta \) is the deflection (= punch penetration) at the sheath center and \( a \) is the sheath radius (15 mm). The sheath tensile strain at failure was estimated as \( \approx 0.37 \) in the current test (Figure 6). This strain value is very close to that measured in very ductile, commercially pure Al sheet in similar LDH testing, thus attesting to the high formability of the sheath material. Note also that the strain estimate obtained is a conservative lower bound value as we have assumed frictionless indentation.

It is also clear from Figure 6b that failure in the sheath occurs by splitting of the outer surface of the sheath in a direction perpendicular to the fiber orientation. This failure is analogous to that observed in the rolling test (Figure 5c). Furthermore, the observed location of the failure at the pole of the sheath (cup) sample in Figure 6b supports our assumption of frictionless punching in the LDH test. It is well known that when the friction between the punch and the sheet material is high in the LDH test, the location of the maximum strain (and failure) shifts away from the pole of the sample to the edges.\(^{28,30}\)

### 2.4. Deformation Strain in Formed Products

The strain imposed in the forming of plates and bowls can also be directly estimated by idealizing the forming process as one of biaxial stretching (see Figure S1, Supporting Information\(^{30,31}\)). For this estimation, we need the initial (sheath) and final (product) configurations of the sample and a model for the deformation that maps material points from the initial to final state. The latter, in the current stretching problem, is determined principally by contact friction conditions at the die–sheath interface. Resolution of this friction condition, as also in the LDH test, requires measurements of deformation at various locations on...
the sheath. As such measurements are not currently available, we consider two extreme cases of these contact boundary conditions—zero friction (frictionless) and high friction (sticking, or no slip tangential to die face)—to estimate the forming strain. This approach provides characterization of limits to the forming strain, as has been demonstrated in sheet metal stretching.\cite{30}

For analysis of the strain limits, we assume the initial state of the sample, the raw sheath, to be a flat disc of thickness \( H \), neglecting any intrinsic variations in sheath thickness and curvature. The final state of the sample (plate/bowl) is obtained using the 3D shape reconstruction technique described in the Experimental Section (see also Figure S2, Supporting Information). Figure 6d, e shows an example of this reconstruction for a bowl.

2.4.1. High-Friction (No-Slip) Case

If there is no slip tangential to the die interface, then material points are displaced only along the die axis (\( z \)-direction) during the punching (Figure S1, Supporting Information). The material points then map as

\[
\begin{align*}
x &= X \\
y &= Y \\
z &= cZ + f(X, Y)
\end{align*}
\]

where \((X,Y,Z)\) and \((x,y,z)\) represent coordinates in undeformed and deformed configurations, respectively (Figure S2, Supporting Information). The origin is taken at the center of the bowl/plate inner surface. The parameter \( c = h/H \) is the fractional compression in the \( z \)-direction; in the forming of the bowls and plates, \( c = 0.8 \). The Lagrangian (Green) strain \( \varepsilon \), radial strain \( \varepsilon_{rr} \), and circumferential strain \( \varepsilon_{\theta\theta} \) are calculated using the measured shape, deformation mapping (Equation (1)), and standard coordinate transformation formulæ.\cite{32}

The radial strain distribution \( \varepsilon_{rr} \) is shown in Figure 6 for the plate and bowl. In the plate (Figure 6f), the maximum radial strain is \( \approx 0.7 \) and occurs at the slant surface along the periphery, whereas the strain in the central region is zero due to the high friction (no slip). The radial stretching at the slant surface is related to the angle that this surface makes with the \( z \)-axis, with the strain increasing with increasing slant angle. A similar radial strain distribution is seen in the bowl (Figure 6g), with the maximum radial strain \( \approx 0.5 \) again occurring at the periphery. This maximum strain value is smaller than in the plate because the bowl periphery is not as steeply inclined as the slant surface of the plate. Also, because the plate is axially symmetric, the radial strain in Figure 6f is independent of \( \theta \), whereas in the bowl, due to its somewhat elliptical shape, there is a \( \theta \) dependence of this strain (Figure 6g), with the strain values being greater along the longitudinal axis compared to the transverse axis. With regard to the other two strains—\( \varepsilon_{\theta\theta} \) is zero for this case as material displacement is purely in the \( z \)-direction, and \( \varepsilon_{zz} \) is constant throughout the sample due to the homogenous compression imposed by the die, specifically, \( \varepsilon_{zz} = |c^2 - 1| = 0.36 \).

