
Supplementary information

Autonomous self-burying seed carriers for aerial seeding

In the format provided by the
authors and unedited

Supplementary Information for

Autonomous Self-burying Seed Carriers for Aerial Seeding

Danli Luo¹, Aditi Maheshwari², Andreea Danielelescu², Jiaji Li³, Yue Yang³, Ye Tao⁴, Lingyun Sun³, Dinesh K. Patel¹, Guanyun Wang^{1,3*}, Shu Yang^{5*}, Teng Zhang^{6,7*}, Lining Yao^{1*}

¹Morphing Matter Lab, Human-Computer Interaction Institute, Carnegie Mellon University, Pittsburgh, PA, United States.

²Accenture Labs, San Francisco, CA, United States.

³College of Computer Science and Technology, Zhejiang University, Hangzhou, China.

⁴School of Art and Archaeology, Zhejiang University City College, Hangzhou, China.

⁵Materials Science and Engineering, University of Pennsylvania, 3231 Walnut Street, Philadelphia, PA 19104, United States.

⁶Department of Mechanical and Aerospace Engineering, Syracuse University, Syracuse, NY, U United States.

⁷BioInspired Syracuse, Syracuse University, Syracuse, NY, United States.

*Correspondence to: guanyun@zju.edu.cn, shuyang@seas.upenn.edu, tzhang48@syr.edu, liningy@andrew.cmu.edu.

This PDF file includes:

Supplementary Table S1 to S5

Supplementary Note S1-S12

Table S1: Summary of selective self-burial grass seeds and engineered seed carriers. Data for dimensional measurements are means $\pm$ SD, $N = 3$. The drilling test to obtain the establishment rate (80% tip burial) was conducted for three triggering cycles with five samples of each type. (Testing procedure and conditions are consistent with “Drilling tests under controlled conditions” in Methods).

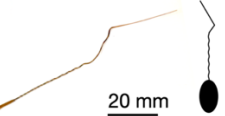
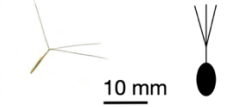
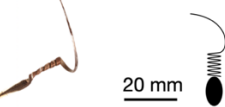
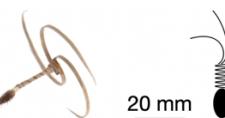
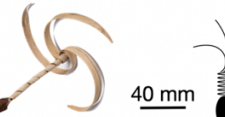
Types	Awn Morphology	Body wet Length (mm)	Seedpod Length (mm)	Seedpod Maximum Diameter (mm)	Seedpod Dry Weight (mg)	Establishment Rate
<i>Stipa comata</i>	- Single awn with one sharp bend and one curve - Twisted body 	142.6 $\pm$ 18.5	11.3 $\pm$ 3.1	1.0 $\pm$ 0.0	7.9 $\pm$ 0.3	40%
<i>Stipa spartea</i>	- Single awn with two sharp bends - Twisted body 	117.7 $\pm$ 6.7	18.3 $\pm$ 1.0	1.3 $\pm$ 0.1	13.0 $\pm$ 0.5	0%
<i>Aristida purpurea</i>	- Triple awns with three sharp bends - Straight body 	34.9 $\pm$ 4.7	8.2 $\pm$ 1.8	0.4 $\pm$ 0.1	0.9 $\pm$ 0.2	0%
<i>Erodium guinum</i>	- Single awn with one curve - Coiled body 	90.4 $\pm$ 0.9	15.1 $\pm$ 0.6	2.4 $\pm$ 0.3	28.3 $\pm$ 9.5	0%
<i>Erodium castellanum</i>	- Single awn with one curve - Coiled body 	48.2 $\pm$ 1.0	9.6 $\pm$ 0.2	1.9 $\pm$ 0.1	12.3 $\pm$ 3.1	20%
Medium-sized Engineered	- Triple awn with three curves - Coiled body 	135.3	13.5	3.1 $\pm$ 0.3	52.0 $\pm$ 10.5	80%
Large-sized Engineered	- Triple awn with three curves - Coiled body 	302.7	20.8	9.0 $\pm$ 0.5	75.3 $\pm$ 0.6	100%

Table S2. Comparison of Young's modulus, availability/cost and processability for cm scale devices with representative examples of water-responsive materials with promising actuation properties.

Water-responsive Actuating Materials		Actuation Type	Bending Amplitude (m ⁻¹)	Cost/Availability	Young's Modulus (MPa) (RH 20%)	Young's Modulus (MPa) (RH 90%)	Processability of cm-scale actuators
Bio-derived Materials	Wood veneer (this work)	Bending & Coiling	480-1854	\$	4937	1251	...
	Wood laminates ¹⁵⁻¹⁷	Bending	0-40	\$	14000	-	...
	Spider silk ²⁸	Linear	NA	\$\$\$	18000	-	•
	Bacteria spore/cells ^{29,57}	Bending	0-203	\$\$\$	7000-13000	-	•
	Keratin ⁵⁸	Bending & Linear	0-200	\$	2000	-	••
	Pollen ⁵⁹	Bending	0-220	\$\$	1460	660	...
	Pollen-toner ³¹	Bending & Coiling	0-800	\$\$	1460	660	...
	Starch/flour ⁶⁰	Bending & Coiling	0 - 200	\$	0.08-0.13		...
	Gelatin- amyloid (Gel-Am) ^{61,62}	Coiling	0 - 500	\$	0.04 – 0.1	-	••
	β -silk ³⁰	Bending	800 - 1600	\$\$	4100-7200	-	...
	Gelatin biogel ³⁴	-	-	\$	0.02-0.11	-	...
	Double-crosslinked cellulose ³⁵	-	-	\$\$	0.1-5	-	...
Biological tissues	Pine cone ⁶³	Bending	-5-58	\$	4530	-	••
	Erodium seed awn ²⁶	Coiling	0~1000	\$	9000	-	••
	Wheat awn ⁶⁴	Bending	5~200	\$	10000-20500	-	••
	Chiral seed pod ⁶⁵	Coiling	0~200	\$	~15000	-	••
Synthesized Materials	Hygrobot ⁴⁷ (PEG)	Bending	0-110	\$	169	-	...
	PDMS-PDOT:PSS ⁶⁶	Bending	0-350	\$\$	2	-	...
	TNF film ⁶⁷ (TiO ₂ nano-capillary)	Bending	0-100	\$\$	700	-	...
	PEE-PPy ⁶⁸ (pentaerythritol ethoxylate-polypyrrol)	Bending	-125-125	\$	2200	650	...
	PPy ⁶⁹ (polypyrrol film)	Bending	0-170	\$	2500	1650	...

Table S3: Young's moduli and elastic ratios for various species with approximately 12% moisture content. Adapted from⁷⁰.

Wood types	E_L (MPa)	E_T/E_L	E_R/E_L
Hardwood			
Oak, white (chosen in this work)	13530	0.072	0.163
Basswood	11110	0.027	0.066
Birch, yellow	15290	0.050	0.078
Cherry, black	11330	0.086	0.197
Cottonwood, eastern	10340	0.047	0.083
Maple, sugar	13860	0.065	0.132
Walnut, black	12760	0.056	0.106
Softwood			
Baldcypress	10890	0.039	0.084
Cedar, northern white	6050	0.081	0.183
Cedar, western red	8470	0.055	0.081
Douglas-fir – Interior Northern	13530	0.050	0.068
Hemlock, western	12430	0.031	0.058
Larch, western	14190	0.065	0.079
Pine, ponderosa	9790	0.083	0.122
Redwood – Old-grown	10120	0.089	0.087
Spruce, Engelmann	9790	0.059	0.128

Table S4. Drilling tests under different natural conditions in two geographical locations. Detailed soil information is shown in Table S5. The photographs of the 136 seeds, monitored for two consecutive days, before and after exposure to rain are shared at doi.org/10.5281/zenodo.7057563

Field Test	Month and Location	Weather Condition: Temp, Rain (Total Precipitation)	Soil Type	Sample Size	Establishing Rate	Anchoring Rate
Drilling test 1 _Day 1	July 5, Pittsburgh, USA	20 - 35 °C ~7 hr light rain (~5.5 mm)	Local topsoil (clay soil)	22	68%	95%
Drilling test 1 _Day 2	July 6, Pittsburgh, USA	22 - 35 °C ~2 hr heavy rain storm (~55 mm)	Local topsoil (clay soil)	22	36%	50%
Drilling test 2 _Day 1	Apr 23, Pittsburgh, USA	10 - 11 °C ~0.75 hr light rain (~2.5 mm)	Fiber soil	20	30%	60%
Drilling test 2 _Day 2	Apr 24, Pittsburgh, USA	15 - 20 °C In sun (0 mm)	Fiber soil	20	30%	60%
Drilling test 3 _Day 1	May 1, Pittsburgh, USA	10 - 16°C ~2 hr heavy rain (~16.5 mm)	Fiber soil	20	30%	55%
Drilling test 3 _Day 2	May 2, Pittsburgh, USA	10 - 22°C ~5 hr in sun (0 mm)	Fiber soil	20	45%	60%
Drilling test 4 _Day 1	Apr 13, Hangzhou, China	12 - 16 °C ~1 hr medium rain (~5 mm)	Sandy steer manure compost	18	33%	61%
Drilling test 4 _Day 2	Apr 14, Hangzhou, China	13 -18 °C Cloudy (0 mm)	Sandy steer manure compost	18	33%	61%
Drilling test 5 _Day 1	Apr 22, Hangzhou, China	25 - 28 °C ~3.5 hr light to medium rain (~8 mm)	Fiber soil	14	50%	91%
Drilling test 5 _Day 2	Apr 23, Hangzhou, China	24 - 28 °C ~1 hr light rain (~1 mm)	Fiber soil	14	50%	86%

Table S5: A summary of the soils used in the drilling and germination experiments. Measurements of granular size, the LSMV, compressive strength and the experiments in which the soil was utilized.

Soil Types	Granular Size (mm)	LSMV(mm ²)	Compressive Strength (kg/cm ²)	Experiments
Perlite 	3.3 ± 1.3	0.78	0.01± 0.01	In the lab: drilling tests in Fig. 1c, Fig. 3a, Fig. 4e,g,h
Fiber soil (Coconut coir) 	1.4 ± 1.0	1.62	0.05 ± 0.03	In the lab: drilling and germination tests in Fig.3d, Fig. 4b,c,d In the field: drilling tests
Local topsoil (clay soil) 	6.2 ± 6.2	4.61	0.09 ± 0.02	In the field, drilling and germination tests
Steer manure compost and sand (9:1 by weight) 	2.4 ± 1.9	0.70	0.09 ± 0.01	In the field, drilling tests

Supplementary Note 1: Additional Drilling Tests of Grass Seeds with Hygroscopic Awns

Comprehensive drilling tests have been performed in the past on different types of grass seeds with hygroscopic awns^{19,22}. However, various studies have different testing methods and conditions, depending on the goals of the study. To directly compare an extended body of seeds with motile awns beyond *Erodium* with our engineered seed carriers under the same testing conditions of ours, we carried out additional drilling tests with additional natural species ($N = 5$ of each species, for three triggering cycles), as summarized in Table S1. The testing procedure and conditions were consistent with “Drilling tests under controlled conditions” in Methods.

During the seed dropping phase from 35 cm above the soil, the three-tailed and lightweight (~ 0.1 mg) *Aristida purpurea* has a $\sim 40\%$ chance to anchor its tip into the gaps of the granules. After three triggering cycles, we did not observe any additional successful anchoring except for one *Erodium castellanum*. The originally anchored tips of *Aristida purpurea* did not show further burial either. Our explanation for the low drilling success is that the natural soil conditions, where these grasses survive, are quite different from ours. As shown in the literature¹⁹, after comparing 30 grass species and 10 awn morphological types, the authors concluded that the awn morphology and types have different functional roles in the dispersal and burial stage, and are highly customized to different environmental conditions. Since biology is often very selective, if we were to leverage biological organisms for aerial seeding, we would first need to understand how they work. Then we can propose where and how to use them. There is no guarantee that a chosen type will work for any habitat or that a natural species can be successfully identified for all potential target payloads and soil conditions.

On the other hand, during our controlled drilling test, we observed certain advantages relating to natural motile awns that aligned with our design principles. The body of *Stipa comata* contains many twists (~ 20), which results in highly effective axial rotation. However, due to its rather short and single tail, it did not form an effective angle between the body and the ground to initiate drilling on relatively flat soil. In contrast, due to the three-tailed arrangement, the body of the *Aristida purpurea* can form an effective (non-zero) angle with the ground. However, unlike the tail of *Erodium* that anchors its tip and uncoils to lift the body upwards for an advantageous drilling pose

during the hydration process, the tails of *Aristida purpurea* unbend and lay the body flat when hydrated.

By understanding how different natural species work and how awn morphology and other geometrical factors affect self-burial, we can design artificial versions to overcome the potential limitations of each individual species and strategically tailor our designs to target payloads and conditions. By taking advantage of the unique structure and function of wood veneers, we offer a new engineering solution that allows for accurate control of the morphology and mechanical properties, and thus self-drilling behaviors of the seed carriers. The interesting coincidence of our three-tailed design with the three-tailed *Aristida* further validates our design, which can combine different lessons and strengths of natural species, e.g., the three-tailed design shown in *Aristida purpurea*, the bent responsive tail that can expand and lift up the body in *Erodium guinum* and the large coiling numbers and elongated body length to increase the rotational speed in *Stipa spartea*.

Supplementary Note 2: SEM Measurements of Cellular Structures in the Bending Samples

We carried out SEM to image the cellular structures in bending samples, which are ~ 0.8 mm thick and have a 1.6 mm molding diameter. We first imaged the sample at a relatively low magnification (500 x) to identify the target cells for imaging their fibrils. We looked for cells at the relative middle section of the arc (-60° to 60° range as shown in Fig. S1a) with open cell walls and exposed S2 layers. We needed to identify three target cells on both the inner and the outer sides (see Fig. S1b). Ideally, the target cells should have equal distance to the neutral axis since the distance may contribute to different levels of compression or tension thus affecting the MFAs. However, in practice, it was almost impossible to find such target cells. Due to our laser-cutting approach for sample preparation, only a portion of cells could be cut in halves to expose the inner walls. Therefore, we looked for target cells that fell within the highlighted regions ($h/4 - h/2$ away from the neutral axis on both sides, as shown in Fig. S1a).

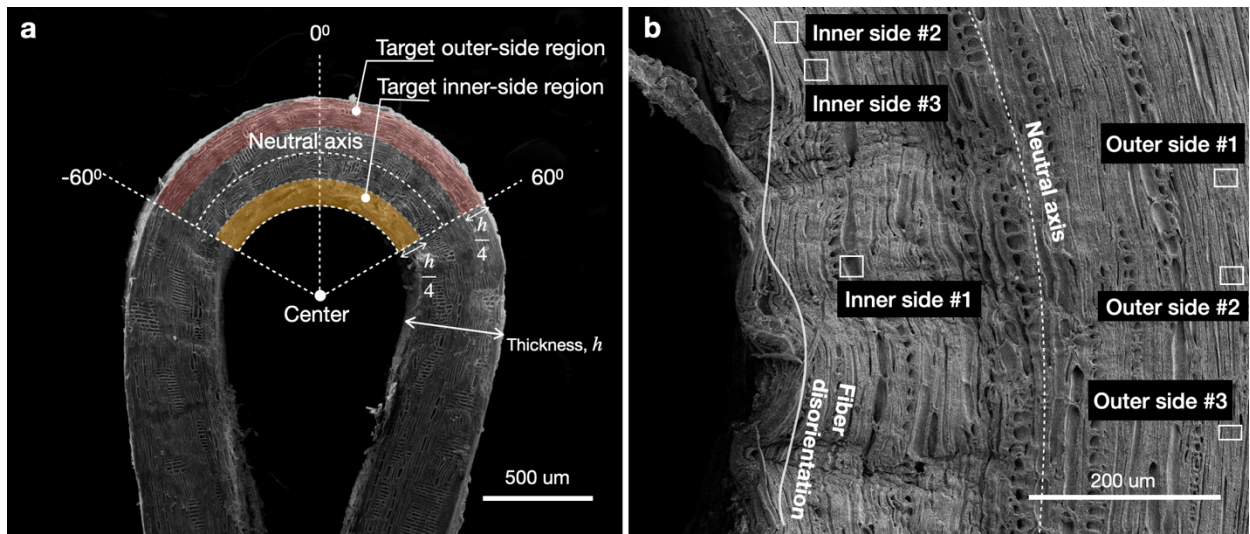


Figure S1. a, Methods to identify the target outer and inner sides of a bending actuator, annotated on top of the scanning electron microscopy (SEM) image of a bending actuator sample in a relatively low magnification (500 x). **b**, For each sample, three cells from the target inner-side region and three from the target outer-side region are imaged. Three samples were imaged.

