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Article

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Wax-coated jute bags preserve seed moisture content and viability over nine months of storage under contrasting humidity and temperature conditions

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Abstract

Jute bags are widely utilized for seed storage across the developing world. However, moisture ingress into these fabrics renders the stored seeds vulnerable to spoilage and deterioration. Here, we evaluated biomimetic, water-repellent, wax-coated jute bags (WCJBs) with uncoated control jute bags (CJBs) over a nine-month storage period with wheat and soybean seeds under two relative humidity (RH) conditions (55% and 75%) and two temperatures (22 °C and 35 °C). Across all eight storage conditions, WCJBs reduced moisture accumulation in the bagseed system by 32%–59%, maintained seed moisture content near the equilibrium values expected at the corresponding ambient RH, and preserved germination rates of 56%–95%, compared with 12%–65% in CJBs. Our experiments and mechanistic insights demonstrate that WCJBs offer a low-cost, breathable complement to hermetic storage for preserving grain in hot, humid environments where exposure to liquid water is possible.

Keywords: seed storage; seed moisture content; post-harvest losses; jute bags; condensation; wetting; germination; wheat; soybean

Introduction

Achieving global food security is a central objective of the United Nations Sustainable Development Goals (SDGs)[1,2]. The widely cited estimate that one-third of all food is lost or wasted is based on data that critical reviews have shown to be sparse, inconsistent, and largely derived from secondary sources[3,4]. In contrast, the FAO Food Loss Index, which is based on primary measurements, estimates that approximately 13%–14% of food is lost between harvest and retail globally, with no measurable progress since 2015[5]. Losses are particularly high in sub-Saharan Africa and South Asia[6,7]. In the smallholder farming systems of these regions, storage is a major stage at which staple grain losses occur. Grain that has been properly dried and bagged can reabsorb moisture under humid conditions, promoting mold growth, mycotoxin contamination, and insect infestation, which collectively account for much of the quantitative and qualitative deterioration that occurs before grain is consumed or sold[8-11]. These losses represent more than the food itself: they also waste the land, water, energy, and fertilizer used in production and contribute to the greenhouse gas emissions associated with food that is never consumed[5,12]. Moreover, they occur in regions where food insecurity is particularly acute[6]. Before expanding agricultural land, potentially at the expense of forests and biodiversity, to meet the food demands of a growing population, greater efforts should be made to ensure the efficient use of already harvested grain[13]. Therefore, interventions aimed at reducing postharvest storage losses among smallholder farmers must be affordable, compatible with existing practices, and effective under the high-temperature, high-humidity, and rainy conditions in which grain is commonly stored[7,11].

For farmers, stored grain serves both as a reserve of food and feed for the coming months and as a source of seed for the next planting season. In either role, its value depends on how long it can be maintained in good condition[14]. The longevity of orthodox seeds, which include all cereal and grain legume species, is governed by three principal factors: seed moisture content (SMC), storage temperature, and storage duration[15-17]. Packaging primarily influences the first of these factors, making it particularly important for seed preservation. Harrington's rule of thumb states that, within the ranges of 5%–14% SMC and 0–50 °C, each 1-percentage-point increase in SMC and each 5 °C increase in temperature halve seed longevity[18-20]. Thus, a seed stored at an SMC 3 percentage points higher and a temperature 15 °C higher would have an expected storage life one-eighth as long. Above approximately 14% SMC, this rule no longer applies because seed deterioration can accelerate through a self-reinforcing process. Respiration by the seeds, fungi, and

insects associated with them increases sharply, generating heat and metabolic water that further elevate SMC and accelerate deterioration[18,21,22].

Water can reach grain stored in porous bags through two physically distinct pathways: vapor-phase exchange and direct liquid-water exposure. First, grain exchanges water vapor with the surrounding air through the pores of the bag fabric until it approaches the equilibrium moisture content (EMC) determined by ambient relative humidity (RH) and temperature. For example, the EMC of wheat is approximately 11% and 14%, whereas that of soybean is approximately 9% and 15%, at 55% and 75% RH, respectively[23]. Although a bag can slow this exchange, it cannot fundamentally alter the equilibrium moisture content that the grain ultimately reaches. Given sufficient time, vapor exchange alone will bring the grain to its EMC, but not beyond it. The second pathway involves direct exposure to liquid water. Grain storage environments are rarely isothermal; diurnal temperature fluctuations, cooling of walls and roofs at night, and exposure to rain or splashing water during transport and storage can all lead to condensation or wetting[24,25]. Because jute is hydrophilic, it absorbs liquid water and transports it through the fabric by capillary action, potentially transferring it to the grain in contact with the bag. Unlike vapor-phase exchange, this pathway is not constrained by the EMC and can raise grain moisture levels substantially above equilibrium, potentially reaching the range in which the self-reinforcing deterioration described by Harrington's rule becomes important. The relative contributions of these two pathways under actual storage conditions are rarely investigated, yet distinguishing between them is essential for determining how protective bag coatings should function. Whether condensed water spreads across a surface as a continuous film and is subsequently absorbed, remains as discrete droplets that re-evaporate when the temperature rises again[26,27], or rolls off or detaches under its own inertia[28] depends on the wetting behavior of the liquid–solid–air interface[29,30].

The type of seed also influences its response to ambient humidity. Oil content lowers the EMC at a given RH because water is primarily sorbed by the carbohydrate and protein fractions rather than by the lipid fraction of seeds[31]. Consequently, soybean (Glycine max), which contains approximately 18%–22% oil[32], equilibrates at a lower SMC than wheat (*Triticum aestivum*), which contains approximately 2%–3% oil on a whole-grain basis[33], under the same humidity conditions. Nevertheless, oilseeds can be more susceptible to chemical deterioration during storage because their unsaturated fatty acids are prone to oxidation and their seed coats can be easily damaged[34-

[36]. Comparing a cereal and an oilseed stored under identical conditions therefore provides an opportunity to determine whether the protective effects of a storage bag depend primarily on moisture exclusion or are also influenced by differences in seed composition and associated deterioration mechanisms.

Jute bags are widely used to store grain and seeds across the Indian subcontinent and much of sub-Saharan Africa because they are inexpensive, durable, breathable, and deeply established in local storage practices[11,25,37,38]. Jute fibers consist primarily of cellulose (≈60%), hemicellulose (≈20%), and lignin (≈10%), along with pectin, and are inherently hydrophilic[39-42]. Therefore, jute bags are both hygroscopic and readily wetted: they absorb water vapor from humid air and wick liquid water from rain or condensation, thereby increasing the risk of moisture-related grain deterioration[9,11,43]. The main alternative promoted for smallholder storage is hermetic packaging, typically using multilayer plastic bags or metal silos. A recent meta-analysis reported that conventional woven bags experience substantially greater insect-related grain losses than hermetic storage systems[44]. Nevertheless, adoption of hermetic bags remains limited by cost and availability[7,44]. Hermetic systems also have a recognized limitation: because they are impermeable, they can trap metabolic moisture and heat when grain is loaded at an excessively high moisture content or becomes wet following damage to the liner. Under such conditions, hermetic storage may perform worse than breathable alternatives[9,11]. Modifying existing jute bags rather than replacing them therefore represents an attractive alternative. Two recent studies have demonstrated that silane-based superhydrophobic coatings can reduce moisture uptake by wheat stored in jute bags over periods ranging from 45 days to two months[45,46]. However, these studies were relatively short, examined only one crop and one storage temperature, and did not investigate how a coating that preserves fabric porosity could limit moisture transfer to the grain.

Our laboratory draws inspiration from water-repellent organisms, including sea skaters (*Halobates* spp.)[47,48] and collembolans (springtails)[49,50], to develop perfluorocarbon-free solutions for a range of applications, including underwater bubble entrapment[51,52], cavitation mitigation[49], separation and purification[53,54], superhydrophobic sand mulch[55-58], and suppression of the Leidenfrost state to enhance heat transfer[59]. For grain storage applications, we previously rendered conventional jute fabrics water-repellent by coating them with paraffin wax[60]. In an eight-week storage experiment at 22 °C, these wax-coated jute bags (WCJBs) reduced moisture uptake and better

preserved the SMC and germination of wheat than untreated control jute bags (CJBs). However, that study left four important questions unanswered. First, does the protective effect persist over a realistic storage season? Harrington's rule predicts that sustained differences in SMC should lead to increasingly pronounced differences in seed viability over time, an effect that an eight-week experiment may be too short to capture. Second, does this benefit extend to oilseeds as well as cereals and persist at the elevated temperatures typical of tropical storage environments? Third, through which of the two water-transport pathways does the coating exert its protective effect? Specifically, does it reduce vapor exchange, decrease the fabric's hygroscopic capacity, or prevent the fabric from absorbing and transporting liquid water originating from condensation, splashing, or rain? Fourth, is it possible to establish retrospectively which water-transport pathway operated during storage? This question is rarely addressed in storage studies, and we investigated it here using evidence recovered three years after the experiment ended. To address these questions, we conducted a nine-month storage experiment using wheat and soybean seeds in WCJBs and CJBs under two RH conditions (55% and 75%) and two temperatures (22 °C and 35 °C). We then performed transport, sorption, humidity-tracking, and wetting experiments to distinguish between vapor-phase and liquid-water pathways. In addition, we used the salts originally employed to regulate storage humidity as an unintended but potentially informative tracer of liquid-water exposure. We found that the wax coating left the vapor-phase properties of jute largely unchanged but substantially altered its interaction with liquid water. Evidence from the storage trial indicated that the bags had been exposed to liquid water as well as water vapor, as would be expected under practical storage conditions. Whereas the CJBs absorbed and transported liquid water, the WCJBs resisted this process. This difference provides a mechanistic explanation for the lower moisture accumulation and substantially higher germination rates observed in grain stored in WCJBs.

Results

Jute surface treatment and the water-repellent properties of WCJBs

We prepared the wax-coated jute fabric following the surface treatment protocol described previously[60]. Briefly, the jute fabric was first subjected to alkali treatment and then exposed to paraffin wax dissolved in hexane in a rotary evaporator (Fig. 1a). The hexane was subsequently evaporated under reduced pressure and recovered in the condenser for reuse (see Methods). The

water-repellent properties of the resulting WCJBs were evaluated by placing water droplets on their surfaces and comparing their behavior with that on untreated CJBs. On CJBs, the droplets were completely absorbed within two minutes, whereas on WCJBs, they remained as intact sessile droplets for several hours before evaporating (Fig. 1b; see also Fig. 10).