Figure 6. Deformation in formed products: a) cup product formed in the LDH test. b) Failure region on the back surface of the cup, showing tensile splitting of the material in a direction perpendicular to the fiber length orientation. c) Load–displacement curve. d–g) Strain distribution in plate and bowl: d) Optical image of bowl and e) bowl-shape reconstruction (see Experimental Section) used for strain estimation (the scale bar defines height contours with respect to the base). Radial strain \( \varepsilon_{rr} \) contours in f) plate and (g) bowl.
2.4.2. Frictionless Case

The deformation strain for the frictionless case may be obtained by considering uniform stretching and bending of the sheath.\(^{13}\) We denote the initial radius of the undeformed sheath by \(R_0\), and the final radius in the deformed product by \(R\). The latter is the radius of a circle with the same surface area as the final deformed shape. The total strain can then be written as

\[
\varepsilon_{\alpha\beta} = \gamma_{\alpha\beta} + \frac{1}{2} \kappa_{\alpha\beta}
\]

(2)

where \(\gamma_{\alpha\beta}\) is the uniform stretching component of the strain, \(\kappa_{\alpha\beta}\) is the curvature tensor, and the second term in the equation is the bending strain. The strain due to uniform stretching, 

\[
\varepsilon_{rr} = \varepsilon_{\theta\theta} = \ln(R/R_0),
\]

was calculated as 0.10 and 0.11, respectively, for the plate and bowl. The bending strain has a maximum value of 0.05. Together, the total strain is \(\approx 0.15\). This compares well with Hill’s solution for bulging of a circular sheet, \(\varepsilon = \ln(1 + \delta/a)^2\) (see discussion related to the LDH test), which gives the maximum strain in the plate and bowl as 0.11 and 0.16, respectively.

These strain values are much smaller than the corresponding maximum failure strain (0.37) obtained in the LDH test. This highlights the potential for forming products such as cups and tumblers, with aspect ratios much higher than those for the plates and bowls, from the sheath material.

The permanent deformation in the sheath is not volume conserving, unlike metals. The ratio of the final volume (product) to the initial volume (raw sheath) in the aforementioned forming is \(c\). As both the matrix and fibers have significant porosity, the permanent deformation is accommodated by pore closure and significant volume change. We have already seen evidence of this type of structural accommodation in compression (Figure 4).

2.5. Summary of Deformation Data and Forming Limits

The strains realized in tension, compression, rolling, and sheath forming processes are summarized in Table 1 and provide a characterization of sheath formability. In the near future, we hope to obtain a complete forming limit diagram for in-plane stretching of the sheath that also includes anisotropy effects.

2.6. Embodied Energy

It is interesting to estimate the embodied energy for foodware produced from palm trees and compare it with that of equivalent plastic and paper products. The embodied energy of a product includes the energy of primary material production and the processing (shaping) energy.\(^{14,15}\) Comparative first-order estimates for food packaging produced from various materials are shown in Figure 7. With plastics, for example, the primary material production contribution includes energy consumed in extracting the raw mineral (natural gas), producing monomer feedstock, and synthesizing polymer resin. The processing/shaping contribution represents the energy needed to convert the polymer resin pellets into a useful shape (e.g., plate) by melting and injection molding. For most materials, the primary production dominates the embodied energy; with molded polystyrene, for example, it represents over 85% of the total. With paper products, often seen as the classic sustainable substitute for plastic foodware, although the processing energy is small, the embodied energy is still about half that of plastics (Figure 7) because intermediate processes such as pulping are quite energy (and water) intensive.

Coming to the case of the palm-leaf products, as the areca palm tree is grown primarily for its nuts and sheds sheath (waste) naturally in seasonal growth cycles, the energy associated with material extraction, that is, primary material production, is essentially zero. Therefore, the embodied energy is just the specific energy (deformation work/mass) expended in the forming process. The load–displacement data of Figure 6c from the LDH test can be used to estimate the (cup forming) process specific energy, which is also representative of the foodware forming process (see Figure S1, Supporting Information). The deformation work per unit mass is the area under the load–displacement curve in Figure 6c divided by the mass of the cup (0.7 g). This calculation then gives the process specific energy as

| Test | Loading | Dry | Wet |
|------|---------|-----|-----|
| Tensile | Uniaxial | 0.04 (LD) | 0.08 (LD) |
| | | 0.07 (TD) | 0.30 (TD) |
| Compression | Uniaxial | 1.2 (DD) | 1.2 (DD) |
| Rolling | Plane strain | Bulk strain | - |
| | compression | (from thickness) | |
| | - | Local strain | |
| | - | (surface profile) | |
| | - | 1.6 (LD) | 1.6 (TD) |
| Biaxial stretching | Biaxial tension | - | 0.37 |
| (LDH) | | | |
| Foodware | Biaxial stretching, no slip | Plate: 0.70 |
| | - | - |
| | - | Bowl: 0.50 |
| | - | Biaxial stretching, zero friction |
| | - | Plate: 0.15 |
| | - | Bowl: 0.16 |