We then imaged the MFA of the target cells. In total, we imaged three bending samples, and a set of images from a single sample is shown in Figures S2 and S3. SEM images show that the cells

on the outer side (Fig. S2) have relatively straight microfibrils, with relatively consistent and small MFAs ($9 \pm 2^\circ$, $N = 3 \text{ cells} \times 3 \text{ samples}$), which are similar to the MFAs ($9 \pm 2^\circ$, $N = 3 \text{ cells} \times 3 \text{ samples}$) in the flat samples before molding.

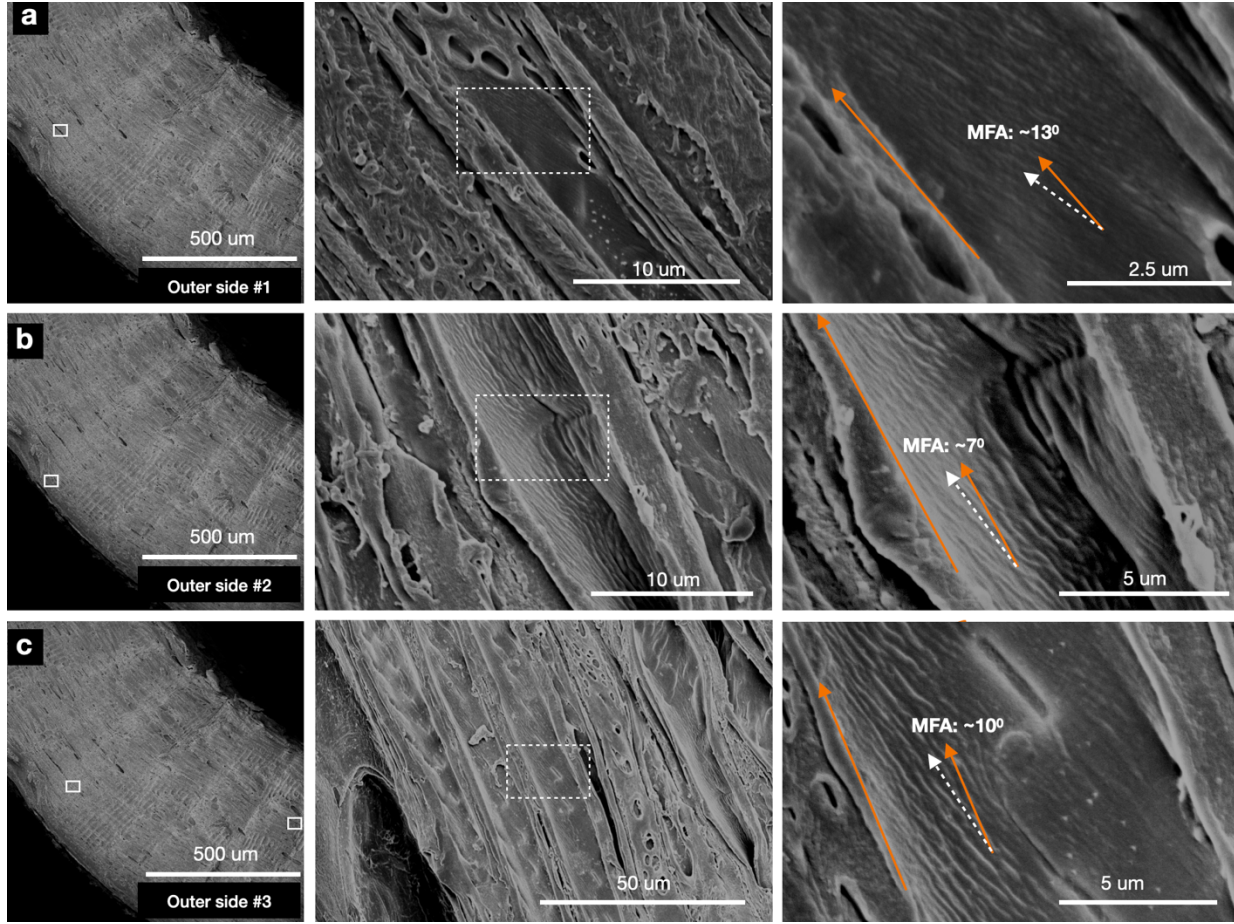


Figure S2. SEM images of cells from the outer side. The microfibrils are relatively straight, and the microfibril angles (MFAs) are relatively small ($9 \pm 2^\circ$, $N = 3 \text{ cells} \times 3 \text{ samples}$) and consistent.

In contrast, the deformed cells towards the inner side under compression (Fig. S3) have disoriented microfibrils. In the case of the disoriented microfibrils identified in our SEM images, we observed a general increase in MFA ($23 \pm 7^\circ$, $N = 3 \text{ cells} \times 3 \text{ samples}$). Previously, a distinct disorientation of the usually relatively straight microfibrils as a result of longitudinal compression was reported⁴¹, and our observation of the deformed cells from the inner side was consistent with the literature.

Note that while certain cells show obvious microfibril disorientation and crinklings (Fig. S3a), cells that are relatively straight and non-deformed (with an MFA of $\sim 11^\circ$ that is comparable to the outer side) also exist on the inner side (Fig. S3b). In the case of some cells, crinklings and fibril disorientation only appear to exist within local regions (Fig. S3c). The non-uniform deformation of the cellular structures is likely to be due to the structural heterogeneities of the wood.

Our hypothesis is that the MFA change exhibits a gradient across the thickness, which is induced by the strain gradient. Although we were able to identify obvious increases in MFAs in a portion of cells towards the inner side but not the outer side, compared to the unmolded samples, it was challenging to quantify the gradient of MFA changes across the thickness. This is due to the cell wall collapsing towards the compression side and the laser cutting approach, therefore, we did not have a large number of cells with exposed S2 layers at different distances away from the neutral axis to quantify the error bars. A systematic study of the cellular network change under mechanical loading and moisture environment changes is needed to more accurately predict the curvature formation and the actuation of the molded wood in future studies.

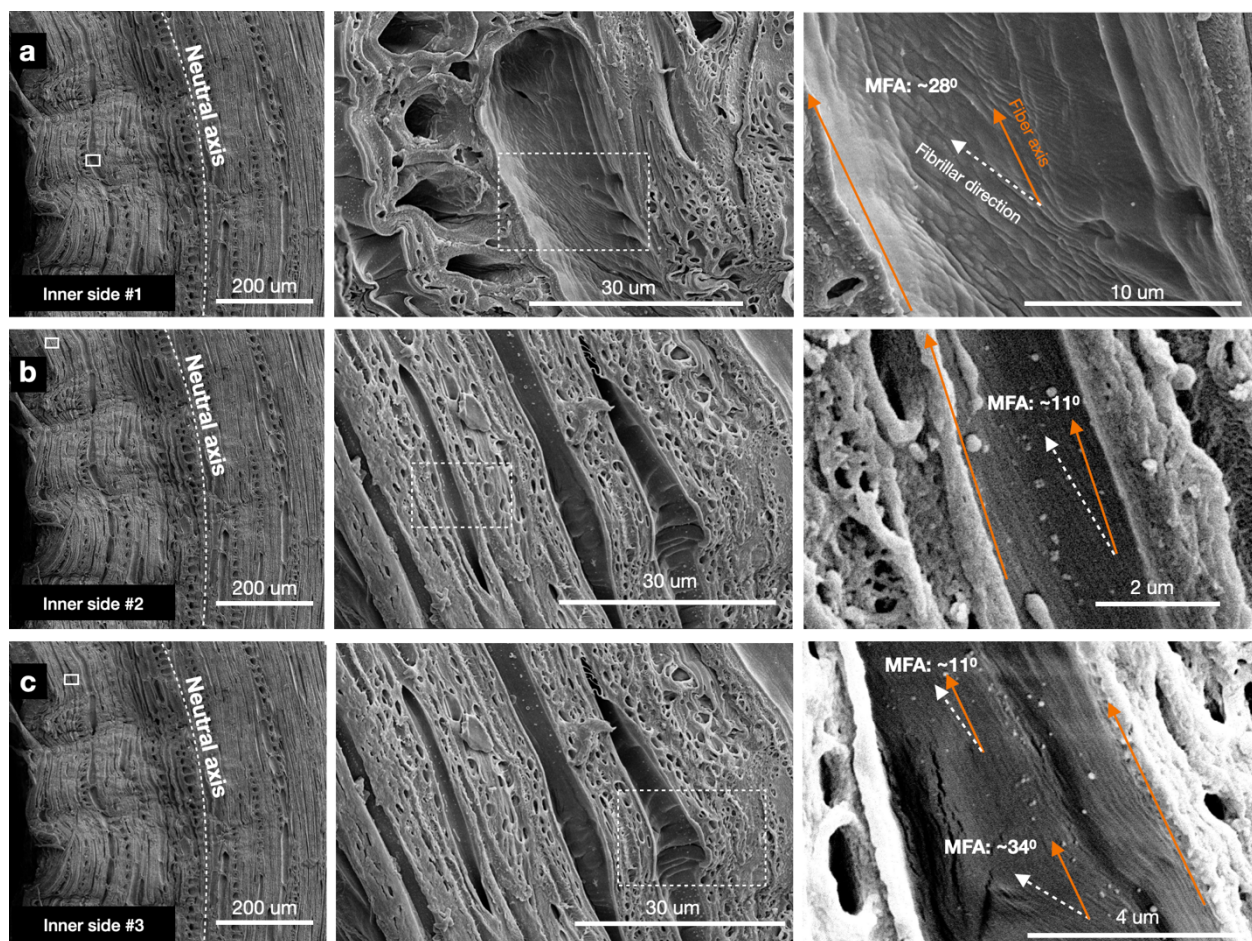


Figure S3. SEM images of cells from the inner side. Certain microfibrils are disoriented with an increased MFA ($\sim 28^\circ$ - $\sim 34^\circ$).

Supplementary Note S3: Cellular Size, Number and Distribution

Sizes of wood fiber cells: The rather small size of our wood strip (13.5 mm in length and 0.5 mm in thickness) compared to the size of the wood log (~500 mm in diameter) helped minimize the fiber cellular size variation induced by the variables in fabrication within a single strip. In addition, a relatively consistent wood log selection (14- to 20-year-old white oak), flat-saw cutting method of the wood sheet and careful selection of cutting strips along the fiber direction were practiced in our sample preparation.

However, due to the heterogeneous nature of wood materials, fiber cellular sizes are inevitably different within one wood strip and among different wood strips. In practice, cellular sizes are likely to have some effect on plastic deformation and hardening deformation, as well as hygromorphic behaviors.

We first investigated the effects of cell diameters of wood fibers. As Fig. S4 shows, we have compared the cell size variations within one sample and across different samples with our wood selection and cutting method. Within the same sample, we imaged the wood cells at two distant ends of the strip (Fig. S4a-b) and observed a ~13% change in the cellular size (Fig. S4c). The cell size changes across the thickness (radial direction) were small, as indicated by region 1 and 2 in Fig. S4d. In addition, we carried out random sampling at four different locations of the wood lumber (Fig. S4e-f). While the current cellular size change did not significantly affect the fabrication process, the heterogeneity of the wood and variability of our manual molding process caused variability in the final curvature across samples. With three wood strips cut from randomly selected locations of the wood lumber, the average curvature was measured as $1865 \pm 70.8 \text{ m}^{-1}$. Since our current analysis did not take into account the heterogeneity in cell sizes across the height or the radius of the trunk, further study is needed to understand the extent to which the cellular size differences contribute to variations in the maximum bending curvatures.

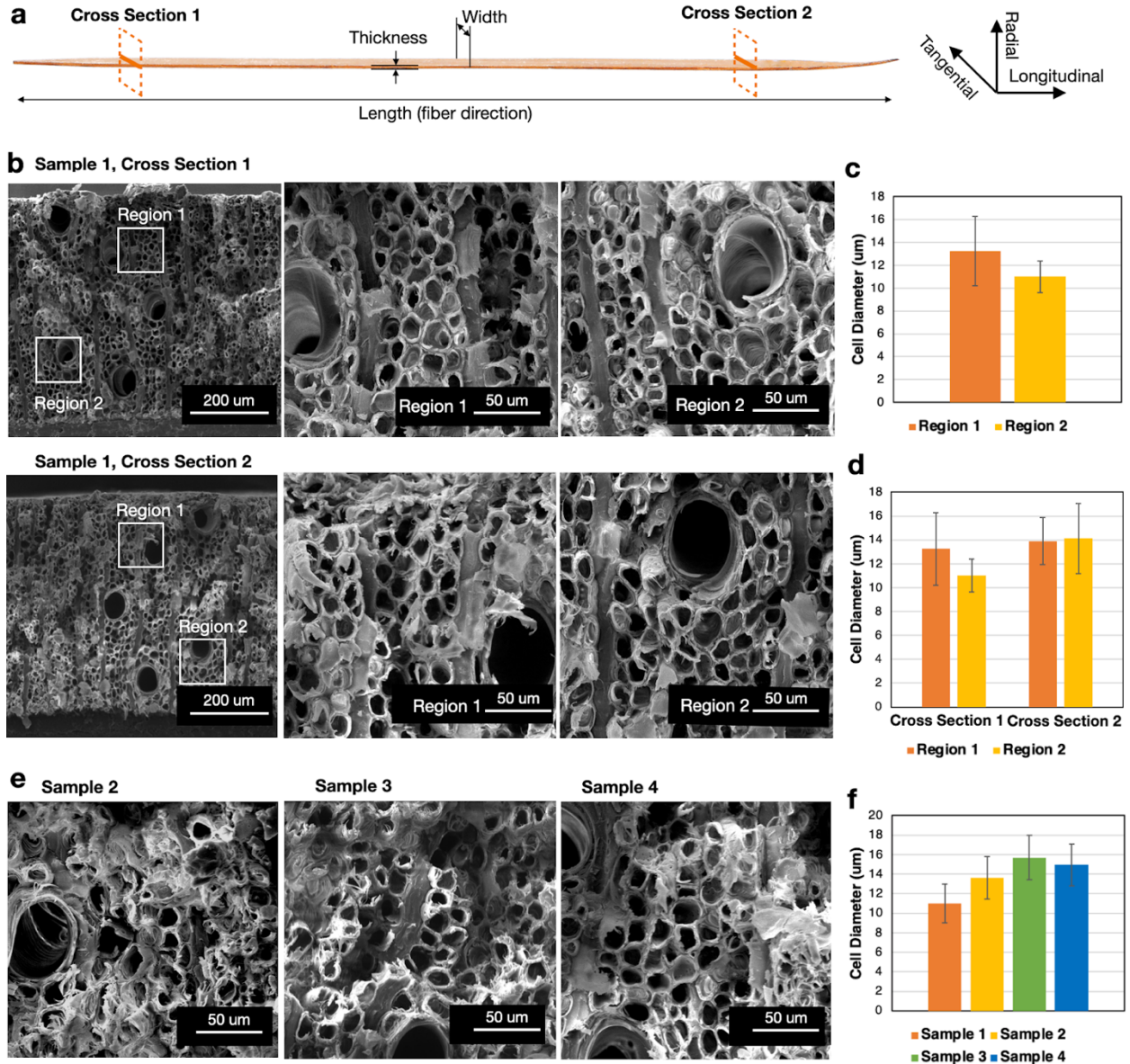


Figure S4. The differences in cellular sizes. **a**, A single wood strip sample was cut from wood lumber. **b**, SEM images of the cross-sections of a single sample. **c**, Cellular size comparison at two cross-sections at opposite ends of the strip along the length (the longitudinal direction). Data are means $\pm$ SD. $N = 20$ cells per cross-section. **d**, Cellular size comparison across the thickness (along the radial direction) at the same cross-section. Data are means $\pm$ SD. $N = 10$ cells per region. **e**, SEM images of the cross-sections of four randomly selected samples at different locations on a white oak log. **f**, Cellular size comparison across four samples shown in (e). Data are means $\pm$ SD. $N = 10$ cells per sample.

The impact of veneer polarity to the molded dry curvature: To further understand whether the polarity within the latewood affects the molding curvature, we molded samples from the same wood strip towards two opposite sides and compared the curvatures achieved. During this test, we used three strips from three randomly selected veneer sheets of latewood. For each strip, we took six samples, with three of them molded towards one side and the other three towards the opposite side (Fig. S5c). The error bar indicates the curvature variations of the three samples on the same side. We did not observe any noticeable role played by the veneer polarity, since the differences between the two sides were smaller than the error ranges of a single side.

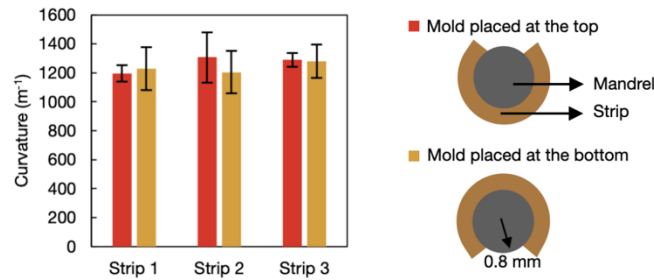


Figure S5. Comparison of the molded dry curvature with samples molded towards two opposite sides. For each strip, ~0.5 mm thick and 2.2 mm wide, six samples of 5mm lengths are prepared, with three of these molded towards one side and the other three towards the opposite side. Data are means $\pm$ SD, $N = 3$.