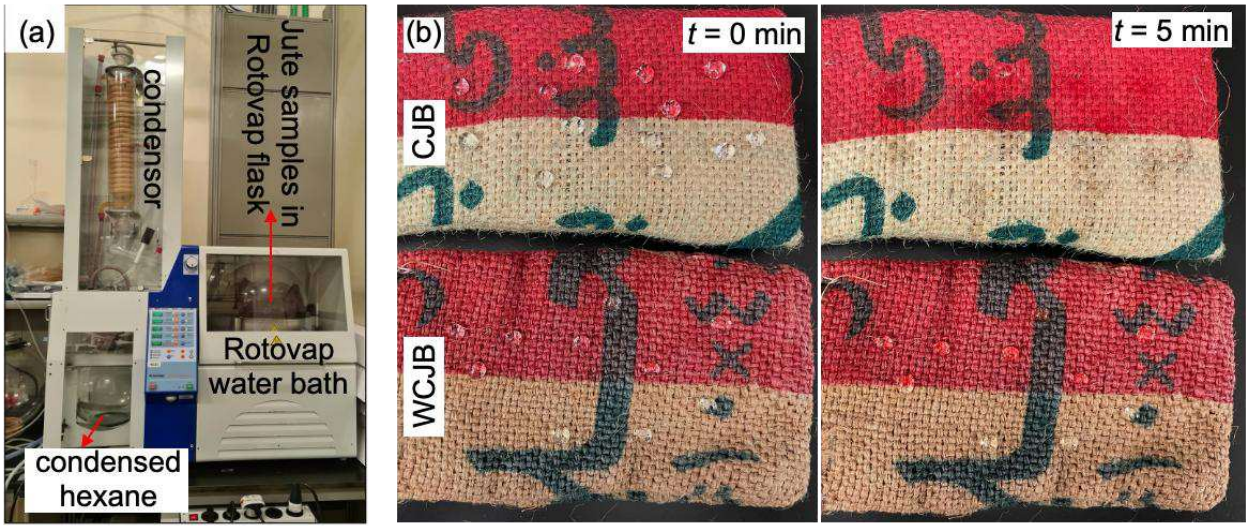


Figure 1. Jute fabric treatment and the water-repellent properties of WCJBs. (a) Jute fabric was loaded into the evaporator flask and sequentially treated with deionized water, 70% ethanol, ammonium acetate–acetic acid, 5% NaOH, and finally a 6 g L^{-1} paraffin wax solution in hexane. The water bath was maintained at 55 °C, and the pressure was reduced to 80 mbar to evaporate the hexane, which was subsequently condensed and collected for reuse. (b) Wettability of CJBs (top) and WCJBs (bottom). Water droplets spread across and wetted the CJB surface upon contact, whereas droplets deposited on the WCJB surface retained their spherical shape and remained intact five minutes after placement.

Nine-month seed storage experiment

Wheat and soybean seeds (100 g per bag) were packed in CJBs and WCJBs (28 g per bag; initial total mass, M_i = 128 ± 3 g) and stored for nine months (April 2022 to January 2023). The bags were placed in sealed containers above saturated salt slurries that maintained RH levels of 55% ($Ca(NO_3)_2$) or 75% (NaCl). Storage was conducted at either 22 °C (in the laboratory) or 35 °C (in a growth chamber), with three replicates for each of the eight bag–RH–temperature combinations (Fig. 2). A humidity sensor in each container continuously monitored RH, and deviations from the target values were corrected by adding water or salt. The mass of the samples stored at 35 °C was monitored monthly in a separate area of the laboratory. For each measurement, the containers were

removed from the growth chamber, transported on a trolley to the weighing area, and subsequently returned to the chamber. During these routine movements, splashes of saline water from the compartment beneath the bags inadvertently reached the bag surfaces. This contamination was not recognized until the end of the study. Its implications for the experimental results are discussed in detail in the Discussion section.



Figure 2. Nine-month seed storage experiment. (a) Wheat and soybean seeds packed in CJBs and WCJBs. (b) One CJB and one WCJB were placed side by side above a saturated salt slurry in each sealed container. (c) The containers were stored at either 22 °C in the laboratory or 35 °C in a growth chamber (GC).

The moisture gain of the bag–seed system was calculated as:

$$\theta(t) = \frac{M_t - M_i}{M_i}, \quad (1)$$

where M_t is the mass of the bag–seed system at time t, and M_i is its initial mass. Figure 3 shows the temporal changes in $\theta(t)$ under all eight experimental conditions. Three main features were observed. First, WCJB samples consistently accumulated less moisture than their CJB counterparts

under all conditions. After nine months of storage, WCJBs reduced moisture gain (θ) by 44% and 38% for wheat and 42% and 32% for soybean at 22 °C under 55% and 75% RH, respectively. At 35 °C, the corresponding reductions were 58% and 46% for wheat and 59% and 49% for soybean. Second, at both temperatures and for both crops, WCJB samples stored at 75% RH accumulated less moisture than CJB samples stored at 55% RH. Thus, the wax coating more than offset the effect of a 20-percentage-point increase in ambient RH.

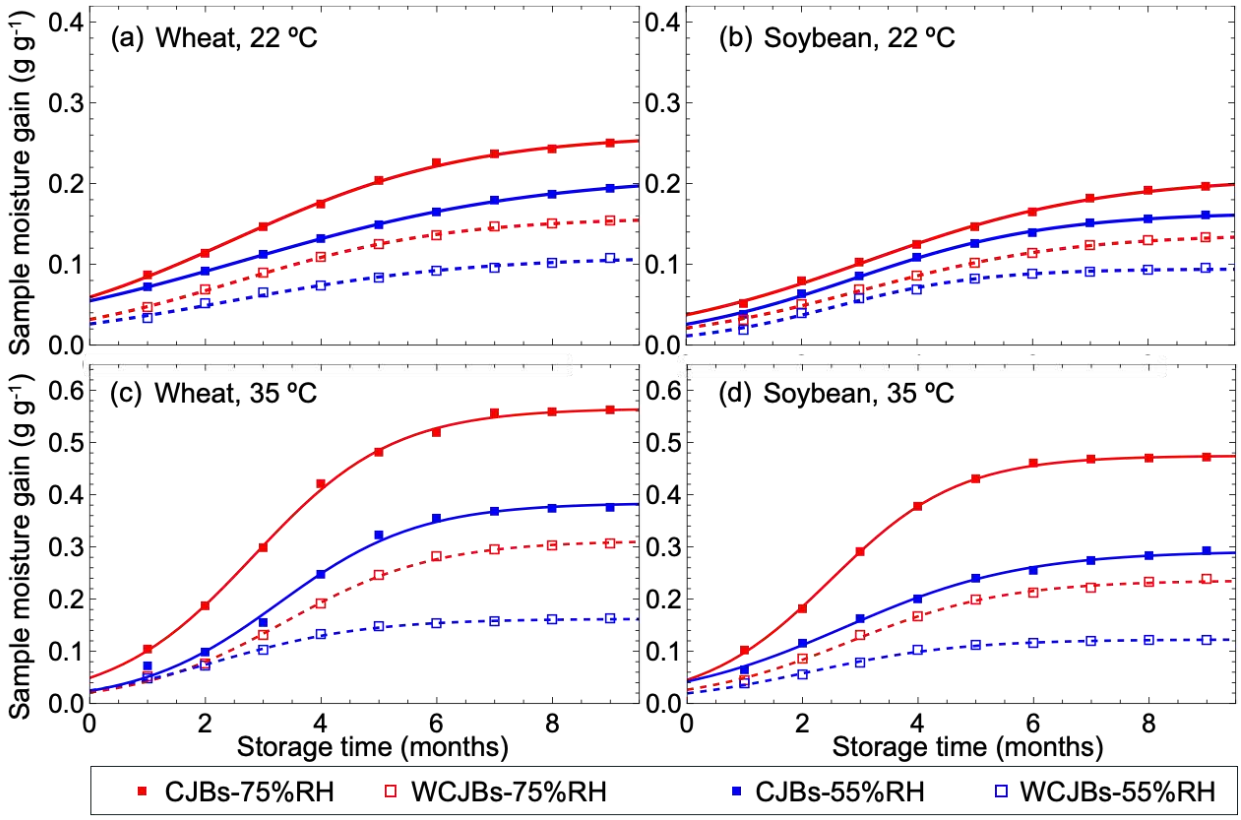


Figure 3. Moisture gain of the bag–seed system during nine months of storage. $\theta(t)$ for wheat (a, c) and soybean (b, d) stored in CJBs (filled symbols, solid lines) and WCJBs (open symbols, dashed lines) at 55% RH (blue circles) and 75% RH (red squares), at 22 °C (a, b) and 35 °C (c, d). Lines represent fits to Eq. (2). Note the lag phase observed at 35 °C, which was absent at 22 °C.

Third, moisture gain increased substantially with temperature at a given RH. The CJB samples stored at 35 °C accumulated approximately twice as much moisture as those stored at 22 °C. All 16 moisture-gain curves exhibited sigmoidal profiles, with inflection times (τ) of 2–3 months at both temperatures (Table 1). The equilibrium moisture gain (θ_e) of the CJB systems approximately doubled as the temperature increased from 22 °C to 35 °C, whereas the corresponding increase in

the WCJB systems was considerably smaller. Because several samples stored at 35 °C were still accumulating moisture at the end of the nine-month experiment, the data were fitted using the empirical sigmoid hydration model proposed by Kaptso et al.[61]:

$$\theta(t) = \frac{\theta_e}{1+e^{-k(t-\tau)}}, \quad (2)$$

where θ_e is the equilibrium moisture gain, k is the rate constant, and τ is the inflection time. The fitted parameters are reported in Table 1.

Table 1. Parameters of Eq. (2) fitted to the moisture-gain data in Fig. 3.