Figure 7. Comparison of embodied energy of palm-leaf foodware with that of plastic and paper products.
≈0.003 MJ kg⁻¹, which can be taken as the embodied energy for the palm leaf products (Figure 7). This embodied energy for the plant leaf products is four to five orders of magnitude smaller than that of equivalent plastic or paper products.

3. Discussion

Our multipronged characterization of the structure and deformation response of areca palm sheath has provided a detailed picture of how this material is strained to large values in loading conditions typical of deformation processing, and the accommodation of these strains by internal structure changes.

The hierarchical structure of the areca palm sheath is broadly similar to that of other palm species[14] and other plant materials such as bamboo.136,37 The vascular bundle is of closed type and composed of the xylem and phloem. The overall volumetric fiber content in the sheath is ≈30%. The volume fraction of the fiber varies from 25% to 35% in the center to smaller values along the transverse edges, and the fiber content in the outer half of the sheath thickness is approximately twice that in the inner half. For comparison, the fiber volume fraction in oil palm stems and meso bamboo is 25–50% and 30–70%, respectively.138 Thus the areca sheath has a larger matrix (nonfiber) fraction than the oil palm or the meso bamboo. Correspondingly, porosity in plant materials varies from as high as 0.95 in balsa wood to 0.12 in lignum vitae (guayacan),139 with the areca sheath (0.5) falling pretty much in the middle. Bamboo wood, one of the most widely used structural plant materials, has a porosity of 0.3–0.7.136,37,39 In general, as the matrix can accommodate large deformation via pore closure, both when dry (Figure 4) and when hydrated, one may expect the areca sheath structure to be more favorable for formability relative to bamboo wood. Although bamboo has been used in foodware products, there is very little product manufacturing via direct forming routes. The 3–4 mm thickness of the areca sheath is also optimum for foodware products, providing the desired combination of stiffness and strength while also simultaneously minimizing permeation of food constituents (e.g., oils, water) through the sheath walls. In comparison, single-ply bamboo leaf sheath, with wall thickness of 0.2–1 mm, is unlikely to possess the structural integrity needed for plates and bowls.

The deformation observed in various loading tests and the direct estimates of strain in formed products have shown that the areca sheath has high formability akin to that of ductile metals. Strains as large as 0.35 in uniaxial tension, 1.2 in uniaxial compression, 1.6–2 in rolling, and 0.35–0.7 in biaxial tension have been demonstrated (Table 1), providing a measure of formability in different orientations. With the exception of the uniaxial tension, these strain values are not quite the forming limits for the various loading cases because they do not always represent the strain at failure. Importantly, the role of hydration, which greatly increases the failure strain in tension, has only been partially explored (Table 1). The observed two- to fourfold increase in ductility/formability in tension due to hydration is much greater than, for example, that documented in bamboo (≈67%, from 0.04 to 0.067), or sisal fiber (from 0.02 to 0.04) used in rope and twine.40 We expect to see similar increases in failure strain and formability due to hydration in the other loading configurations. Although prolonged hydration (12 h) reduces the strength significantly, a short (2 h) duration hydration treatment is just as effective as the long-duration one in increasing the formability (Figure 3). The LDH cup-forming test results have shown that the failure strain of the sheath in biaxial tension is very similar to that measured with commercially pure Al sheet, often considered to be one of the most ductile metals. Interestingly, the cup formed in the LDH test also has a higher depth-to-diameter aspect ratio than commercial foodware (Figure 6). This cup forming is a direct analog of the commercial sheath forming process. These observations could be used not only for process optimization, but also to expand the range of shapes that can be formed (e.g., cups, storage boxes, tumblers), including high-aspect-ratio products.