Vessel number and distribution: To understand this aspect, we chose to prepare three veneer sheets from the same white oak lumber, with the sheets ~2 years apart from one other (Fig. S6a). On each sheet, we randomly chose five locations to derive five samples, 5 mm in length and 2.2 mm in width. We imaged one cross-section of each sample under SEM (Fig.S6b), counted the vessels that are larger than 25 μ m and compared the dry curvature after the samples were molded on a 0.8 mm mandrel.

Figure S6c shows that the total number of vessels decreases as the sample is obtained closer to the center of the trunk. It also shows that the curvature of the molded sample decreases from $1318.4 \pm 110.5 \text{ m}^{-1}$ to $1079.7 \pm 95.5 \text{ m}^{-1}$ as the total vessel number increases from 11 ± 3 to 35 ± 7 .

To investigate the vessel distribution, we counted a total of five samples from each sheet and mapped them out spatially (Fig. S6d). Since our sample is relatively thin (~0.5 mm), the vessel is

relatively evenly distributed across the thickness, especially in the case of sheet 1 and sheet 2 (Fig. S6e). Despite the fact that sheet 3 exhibited a comparably larger difference (with a 17.8% difference) in total vessel numbers between the top and bottom halves, we did not observe a greater standard deviation in curvature than that of sheet 1 in Fig. S6c. Therefore, we do not believe that the gradient of the vessel across the thickness played as significant a role as the other factors (e.g., the unavoidable variations of the manual molding process and the total changing number of the vessels) in the curvature variation, which is also verified in Fig. S5.

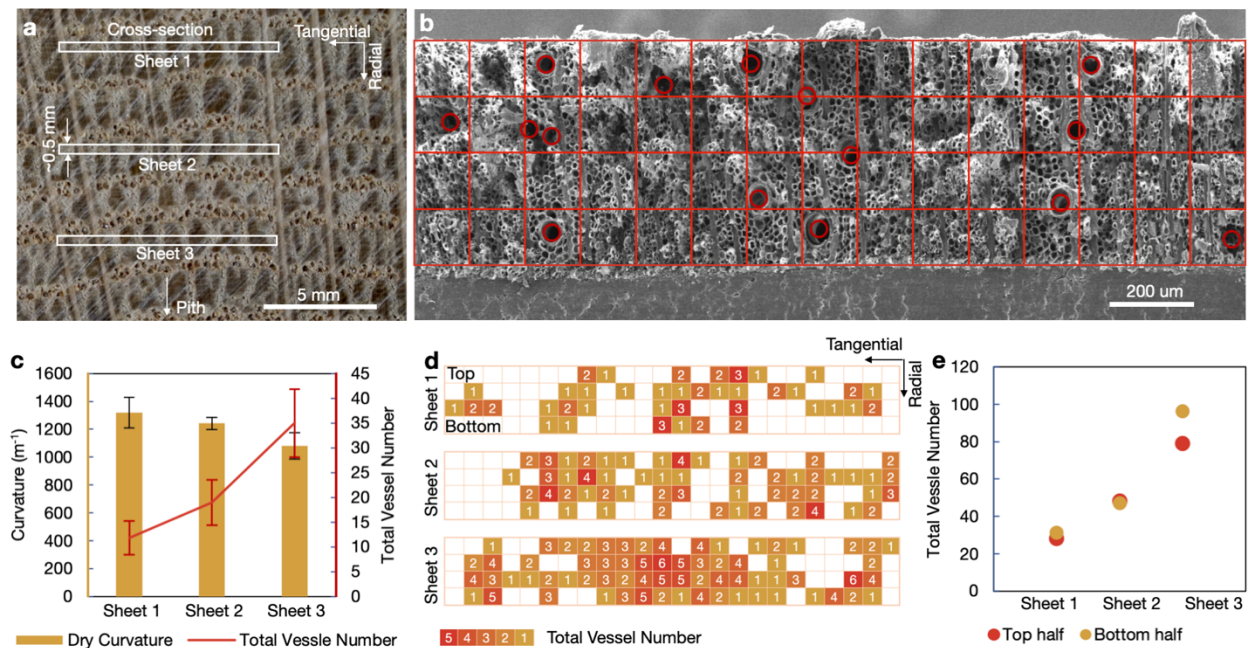


Figure S6: The effects of vessel numbers and distribution. **a**, The cross-section of the white oak lumber used for our sample preparation. The wood strips used to mold the samples are prepared from latewood, with relatively small vessel diameters of $\sim 25 - 50 \mu m$. Five samples, 2.2 mm wide, 5 mm long and ~ 0.5 mm thick are prepared from each sheet. **b**, Vessels with a diameter larger than $\sim 30 \mu m$ were identified and counted in the cross-section SEM image of each sample. **c**, Comparison of molded dry curvature and total vessel size of each sheet. $N = 5$ samples from each sheet. Data are means $\pm$ SD. **d**, Spatial distribution of the total vessels of the five samples from each sheet. **e**, Comparison of the total number of vessels for the top and bottom halves of all five samples of each sheet.

Supplementary Note 4: Extension Force of the Coiling Actuators

Extension forces are measured inside a chamber of 20 cm³ (Fig. S7). A load cell with a capacity of 100 g (TAL221, HTC sensors) was connected to a signal amplifier (HX 711, Sparkfun) and a combined temperature and humidity sensor (SHTC3, Sparkfun) was placed inside the chamber to monitor the conditions. A mixture of hot steam and ultrasonic-generated mist was fed into the chamber constantly during all hydration processes. The temperature and relative humidity were kept at ~30°C and ~93% during hydration for 90 mins, until the sample was fully hydrated and the curvature did not change further. The force measurement stayed constant during prolonged hydration beyond 90 mins. During dehydration, the temperature was kept at 25°C, with the relative humidity in the range of 30~40% for another 30 mins until the sample shortened to detach from the measuring plate and the measurement dropped to zero. For dehydration processes, the mist was turned off and a fan turned on to promote ventilation.

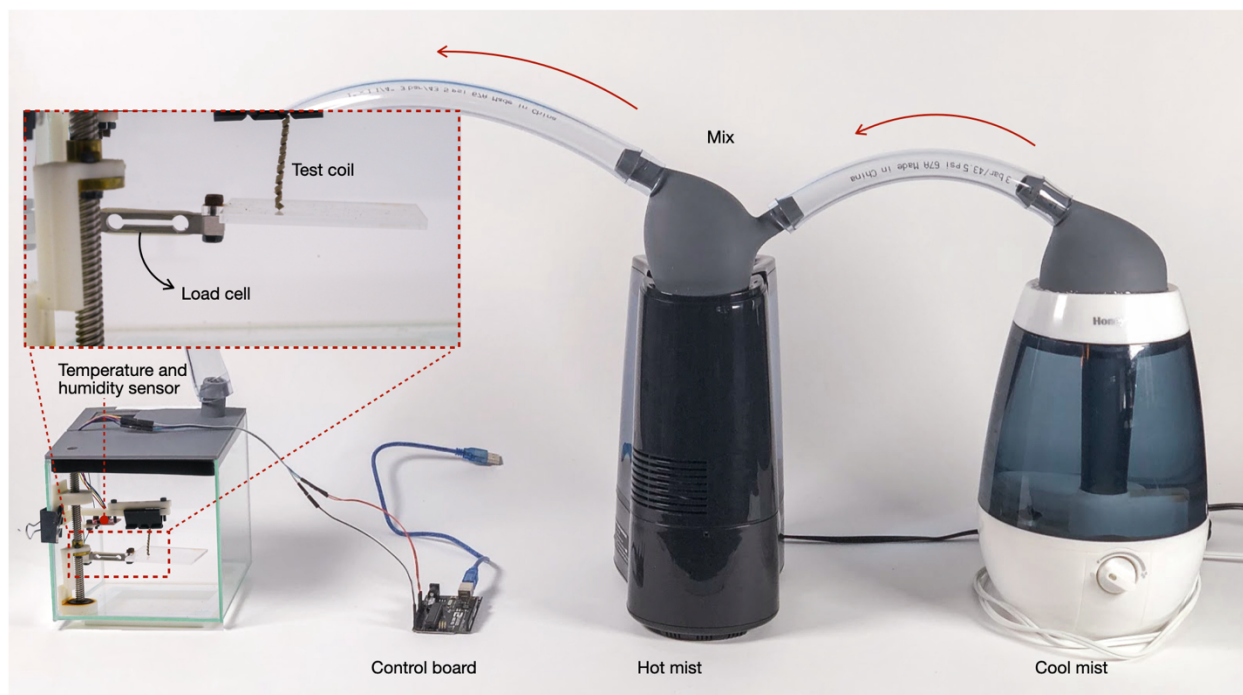


Figure S7. Customized set-up for extension force measurements.

We compared the extension force profiles of coils of two different thicknesses (0.74 ± 0.06 mm and 0.50 ± 0.02 mm) and three different coiling numbers (3.5, 7 and 10.5 coils) (Fig. S8). The *Erodium* bodies with three coils of uneven diameters were also tested. We observed that the 3.5 coil with a 0.74 mm thickness provided the largest peak extension force, 55.18 ± 6.82 mN, which

is $\sim 34\%$ larger than that of natural *Erodium*, 36.57 ± 6.82 mN. However, while we observed a general increase in peak extension forces when increasing the thickness of the strips, the percentage of the increase was not the same: when the thickness increased from ~ 0.5 mm to ~ 0.7 mm, the peak force of the 3.5 coil increased $\sim 38\%$, while that of the 7 coil only increased $\sim 7\%$. In addition, most peak forces were reached within the first 30 minutes. Therefore, we expect an effective natural rain that can promote self-drilling of a seed carrier should last for at least 30 minutes. Of course, this is only an estimate since other natural conditions, such as rain intensity and temperature, may also play important roles in relation to the extension force of the actuators.

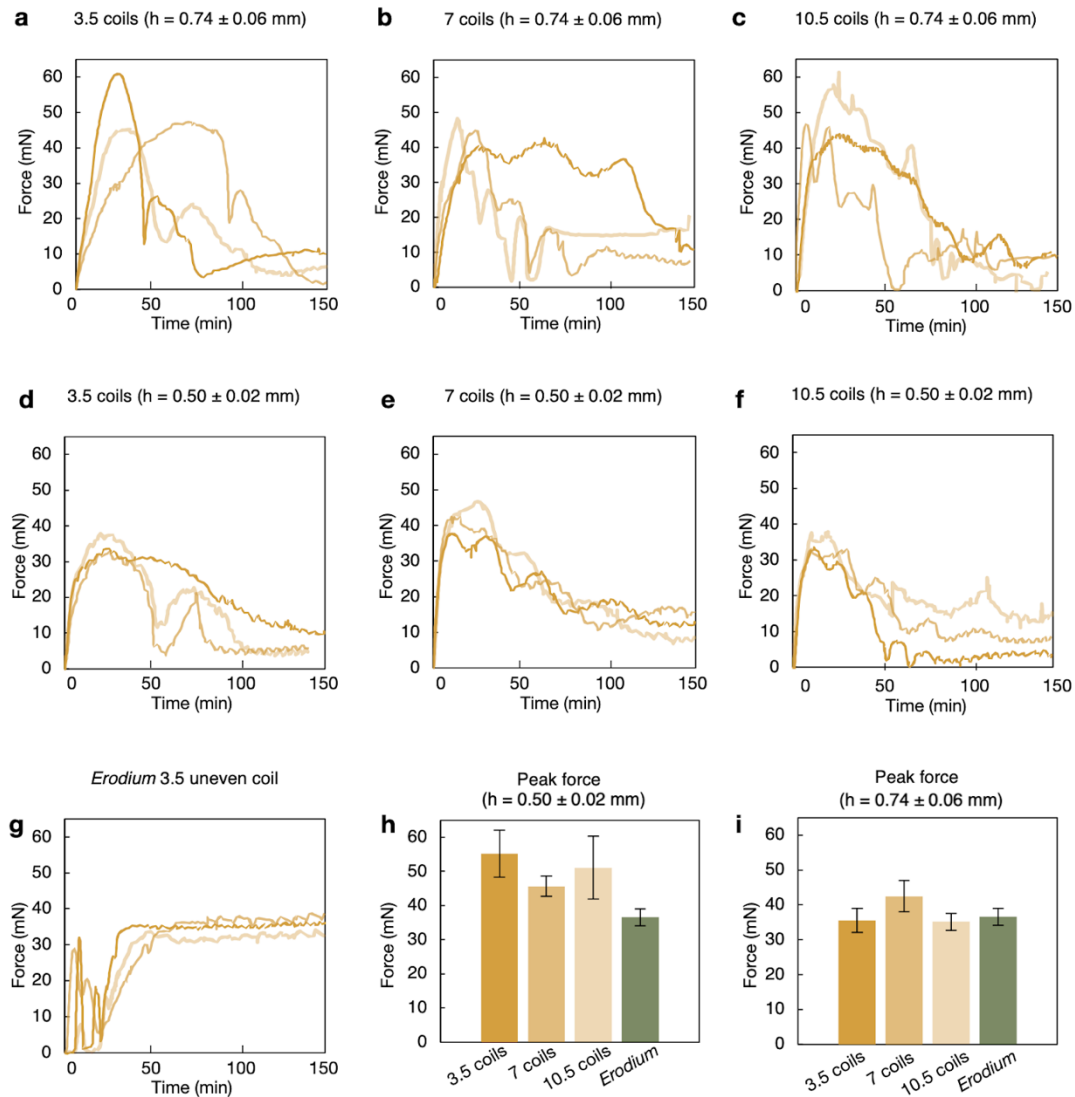


Figure S8. Measurement and comparison of extension forces generated by different coiling actuators. **a-c**, Extension force curves of 3.5 coils, 7 coils and 10.5 coils with a ~ 0.74 mm

thickness. **d-f**, Extension force curves of 3.5 coils, 7 coils and 10.5 coils with a ~0.50 mm thickness. **g**, Extension force curves of *Erodium guinum* coils. Note that the three coils of *Erodium* have varying diameters, with the largest diameter coil touching the load cell. **h-i**, Comparison of the peak extension forces, with data as means $\pm$ SD and $N = 3$. In all the tests, the engineered coils are prepared from white oak strips of 2.2 mm in width and molded on mandrels with a diameter of 0.8 mm. The extension force measurement protocol is described in Methods.

Supplementary Note 5: Drilling and Germination Performances in Field Tests

Temperature Effects. It appears that the temperature affects the drilling performance. Tests 2-4 from Table S4 had an average temperature of $\sim 12-17^{\circ}\text{C}$, with a 33.5% establishing rate, while test 1 and 5 experienced an average temperature of $\sim 23-32^{\circ}\text{C}$ with a 51% establishing rate. To understand how temperature may affect the thrust force generated by the coiled body, we conducted a controlled test to compare the 7 coils extension force under two different temperature conditions (Fig. S9). This showed that the peak force decreased from 42.47 ± 4.48 mN to 31.45 ± 2.63 mN when the testing temperature dropped from $\sim 30^{\circ}\text{C}$ to $\sim 18^{\circ}\text{C}$. The coil under a higher temperature also exhibited a greater rate of force increase within the first 5 mins.

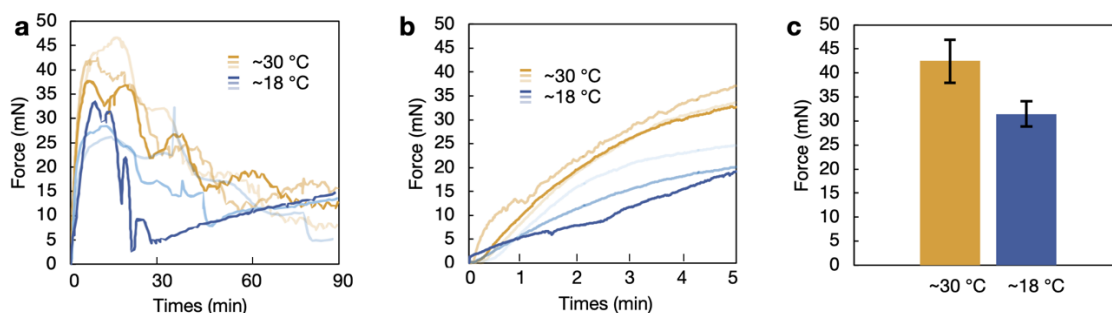


Figure S9. Comparison of coil extension forces under different temperature conditions. a, Extension force profiles during the 90 min hydration process under $\sim 30^{\circ}\text{C}$ and $\sim 18^{\circ}\text{C}$. **b,** The rate of increase in the extension force is larger at $\sim 30^{\circ}\text{C}$ than $\sim 18^{\circ}\text{C}$ for the initial 5 minutes. **c,** The comparison of peak forces under two different temperatures. All the tests were conducted in the controlled chamber (Methods), with 7 coils of ~ 0.5 mm thickness. For (c), data are means $\pm$ SD, $N = 3$.