Samples	T (°C)	RH (%)	θ_e (g g^{-1})	k (months^{-1})	τ (months)
Wheat in CJB	22	75	0.26	0.49	2.48
Wheat in WCJB	22	75	0.16	0.54	2.55
Wheat in CJB	22	55	0.21	0.39	2.70
Wheat in WJCB	22	55	0.11	0.47	2.46
Soybean CJB	22	75	0.21	0.48	3.13
Soybean WCJB	22	75	0.14	0.55	3.01
Soybean CJB	22	55	0.16	0.58	2.90
Soybean WCJB	22	55	0.09	0.78	2.56
Wheat in CJB	35	75	0.57	0.83	2.83
Wheat in WCJB	35	75	0.31	0.78	3.37
Wheat in CJB	35	55	0.38	0.83	3.26
Wheat in WJCB	35	55	0.16	0.77	2.21
Soybean CJB	35	75	0.47	0.90	2.50
Soybean WCJB	35	75	0.24	0.74	2.81
Soybean CJB	35	55	0.29	0.65	2.74
Soybean WCJB	35	55	0.12	0.77	2.15

Post-storage seed moisture content

After nine months of storage, the seeds were removed from the bags, weighed, and oven-dried at 80 °C for three days. The post-storage seed moisture content (SMC, wet basis), θ_{sf}, was calculated as follows:

$$\theta_{sf} = \frac{m_{sf} - m_{s0}}{m_{sf}} \times 100\% \quad (3)$$

where m_{sf} is the seed mass after storage and m_{s0} the oven-dry mass. is the oven-dry seed mass. The pre-storage SMC (θ_{si}), determined using the same procedure, was 8.3% for wheat and 9.1% for soybean. Both values were within the safe moisture range for orthodox seeds[19,21]. Figure 4 and Table 2 present the post-storage SMC (θ_{sf}) for all 16 bag–crop–condition combinations.

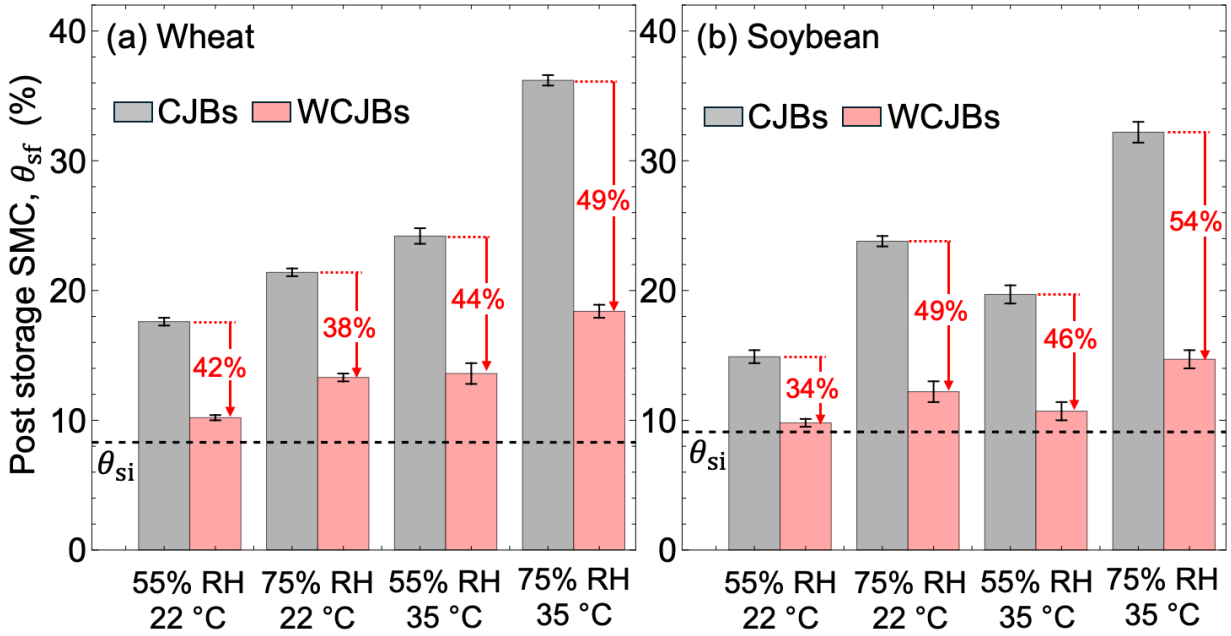


Figure 4. Post-storage seed moisture content. Seed moisture content (θ_{sf}) of (a) wheat and (b) soybean after nine months of storage in CJBs (gray) and WCJBs (pink) under the four RH–temperature combinations. Dashed lines indicate the pre-storage values (θ_{si}) of 8.3% for wheat and 9.1% for soybean. Bars represent means ± standard deviations (SD) for three bags.

Seeds stored in CJBs accumulated substantial amounts of moisture under all conditions. At 75% RH and 35 °C, the post-storage SMC (θ_{sf}) of wheat and soybean seeds in CJBs reached 36.2% and 32.2%, respectively, corresponding to approximately 4.4 and 3.5 times their initial values. Under the same conditions, θ_{sf} in WCJBs increased to only 18.4% and 14.7%, respectively. Relative to CJBs, WCJBs reduced θ_{sf} by 42%, 38%, 44%, and 49% for wheat and by 34%, 49%, 46%, and 54% for soybean at 22 °C/55% RH, 22 °C/75% RH, 35 °C/55% RH, and 35 °C/75% RH, respectively. Soybean seeds stored in WCJBs at 55% RH remained within 1.6 percentage points of their initial SMC at both temperatures.

Two features of the data in Table 2 are particularly relevant to the mechanism discussed below. First, the final SMC of seeds stored in WCJBs was close to the EMC expected at the corresponding ambient RH, based on published EMC data[23]. The expected EMC values were approximately 11.4% and 14.7% for wheat and 9.7% and 15.4% for soybean at 55% and 75% RH, respectively. In contrast, the final SMC of seeds stored in CJBs was substantially higher than the expected EMC. Second, at a given RH, the final SMC of seeds stored in CJBs was considerably higher at 35 °C than at 22 °C. For wheat, for example, θ_{sf} was 24.2% versus 17.6% at 55% RH and 36.2% versus 21.4% at 75% RH. This pattern contrasts with the slight decrease in grain EMC with increasing temperature at a given RH reported in the literature[23]. The visual appearance of the bags and their contents (Supplementary Figs S1 and S2) was consistent with these measurements. CJBs and their contents were visibly damp and discolored under all conditions except 22 °C/55% RH, and fungal growth was observed at 35 °C/75% RH. In contrast, WCJBs and their contents appeared dry and unchanged, except for slight dampness on the undersides of the bags at 35 °C/75% RH.

Table 2. Post-storage seed moisture content (θ_{sf}) and germination rate (G_f) after nine months of storage. Values are means of three bags; germination was assessed using 150 seeds per bag. Pre-storage values were as follows: wheat, θ_{si} = 8.3% and G_i = 98%; soybean, θ_{si} = 9.1% and G_i = 89%.

Crop	T (°C)	RH (%)	θ_{sf} CJB (%)	θ_{sf} WCJB (%)	G_f CJB (%)	G_f WCJB (%)
Wheat	22	55	17.6	10.2	65	95
Wheat	22	75	21.4	13.3	48	86
Wheat	35	55	24.2	13.6	39	84
Wheat	35	75	36.2	18.4	12	56
Soybean	22	55	14.9	9.8	65	88
Soybean	22	75	23.8	12.2	51	72
Soybean	35	55	19.7	10.7	45	82
Soybean	35	75	32.2	14.7	18	67

Post-storage germination

Post-storage germination (G_f) was assessed after nine months by incubating 150 seeds from each bag at 22 °C for one week (Eq. 5 in Methods). The results were compared with the pre-storage germination rates (G_i) of seeds from the same lots (98% for wheat and 89% for soybean). For both crops, germination was significantly higher in WCJBs than in CJBs under all storage conditions (Fig. 5 and Table 2; $p < 0.05$). Wheat stored in WCJBs had germination rates of 95% and 86% at 22 °C and 84% and 56% at 35 °C, under 55% and 75% RH, respectively. The corresponding rates in CJBs were 65%, 48%, 39%, and 12%. For soybean, germination rates were 88%, 72%, 82%, and 67% in WCJBs, compared with 65%, 51%, 45%, and 18% in CJBs, under the same sequence of storage conditions. Thus, after nine months at 22 °C and 55% RH, wheat stored in WCJBs had lost only three percentage points of its initial germination capacity, whereas wheat stored in CJBs had lost 34% points. At 35 °C and 75% RH, germination of wheat stored in CJBs had declined to 12%, indicating near-complete loss of viability, whereas wheat stored in WCJBs retained a germination rate of 56%.

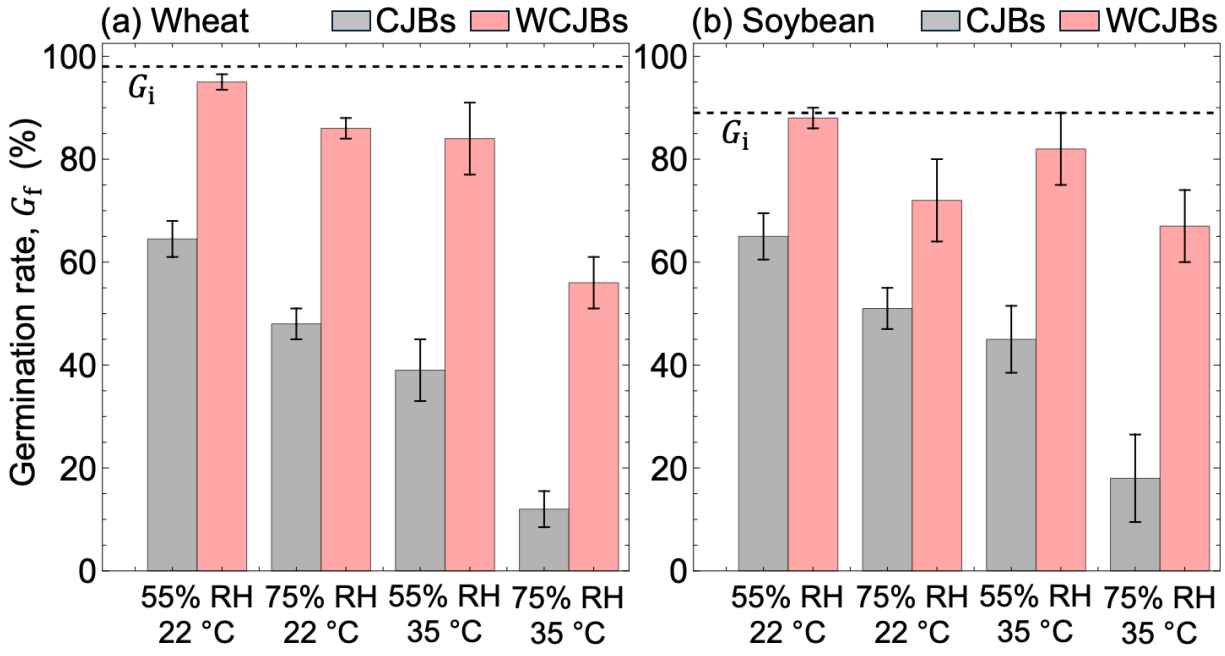


Figure 5. Post-storage germination. Germination rate (G_f) of (a) wheat and (b) soybean after nine months of storage in CJBs (gray) and WCJBs (pink) under the four RH–temperature combinations. Dashed lines indicate the pre-storage germination rates (G_i) of 98% for wheat and 89% for soybean. Bars represent means ± standard deviations (SD) based on 150 seeds per bag and three bags per treatment.