The areca sheath is quite deformable at the local (surface) scale too, for example, withstanding strains as large as 1.6 at the striation level, as seen in the rolling experiments. This local deformation characteristic has implications vis-à-vis modifying the die–sheath contact condition and product quality. By tailoring the die surface topography and/or enhancing the die contact pressure, it may be feasible to reduce the striation heights and therefore, the surface roughness. Also, the striations could act as natural grooves for holding lubricant, which can reduce friction at the die–leaf interface in lubricated forming; this will be beneficial for imposing larger shape changes and improving the surface quality (e.g., finish, minimizing defects). Lubrication is not used in current areca leaf forming processes.

Examination of changes in structure with increasing deformation in uniaxial compression has shown that the imposed large strains are initially accommodated by pore-size reductions (dilatation strain), followed by deformation of nonporous areas as well as pore closure (see Figure 4). At 70% thickness reduction, nearly all the pores in the matrix and fibers are closed, followed by failure soon thereafter. More generally, this condition of complete pore closure, followed by failure in the matrix, or fiber–matrix interface, may well represent the strain limit for any type of compressive deformation process with the palm (Figure 5). In conjunction with direct observations (e.g., SEM, μCT), the changes in structure could also be tracked by analysis of the load–deformation response in the test, although the results are not presented here. Similar to other plant materials, the deformation response of areca sheath showed significant anisotropy.14,15,36,39,40 Consistent with its fibrous, hierarchical structure; the strength and Young’s modulus in the LD orientation (also, fiber length) are as much as 1.5 orders of magnitude larger than in the TD orientation. The effect of hydration on these properties is also influenced by the loading direction, with a larger hydration influence observed for the TD than the LD orientation.

The structure–deformation correlations observed with the areca palm leaf sheath suggest certain attributes that favor high formability in plant materials, critical for product manufacturing by single-step deformation processing. These include sufficient porosity in the material structure to accommodate dilatational strains; hydration to increase shape change limits; orientation of the plant material relative to the LD, for example, with fibers lying in the plane of the sheet (sheath) being stretched; suitable heat application to minimize material spring back after the forming-load release; and sufficient material wall thickness and strength to ensure product integrity. The A. catechu palm
leaf sheath can thus also serve as a model material system for screening various palm and plant materials for product manufacturing by deformation processing.

The manufacture of foodware from palm leaf also represents a fundamentally different class of material processing from the standpoint of embodied energy and various sustainability attributes. The palm tree sheath leaf sheaths naturally in seasonal growth cycles. Not only is the plant not sacrificed in harvesting the sheaths, but the sheaths are then formed directly without the energy-intensive pulping process necessary for production of paper (wood or bagasse). In this regard, the primary form of the material literally “falls from the tree.” The forming forces are quite small because of the relatively low strength of the sheath. Therefore, the embodied energy ($\approx 0.003 \text{ MJ kg}^{-1}$) estimated from the cup forming process (LDH test) is four to five orders of magnitude less than that of paper and plastic foodware (Figure 7).[34,35] Similarly, the direct use of plant leaf materials, without pulping, circumvents the high water use of paper production. With only a small amount of energy needed for processing to shapes, the CO$_2$ emission through the entire product life cycle is essentially that emitted in the natural decay of the disposal process (composting), a process that would occur in any event. Finally, the sheath material biodegrades in $\approx 100$ days. These sustainability attributes of the palm material make it especially attractive for the production of food packaging.[41]

In summary, a study has been made of the microstructure, deformation response, and embodied energy of a model plant material system—the areca palm leaf sheath—with the goal of developing new single-step deformation processing routes for plant-based materials. The areca sheath is shown to have remarkable forming withstanding strains of 0.5–2 in loading configurations such as stretching, compression, and rolling, typical of forming processes. This large strain accommodation is observed in both bulk and surface length scales. It was possible to reconstruct a conceptual picture of how the large forming strains are accommodated, for example, dilatation in compression, thus providing a basis for the high formability of the areca sheath and of its deformation anisotropy. The forming limits can be significantly enhanced by hydrating the sheath prior to the deformation, suggesting opportunities for new deformation processing routes. With further development of a detailed forming limit diagram for in-plane stretching, and utilizing the interactive effects of hydration, temperature, and material anisotropy on deformation, it will be feasible to manufacture a wide range of sustainable foodware from the palm leaf materials, including high-aspect-ratio product shapes. Furthermore, the results can be used to significantly improve and optimize the current heuristically devised manufacturing process. The results also suggest opportunities for expanding the deformation processing approach to manufacture foodware/packaging from a broader class of palm tree and plant materials.