Soil Granularity. We analyzed the two-day averaged establishing rate on soils with different granularities in the field tests (Table S4) and summarized the data as follows: in fiber soil (tests 2, 3 and 5), the averaged establishing rate of the three tests was 38%; in local topsoil (test 1), the averaged establishing rate was 52%; in sandy steer manure compost (test 4), the establishing rate was 33%. The two-day averaged establishing rate is used to take account of the environmental variations on day 1 and day 2. These data show that the establishing rate has a positive correlation with the LSMV measured in Table S5. However, the establishing rate can also be

influenced by other factors (e.g., temperature and rains), as the referee pointed out. More controlled field tests are needed to draw a concrete conclusion.

Germination Results. We tracked the germination performance across five tests in Table S4. However, we had to give up test 4 as most of the seed carriers, including the ones with tips buried from this test, went missing over the fifth night. We suspect nocturnal animals such as raccoons took the seeds since dug holes were observed. We managed to track the germination performance in the remaining four field tests (tests 1-3 and 5 in Table S4) for 15 days. Initially, there were 47 anchored seed carriers and 29 unanchored ones. Over the testing period, three anchored seed carriers were dislodged, and an additional anchored one went missing. On day 15, we observed that 26 of out 43 anchored seeds geminated successfully with a 60.5% germination rate, and 4 out of 32 unanchored or dislodged ones germinated with a 12.5% germination rate. Note that while we embedded five arugula seeds (Eden Brothers, USA) into each seedpod, a seed carrier was considered to have successful germinated if we observed at least one sprout. The sprouts totaled 82 in the 26 anchored seed carriers and 6 in the 4 unanchored ones.

The above tests were conducted from April to early July, which is the most suitable season for germinating most vegetable and flower seeds in both of our testing sites. To understand whether the seed carriers could germinate seeds in later seasons with varying seed types, we conducted an additional germination test in fiber soil from August to September, when the average temperature was 35 – 40 °C. 400 seed carriers were deployed in the field. 200 of those had their seedpods 80% buried beneath the soil manually, and the other 200 were placed on the soil surface and unburied. Two hot pepper seeds known to germinate at relatively high temperatures (27 – 32 °C) were embedded in each seedpod. After a month, we observed a 35.5% germination rate for the buried seed carriers and 2% for the unburied ones. While we observed a consistent advantage of the buried seeds over the unburied ones in their germination performance, we obtained an overall lower germination rate than the tests conducted in earlier seasons.

Supplementary Note 6: Fabrication Details

The five-step approach involves the processing of bulk wood into wood veneers with suitable dimensions, the partial removal of lignin and hemicellulose via a short boiling process in an aqueous mixture of sodium hydroxide (NaOH) and sodium sulfite (Na₂SO₃) to improve the moldability of the wood veneer, followed by three-step mechanical molding including a wet molding, a releasing and a drying step.

Wood veneer processing (Extended Data Fig. 4a-h). 3 cm-thick white oak (*Quercus alba*) lumber was acquired from a local lumberyard in North America and prepared in-house. The lumber was flat-sawn into a block with dimensions of roughly 20 cm by 40 cm, with the long edge being parallel to the fiber direction. The block was then sliced into four to five thin sheets, each running through a drum sander to further reduce the thickness until it reached the desired value. The wood veneers obtained after this step had a range of thickness of between 0.4 mm and 0.8 mm. All the test samples and application examples are outlined in Rhinoceros. The outlines were sent to a laser cutter (Universal Laser Systems) and cut from the wood veneer to the required thickness.

Note that within each annual ring of white oak, the earlywood has larger vessel diameters of ~250 - 500 μm than that of latewood at ~20-50 μm ⁷¹. Since our sample is quite thin, relative to the thickness of each annual ring (Fig. S10a), we chose only to use the latewood. We believe that excluding the earlywood with relatively large vessels helps decrease the effects of vessel polarity or the distribution on the bending performance. Before cutting, the exact location of the outlines was visually inspected to avoid the earlywood region with large vessel pores with diameters of ~0.25-0.5 mm in the white oak. As shown in Fig. S10b below, the earlywood regions where large vessels concentrate can be identified at low magnification with the naked eye in the case of white oak. In regions where visually identifiable pores exist, these will be excluded for sample preparation. In addition, to ensure a relatively uniform fiber direction, we laser cut the strip along the wood fiber direction (see Extended Data Fig. 4g).

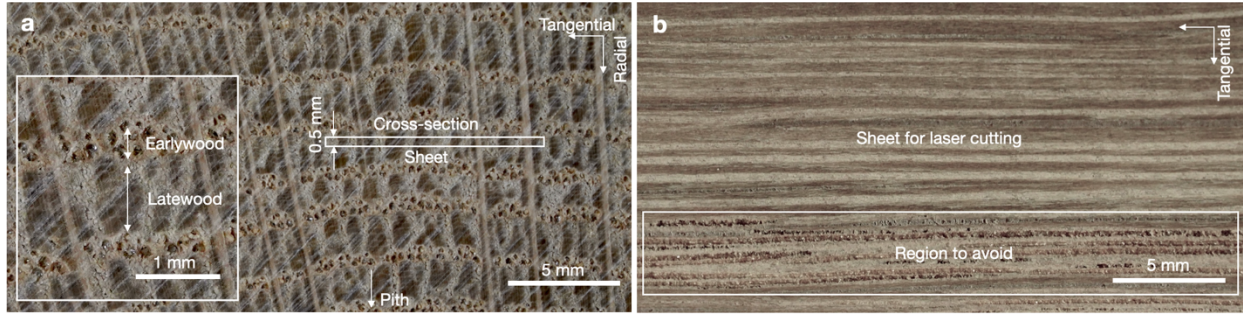


Figure S10. a, The relative size and location of a sample sheet situated on a tangential-radial plane of a white oak lumber. The sheet is prepared from the latewood region with relatively small vessels. **b,** Regions with large vessels are excluded before the laser cutting and strip sample preparation through a visual inspection process relying on human naked eyes.

Chemical washing. Sodium hydroxide (NaOH, Innovating Science, laboratory-grade), sodium sulfite (Na_2SO_3 , LabChem, ACS grade) and filtered water were used for partial delignification chemical baths. The obtained wood strips were immersed in a boiling aqueous solution of 2.5 M NaOH and 0.4 M Na_2SO_3 for different durations specified in each test (Extended Data Fig. 4i), followed by rinsing in boiling water with gentle agitation three times until the water was clear.

Mechanical molding. To make coiling actuators, the chemically washed veneer strips were pat-dried on a paper towel and placed in the open air for 1 min before being molded tightly on a 3D-printed mold (by Formlabs 3, Extended Data Fig. 4j and k). The body coiling diameter can be varied by inserting mandrels of varying diameters into the mold. The molded wood veneer was released from the mold when still wet, and dried at room temperature for 12 h (Extended Data Fig. 4l-n). The coil pitch is predominantly determined by three factors: the initial coiling angle, the variability caused by the manual coiling process, and the varied tightening performance during the released and drying step. To achieve a fixed initial coiling angle, we customized a mold integrating guiding helical steps, with a pre-determined coiling angle, to facilitate the starting point of the manual coiling process (Fig. S11a). During the coiling process, we ensured that the edge of the strip was always tightly connected without gaps or overlaps in between. In addition, due to the differences in cellular structures from different wood strips, the total shrinkage ratio between the released (Extended Data Fig. 4m) and drying (Extended Data Fig. 4n) stages may vary, which could also result in variability in the pitch. We measured the first five pitches of the coiled body ($N = 3$) and observed that while the first two pitches had relatively large standard deviations, which

was likely to be due to boundary effects; the third to the fifth pitches were reasonably consistent (Fig. S11b-d).

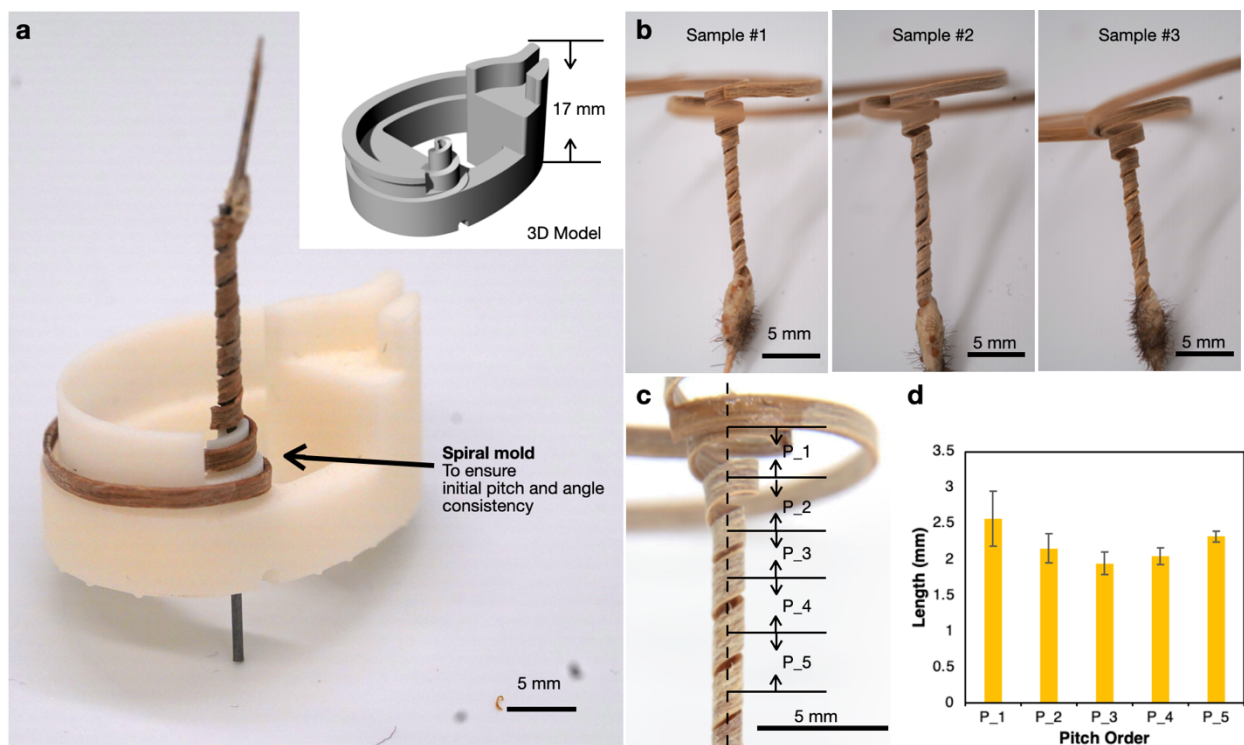


Figure S11. Spiral mold design and measurements of pitch variations in coiled bodies. **a**, The customized spiral mold to control the initial pitch angle consistency. **b**, Three samples show variations in pitch. **c-d**, Comparison of five pitches across the three samples shown in (b). Data are means $\pm$ SD.

Tip fabrication (Extended Data Fig. 4r-w). In the case of the fully biodegradable seed carrier, the tip was made of a dough by mixing 42 g flour and 112 mL water, shaped by a two-part mold. After the dough dried completely after 12 h, the tip was dipped into a 20 wt% ethyl cellulose/ethanol solution twice for waterproofing, following the literature procedure²⁴. Immediately after the second dip, the tip was coated with a uniform layer of horse mane hairs, cut into 2 mm fibers by electrostatic flocking.

The three-tailed seed carriers were made with two separately molded tails, which were glued to the end of the active coil (Extended Data Fig. 4o-q).

The double-coiled seed carriers were made with two layers of washed wood veneer for the coiling body. Once the first layer was molded, the coil was clamped and dried at room temperature for 12 hours. The second layer was then wrapped around the first layer and clamped to dry below room temperature for another 12 hours (Extended Data Fig. 4x).

The large-sized seed carrier was made of a wood veneer with 0.8 mm thickness, a 12 mm width and a 300 mm length, molded around a mandrel with 3 mm diameter. Two extra tails were glued at the end of the active coil. A whitebark pine seed (*Pinus albicaulis*) was embedded inside the flour dough tip, then hairs were added.

To make the bending actuators in Fig. 2 using the aforementioned five-step process, the washed veneer strips were molded against the mandrel (convex) with an acrylic-based negative mold (concave) on the outer peripheral. The size of the mandrel and the acrylic mold varied based on the desired bending curvature and the sample thickness.

Supplementary Note 7: Guidelines for Choosing Wood Types

We need wood that (i) is moldable into the large target curvature (a tight coil with a maximum curvature of 1854 m^{-1}), (ii) forms stiff coils to maximize thrust force and prevent bending of the coiled body, (iii) has a large actuation amplitude and good reversibility. We further propose benchmark tests to evaluate these criteria and discuss the potential challenges in choosing wood types to optimize the actuator performances.

Since multi-physics factors are involved in determining the wood choices, we suggest a straightforward procedure experimentally, to identify the suitable wood types that fulfill (i-iii): choosing a few types of wood of interest (in our experiment, we chose four commercially important⁷² wood types and bamboo that have relatively parallel fibers, then conducting the test shown in Extended Data Fig. 8a to select the type that provides the largest dry curvature on a target mandrel (0.8 mm in diameter) and the largest actuation amplitude with good reversibility, by measuring at least three actuation cycles. If the design goal is changed, e.g., a larger coiled body with a thicker strip is molded, we would suggest re-doing the benchmarking test to select the most suitable wood types.

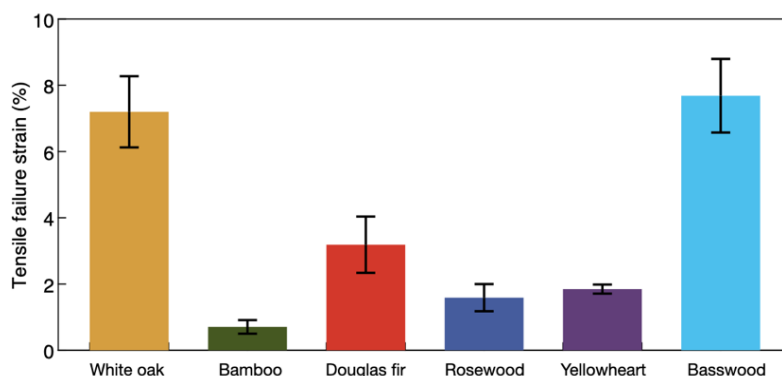


Figure S12. Tensile test to compare the tensile failure strain of the chosen wood types. The samples are 2.2 mm in width, ~0.5 mm in thickness and 80 mm in length. To match our sample molding process, the chemically washed and fully hydrated samples were left in an open environment for 10 min before the tensile test. Data are means $\pm$ SD. $N = 3$.

To fulfill our criterion (i), it can be observed in Extended Data Fig. 8a-b that certain woods (such as white oak, basswood and Douglas fir) can be molded more easily into large curvatures than others. With regard to the wood types that failed, the fractures often occurred on the outer

(tensioned) side of the coil. We suggest choosing a wood type with a large failure strain under tension, which can be obtained through a tensile test. White oak and basswood stood up to larger failure strains among the wood types we tested, following the same chemical washing process (Fig. S12).

In the case of (ii), in order to achieve stiff coils, we suggest choosing a wood type with a relatively large Young's modulus after chemical washing. However, other factors such as the potential damage during molding (Extended Data Fig. 8e) can also affect the coil stiffness. We recommend further characterization of the molded coils to directly evaluate the effective extension force of the coiling actuators (refer to the extension force test described in Methods and Supplementary Note 4).

In the case of (iii), the large amplitude of the actuation from the wet to the dry state of the coil is determined by the gradient of the moisture shrinkage ratio, caused by deformation during molding. We would suggest choosing wood with strong coupling between the mechanical deformation and moisture induced shrinkage. The good reversibility of an actuator requires little plasticity and minimal local damage under deformation, driven by moisture content change. Since the couplings between moisture and mechanical deformation among wood types are usually highly nonlinear and may also depend on the applied stress state, it is challenging to establish a single criterion that can optimize both amplitude and reversibility at the same time. We recommend measuring the curvature changes of a simple bending actuator for three-cycles as benchmark tests (exemplified in Extended Data Fig. 8a), so as to evaluate the wood materials.

Among the chosen wood materials tested, white oak is the most suitable in terms of its largest initial curvature, actuation amplitude and good reversibility (Extended Data Fig. 8a). However, it should be pointed out that these criteria are based on our experimental observations and serve as guidelines for our design, as it is a challenging, multi-objective optimization problem. In addition, the wood properties are influenced by the chemical washing conditions and manufacturing methods. Our preliminary tests have already shown that rosewood coils also exhibit a promising performance with a smaller actuation amplitude yet better reversibility in three actuation cycles (Extended Data Fig. 8a), showing the possible extensions of the current framework to other wood types and applications. The detailed evaluations and optimizations of

the wood materials, tailored to different applications, are important but beyond the current scope, which will be studied in the future.