Germination is a single function of post-storage moisture content

When post-storage germination (G_f) was plotted against seed moisture content (θ_{sf}) for all 16 treatment combinations (Fig. 6), the data for each crop followed a single monotonic curve, regardless of bag type, RH, or temperature (Pearson's r = −0.98 for wheat and −0.95 for soybean). Data points for WCJBs at 35 °C overlapped with those for CJBs at 22 °C when the seeds had similar θ_{sf} values. For example, wheat stored in WCJBs at 35 °C/55% RH (θ_{sf} = 13.6%, G_f = 84%) showed a response similar to that of wheat stored in WCJBs at 22 °C/75% RH (θ_{sf} = 13.3%, G_f = 86%). These results suggest that the wax coating does not directly affect seed viability but preserves germination primarily by limiting moisture accumulation. The absence of WCJB data points below the common curve further suggests that the coating did not adversely affect viability under the conditions tested. This finding provides a longer-term assessment of Harrington's rule than was possible in our previous eight-week storage study[60]. Over nine months, the differences in SMC maintained by WCJBs were accompanied by differences of approximately 30–50 percentage points in germination.

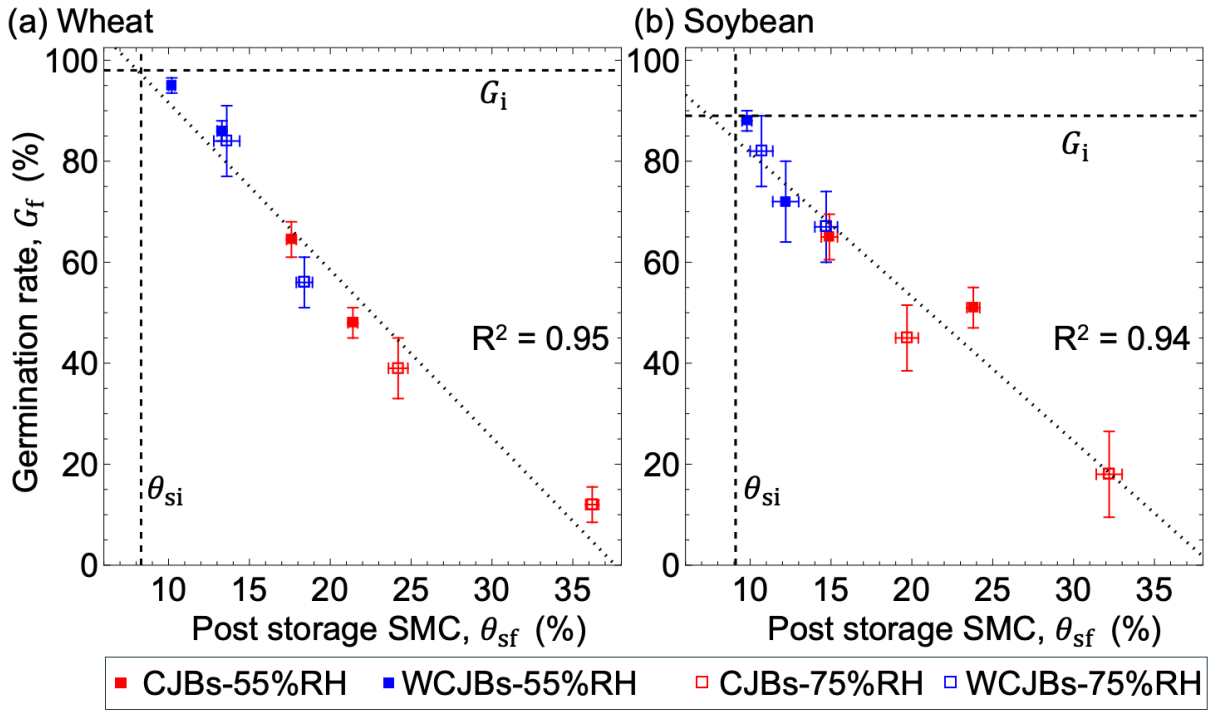


Figure 6. Post-storage germination as a function of seed moisture content. Post-storage germination (G_f) plotted against post-storage seed moisture content (θ_{sf}) for (a) wheat and (b) soybean across all storage conditions. Red symbols represent CJBs and blue symbols represent

WCJBs; filled symbols denote storage at 22 °C and open symbols storage at 35 °C, at 55% and 75% RH (Table 2). Dotted lines indicate linear regressions fitted to all eight data points for each crop, and dashed lines indicate the pre-storage values of seed moisture content (θ_{si}) and germination (G_i). Error bars represent standard deviations (SD).

Mechanism of moisture transport through the bags

The storage experiment demonstrated that WCJBs slowed moisture accumulation, limited post-storage SMC, and preserved seed viability. Moisture can reach seeds inside a jute bag through two pathways: (i) water vapor can diffuse through the pores of the fabric and subsequently be sorbed by the seeds, or (ii) liquid water, such as condensate, rainwater, or splashed water, can be absorbed by the fabric and then redistributed to seeds in contact with it through capillary wicking. A wax coating could reduce moisture uptake through either pathway by decreasing the vapor permeability of the fabric, reducing its hygroscopic capacity, or preventing wetting by liquid water. We therefore conducted four experiments to distinguish among these possibilities.

Vapor permeability. The rate of water evaporation from jars covered with either control or wax-coated jute fabric was measured in an oven at 35 °C (Fig. 7a), with the RH maintained at 60% inside the jars and 40% outside. Mass loss was linear over time (Fig. 7b), yielding evaporation rates of 0.8 and 0.7 g h^{-1} for the control and wax-coated fabrics, respectively. These rates corresponded to vapor fluxes J of 4.8×10^{-5} and 4.2×10^{-5} kg m^{-2} s^{-1}, respectively, through the jar opening (7.7 cm in diameter). According to Fick's first law,

$$D = \frac{JL}{\Delta C}, \tag{4}$$

where L is the fabric thickness (approximately 1 mm) and ΔC is the water vapor concentration difference across the fabric, calculated as $\rho_{sat}\Delta RH$, with ρ_{sat} = 39.6 g m^{-3} at 35 °C. The resulting effective vapor diffusion coefficients were 6.0×10^{-6} and 5.3×10^{-6} m^2 s^{-1} for the control and wax-coated fabrics, respectively. Thus, the wax coating reduced the effective vapor diffusion coefficient by approximately 12%.

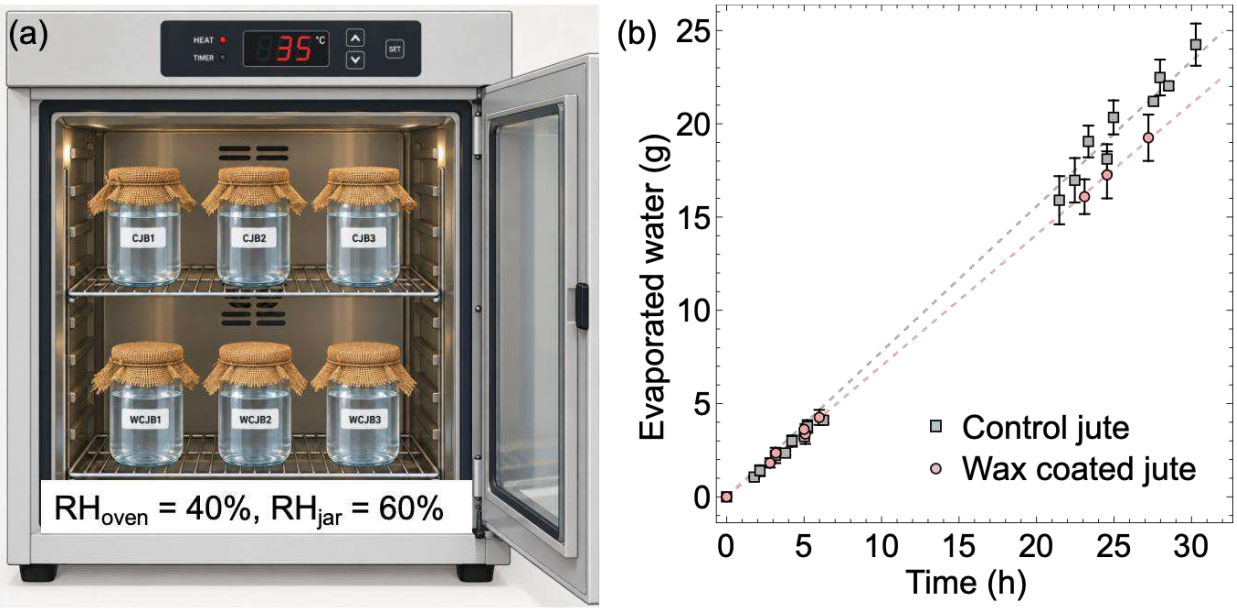


Figure 7. Vapor transport through the fabrics. (a) Water-filled jars covered with control or wax-coated jute fabric and placed in an oven at 35 °C, with the RH maintained at 40% outside the jars and 60% inside. (b) Cumulative mass of evaporated water over time. The slopes correspond to evaporation rates of 0.8 g h^{-1} for the control fabric and 0.7 g h^{-1} for the wax-coated fabric.

Humidity inside the bags. The storage experiment was replicated using humidity sensors placed inside a CJB, inside a WCJB, and in the container headspace. The sensors recorded RH continuously through a microcontroller (Fig. 8a). Starting from laboratory conditions (approximately 55% RH), the headspace RH increased immediately after the container was sealed above the NaCl slurry. The RH inside both bags increased more gradually, initially lagging behind the headspace RH, but all three measurements converged at approximately 75% RH within four days (Fig. 8b). These results indicate that neither fabric prevents the air inside the bag from equilibrating with the ambient humidity. The wax coating may delay this equilibration by only a few hours, consistent with the behavior of evaporating liquid marbles[62].