4. Experimental Section

Areca sheaths are long and slender structures (Figure 1, top right and middle left) that serve to protect inflorescence during the early stage of development but are shed in the later stage. The sheath is a thin sheet-like material with typical length and width of 0.5–1 and 0.1–0.5 m, respectively, thickness $\approx 3–4$ mm, and density of $0.4 \pm 0.1 \text{ g cm}^{-3}$ (measured). It is composed primarily of lignin (39%), cellulose (26%), and hemicellulose (16%). It is the sheath that forms areca by machining or stretch-type forming process into plates and bowls. Examples of some commercially available plates and bowls are shown in Figure 1 (middle).

The surface of the sheath that faces the palm tree stem is called the adaxial surface (or inner surface, henceforth) and forms the inner side of the foodware product. The other side of the sheath, called the abaxial surface (or outer surface), forms the outer side of the product.[42] The outer surface of the sheath has a much darker appearance than the inner surface, apart from being stiffer and stronger. The inner and outer surfaces have striations that run along the length direction of the sheath. These striations are the principal source of the surface roughness, both in the sheath and in the formed product.

The forming process used to make plates and bowls from sheath was developed largely on the basis of tradition, and trial and error, and is as follows. After harvesting, sheaths are cleaned and dried to prevent formation of mold before being stored in a dry environment. In the dried condition, the sheath is brittle and not amenable to deformation; the formability is obtained by first immersing each sheath in water for 1–2 h, followed by sealing with a wet cloth for $12$ h. Following this, foodware products (e.g., plates) are formed using the deformation processing configuration shown in Figure S1, Supporting Information. Here, a “flat” sheath of initial thickness $h$ is deformed into the desired form by the gap between two dies heated at $\approx 100^\circ \text{C}$, by means of a force applied to the movable upper die (punch). The process is similar to stretching of a plate by a circular punch, with the final thickness being equal to the gap between the dies, $h$. To prevent springback of the sheath after load release, the moisture content is removed by holding the formed sheath for 3–4 min between the heated dies.[43,44]

For the experiments in this study, raw (unformed) areca leaf sheaths and finished foodware products for the measurements were obtained from a plantation and manufacturing facility in Tumkur near Bangalore, India. The sheaths, taken from a group discarded in the summer season, were cleaned using dry compressed air and stored in a plastic zipper bag to avoid contact with moisture. Samples for the experiments were prepared as needed. Various microscopy and material testing techniques were used in conjunction with more special experimental methods to characterize the microstructure, mechanical properties, and formability of the sheath and establish correlations between the structure and formability. Details of these techniques are described in this section. Background details on areca palm are provided in the Supporting Information.

Structure Characterization: As the mechanics of deformation is strongly influenced by the microstructure, the structure of each sheath was characterized at different length scales using optical microscopy, µCT and SEM. µCT scans were performed on a Zeiss Xradia 510 tomography system to obtain the 3D internal structure at voxel resolution of 2.3 $\mu$m. For this purpose, a $5 \times 5 \text{ mm}^2$ sample was cut out from the central region of a sheath using a sharp scalpel blade. Additional details of microstructure features (e.g., fiber, matrix, porosity) were obtained from cross-section observations with a high-resolution field emission gun-SEM (Quanta 3D) operating in low-vacuum mode. The cross-sections were prepared by dissecting the cut-out samples with a fine scalpel. The SEM images were processed and analyzed using ImageJ software, an open source image analysis software. Porosity, the area fraction of pores, was computed from the SEM images (500×) after smoothing and thresholding. In each image, the solid regions and pores appeared as white and black regions, respectively. The porosity reported for each cross-section is that measured over the full cross-section, without differentiating between fibers and matrix.