Supplementary Note 8: Seeds Entanglement in Drone Deployment

When multiple seeds are randomly placed together, they entangle (Fig. S13a). In our original drone deployment solution, we used dividers in the storage box to prevent entanglement (Extended Data Fig. 3). This was sufficient for our smaller-scale test described in the paper. However, for a much larger scale deployment in the future, further investigation into the entanglement behavior and alternative engineering solution is needed. To date, we have conducted a preliminary test by storing 10 seeds inside one container and dropping them from ~5 m above the local topsoil. We observed entanglement inside the box. When dropped, due to the impact force, the seeds tended to separate after hitting the ground. However, small clusters were still observed from two of the four dropping tests (Fig. S13b-d). Further tests are needed in the future when seeds are dropped onto different soil types and from different heights, which are beyond the scope of this manuscript.

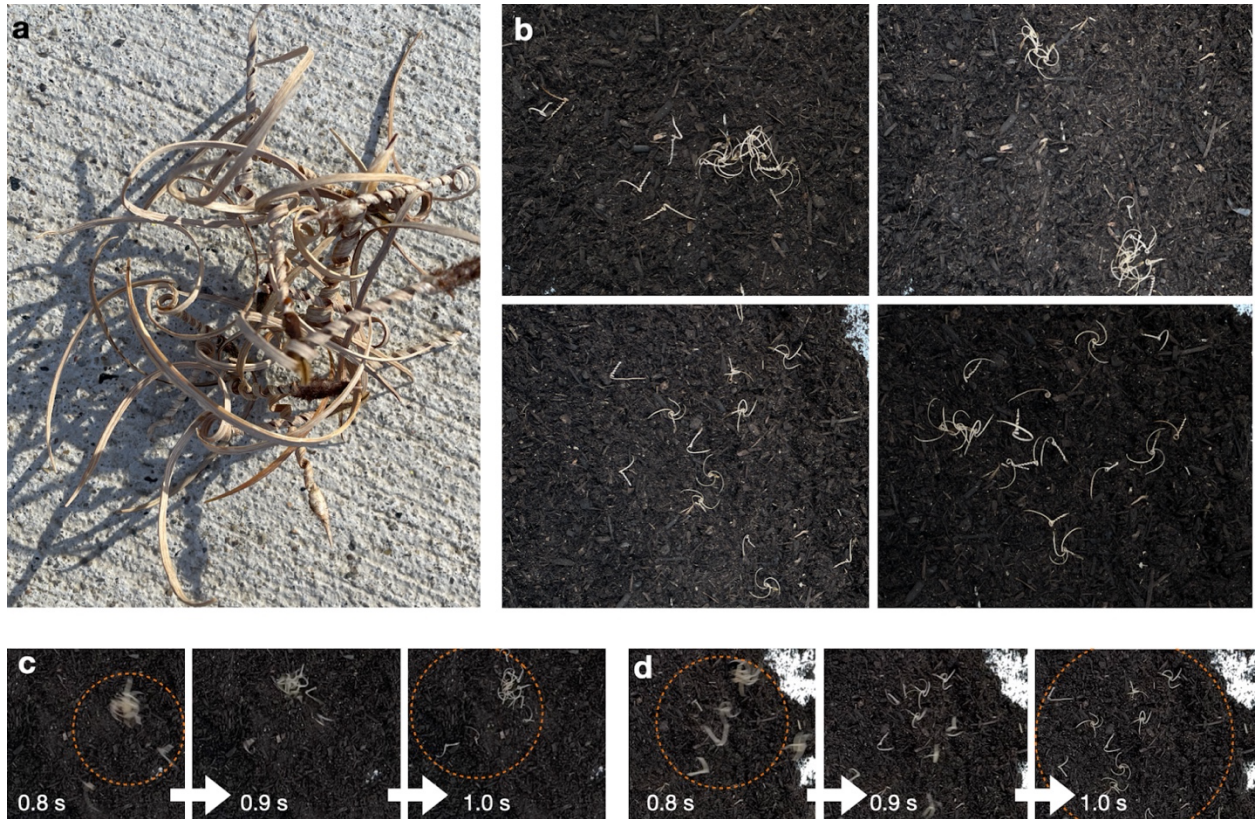


Figure S13. Seed dropping tests. **a**, Entanglements when seeds are stacked together randomly. **b**, Results of four dropping tests from ~5m above the local topsoil. **c-d**, The degree of separation varies between the two dropping tests.

We also believe that further engineering efforts are needed to design more effective storage and deployment mechanisms that minimize entanglement. For example, Figure S14 shows one potential solution with an extendable accordion structure.



Figure S14. Conceptualized storage and delivery mechanism. **a**, The assembly of seeds on an extendable accordion structure to avoid entanglement. **b**, The dropping of the seed through the extension of the seed storage device. **c**, Seeds delivered and dropped on the ground. Scale bar: 10 mm.

Supplementary Note 9: Curvature of Bending Actuators in the Wet State just After Release

This note aims to establish a relationship between the bending curvature in the wet state just after release (κ_w) and the material (e.g., plastic deformation behaviors) and geometrical (e.g., thickness h) properties of the wood veneers and the radius of the mold (R). Since our focus is on bending actuators, the wood veneer can be modeled as a beam. In the analysis, the wood veneer thickness, h , and the mold radius, R , can be directly measured from the experiments. The key material properties included two critical strains associated with plastic deformation, ϵ_{Y_1} and ϵ_{Y_2} , which are fitting parameters and will be extracted by comparing the theoretical predictions with experimental results. We first analyzed κ_w for wood veneers within the ideal plastic deformation region. During the molding process (Fig. S15a), the deformation strain was:

$$\epsilon = (y_1 - y)\kappa, -h/2 < y < h/2, \quad (1)$$

where y_1 is the coordinate of the neutral axis and κ is the bending curvature in respect to the neutral axis.

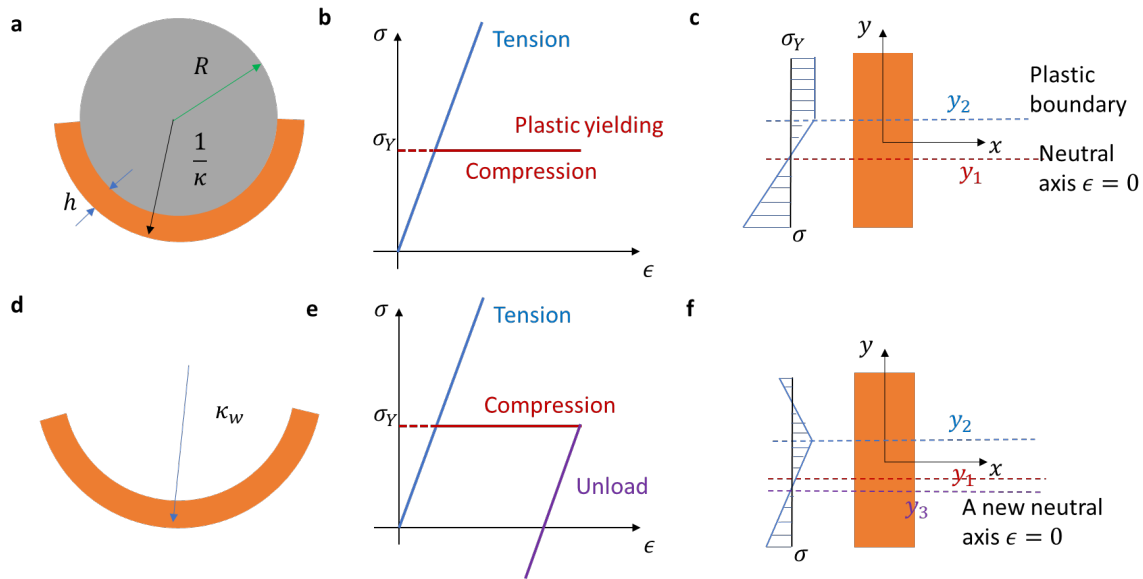


Figure S15. Bending curvatures after release of the wood veneer from the mold within the ideal plastic region. **a**, Molding the chemically washed wood veneer with a thickness, h , on a mandrel with a radius, R . **b**, Plastic stress-strain relations during loading. **c**, The stress distribution

along the thickness direction. **d**, Released configuration. **e**, Plastic stress-strain relations during unloading. **f**, The stress distribution in the released sample.

The associated stress distribution along the thickness direction can be expressed as (Fig. S15b, c)

$$\sigma = \begin{cases} (y_1 - y)\kappa E, & y < y_2, \\ -\sigma_Y, & y > y_2, \end{cases} \quad (2)$$

where E is Young's modulus along the longitudinal direction, σ_Y is the absolute value of the plastic yielding stress and y_2 is the boundary between the elastically and plastically deformed regions. The governing equations include the stress continuity at y_2 and the stress equilibrium equation, such that:

$$(y_1 - y_2)\kappa E = -\sigma_Y, \quad (3a)$$

$$\int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma dy = 0. \quad (3b)$$

Solving Equations (3a-b) gives

$$y_1 = -\frac{h}{2} + \sqrt{\frac{2\epsilon_{Y1}h}{\kappa} - \frac{\epsilon_{Y1}}{\kappa}} \text{ and } y_2 = -\frac{h}{2} + \sqrt{\frac{2\epsilon_{Y1}h}{\kappa}}. \quad (4)$$

We next apply the condition $\frac{1}{\kappa} - \left(\frac{h}{2} - y_1\right) = R$ and solve the unknown curvature, κ , as:

$$\kappa = \frac{4(1 - \epsilon_{Y1})^2}{\left(\sqrt{2\epsilon_{Y1}h + 4(R+h)(1 - \epsilon_{Y1})} - \sqrt{2\epsilon_{Y1}h}\right)^2}. \quad (5)$$

The plastic deformation strain in the inner part is:

$$\epsilon_p = (y_2 - y)\kappa, y > y_2. \quad (6)$$

After being released from the mold, the elastic part tends to recover to the flat state, while the plastically deformed part prefers to remain in the deformed configuration, which leads to an unknown intrinsic curvature κ_w (Fig. S15d). The deformation strain at the released state is:

$$\epsilon = (y_3 - y)\kappa_w, \quad (7)$$

where y_3 is a new neutral axis and an unknown variable. The stress distribution in the released sample can be expressed as:

$$\sigma = \begin{cases} (y_3 - y)\kappa_w E, & y < y_2, \\ ((y_3 - y)\kappa_w - (y_2 - y)\kappa)E, & y > y_2. \end{cases} \quad (8)$$

Since the wood veneer is in self-equilibrium, we have the following stress and moment equilibrium equations:

$$\int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma dy = 0, \quad (9a)$$

$$\int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma y dy = 0. \quad (9b)$$

We can obtain κ_w from Equations (9a-b):

$$\frac{\kappa_w}{\kappa} = \left(\frac{1}{2} + 2 \left(-\frac{1}{2} + \sqrt{\frac{2\epsilon_{Y1}}{\kappa h}} \right)^3 - \frac{3}{2} \left(-\frac{1}{2} + \sqrt{\frac{2\epsilon_{Y1}}{\kappa h}} \right) \right). \quad (10)$$

Equation (10) shows that wood veneers with different thicknesses and mold curvatures will follow a master curve, which is validated by our experimental data (Fig. 2g).

We next apply the same analysis to wood veneers within the stiffening deformation region. Although the deformation strain formula remains the same, we need to rewrite the stress during the molding (Fig. S16b, c) as:

$$\sigma = \begin{cases} (y_1 - y)\kappa E, & y < y_2 \\ -\sigma_Y, & y_2 < y < y_4 \\ -\sigma_Y + ((y_1 - y)\kappa + \epsilon_{Y2})E, & y > y_4 \end{cases}, \quad (11)$$

where ϵ_{Y_2} is the critical strain for stiffening and $y_4 = y_1 + \epsilon_{Y_2}/\kappa$ denotes the boundary of the stiffening region. Substituting the stress into the same governing equation (Equations (3a-b)), we can obtain:

$$\kappa = \frac{\frac{R}{h}(\epsilon_{Y_2} - \epsilon_{Y_1}) + 1 + \sqrt{\left(\frac{R}{h}(\epsilon_{Y_2} - \epsilon_{Y_1}) + 1\right)^2 - 4\left(\frac{R}{h} + \frac{1}{2}\right)\left((\epsilon_{Y_2} - \epsilon_{Y_1}) - \frac{1}{2}(\epsilon_{Y_2}^2 - \epsilon_{Y_1}^2)\right)}}{2R + h}, \quad (12)$$

and

$$y_1 = (\kappa h + \epsilon_{Y_1} - \epsilon_{Y_2})^{-1} \left(\frac{1}{2\kappa} (\epsilon_{Y_2}^2 - \epsilon_{Y_1}^2) - \frac{h}{2} (\epsilon_{Y_2} - \epsilon_{Y_1}) \right), \quad (13)$$

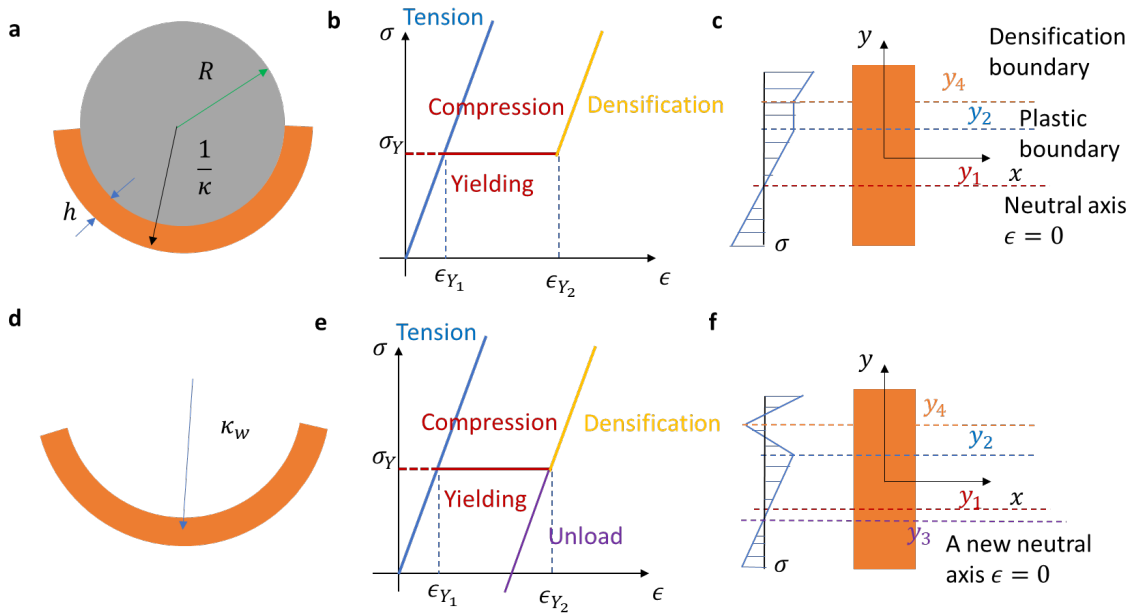


Figure S16. Bending curvatures after release of the wood veneer from the mold within the stiffening region **a**, Molding. **b**, Plastic stress-strain relations during loading. **c**, The stress distribution along the thickness direction. **d**, Released configuration. **e**, Plastic stress-strain relations during unloading. **f**, The stress distribution in the released sample.

The plastic deformation strain in the wood veneer is:

$$\epsilon_p = \begin{cases} 0, & y < y_2 \\ (y_2 - y)\kappa, & y_2 < y < y_4 \\ \epsilon_{Y_1} - \epsilon_{Y_2}, & y > y_4 \end{cases} \quad (14)$$

After being released from the mold, the stress distribution in the released sample can be expressed as:

$$\sigma = \begin{cases} (y_3 - y)\kappa_w E, & y < y_2 \\ ((y_3 - y)\kappa_w - (y_2 - y)\kappa)E, & y_2 < y < y_4 \\ ((y_3 - y)\kappa_w + \epsilon_{Y_2} - \epsilon_{Y_1})E, & y > y_4 \end{cases} \quad (15)$$

The same stress and moment equilibrium equations (Equation (9a-b)) still hold for this case, from which we can obtain κ_w as:

$$\frac{\kappa_w}{\kappa} = 3 \frac{(\epsilon_{Y_2} - \epsilon_{Y_1})}{\kappa h} \left(1 - 4 \left(\frac{y_4}{h} \right)^2 \right) + \left(4 \left(\frac{y_4}{h} \right)^3 + 2 \left(\frac{y_2}{h} \right)^3 - 6 \frac{y_2}{h} \left(\frac{y_4}{h} \right)^2 \right), \quad (16)$$

where $\frac{y_2}{h} = \frac{y_1}{h} + \frac{\epsilon_{Y_1}}{\kappa h}$ and $\frac{y_4}{h} = \frac{y_1}{h} + \frac{\epsilon_{Y_2}}{\kappa h}$ and y_1 is given by Equation (13).