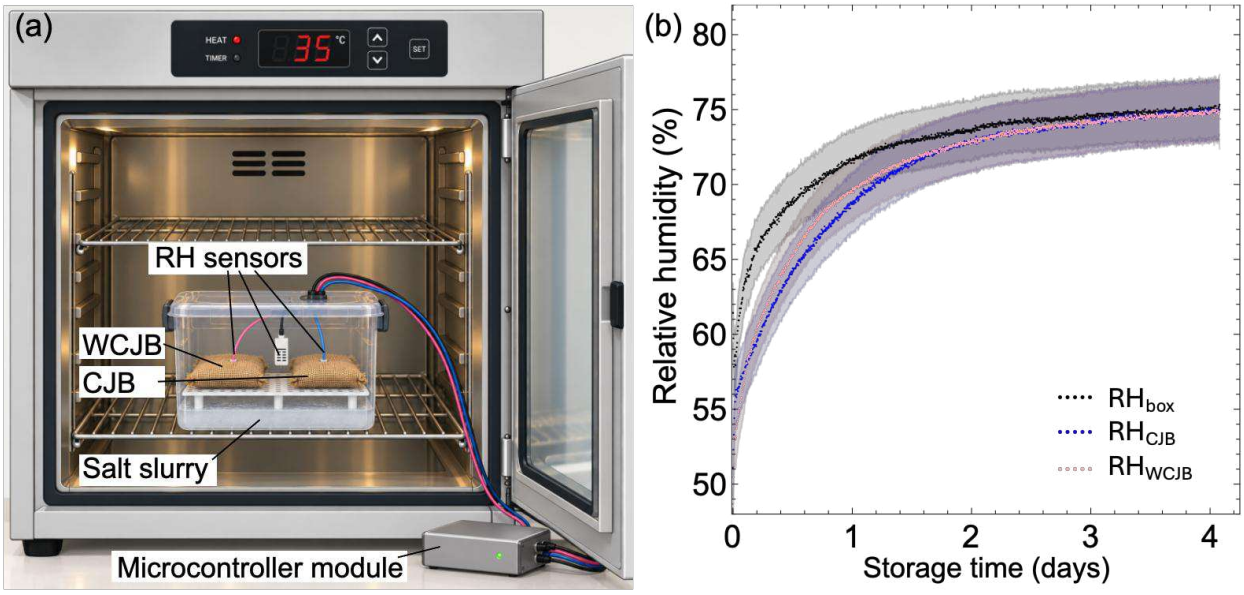


Figure 8. Humidity inside CJBs and WCJBs. (a) Schematic of the experimental setup, showing a CJB and a WCJB containing seeds inside a sealed container positioned above a salt slurry in an oven at 35 °C. Humidity sensors were placed inside each bag and in the container headspace. (b) RH in the headspace, CJB, and WCJB over time. Shaded bands indicate the sensor accuracy.

Hygroscopic capacity. The vapor sorption behavior of the control fabric, wax-coated fabric, wheat seeds, and soybean seeds was measured using a vapor sorption analyzer. The target RH was increased from 10% to 55%, decreased back to 10%, and then increased to 75%. Mass was recorded until the rate of change was less than 0.01% per hour (Fig. 9, see Methods). Both fabrics responded to each RH step within minutes and reached similar moisture contents: approximately 6% at 55% RH for both fabrics and approximately 10% for the control fabric and 8% for the wax-coated fabric at 75% RH. In contrast, the seeds responded much more slowly. Wheat and soybean seeds had not reached equilibrium at 75% RH after 15 and 40 h, respectively, reflecting the longer diffusion path within a seed kernel than within a jute fiber. These results indicate that the wax coating leaves the hygroscopic capacity of jute largely unchanged.

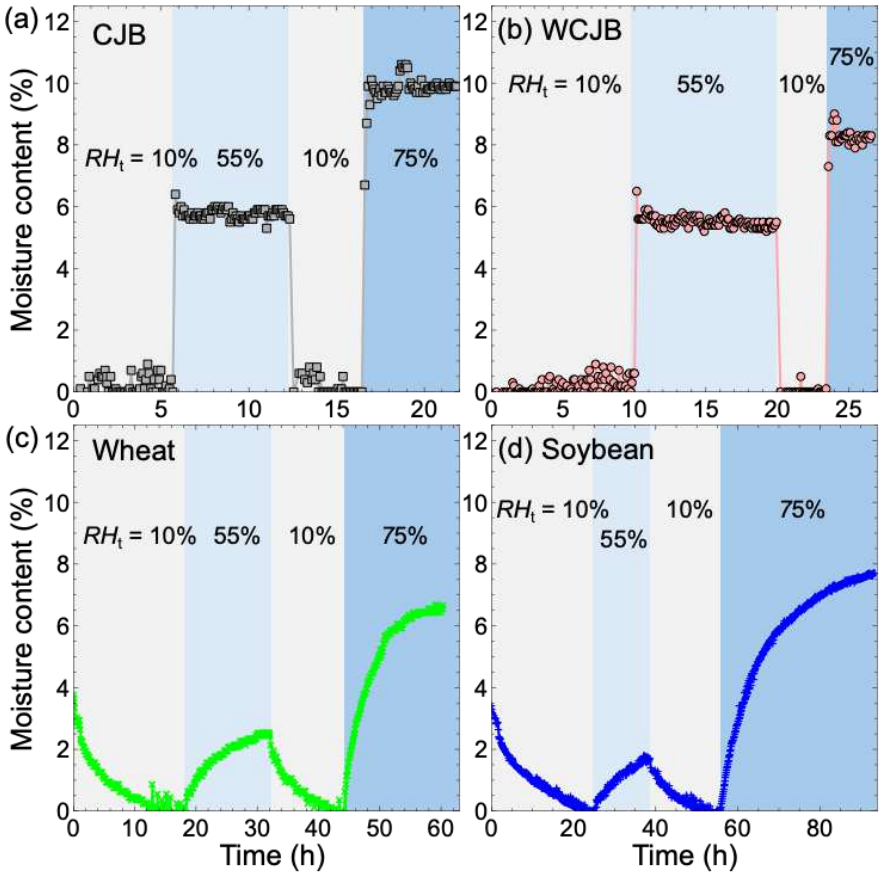


Figure 9. Vapor sorption. Moisture content over time for (a) control jute, (b) wax-coated jute, (c) wheat seeds, and (d) soybean seeds measured using a vapor sorption analyzer at 35 °C as the target RH (shaded regions) was sequentially adjusted from 10% to 55%, back to 10%, and then to 75%. Moisture content is expressed on a wet basis, with the dry mass defined as the equilibrium sample mass at 10% RH.

Liquid water. A water droplet was placed on each fabric surface, and its behavior was recorded at 1-min intervals (Fig. 10). On the control jute, the droplet spread and was fully absorbed within 2 min. In contrast, on the wax-coated jute, the droplet remained spherical and showed no apparent absorption for 3.5 h, by which time it had largely evaporated. Thus, the wax coating had little effect on the fabric's interaction with water vapor but substantially altered its interaction with liquid water.

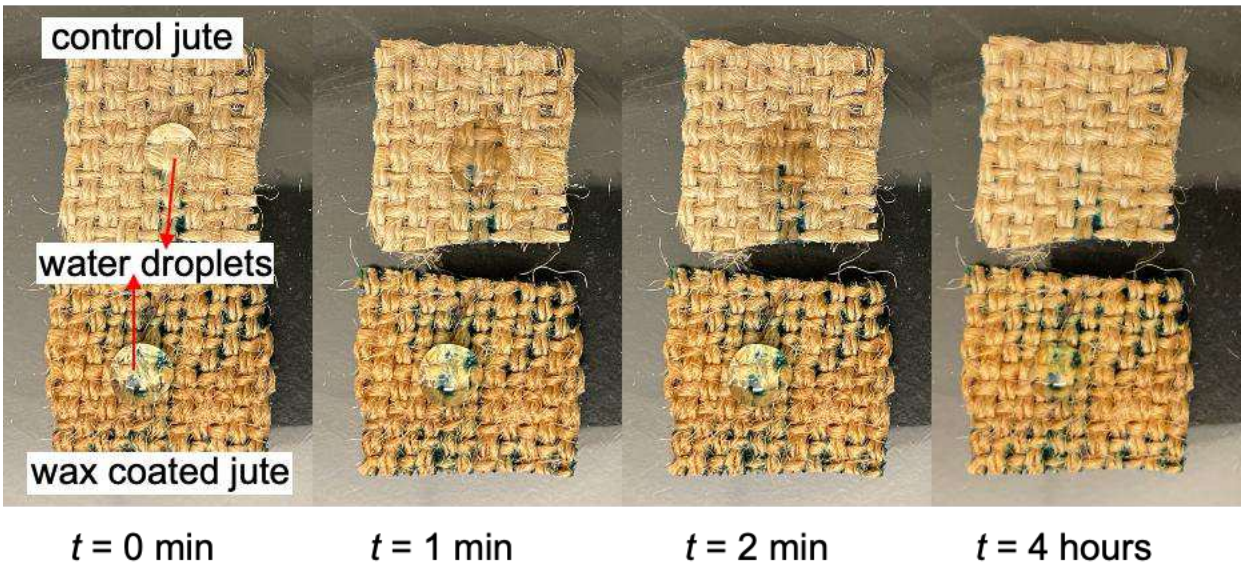


Figure 10. Liquid water on the fabrics. Snapshots of a water droplet on control (top) and wax-coated (bottom) jute fabric at the indicated times.