Deformation Response: Mechanical Properties and Formability: The deformation response of areca sheath was studied using multiple mechanical loading tests—tension, compression, limiting dome height (LDH) test and rolling; these provided comprehensive information about strength, ductility, and formability, and of anisotropy in the deformation response. In addition, observations of deformed microstructure constituents revealed how macroscopic shape changes are accommodated at the microscale. The loading configurations capture key features of the forming processes (e.g., punching, stretching, and compression) relevant to product manufacturing.
Uniaxial tensile testing was performed (MTS tensile tester, 2 kN capacity) to obtain stress–strain curves, as well as the strength, Young’s modulus, and uniform elongation of the sheath. Test samples were in the form of rectangular strips of dimension 35 × 2 mm² × sheath thickness (≈3 mm) and were cut from the central region of a sheath in the LD–TD plane. Special loading grips for the sample were prepared by casting a cold mount acrylic resin (LECOSET 100) around the sample ends. The casting was one part of liquid monomer and two parts of resin polymer powder, the mixture being allowed to air cure around the sample ends for 24 h. Each grip was ≈10 mm in length × 10 mm in width × 7 mm in thickness. This type of grip ensured correct clamping of the sample in the machine jaws, without any slippage or sample failure at the grips during loading. The sample gauge length was maintained at 15 mm and tests were conducted in displacement control mode with cross-head speed of 1 mm min⁻¹ (strain rate ≈10⁻⁵ s⁻¹). The gauge displacement was measured in two different ways—from the cross-head motion, and via digital image correlation (DIC) using markers imprinted at the ends of the gauge length. Both measurements were in very close agreement; the strain data reported are those obtained from the cross-head displacement. From the load–displacement measurements, an engineering stress–strain curve was computed along with properties such as strength, uniform elongation (ductility), and Young’s modulus. The effects of anisotropy and water exposure (hydration) were evaluated by testing sheath samples cut at different orientations to the LD and samples that had been submerged in water for 2 and 12 h prior to the testing, respectively.

Sheath formability in the dry condition was examined in three different ways: via uniaxial compression, LDH (see main text), and plane-strain rolling.

The uniaxial compression response was studied by loading the sheath (dry condition) parallel to the DD between steel platens. Test samples (5 × 5 × 3 mm³ thickness) were compressed to 25%, 50%, and 70% of their initial thickness. The deformation of the principal sheath microstructure constituents, viz., fibers, pores, and matrix, was quantified by SEM observations of sample cross-sections in the transverse plane. As individual fibers are typically >50 mm in length, it was possible to track the deformation of specific fibers (markers) in the SEM images by compressing multiple samples cut out from the same sheath to varying reduction strains (each sample with dimension 5 mm in the fiber length direction).

The rolling response was studied using rectangular sheet samples of 30 mm length × 10 mm width × ≈3 mm thickness, cut out of the central portion of the sheath, and then dry rolled parallel to LD and TD orientations in a rolling mill with steel rolls of 100 mm diameter. Rolling was done in incremental steps of 0.3 mm thickness reduction until failure. The length of the sample was kept parallel to the rolling direction, and the sample thickness was equal to the sheath thickness, so that the top and inner surfaces of the sheath comprised the surfaces in contact with the rolls.

The thickness strain imposed on the material was calculated as

$$\ln \frac{1}{1 - r} = \ln \frac{t_i}{t_f}$$ (3)

Here, $t_i$ and $t_f$ are the initial and final thickness of the sheath sample, respectively, and $r$ the reduction ratio. After each incremental reduction, the rolled samples were examined under the optical microscope to identify onset of cracking and the failure mode. The formability was quantified in terms of the strain to failure in the LD and TD orientations.

In the same vein, another complementary estimate of the formability, in terms of a local (surface) deformation strain, was obtained based on changes in height and width of the surface striations in the sheath due to the rolling. These dimension changes were derived from measurements of surface topography (see next section), made on the rolled surfaces, after each incremental thickness reduction.

**Surface Topography and Sheath Thickness:** The surface topography on the unformed sheath, rolled samples, and formed surfaces of plates and bowls was characterized using a stylus profilometer (Rank Taylor-Hobson Talysurf) by making line profiles in the TD and across the striations (sample lay). The sampling length for each profile was 10 mm.

The topography is reported in terms of the actual profiles over the sampling length, and as the roughness parameter $R_t$ (maximum peak-to-valley height). The topography measurements provided a direct measure of the surface roughness evolution (finish) in a typical forming process, a key quality parameter in product manufacturing. It also provided a characterization of formability based on local deformation data obtained from changes in surface profile heights.

**Shape Mapping of Formed Products:** The strain imposed in the foodware forming process was directly estimated from measurements of shape change occurring in processing of the sheath into plates and bowls. For this purpose, a special method was developed to map product shapes and displacements.

Two geometries—plates (circular) and bowls (elliptical)—made from sheaths (Figure 1, middle) were considered. The plate has a circular flat-bottomed surface in the middle (diameter ≈150 mm) and a straight slanted surface at the periphery. The outer diameter and depth of the plate are ≈220 and 30 mm, respectively. In contrast, bowls are elliptical in plan view and lack a central flat region. The minor and major axes (diameters) of a bowl are ≈140 and ≈160 mm, respectively, with its height changing gradually from the center (bottom) to the periphery by a vertical distance of 30 mm. The minor and major axes in a bowl are parallel and perpendicular to the striations, respectively.