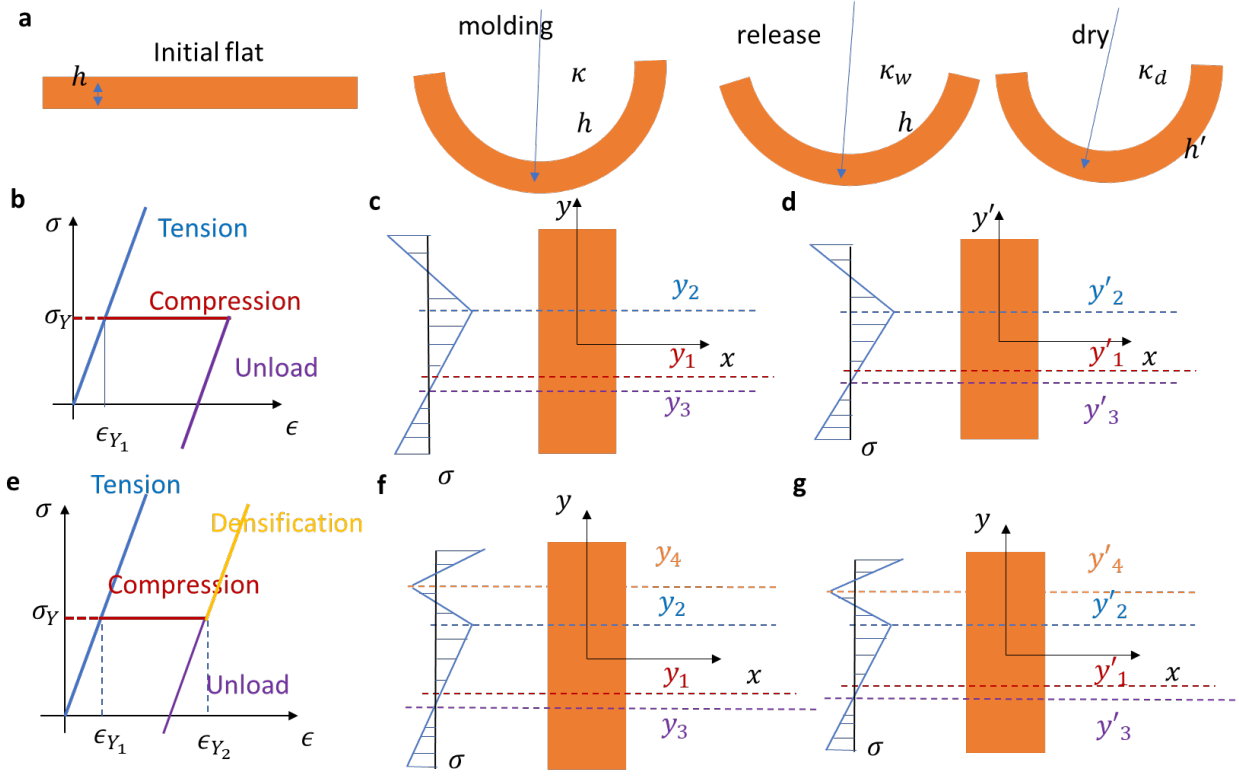


Figure S17. The thickness shrinkage effect during drying on the curvature change. **a**, The manufacturing processes. **b**, Ideal plastic model. **c**, The stress distribution in the wet state for wood veneers in the ideal plastic deformation regime. **d**, The stress distribution in the dry state for wood veneers in the ideal plastic deformation regime. **e**, Plastic deformation with stiffening. **f**, The stress distribution in the wet state for wood veneers in the plastic deformation regime with stiffening. **g**, The stress distribution in the dry state for wood veneers in the plastic deformation regime with stiffening. The wet and dry y-axis satisfy $\frac{y}{y'} = \frac{h}{h'}$.

Supplementary Note 10: A Phenomenological Model of the Wood Coils

This note presents a phenomenological model, capable of reproducing the configuration change and the associated extension forces of wood coils during the hydration and dehydration cycles in the experiments. These are the key mechanical factors to determine drilling performances of the designed seed carriers. Inspired by manufacturing and deployment of the wood-based seed carriers, we model the coiling and uncoiling process of wood coils, such as shape morphing of a mechanically anisotropic strip, driven by anisotropic contraction and expansion that mimic the effect of moisture change (Fig. S18). The model will be numerically solved with the FE method and implemented in ABAQUS/Implicit. It is noted that we do not intend to capture the detailed structure-property relationship of the wood materials but aim to predict the shapes and forces of the wood coils by tuning the elastic constants and hydration strain to match the experimental data. Even in the case of this simplified model, we still have a large set of parameters to calibrate with experiments, the process of which will be detailed in the following discussion.

We start with an initially straight wood strip and introduce a hydration strain field to the strip, the principal direction of which has an inclined angle with the longitudinal center line of the strip forming a helix. The wood material is anisotropic both in terms of mechanical and hydration properties, which are defined in the local coordinate (x', y', z') . Here, the local longitudinal direction, x' , represents the direction with maximum stiffness and hydration strain, and is defined by a rotation angle, θ_l , with respect to the globally horizontal direction (x). The anisotropic moduli are defined by engineering constants, including three moduli E_1, E_2, E_3 ; Poisson's ratios $\nu_{12}, \nu_{13}, \nu_{23}$ and shear moduli G_{12}, G_{13}, G_{23} , which are associated with the material's principal directions. Here the direction 1, 2 and 3 corresponds to x', y' and z' , respectively. These material parameters define the elastic compliance as:

$$\begin{Bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{Bmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_2 & -\nu_{31}/E_3 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & -\nu_{32}/E_3 & 0 & 0 & 0 \\ -\nu_{13}/E_1 & -\nu_{23}/E_2 & 1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{23} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix}, \quad (17)$$

where v_{ij} has the physical interpretation of Poisson's ratio, that characterizes the transverse strain in the j -direction when the material is stressed in the i -direction. In general, v_{ij} and v_{ji} are related to $v_{ij}/E_i = v_{ji}/E_j$. As shown in Table S3, white oak has different anisotropic modulus ratios, along with the width and thickness directions, with an average value around 0.1. To simplify the material property calibration, we adopted this average value in our simulated model, such that $\frac{E_2}{E_1} = \frac{E_3}{E_1} = 0.1$. We further assumed that $\frac{G_{12}}{E_1} = \frac{G_{13}}{E_1} = \frac{G_{23}}{E_1} = 0.1$ and $v_{12} = v_{13} = v_{23} = 0.3$. After these simplifications, the only fitting material parameter is E_1 , which will be extracted from the extension force measurements of wood coils in Supplementary Note 8. Despite the limited parameter space of the material properties, our model can fit the experimentally measured extension force by tuning Young's modulus, E_1 .

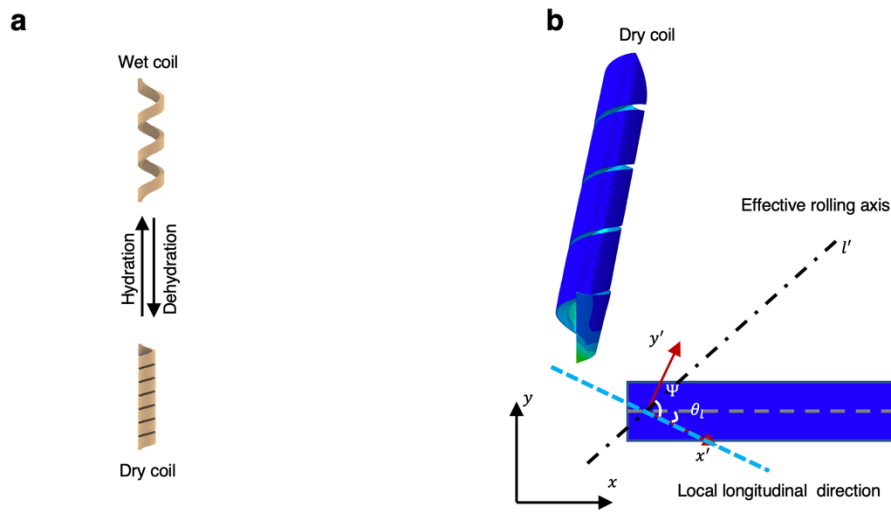


Figure S18. Development of the simulation model for the engineered seed coil. **a**, Schematic of the experimental seed coils in the wet and dry states. **b**, Simulated coils from the straight sheets. The local coordinate (x', y', z') is defined by a rotation (θ_l) from the global coordinate (x, y, z) with respect to the z axis. The rolling axis, l' , has an inclined angle, Ψ , with x' .

The hydration strains were generated by virtually rolling the wood strip with respect to a given axis (l') to form a helix with the same diameter and pitch of the dry coil in the experiments (Fig. S18). The corresponding active hydration strain field⁷³ can be defined as:

$$\begin{aligned}
\epsilon_{x'x'}^h &= (z' - h)\kappa_{\text{coil}} \sin^2 \Psi + \epsilon_{x'x'}^u, \\
\epsilon_{y'y'}^h &= (z' - h)\kappa_{\text{coil}} \cos^2 \Psi + \epsilon_{y'y'}^u, \\
\epsilon_{x'y'}^h &= -(z' - h/2)\kappa_{\text{coil}} \sin \Psi \cos \Psi,
\end{aligned} \tag{18}$$

where κ_{coil} is the bending curvature of the coil, Ψ is the angle of the effective rolling axis, $\epsilon_{x'x'}^u$ and $\epsilon_{y'y'}^u$ are uniform hydration strain components and $0 \leq z' \leq h$. In addition, there was a contraction along the thickness direction, which was assumed to be uniform and denoted as $\epsilon_{z'z'}^h$. The non-uniform hydration strain field in Eq. (18) creates a driving force to deform the initially flat wood strip into helical configuration, to mimic the molding of the wood coils and the actuation of coils from the wet to the dry state. It is important to note that the helix configuration is not purely determined by the geometrical mapping from the hydration strain field. It is achieved through the balance between the stress associated with mechanical deformation and the hydration strain. Therefore, we could not directly adopt all the experimentally measured coil geometries to create the hydration strain field. We treated the angle of the local longitudinal direction (θ_l), the angle of the effective rolling axis (Ψ) and (κ_{coil}) as fitting parameters in the simulations and employed the experimental measurements as initial guesses of the fitting.

To effectively represent the hydration state, we introduced a variable ξ ($0 \leq \xi \leq 1$) to control the shape morphing from a straight strip to a tightly packed dry coil. To simplify the model, we assumed that the κ_{coil} , Ψ , $\epsilon_{x'x'}^u$, $\epsilon_{y'y'}^u$ and $\epsilon_{z'z'}^h$ were linear functions of ξ , with $\xi = 1$ denoting the dry state and $\xi = 0$ corresponding to the initially straight state. Therefore, the curvature (κ_{coil}) and rolling axis angle (Ψ) can be defined by:

$$\kappa_{\text{coil}}(\xi) = \gamma \frac{2D_{\text{coil}}^d}{(D_{\text{coil}}^d)^2 + (P_{\text{coil}}^d/\pi)^2} \xi, \tag{19}$$

$$\Psi = \Psi_0 + (\Psi_1 - \Psi_0)\xi, \tag{20}$$

$$\epsilon_{x'x'}^u = \epsilon_{x'x'}^0 \xi, \epsilon_{y'y'}^u = \epsilon_{y'y'}^0 \xi, \text{ and } \epsilon_{z'z'}^h = \epsilon_{z'z'}^0 \xi, \tag{21}$$

where D_{coil}^d and P_{coil}^d are the diameter and pitch of the dry coil in the experiments, Ψ_0 and Ψ_1 are two fitting parameters, $\epsilon_{x'x'}^0$, $\epsilon_{y'y'}^0$ and $\epsilon_{z'z'}^0$ represent the slope of uniform hydration strain components, and γ is a fitting parameter to match the simulated coil pitch and diameter with experimental measurements at the dry state ($\xi = 1$). The wet coil is modeled as an intermediate configuration from a non-zero ξ ($\xi = \xi^w$), which leads to the same diameter (D_{coil}^w) and pitch (P_{coil}^w) in experiments in the wet state. We chose a state dependent rolling axis angle (Ψ), as our experiments show the change of the helix angle between the wet and dry wood coils. Physically, the dynamical hydration and dehydration processes are determined by the water transport. Here we used an indirect method to mimic the time variation of the hydration strain, by prescribing a time dependent sequence of ξ . For water transport under constant moisture environment, the hydration strain can be modeled as an exponential function of time ($\sim \exp\left(-\frac{t}{t_d}\right)$) with a characteristic time scale, t_d . We identified the characteristic time scale through the time variation of the coil pitch and diameter in controlled hydration experiments, as detailed in the following section.

Supplementary Note 11: Model Calibrations and Simulations of the Extension Forces

This note details the model calibrations and simulations of the extension force measurements. These simulations have two goals. One is to calibrate the material properties from controlled experiments. The other is to investigate the relationship between the extension forces and the coil length. For coils with the same pitch, their length is proportional to the coil number. We first introduced the simulation set-up for representative experimental structures (Fig. S19), as this will also be used to extract material properties. The model developed in Supplementary Note 10 is highly nonlinear, therefore, we performed FE simulations with ABAQUS/implicit to numerically solve the problems. We discretized the structure with 3D wedge elements (C3D6) and created five elements along the thickness direction to capture the gradient of the hydration strain and the large bending curvature. Each layer of the elements was assigned a different and anisotropic expansion coefficient to mimic the hydration strain, by prescribing a time-dependent temperature. The mesh size on the wood plane was set at 0.2 mm. Moderate dissipation was adopted to help the convergence of the simulations.

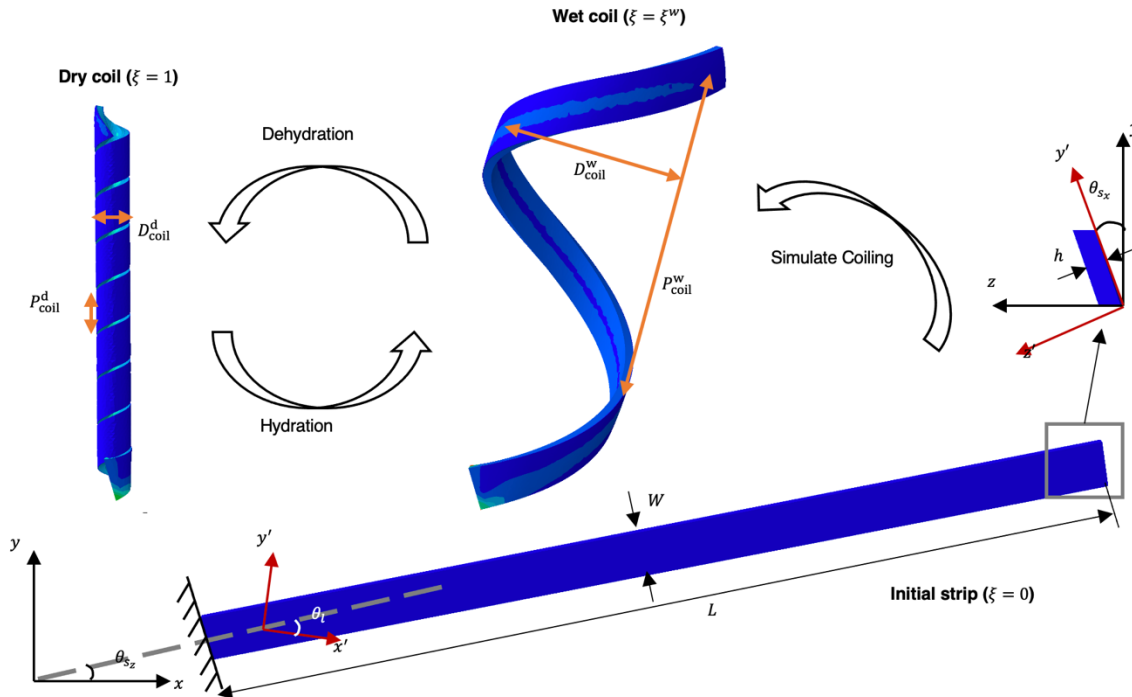


Figure S19. A schematic of the modeling process of the formation and actuation of wood coils.

The wood sheet has a length of L , width of W , and thickness of h . Before deformation, the wood

sheet is placed at a position of θ_{S_x} and θ_{S_z} , with respect to the x and z axis, respectively. A local coordinate system is introduced to quantify the anisotropy of the wood sheet with the local longitudinal direction as x' . The wet and dry coils are described by their diameters (D_{coil}^w and D_{coil}^d) and pitches (P_{coil}^w and P_{coil}^d). The color represents the maximum principal deformation strain.