Water splashing and creeping

After nine months of storage, the bags themselves contained 33%–50% water on a wet basis at 35 °C, equivalent to 0.5–1.0 g of water per gram of dry fiber (Fig. 11a). These values were substantially higher than the hygroscopic regain of approximately 10% at 75% RH (Fig. 10a). At 22 °C, the bags contained 17%–35% water on a wet basis. Thus, both types of bags became visibly wet during storage, although the amount of water transferred to the seeds differed between treatments (Table 2). Under the nominal storage conditions, we did not expect water vapor to condense inside the containers. Two possible sources of liquid water were: (i) splashing from the salt slurry when the 35 °C containers were transported for weighing (Methods); (ii) salt creeping[63]. Because the salts in the slurries are nonvolatile, their presence in the fabric could provide a persistent indicator of liquid-water contact, even years after the experiment. Accordingly, in 2026, three years after the trial ended, we retrieved all bags and collected approximately 1 g of fabric from the upper and lower faces of each bag. Each sample was soaked in 40 mL of deionized water and shaken for 1 h at 35 °C. The electrical conductivity of each extract was then measured (Fig. 11b). For CJBs stored in the laboratory at 22 °C, the extracts from the upper and lower faces had conductivities of approximately 200 and 1,000 µS cm^{-1}, respectively. Although relatively low,

these values exceeded the conductivity of extracts from fresh jute by approximately an order of magnitude at the lower face. They also showed the same bottom-to-top gradient observed in the bags stored in the growth chamber. This finding is notable because the laboratory containers were never transported, and the bags were removed during slurry replenishment (see Methods). Thus, salt from the slurry also reached these bags without container transport, most plausibly by salt creeping along the container wall and mesh (see Limitations). The extracts from WCJBs stored at both 22 and 35 °C had similar conductivities of approximately 5,000 μS cm^{-1} at the upper and lower faces. This relatively high background conductivity likely resulted from residual sodium-containing salts introduced during the acid–base treatment used to fabricate the WCJBs, specifically during the NaOH and ammonium acetate treatment steps. Consequently, any additional contribution from salt originating in the slurry could not be distinguished in the WCJB samples. In contrast, the CJBs stored in the growth chamber had extract conductivities of approximately 7,600 μS cm^{-1} at the upper face and 44000 μS cm^{-1} at the lower face. These values were approximately 40 times higher than those measured for the corresponding faces of the laboratory-stored CJBs. The pronounced difference between the upper and lower faces indicates that liquid from the salt slurry had reached the bags and entered the fabric at the lower face, before moving upward through it (via splashing and/or creeping). This interpretation is consistent with the capillary rise observed from the bottom seams during the experiment. By comparison, the WCJB extracts showed no comparable difference between the two faces. Although the high background conductivity prevented us from resolving any additional slurry-derived salts in these samples, the absence of a vertical conductivity gradient is consistent with the wax coating limiting liquid-water absorption and capillary wicking.

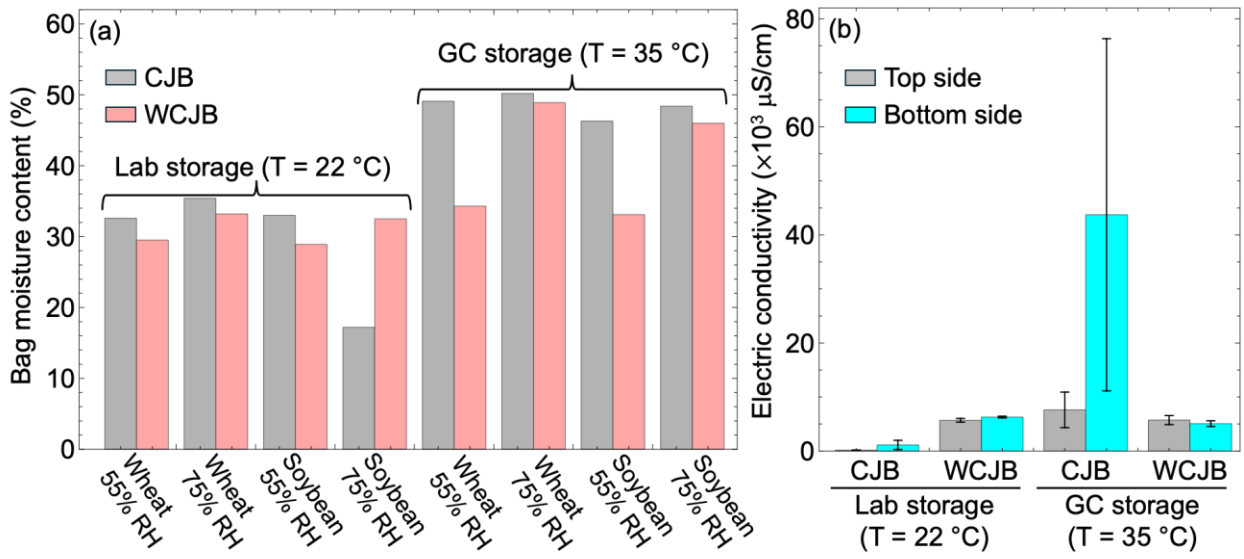


Figure 11. Post-storage assessment of jute bags. (a) Moisture content of the bags after nine months of storage in the laboratory (22 °C) or growth chamber (35 °C). (b) Electrical conductivity of extracts prepared by soaking 1 g of bag fabric in 40 mL of deionized water.

Discussion

The four questions raised in the Introduction can now be addressed. Over the nine-month storage period, WCJBs maintained lower moisture contents and higher germination rates than CJBs under every condition tested, for both a cereal (wheat) and an oilseed (soybean), at 22 and 35 °C. The larger differences in germination observed after nine months, compared with those observed after eight weeks, are consistent with the cumulative effects of seed moisture content on viability described by Harrington's rule. The germination advantage of WCJBs was 30%–50% after nine months, compared with 12%–35% after eight weeks[60]. The coating appears to act primarily by preventing the fabric from absorbing and wicking liquid water, rather than by substantially altering its vapor-phase properties. We first discuss the mechanism, because it determines the conditions under which this approach is likely to be effective, and then consider the implications of the storage trial for practical seed storage.

First, Figures 7–9 show that the coating has little effect on the two vapor-phase properties of jute examined in this study. The effective vapor diffusion coefficient decreased by only approximately 12%. This relatively small change is plausible given that only a few weight percent of paraffin was distributed over a rough, open-weave fabric approximately 1 mm thick; the coating did not seal

the pores through which water vapor diffuses. Similarly, the hygroscopic capacity of the fabrics was largely unchanged: both fabrics reached approximately 6% moisture content at 55% RH, while their moisture contents at 75% RH were approximately 10% and 8% for the control and wax-coated fabrics, respectively. This behavior is consistent with the location of the sorbed water. A monolayer of water on the external surface of jute would account for only a small fraction of the fabric mass, approximately 0.03%, or roughly 200 times less than the water absorbed by the fabric at 55% RH. Thus, most of the water was likely sorbed within the cellulose and hemicellulose structure of the fibers, a process that the wax coating did not prevent, presumably because the coating was not continuous. Similar behavior has been reported for durable water-repellent finishes on cotton and waxed or silanized wood, which can remain hygroscopic while becoming resistant to liquid-water wetting[64,65]. The slightly lower moisture content of the wax-coated fabric at 75% RH may reflect reduced capillary condensation in the narrowest interfibrillar spaces. Such condensation below 100% RH is favored by hydrophilic surfaces with contact angles below 90°. However, the difference amounted to only approximately 2% of the fabric mass, or about 0.5 g per bag, and is too small to explain the differences observed in seed moisture content. Consistent with this interpretation, the RH inside both bag types approached the ambient RH within a few days (Fig. 8). Thus, for most of the nine-month storage period, seeds in WCJBs were exposed to approximately the same water activity as seeds in CJBs.

Vapor sorption alone would therefore be expected to bring the seeds in both bag types toward the same EMC at a given ambient RH and temperature. Based on the published values used in this study, the expected EMCs were approximately 11.4% and 14.7% for wheat and 9.7% and 15.4% for soybean at 55% and 75% RH, respectively[23]. The seeds stored in WCJBs approached these values (Table 2): in six of the eight WCJB treatment combinations, the final seed moisture content (θ_{sf}) was within 2 percentage points of the expected EMC, and soybean seeds stored at 55% RH showed little change from their initial moisture content. The seeds stored in CJBs behaved differently. At 75% RH and 35 °C, their moisture contents reached 36% for wheat and 32% for soybean, more than twice the expected EMCs. Even at 55% RH, their final moisture contents were 10%–13% above the expected values. These findings indicate that vapor sorption alone cannot explain the moisture accumulation in CJB-stored seeds and support the involvement of liquid-water uptake.

Liquid water–fabrics interactions

Several observations support the conclusion that liquid water, rather than water vapor alone, accounted for the excess moisture in the control bags. First, the bags themselves: after nine months, the fabric of every bag stored at 35 °C contained 33%–50% water on a wet basis, equivalent to 0.5–1.0 g of water per gram of dry fiber (Fig. 11a). These values were substantially higher than the approximately 10% moisture content reached by jute through vapor sorption at 75% RH (Fig. 10). Second, the temperature dependence was inconsistent with vapor sorption as the sole source of moisture. At a fixed RH, the EMC of grain generally decreases slightly as temperature increases. Thus, if vapor sorption had governed the outcome, the seeds stored in CJBs would be expected to have been marginally drier at 35 °C than at 22 °C. Instead, they were substantially wetter (Fig. 4), and the equilibrium moisture gain of the CJB–seed systems was approximately twice as high at 35 °C as at 22 °C (Table 1)[23]. Third, and most directly, the conductivity measurements provided evidence of salt transfer from the storage containers to the fabric. The storage RH was maintained using saturated NaCl and $Ca(NO_3)_2$ slurries, and water vapor does not transport dissolved ions. The extracts from CJBs stored in the growth chamber had approximately 40 times the conductivity of those from CJBs stored in the laboratory. Moreover, the conductivity of extracts from the lower face of the growth-chamber bags was approximately six times that of extracts from the upper face. These results indicate that salt-containing liquid reached the bags, entered the control fabric at the lower face, and moved upward through it. In contrast, the conductivity values for WCJBs were similar between the growth-chamber and laboratory storage conditions and between the upper and lower faces, consistent with the coating limiting liquid-water absorption and wicking. One likely source of liquid water was the handling required by the experimental protocol (see Methods). The containers stored in the growth chamber were transported on a trolley for monthly weighing, over cable protectors on the floor. During transport, the salt slurry in the lower compartment splashed onto the mesh and the undersides of the bags. The capillary rise observed from the bottom seams of the control bags during the trial, together with the bottom-to-top salt gradient detected afterward, is consistent with this explanation. However, liquid could also have reached the bags without transport or direct splashing. Saturated salt solutions can creep along container walls as thin liquid films, a phenomenon known as salt creeping[63]. Evaporation at the edges of these films deposits salt crystals, which can then wick additional solution upward, allowing a salt crust to extend progressively along the wall[63,66]. In a

493 reconstruction of the storage setup, we subsequently observed such a crust extending from the
494 slurry, across the mesh, and toward the undersides of the bags. A crust of this type can retain a
495 film of saturated brine, allowing a bag resting on it to contact liquid without directly touching the
496 slurry (Supplementary Fig. S3). This creeping mechanism could explain the salt gradient detected
497 in the CJBs stored at 22 °C, which were neither transported nor present during slurry
498 replenishment. It may also have contributed to liquid-water exposure in the 35 °C containers,
499 where splashing during transport could have provided an additional source.