Macroscopic details of the forming process were first established using measurements of sheath thickness in the $z$-direction, before and after the deformation. In a typical process, sheath of initial thickness ($H$) ≈3 to 4 mm was formed by a punching/stretching process (Figure S1, Supporting Information) into a plate/bowl with wall thickness $h = 0.8 H$. The thickness values $H$ and $h$ were directly measured at multiple locations on the sheet and plate/bowl, respectively. The standard deviation on measured thickness was <10%. These thickness values are input data needed for estimating the strain in the bowls and plates.

Next, the final shapes of the plate and bowl samples were mapped using a simple imaging technique (see Figure S2, Supporting Information). Each sample was first filled with a colored liquid to a known depth ($z_0$) and then imaged from above. The sample inner surface was coated with a layer of thin plastic sheet to prevent water from seeping into the sheath. By tracing the boundary of the liquid, the loci of points at constant $z$ from the bottom were determined. This procedure was repeated for various $z_0$ values; by collating the results, an accurate 3D representation of the sample was obtained. For the imaging, a camera was placed vertically above the center of the sample. The origin ($x = y = z = 0$) was fixed at the center of the sample, on the inner surface. The $x$ and $y$-axes were taken parallel to the LD and TD, respectively (Figure S2, Supporting Information), and the $z$-axis was perpendicular to the inner surface and coincided with the optical axis of the camera. The resolution of this representation is determined only by the height intervals at which the measurements are made; in this study, this height interval was 1 mm. Digitized images were then analyzed using ImageJ to obtain the $x$ and $y$ coordinates of the pixels at the liquid–sample boundary. These pixel coordinates were then transformed into actual distances from the origin as

$$x = \alpha(i - i_0)$$ and $$y = \beta(j - j_0)$$ (4)

Here, $(i_0, j_0)$ and $(i, j)$ are pixel coordinates of the surface and center points, respectively, and $\alpha$ and $\beta$ represent the pixel scale (mm per pixel) in the $x$- and $y$-directions, respectively. The strain field at every point on the plate or bowl surface was then derived from this shape data (see Results).

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.
Acknowledgements

The authors would like to acknowledge the assistance of Prof. Laura J Pyrak-Nolte’s group at Purdue University for the μCT scanning.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

foodware, forming, mechanical behavior, plant materials, sustainable manufacturing

Received: November 23, 2020
Revised: January 26, 2021
Published online: March 7, 2021