We next outlined the calibration process of material properties. The flat wood sheet has a thickness (h) of 0.5 mm, and width (b) of 2.4 mm, according to our direct experimental measurement. The bending curvature in the dry state, κ_{coil} , was computed from Eq. (18) with $D_{coil}^d = 1.49 \text{ mm}$ and $P_{coil}^d = 2.43 \text{ mm}$ obtained from the average of 3 experiments (Fig. S20a) and $\xi = 1$. By checking the thickness change of the wood strips from the wet to the dry state, we could obtain $\epsilon_{z'z'}^0 = -0.20$. The density of the wood material was taken as $\rho = 1000 \text{ kg/m}^3$. Since the actuation is a slow process within the time scale of an hour, we do not expect that the kinetic energy, associated with density, will play a significant role in the coil deformation and force generation. We also included a small damping coefficient ($\alpha = 0.10$ for the mass proportional contribution to Rayleigh damping) to help the convergence of simulations. Following these analyses, we still needed to calibrate the following parameters, θ_l , Ψ_0 , Ψ_1 , $\epsilon_{x'x'}^0$, $\epsilon_{y'y'}^0$, γ , t_d , E_1 and expected that the modulus, E_1 and the parameters associated with the hydration strain were only determined by the coil shape. Therefore, we first set a constant value of E_1 and conducted ABAQUS simulations to extract these parameters by comparing the simulations with experiments. During the simulation, we gradually increased the hydration state variable, ξ , from 0 to 1 to generate the dry coil. To calibrate the characteristic time scale, t_d , we decreased ξ from 1 following an exponential decay in the simulation to mimic the controlled hydration tests in the humidity chamber, such that:

$$\xi = \exp\left(-\frac{t}{t_d}\right). \quad (22)$$

We identified t_d by matching the time variation of the measured coil pitch and diameter in the experiments. We found a set of parameters, namely, $\theta_l = 20^\circ$, $\Psi_0 = 50^\circ$, $\Psi_1 = 70^\circ$, $\epsilon_{x'x'}^0 = 0.10$, $\epsilon_{y'y'}^0 = -0.18$, $\gamma = 1.35$ and $t_d = 180 \text{ min}$ that could result in a good agreement with the humidity chamber experiments, as shown in Fig. S20. Note that t_d depends on both the material properties and the environment conditions.

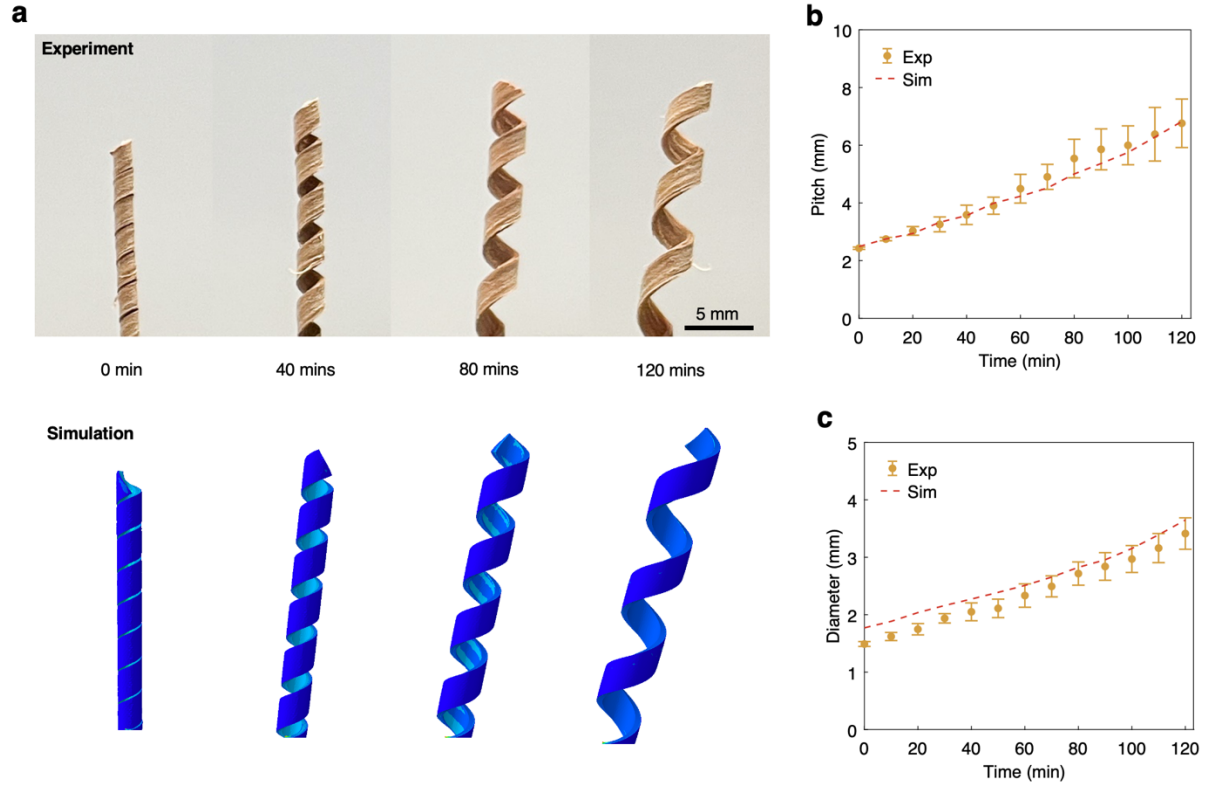


Figure S20. Calibration of the time-dependent variations of the coil pitch and diameter during hydration. **a**, Representative experimental and simulated coil configurations at different hydration time spans. **b**, Comparison of the coil pitch obtained from experiments with that from simulations. **c**, Comparison of the coil diameter obtained from experiments with that from simulations. Experimental data are means $\pm$ SD. $N = 3$ samples.

It is known that the modulus of wood strongly depends on the water content inside the materials⁵⁴. To study the effect of hydration on the tensile modulus properties of the processed wood samples, we conducted tensile tests on progressively hydrated wood strips in a test chamber, with well-controlled humidity and temperature (Fig. S7). The temperature of the chamber was maintained at $\sim 30^{\circ}\text{C}$ and the humidity at $\sim 93\%$. The wood sample size for the test was ~ 2 mm wide, ~ 80 mm long and ~ 0.5 mm thick in the dry state. Multiple wood strips were put in the chamber at time 0. For a period of 180 min, three wood samples were taken out of the chamber every 15 min for tensile testing. The tensile test of the samples was carried out with the universal testing machine (Instron 5969) using 1 kN load cell at 10 mm/min.

Figure S21a shows the representative stress-strain plot of the hydrated samples at different hydration times. Young's modulus was computed from a linear fitting of the stress-strain curve up to a strain of 0.5% (0.005 mm/mm) as shown in Fig. S21b. It was observed that as the hydration time increases, Young's modulus decreases, as seen in Fig. S21b. Young's modulus can be fitted well using the following relationship

$$E = E^d \left(\left(1 - \frac{E^w}{E^d} \right) \exp \left(-\frac{t}{t_E} \right) + \frac{E^w}{E^d} \right), \quad (23)$$

where E^d and E^w represent the modulus in the dry and wet states, and t_E is a characteristic time scale of modulus change associated with water transport. The best fitted parameters are $E^d = 4.88 \text{ GPa}$, $E^w = 1.21 \text{ GPa}$ and $t_E = 38.56 \text{ min}$. Note that the characteristic time scale of modulus t_E is different from that of shape change, which is probably due to nonlinear swelling and mechanical coupling. It was observed that Young's modulus decreases four-fold with respect to the non-hydrated sample. This large change in the modulus cannot be ignored and should be included in the simulations. Note that these measurements are based on unmolded samples and that the exact values are different from the modulus of wood coils, which has been modified by the molding process. During the simulations, we treated the dry modulus, E_1^d , as a fitting parameter to match the extension force measurements, while keeping the experimentally fitted, t_E and the ratio $r_d^w = \frac{E^w}{E^d}$. Then, the modulus E_1 can be expressed as:

$$E_1 = E_1^d \left((1 - r_d^w) \exp \left(-\frac{t}{t_E} \right) + r_d^w \right). \quad (24)$$

The same time-dependent function is also applied to the rest of the moduli with $E_2^d = E_3^d = G_{12}^d = G_{13}^d = G_{23}^d = 0.1E_1^d$.

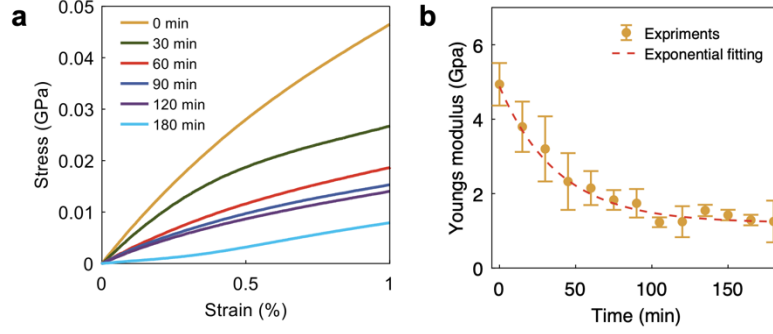


Figure S21. Experimental measurements and calibration of the moisture dependent modulus of white oak. (a) The stress-strain plot of wood strips under different hydrated states and (b) Young's modulus of the hydrate samples at an interval of 15 min. Experimental data in (b) are means $\pm$ SD, $N = 3$ samples.

We next applied the calibrated model to simulate the extension force measurements. These simulations will also enable us to extract the modulus, E_1^d . Based on these simulations of coil configurations, we identified three different lengths of the wood strip (including 22 mm, 44 mm and 64 mm) to reproduce 3.5 coils, 7 coils and 10.5 coils in experiments, respectively. If we directly simulate a wood strip with the left end clammed, as shown in Fig. S17b, the simulated dry coil will be inclined, which cannot be used for the extension force simulations. To reproduce the extension force measurements, we rotated the straight strip along the x and z axis to generate a vertically aligned coil in the dry state with the bottom surface clammed (Fig. S18). The rotation angles, θ_{S_x} and θ_{S_z} , are not fitting parameters and can be identified as $\theta_{S_x} = 17.52^\circ$ and $\theta_{S_z} = 11.51^\circ$ from the coil orientation in the initial numerical simulation without rotations. During the first coiling process to form the dry coil, we set the hydration state variable to follow a slow linear ramp from 0 to 1. This is a simplified setting for a quasistatic process. After the coil reached the dry state, a rigid plate was placed at the coil tip to constrain the elongation of the coil body during the hydration process. To simulate the uncoiling process under hydration, we decreased ξ from 1 following an exponential decay defined in Eq. (22) to simulate the force measurement during the uncoiling process. We tuned the modulus, E_1^d , to match the force-time relationships of wood coils in our experiments. To model the contact between the wood and the hard surface, we needed to adjust the coefficient of friction. We found that $E_1^d = 0.33 \text{ GPa}$ and a coefficient of friction as 0.45 provided a good prediction for all three coils of different lengths. Using these calibrated materials and contact properties, our model can capture the nonlinear force-time relations for all

three coils, including the values and time for the peak forces, initial stiffness and decay over a longer period (Fig. 3f and Fig. S22a-b). The simulations further showed that the peak force of the 3.5 coil is determined by the sliding of the contact tip, and the peak force of the 7 and 10.5 coils are determined by compressive buckling (Fig. S22c).

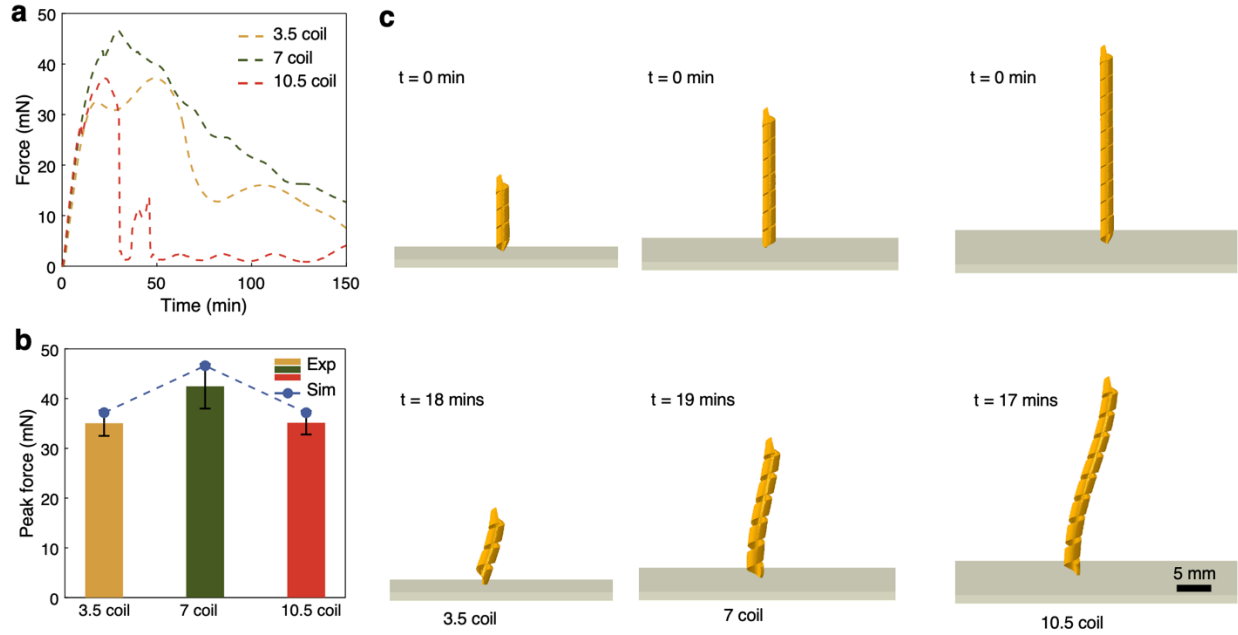


Figure S22. Simulations of the extension force measurements. (a) Simulated extension forces versus time for coils of different lengths. (b) Comparison of peak extension forces in simulations and experiments. (c) Simulation snapshots of the coil configurations near the first peak of the forces. Experimental data in (b) are means $\pm$ SD. $N = 3$ samples.

Note that these parameters are fitted by comparing the simulations with experiments and are generally not unique. However, we do not expect the non-uniqueness of the material parameters will qualitatively change the conclusions, since the current material parameter set has been shown to be able to capture the configuration change and the associated extension forces of wood coils during the hydration and dehydration cycles in the experiments. These are the key factors that determine the drilling performance.

Supplementary Note 12: Simulations of the Drilling Process

This note presents the details of the simulations of the drilling process of engineered seed carriers with different tails. All the simulations are conducted with ABAQUS/Implicit. We first describe the setting for incorporating three tails into the FE simulation framework. The single-tailed structure is a subset of the three-tailed structure; therefore, we could follow the same process and only add the first tail. In the simulation, the tails were glued to the coil body through the “Tie” command in ABAQUS, inspired by the experimental procedure of gluing tails onto the coil. The initial modeling set-ups were applied to the initially flat configuration ($\xi = 0$). As shown in Fig. S23a, the first tail shares the same surface of the body, while a narrow region (i.e., 0.4 mm long) of the second and third tails are attached to the top surface of the body. The locations of the bonding sites were chosen to reproduce the tail configurations in the three-tailed design, shown in Fig. 3d. Unlike the coil body, our experiments show the tails usually do not have very large deformations. This motivated us to choose a simple bilayer model to describe the shape of the tail with one passive layer and one active layer that are responsive differently to the moisture change. To keep the model simple, we set the same mechanical properties of tails as the coil body, the only difference being the local longitudinal direction. For the three tails, the local longitudinal directions are given by $(\theta_l)_1 = 0^\circ$, $(\theta_l)_2 = -5^\circ$, $(\theta_l)_3 = -10^\circ$, which are fitting parameters to match with the experimental configuration. The hydration strains in the active layer are defined by

$$(\epsilon_{x'x'}^h)_{tail} = -0.03\xi, (\epsilon_{y'y'}^h)_{tail} = -0.2\xi, \text{ and } (\epsilon_{z'z'}^h)_{tail} = -0.2\xi. \quad (25)$$

For the passive layer, we set the hydration strain along the longitudinal directions equal 0 and hydration strains along the other two directions the same as the active layer.

The corresponding configurations for wet and dry coils with tails are recorded in Figs. S23b and c, respectively. Since the simulations did not explicitly model the seed tip, we did not follow the exact length of the tails. Instead, we chose the tail lengths to make the inclined angle between the three-tailed structure and the ground (Fig. S23d) in the simulation match with experimental observations. All three tails have the same width (2.4 mm) and thickness (0.5 mm) as the coil body. Configurations with one to three tails in the dry state are noted in Fig. S24, from which the bonding sites can be clearly observed.