500 The brine, whether transferred by splashing or by creeping along the container surfaces, was
501 saturated and therefore had a water activity close to that of the container atmosphere
502 (approximately 0.75 or 0.55). Although such brine can keep a fabric wet, it cannot, by itself,
503 explain seed moisture contents substantially above the EMC corresponding to the ambient RH.
504 For example, grain with a moisture content of approximately 36% has a water activity approaching
505 0.98 and must therefore have received water with a substantially higher water activity than that of
506 the saturated salt solutions. The seeds may also have been exposed to relatively fresh condensate.
507 Because the bags were removed during slurry replenishment (see Methods), one possible source
508 of this condensate was water that formed on the lids and walls of the 35 °C containers during their
509 monthly transfer to the 22 °C laboratory for weighing. The thin plastic walls could cool rapidly
510 while the slurry remained warm, potentially causing condensation. Condensation may also have
511 occurred in either storage condition whenever temperature fluctuations caused the lid or walls to
512 fall below the dew point of the headspace. Thus, the salt measurements indicate that salt-containing
513 liquid reached the bags and provide clues about its route of transport, whereas condensate may
514 have contributed to the additional water that accumulated in the seeds. The salt content of the
515 stored seeds, which could have helped distinguish water derived from brine from water derived
516 from condensate, was not measured.

517 The key difference between CJBs and WCJBs was therefore how their surfaces interacted with
518 liquid water. When liquid water contacted uncoated jute, it spread across the surface and was
519 rapidly absorbed by capillary action through the yarns and along the seams, potentially allowing
520 water to reach seeds in contact with the fabric. This behavior is consistent with the rapid droplet
521 absorption observed in Fig. 10 and the salt gradient detected in the CJBs (Fig. 11b). In contrast,
522 water droplets on WCJBs remained beaded on the surface, with no apparent absorption during the

observation period. Such droplets could roll off, collect between yarns, or remain on the surface until they evaporated. This behavior is consistent with the prolonged persistence of droplets on WCJBs (Fig. 10) and the absence of a detectable bottom-to-top conductivity gradient (Fig. 11b), although the high background conductivity of the coated fabric limits the interpretation of the latter observation. The moisture content of a bag can therefore be viewed as the balance between episodic inputs of liquid water and continuous evaporative loss through the fabric. This framework may help explain why the moisture-gain curves in Fig. 3 differed between the RH treatments, even though the potential sources of liquid water, including salt creeping and, at 35 °C, splashing, were present in both. Evaporative loss from a wet fabric increases as the difference between the water vapor concentration at its surface and that in the surrounding air increases. Consequently, a wetted control bag would be expected to dry more rapidly at 55% RH than at 75% RH and to retain less water at the lower RH. However, brine absorbed into the jute would remain in equilibrium with the surrounding atmosphere and could sustain prolonged wetting. Once wetted, a control bag could therefore act as a persistent source of moisture, increasing the RH inside the bag and facilitating further moisture accumulation by the seeds. Under sufficiently favorable conditions, this could also promote fungal growth. By contrast, a coated bag would be more likely to shed liquid water and dry between wetting events, while allowing its internal RH to track the container headspace. Its seeds would consequently remain closer to the EMC imposed by vapor sorption. A similar distinction may apply to condensate: on hydrophilic jute, water can nucleate on the fibers and rapidly spread and wick through the fabric, whereas on a wax-coated surface, it may form discrete droplets that coalesce and re-evaporate as the temperature rises[26,27]. The difference in water accumulation was substantial. Of the approximately 73 g gained by the CJB–wheat system at 35 °C and 75% RH, approximately 44 g accumulated in the seeds. By comparison, the WCJB–wheat system gained approximately 40 g, of which approximately 12 g accumulated in the seeds. These observations are consistent with the wax coating limiting the transfer of liquid water from the fabric to the seeds, even though it did not prevent the fabric from sorbing water vapor.

The bags stored at 22 °C provide additional evidence that liquid-water exposure was not limited to the transported growth-chamber containers. These containers were never transported, and the bags were removed during slurry replenishment. Nevertheless, the seeds in the CJBs finished storage with moisture contents 5–10 percentage points above the expected EMC, the bags themselves were wet, and the control fabric contained salt with a bottom-to-top gradient (Fig. 11b).

554 The conductivity values were approximately 40 times lower than those measured in the transported
555 growth-chamber bags but remained substantially higher than those of fresh jute. These findings
556 are consistent with salt creeping from the slurry along the container surfaces, resulting in gradual
557 wetting of the lower face of the bags. Additional fresh water may have been supplied by
558 condensation. The containers were stored on a trolley beside large windows in an air-conditioned
559 corridor, where daytime solar heating followed by cooling under the air supply could have caused
560 daily temperature fluctuations of a few degrees in the slurry and container lid. At 75% RH, the
561 dew-point margin was approximately 4.6 °C, making condensation possible during these
562 fluctuations; at 55% RH, the corresponding margin was approximately 9.5 °C, making
563 condensation less likely. A small, intermittent supply of condensate, combined with the slower
564 supply of brine from below, could therefore help explain both the smaller excess moisture above
565 EMC at 22 °C and the differences between the two RH treatments.

566 **Implications for storage practice**

567 The storage trial exposed the bags to both water vapor and liquid water, as can occur under
568 practical storage conditions. This combined exposure may make the findings more relevant to real
569 storage environments, although it also limits the extent to which the effects of the two moisture-
570 transfer pathways can be separated. In smallholder storage systems, sacks may be exposed to rain
571 during transport, damp floors, roof leaks, and condensation that forms when daily temperature
572 fluctuations of 10–15 °C cause the air inside a storage facility to reach its dew point[24]. Bags at the
573 bottom of a stack, particularly those in contact with cool floors, are especially vulnerable. The
574 mechanism identified here suggests that WCJBs may be most beneficial wherever liquid water,
575 rather than water vapor, is a major route of moisture ingress. Such conditions may occur in humid
576 climates with large diurnal temperature fluctuations, during wet-season transport, and in stores
577 with inadequate roofing or unpaved floors. In storage environments that are humid but thermally
578 stable and dry at floor level, the advantage of WCJBs may be smaller because the coating has little
579 effect on vapor-phase transport. Under those conditions, drying grain to a safe moisture content
580 before storage remains essential[9].

581 Two additional implications deserve consideration. First, because the coating leaves the fabric
582 relatively permeable to water vapor, WCJBs are not expected to trap metabolic moisture and heat
583 in grain loaded above a safe moisture content in the same way that hermetic liners can[9,11,44]. The

two technologies may therefore be complementary: WCJBs may be useful in situations where grain cannot be guaranteed to be sufficiently dry at loading or where the integrity of a hermetic liner cannot be assured. However, this potential advantage requires further testing under conditions involving grain with excessive initial moisture content and active respiration. Second, the close relationship between final seed moisture content and germination rate (Fig. 6) suggests that the germination advantage of WCJBs was primarily associated with their ability to limit moisture accumulation. The data do not indicate an additional effect of the coating treatment on seed viability independent of moisture content. In other words, the alkali and paraffin treatments, as well as any residual hexane, did not appear to provide a detectable additional protective or adverse effect under the conditions tested. The comparison between the two crops is consistent with this interpretation. Soybean seeds, which contain approximately 18%–22% oil, had lower equilibrium moisture contents than wheat seeds under all storage conditions, consistent with their respective sorption isotherms[31]. At 35 °C and 75% RH, soybean seeds stored in WCJBs retained a larger proportion of their initial germination capacity than wheat seeds (67% of the initial 89%, compared with 56% of the initial 98%). This difference should not be interpreted as evidence that soybean seeds are inherently more robust. Oilseeds are generally considered more susceptible to chemical deterioration than cereal seeds[34-36], and soybean germination in CJBs under the same conditions declined to 18%. Rather, the lower final moisture content of soybean seeds in WCJBs (14.7%) was close to their expected EMC, whereas wheat seeds reached 18.4%, approximately 4 percentage points above their expected EMC and within a range in which fungal growth may become more likely.

A third implication concerns the identification of liquid-water exposure. The splashing of salt slurry onto the bags during transport was not recognized during the original trial, which ran from April 2022 to January 2023. Instead, evidence of this exposure was obtained in 2026 by analyzing the salts retained in the fabric. Because the buffer salts are nonvolatile, they provided a persistent record of liquid contact that remained detectable after the water itself had evaporated or redistributed. This approach may therefore help distinguish liquid-water exposure from vapor-mediated moisture uptake in storage studies. We suggest that measurements of residual salts or other suitable tracers be considered in future storage experiments and in field assessments of damp grain sacks, provided that the source and background levels of the relevant ions can be established.

Limitations

The storage trial was conducted from April 2022 to January 2023. The splashing of salt slurry onto the bags stored at 35 °C during their monthly transport was not recognized until the trial had ended, and its extent was investigated only in 2026, when the surviving bags were analyzed for residual salts. Moreover, the containers were neither isothermal nor completely isolated from environmental temperature fluctuations. The entire containers were transported to a 22 °C laboratory each month, and the slurries were opened and replenished weekly. Condensation was also observed on the lids of the containers maintained at 75% RH. Consequently, the trial assessed the performance of the two bag types under combined vapor and liquid-water exposure, rather than under vapor-only conditions. The absolute moisture gains observed at 35 °C therefore reflect conditions involving intermittent liquid-water exposure and should not be interpreted as representative of a sealed container maintained continuously at 55% or 75% RH. Although this combination of exposures may resemble some field storage conditions[9], the two moisture-transfer pathways were not independently controlled. Thus, the relative contributions of brine delivered by splashing, salt creeping along the container surfaces, and condensation cannot be determined from the available data. Salt creeping along container surfaces also warrants further investigation. Although this phenomenon has been characterized in crystallization vessels[63,66], we are not aware of previous studies examining its potential occurrence in humidity-controlled storage experiments, where saturated salt slurries are commonly used to maintain RH[67] in seed longevity and accelerated-aging studies[68-70]. In our study, the formation of a salt crust extending from the slurry toward the bags was observed in a reconstruction of the experimental setup after the trial. However, the rate of salt creeping in a sealed, humidity-buffered container, where the evaporative driving force may be limited, was not measured. The residual salt detected in the untransported CJBs stored at 22 °C provides evidence that this process may have contributed to liquid-water exposure over the nine-month period, but it does not quantify the rate or extent of creeping. A dedicated experiment using containers that remain undisturbed throughout storage, with periodic measurements of salt accumulation and mass changes at the bag undersides, would help establish how quickly this process can bring bags into contact with liquid. It could also determine whether increasing the distance between the slurry and the bags or adding a suitable creep-suppressing additive[63] can prevent this form of unintended exposure. The 22 °C treatment also had limitations because the containers were kept on a laboratory trolley beside large windows rather than in a