[1] R. Geyer, J. R. Jambeck, K. L. Law, Sci. Adv. 2017, 3, e1700782.
[2] E. Moss, R. Grousset, The Dirty Truth about Disposable Foodware, www.mossandmollusk.com/the-dirty-truth (accessed: October 2020).
[3] M. Haward, Nat. Commun. 2018, 9, 1.
[4] P. Kalita, U. Dixit, P. Mahanta, U. Saha, J. Sci. Ind. Res. 2008, 67, 807.
[5] O. K. Jong, T. M. Yong, M. R. Jaafar, IOP Conference Series: Materials Science and Engineering, Vol. 824, IOP Publishing, Ayer Keroh, Malaysia 2020, p. 012014.
[6] K. B. Metheny, M. C. Beaudry, Archaeology of Food: An Encyclopedia, Rowman & Littlefield, Lanham, Maryland 2015.
[7] V. Raghavan, H. Baraah, Econ. Bot. 1958, 12, 315.
[8] G. W. Staples, R. F. Bevacqua, in Species Profiles for Pacific Island Agroforestry (Ed: C. R. Elevitch), Permanent Agriculture Resources (PAR), Holualoa, HI 2006, pp. 1–17.
[9] R. Ashok, C. Srinivasa, B. Basavaraju, Sci. Technol. Mater. 2018, 30, 120.
[10] A. L. Andrady, Mar. Pollut. Bull. 2011, 62, 1596.
[11] J. Song, C. Chen, S. Zhu, M. Zhu, J. Dai, U. Ray, Y. Li, Y. Kuang, Y. Li, N. Quispe, Y. Yao, A. Gong, U. H. Leiste, H. A. Bruck, J. Y. Zhu, A. Vellore, H. Li, M. L. Minus, Z. Jia, A. Martini, T. Li, L. Hu, Nature 2018, 554, 224.
[12] Q.-F. Guan, H.-B. Yang, Z.-M. Han, L.-C. Zhou, Y.-B. Zhu, Z.-C. Ling, H.-B. Jiang, P.-F. Wang, T. Ma, H.-A. Wu, S.-H. Yu, Sci. Adv. 2020.
[13] J. E. Gordon, The New Science of Strong Materials, Princeton University Press, Princeton, NJ 2018.
[14] P. B. Tomlinson, The Structural Biology of Palms, Oxford University Press, Oxford 1990.
[15] L. J. Gibson, J. R. Soc. Interface 2012, 9, 2749.
[16] L. J. Gibson, M. F. Ashby, B. A. Harley, Cellular Materials in Nature and Medicine Cambridge University Press, Cambridge 2010.
[17] P. Fratzl, R. Weinkamer, Prog. Mater. Sci. 2007, 52, 1263.
[18] M. Frey, G. Biffi, M. Adobes-Vidal, M. Zirkebach, Y. Wang, K. Tu, A. M. Hirt, K. Masania, I. Burgert, T. Keplinger, Adv. Sci. 2019, 6, 1802190.
[19] T. Tan, N. Rahbar, S. Allameh, S. Kwofie, D. Dissmore, K. Ghavami, W. Soboyejo, Acta Biomater. 2011, 7, 3796.
[20] G. Guerriero, J. Hausman, S. Legay, Front. Plant Sci. 2016, 7, 1.
[21] B.-L. Cao, Q. Ma, Q. Zhao, L. Wang, K. Xu, Sci. Hortic. 2015, 194, 53.
[22] M. Ye, Y. Song, J. Long, R. Wang, S. R. Baerson, Z. Pan, K. Zhu-Salzman, J. Xie, K. Cai, S. Luo, R. Zeng, Proc. Natl. Acad. Sci. 2013, 110, E6361.
[23] D. G. Hunt, Proc. R. Soc. London Ser. A 1999, 455, 4077.
[24] E. Obataya, M. Norimoto, J. Grill, Polymer 1998, 39, 3059.
[25] Atlas of Stress-Strain Curves (Ed: C. Moosbrugger), 2nd ed., ASM International, Materials Park, OH, USA 2002.
[26] G. E. Dieter, Mechanical Metallurgy, 2nd ed., McGraw-Hill, New York 1976.
[27] Y. Chen, K. Zhang, T. Zhang, F. Yuan, N. Su, B. Weng, S. Wu, Y. Guo, Cellulose 2019, 26, 9831.
[28] S. P. Keeler, W. Backofen, Trans. Am. Soc. Met. 1963, 56, 25.
[29] R. Hill, Philos. Mag. 1950, 41, 1133.
[30] Z. Marciniai, J. Duncan, Mechanics of Sheet Metal Forming, Edward Arnold, Sevenoaks, UK 1991.
[31] W. A. Backofen, Metall. Trans. 1973, 4, 2679.
[32] P. Chadwick, Continuum Mechanics, Wiley, New York/Chichester, UK 1976.
[33] S. P. Timoshenko, S. Woinowsky-Krieger, Theory of Plates and Shells, McGraw-Hill, New York 1959.
[34] M. F. Ashby, Materials and the Environment: Eco-Informed Material Choice, Elsevier, Amsterdam/New York 2012.
[35] R. Costanza, Science 1980, 210, 1219.
[36] P. G. Dixon, L. J. Gibson, J. R. Soc. Interface 2014, 11, 20140321.
[37] P. Dixon, K. Semple, A. Kutznar, F. Kamke, G. Smith, L. Gibson, Eur. J. Wood Wood Prod. 2016, 74, 633.
[38] S. Srivaro, J. Rattanarat, S. Noothong, J. Wood Sci. 2018, 64, 186.
[39] P. Huang, W.-S. Chang, M. P. Ansell, C. Y. John, A. Shea, Wood Sci. Technol. 2017, 51, 11.
[40] G. Chen, H. Luo, H. Yang, T. Zhang, S. Li, Acta Biomater. 2018, 65, 203.
[41] B. C. Rao, R. Soc. Open Sci. 2019, 6, 180421.
[42] R. Nagaraja, B. Gurumurthy, M. Shivanna, Int. J. Res. Appl., Nat. Soc. Sci. 2014, 2, 105.
[43] N. Matan, W. Saengkrajang, N. Matan, Int. Biodeterior. Biodegrad. 2011, 65, 212.
[44] J. Keckes, I. Burgert, K. Frühmann, M. Müller, K. Kölhn, M. Hamilton, M. Burghammer, S. V. Roth, S. Stanzi-Tschegg, F. Fratzl, Nat. Mater. 2003, 2, 810.