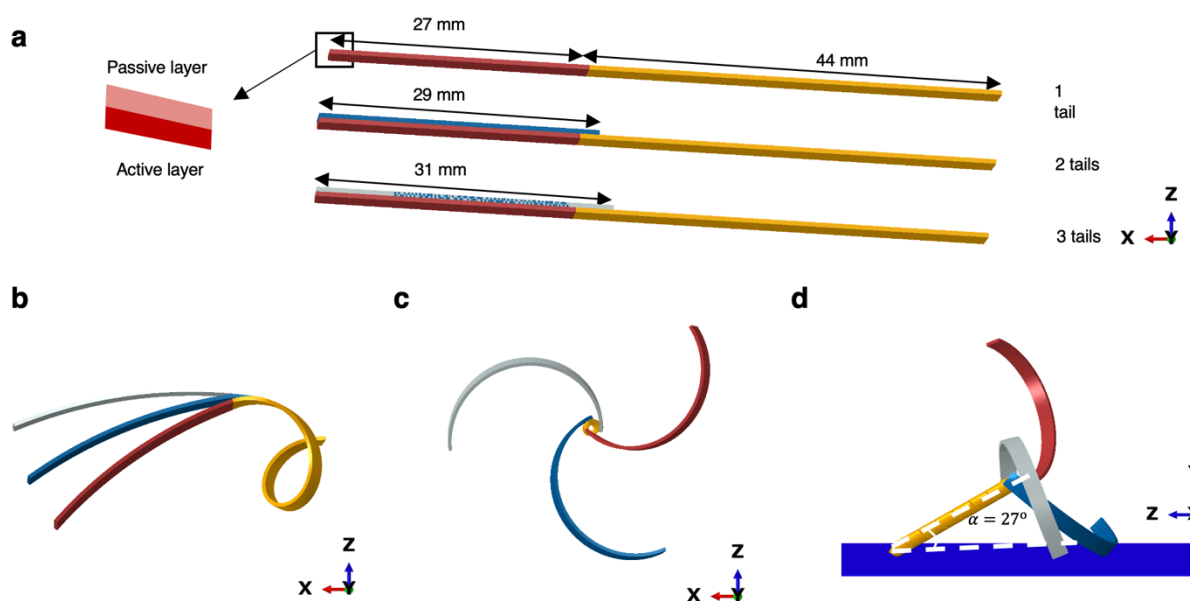


Figure S23. Modeling set-up of the coil body and tails. (a) The initial configuration at $\xi = 0$ with coil body highlighted in yellow, tail 1 in red, tail 2 in blue and tail 3 in grey. (b) The configuration at $\xi = 0.2$. (c) The configuration at $\xi = 1$. (d) Simulated three-tailed coil resting on the ground.

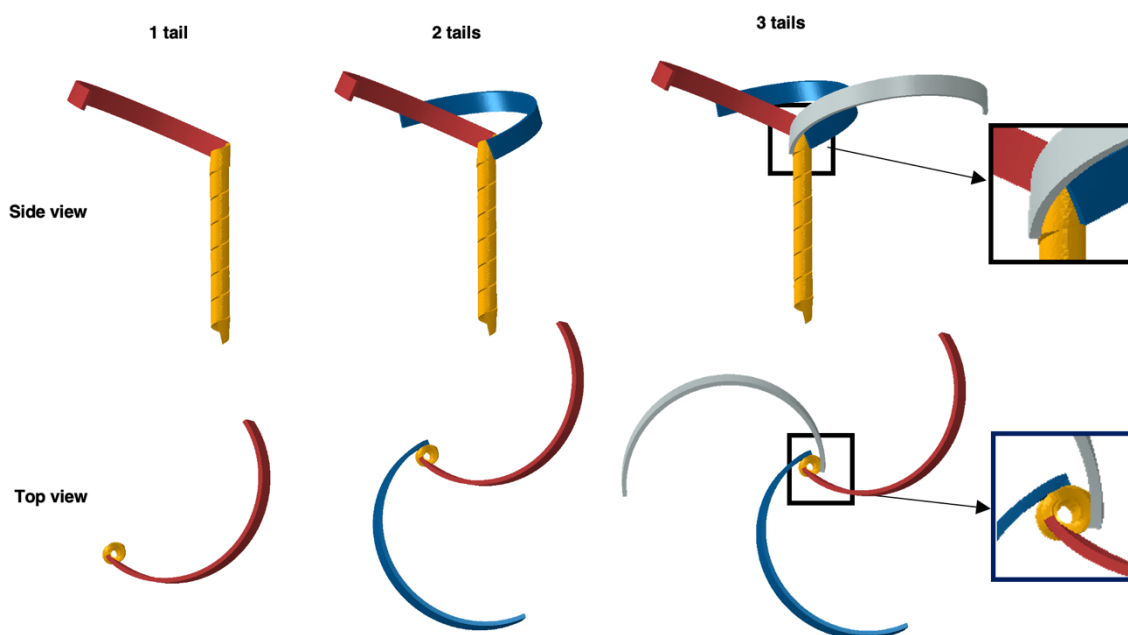


Figure S24. The dry seed coil body with different configurations of tails.

To numerically model the drilling process, we developed a three-step simulation (Fig. S25). Since the detailed tail label does not constitute critical information, we set the tail color as yellow, as well as in the following discussion. In the first step, the body and tails of the coil were formed from an initially straight strip, driven by prescribed hydration strain. During this step, the bottom surface of the coil body was fixed. In the second step, we released the bottom surface of the coil body to allow the coiling system to be subjected to gravity and to maintain its dry state. In the third step, we simulated the drilling motion during hydration. Hydration is controlled by the state variable ξ defined in Eq. (22).

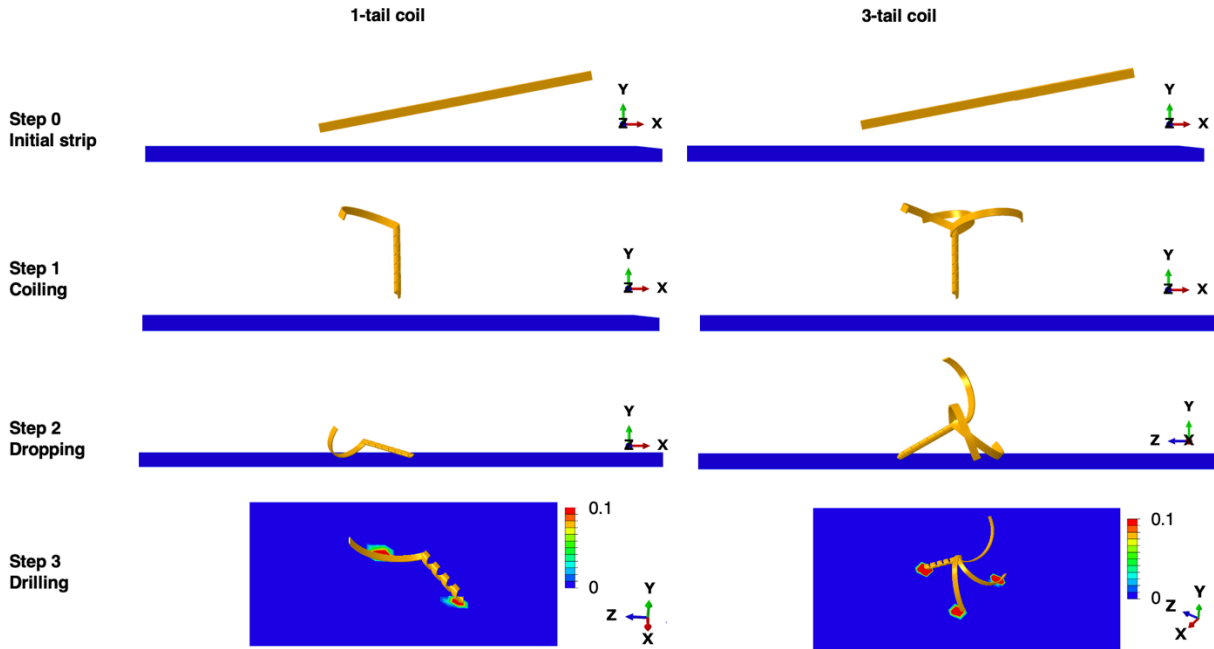


Figure S25. The three-step simulations of the coil drilling process. The color represents the contact pressure (unit kPa). Note that the maximum contact pressure is greater than 0.1. The choice of the current color bar is to help with the visualization of the contact regions.

The interactions between the coiling system (body and tails) and the ground are especially important in correctly reproducing the drilling process in the experiments. Here, the soil surface was treated as a rigid flat surface, which interacts with the seed body and tails through normal

contact and frictional forces (Fig. S26). The effect of deformability and the roughness of the soil surfaces were lumped into the effective coefficient of friction between the surfaces of the seed body and tip, and the soil surface. We indeed observed that the tail end and the seed carrier tip could penetrate the soil surface in our experiments and served as anchoring points to enhance the drilling forces (Fig. 3d). To mimic the tail anchoring, we set a higher coefficient of friction in a small region near the tail tip (purple regions in Fig. S26). The seed tip was not included in the simulation model, as it is challenging to connect the tip with the non-stress-free seed carrier body. Thus, we could not model the anchoring effect by simply adjusting the friction coefficient near the coil end. We chose one corner point of the coil body (point A in Fig. S26) and constrained its motion on the ground (along the x and z directions) to mimic the anchoring of the seed carrier tip.

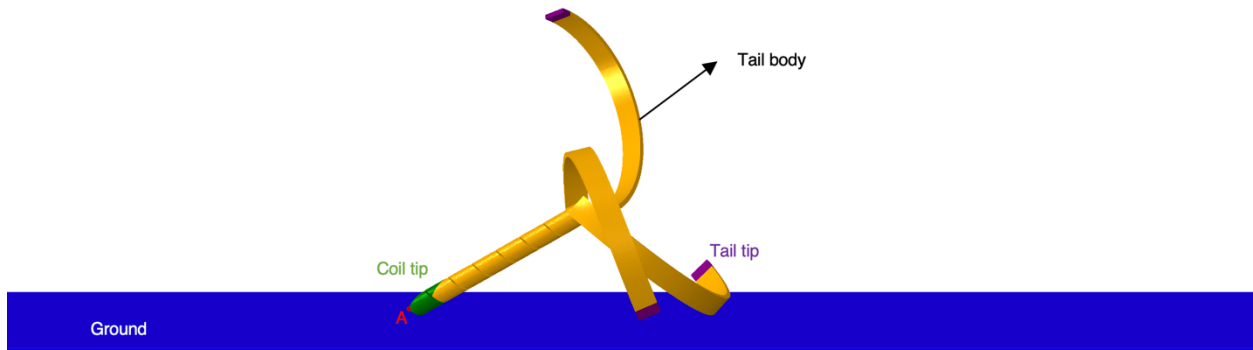


Figure S26. Interaction between the coil system and the ground. The tail tip (purple) has a higher coefficient of friction than the body of tails (yellow) and the coil (yellow and green) to mimic the anchoring of the tail tip. The coil end (green) is defined for computing the contact forces near the coil tip. The in-plane motion of point A (red) will be constrained for simulations with the anchoring seed tip.

In ABAQUS, the friction was implemented through the penalty method. The contact interaction was also stabilized by a small damping factor (0.0001 for automatic stabilization and tangent fraction in the contact control setting in ABAQUS) to overcome the convergence issue. For the drilling processes in the experiments (Fig. 3d-e) on coconut coir, we set the friction coefficient between the seed carrier, including the coiled body and tails, and the ground to 0.8, taking into account the considerable roughness on the soil surface. To mimic the anchoring points, we set the frictional coefficient of the tail ends (purple regions) as 2.0 greater than the tail body (yellow region)

in Fig. S26. We further defined a coil end region (highlighted in green in Fig. S26) to facilitate the calculation of the interaction forces between the coil and the ground. The friction coefficient between the coiled body and the ground remained at 0.8, as the anchoring effect is described by the displacement constraint of point A. The force applied to the coil end will be the superposition of the contact forces between the coil end and the ground, and the reaction forces at point A. A similar set-up is also applied to the single-tailed structure. To compare the seed tip anchoring effects, we also simulated the cases without constraining point A. Seed carrier drilling was simulated from four possible scenarios, including single-tailed design without anchor, single-tailed design with anchor, three-tailed design without anchor and three-tailed design with an anchor. The simulated thrust force between the seed tip and the ground is shown in Fig. 3b, suggesting that the three-tailed design with an anchor can generate the largest thrust force. In these drilling simulations, we adopted the same time-dependent state variable in Eq. (22) to describe the uncoiling process. The time scale was obtained from the thrust force measurements with controlled environmental moisture, which is likely to change, subject to the environmental conditions of the indoor and field tests. The time scale may not be very meaningful by comparing the simulation with experiments. Therefore, we presented the forces in terms of the hydration state, instead of time, as shown in Fig. 3b,c. The normalized hydration state, denoted as η , was equal to 0 in the dry state and 1 in the wet state, respectively, which can be computed through a linear mapping of the state variable ξ as:

$$\eta = \frac{1-\xi}{1-\xi^w}. \quad (26)$$

We identified $\xi^w = 0.2$ from the rotation speed experiments where the initial 7 coils will saturate to 1.4 coils at the end of the hydration test (Fig. 3g).

It should be noted that both scenarios with and without tip anchoring are observed in experiments. Our experiments show that it is more difficult to establish drilling success in the case without tip anchoring than that with tip anchoring (Supplementary Video S4), which is consistent with the force levels found in the simulations. To demonstrate the importance of the contact interaction between the seed carrier and the soil surface, we conducted experiments and simulations of drilling into a surface, which is hard and smooth. In the experiments, we placed both single-tailed and three-tailed carriers on top of an acrylic board and triggered the anchoring with one hydration circle for 30 min under the controlled drilling test condition described in Methods. The smooth

surface and large Young's modulus led to a small coefficient of friction on the acrylic board. Furthermore, it was difficult for the tails and seed to penetrate the acrylic board to establish anchoring points. During the simulation, we found that a uniform friction coefficient of 0.45 for the interfaces between the seed carrier and ground can reproduce the seed carrier motion in experiments. The contact interaction in the low friction cases was modeled as “general contact” to overcome convergence issues. Both experiments and simulations demonstrated a substantial rotation of the seed carriers, due to the low frictional force and lack of anchoring points (Extended Data Fig. 9). The three-tailed design rotated less than the single-tailed design, as it can establish contact not only at the two tails but also at the seed tip, thanks to the initially inclined angle on the surface.

References

57. Wang, W. *et al.* Harnessing the hygroscopic and biofluorescent behaviors of genetically tractable microbial cells to design biohybrid wearables. *Sci. Adv.* **3**, e1601984–e1601984 (2017).
58. Quan, H., Kisailus, D. & Meyers, M. A. Hydration-induced reversible deformation of biological materials. *Nat. Rev. Mater.* **6**, 264–283 (2021).
59. Zhao, Z. *et al.* Actuation and locomotion driven by moisture in paper made with natural pollen. *Proc. Natl. Acad. Sci.* **117**, 8711–8718 (2020).
60. Tao, Y. *et al.* Morphing pasta and beyond. *Sci. Adv.* **7**, eabf4098 (2021).
61. Lutz-Bueno, V., Bolisetty, S., Azzari, P., Handschin, S. & Mezzenga, R. Self-winding gelatin–amyloid wires for soft actuators and sensors. *Adv. Mater.* **32**, 2004941 (2020).
62. Czerner, M., Fellay, L. S., Suárez, M. P., Frontini, P. M. & Fasce, L. A. Determination of elastic modulus of gelatin gels by indentation experiments. *Procedia Mater. Sci.* **8**, 287–296 (2015).
63. Quan, H., Piroso, A., Yang, W., Ritchie, R. O. & Meyers, M. A. Hydration-induced reversible deformation of the pine cone. *Acta Biomater.* **128**, 370–383 (2021).
64. Elbaum, R., Zaltzman, L., Burgert, I. & Fratzl, P. The role of wheat awns in the seed dispersal unit. *Science* **316**, 884–886 (2007).
65. Armon, S., Efrati, E., Kupferman, R. & Sharon, E. Geometry and mechanics in the opening of chiral seed pods. *Science* **333**, 1726–1730 (2011).
66. Taccola, S. *et al.* Toward a new generation of electrically controllable hygromorphic soft actuators. *Adv. Mater.* **27**, 1668–1675 (2015).
67. Kang, H., Lee, M., Lim, H., Stone, H. A. & Lee, J. Hygromorphic actuator from a metal oxide film driven by a nano-capillary forest structure. *NPG Asia Mater.* **9**, e417–e417 (2017).
68. Ma, M., Guo, L., Anderson, D. G. & Langer, R. Bio-inspired polymer composite actuator and generator driven by water gradients. *Science* **339**, 186–189 (2013).
69. Okuzaki, H., Kuwabara, T. & Kunugi, T. Theoretical study of sorption-induced bending of polypyrrole films. *J. Polym. Sci. Part B Polym. Phys.* **36**, 2237–2246 (1998).

70. Green, D. W., Winandy, J. E. & Kretschmann, D. E. *Mechanical properties of wood*. 4.1-4.45 <https://www.fs.usda.gov/treearch/pubs/7149> (1999).
71. Maeglin, R. R. & Quirk, J. T. Tissue proportions and cell dimensions for red and white oak groups. *Can. J. For. Res.* **14**, 101–106 (1984).
72. Miller, R. B. *Characteristics and availability of commercially important woods*. 1.1-1.34 <https://www.fs.usda.gov/treearch/pubs/7141> (1999).
73. Chen, Z., Majidi, C., Srolovitz, D. J. & Haataja, M. Tunable helical ribbons. *Appl. Phys. Lett.* **98**, 011906 (2011).