645 temperature-controlled chamber. In addition, the laboratory setup exposed approximately 3 cm^2 of
646 fabric per gram of grain, about ten times the fabric-to-grain area ratio of a 50-kg sack.
647 Consequently, moisture transfer through the fabric may have been amplified relative to that in a
648 typical field-scale sack, and the moisture gains reported in Table 1 may represent upper estimates
649 for comparable storage conditions. The mechanism experiments (Figs 7–10) were conducted only
650 at 35 °C. Furthermore, the vapor-sorption comparison would be strengthened by including an
651 alkali-treated, uncoated jute control and by expressing the sorption capacity of the coated fabric
652 relative to its cellulose content. These additions would help distinguish the effects of the wax
653 coating from those of the chemical pretreatment and the mass contributed by the coating itself.
654 Three additional experiments would help address these limitations. First, a storage trial in which
655 each container is continuously monitored using a balance and remains undisturbed throughout the
656 experiment would help isolate vapor-mediated moisture transfer from handling-related liquid
657 exposure. Second, a deliberately temperature-cycled trial, involving daily fluctuations of
658 approximately 10 °C in a humidified chamber, would quantify condensate formation and its
659 transfer to different bag types under conditions resembling the diurnal temperature fluctuations
660 experienced in actual stores. Third, a controlled liquid-exposure experiment using a known tracer,
661 with the salt slurry physically isolated from the bags to prevent creeping, would allow liquid-water
662 transfer to be quantified directly. Analyzing the bags and seeds immediately after exposure would
663 also help establish how the tracer is distributed between the fabric and grain. Such an approach
664 would convert the retrospective forensic method used in this study into a planned experimental
665 measurement. Finally, because the paraffin coating was applied using hexane, scaling up the
666 process will require the development of a solvent-free or aqueous application method, which is the
667 subject of ongoing work.

668 **Conclusion**

669 Over nine months of storage at 55%–75% RH and 22–35 °C, WCJBs reduced moisture gain in
670 stored wheat and soybean by 32%–59%, maintained seed moisture content closer to the expected
671 EMC under the ambient humidity conditions, and preserved germination rates of 56%–95%,
672 compared with 12%–65% in CJBs. For both crops, post-storage germination was closely
673 associated with final seed moisture content, regardless of bag type, RH, or temperature. These
674 findings suggest that the primary benefit of the coating was to limit moisture accumulation rather

than to exert a direct effect on seed viability. The transport, sorption, and wetting experiments further indicated that the coating did not substantially alter the fabric's vapor permeability or hygroscopic capacity. Instead, its principal function was to reduce liquid-water absorption and capillary wicking, which were readily observed in CJBs but limited in WCJBs. Notably, liquid-water exposure was not part of the original experimental design and was not recognized during the trial. It was investigated retrospectively, three years later, using residual salts in the fabric. This finding highlights both a potential source of unintended liquid-water exposure in humidity-controlled storage experiments and a possible approach for detecting such exposure in bagged-grain systems. WCJBs may therefore offer a breathable, potentially low-cost intervention for reducing moisture-related deterioration in traditional jute storage, particularly in hot, humid environments with substantial temperature fluctuations. Their performance should be evaluated in farm-level trials alongside hermetic storage systems and in controlled laboratory experiments involving continuous weighing, deliberate temperature cycling, and planned liquid-water exposure using a suitable tracer.

MATERIALS AND METHODS

Materials

Paraffin wax (common white candles, IKEA, Sweden) was purchased from a local supermarket in Jeddah, Saudi Arabia. Hexane and ethanol (VWR International, Fontenay-sous-Bois, France), ammonium acetate, glacial acetic acid, and calcium nitrate tetrahydrate ($Ca(NO_3)_2 \cdot 4H_2O$) (Sigma-Aldrich, St. Louis, MO, USA), as well as sodium chloride and sodium hydroxide (Fisher Scientific, NJ, USA), were used as received, except that ethanol was diluted to 70% (v/v). Standard 50-kg jute sacks (Indian Sela Basmati Rice) were obtained from Al Jawahir Company (Jeddah). Wheat (*Triticum aestivum*) was harvested during the 2020 season at the King Abdulaziz University Agricultural Research Station, Hada Al-Sham (21°45′–22°10′ N, 39°30′–40°15′ E, Makkah, Saudi Arabia). Soybean (*Glycine max*) of US origin was purchased from Ahmed Bin Afif Trading Company (Jeddah).

Preparation and treatment of jute bags

Jute fabric (approximately 1 mm thick) was cut into 15 × 10 cm pieces and sewn into bags weighing 28 ± 3 g. The bags were loaded into a rotary evaporator flask (Fig. 1a) and subjected to the following sequential treatments. (i) Prewashing: The bags were washed with 2.5 L of deionized (DI) water for 10 min with swirling and then drained. (ii) Ethanol treatment: The bags were immersed in 2.5 L of 70% ethanol for 20 min and drained, rinsed with DI water in a tray, and oven-dried at 70 °C for 15 min. (iii) Ammonium acetate treatment: The bags were immersed in 0.5 M ammonium acetate adjusted to pH 5 with glacial acetic acid for 30 min, drained, rinsed, and oven-dried as described above. (iv) Alkali treatment: The bags were immersed in 5% (w/v) aqueous NaOH (1.25 M, pH approximately 14) for 4 h, drained, rinsed, and oven-dried as described above. (v) Wax coating: Paraffin wax dissolved in hexane at a concentration of 6 g L^{-1} was added to the flask containing the bags. The rotary evaporator was operated overnight at a bath temperature of 55 °C and a pressure of 80 mbar until the hexane had evaporated and been condensed and collected for reuse. Control jute bags (CJBs) were used as received, without treatment.

Wetting tests

Droplets of DI water (approximately 1 mL), with or without food coloring, were placed on the upper and lower surfaces of CJBs and wax-coated jute bags (WCJBs) using a dropper. The droplets were observed until they were absorbed by the CJBs or evaporated from the WCJBs. For the droplet-spreading experiment (Fig. 10), a single droplet was placed on each fabric type, and images were captured at 1-min intervals for 4 h at room temperature.

Seed storage experiment

Undamaged wheat and soybean seeds were selected, weighed (approximately 100 g per bag), and packed into CJBs and WCJBs. The pre-storage seed moisture content (SMC; θ_{si}) was determined using separate subsamples dried at 80 °C for 3 days to constant mass (Eq. 3, with m_{si} in place of m_{sf}). Each storage container consisted of a lidded plastic box with a lower compartment containing a saturated salt slurry and a plastic mesh positioned above the slurry. One CJB and one WCJB containing the same crop were placed side by side on the mesh (Fig. 2b). Target RH levels of 55% and 75% were established using saturated slurries (approximately 3:1 salt-to-water mass ratio) of $Ca(NO_3)_2 \cdot 4H_2O$ and NaCl, respectively[60,61]. The slurries were prepared by gradually adding salt to 200–400 mL of DI water with stirring until the RH measured by a sensor inside the container (HTC-2; stated accuracy, ±5% RH and ±1 °C) remained within ±2% of the target value for 4 h. A total of 24 containers were prepared: 2 crops × 2 RH levels × 2 temperatures × 3 replicates. Because each container held one CJB and one WCJB, the experiment included 48 bags.

The two temperature treatments were conducted at different locations and involved different handling procedures, which are relevant to the interpretation of the results (see Discussion). The twelve containers assigned to 35 °C were kept in a Percival growth chamber in the KAUST Plant Science core facility, which was set to 35 °C. Because no balance was available in the chamber room, the entire containers, including the salt slurries, were removed from the chamber once a month and placed on a trolley. The trolley was then wheeled to a laboratory in another part of the building, passing over cable protectors along the route. In the laboratory, each bag was removed, weighed, and returned to its container. The containers were then wheeled back to the growth chamber. Only at the end of the trial did we realize that this transport procedure had repeatedly caused slurry to splash from the lower compartment onto the mesh and the undersides of the bags (Results, Water splashing). The twelve containers assigned to 22 °C remained on a trolley throughout the experiment in an air-conditioned laboratory alley beside large exterior windows, where the nominal room temperature was 22 °C. These containers were weighed in place and were not moved; therefore, the bags were not exposed to transport-related splashing. However, they were exposed to daytime solar heating through the windows. In both temperature treatments, the containers were opened weekly to check the sensor readings, and the slurries were replenished with DI water or salt as needed to maintain the target RH. Before replenishment, the bags were removed from the containers and returned afterward to prevent direct wetting. The experiment ran from April 2022 to January 2023. After nine months, the bags and seeds were photographed. The seeds from each bag were homogenized and subsampled, and θ_{sf} was determined by drying at 80 °C for 3 days (Eq. 3). The bags were weighed before and after drying to determine their water content (Fig. 11a). The bags were subsequently stored in a sealed container at room temperature in the laboratory and retrieved in 2026 for the salt-tracing measurements.

Germination

For each bag, 150 seeds were placed on Whatman filter paper moistened with DI water in Petri dishes and incubated in the dark at 22 ± 0.5 °C for 1 week. Germination was calculated as follows:

$$G = \frac{n_g}{N} \times 100\%, \tag{5}$$

where n_g is the number of germinated seeds and N is the total number of seeds (150). Pre-storage germination (G_i) was determined using the same procedure with seeds from the corresponding lots that had not undergone storage.

Mechanism experiments

Evaporation. Glass jars (opening diameter, 7.7 cm) were filled to 80% of their capacity with DI water, covered with control or wax-coated jute fabric secured with a cable tie, and placed in an oven at 35 °C (Fig. 7a). The mass of each jar was measured hourly for 1.5 days using a balance. The RH inside the jars (60%) and in the oven (40%) was measured using HTC-2 humidity sensors. The water vapor flux was calculated by dividing the slope of the mass-loss curve by the area of the jar opening. The effective diffusion coefficient was then calculated using Eq. 4, with ρ_{sat} = 39.6 g m^{-3} at 35 °C and L = 1 mm.

Humidity inside the bags. A CJB and a WCJB, each containing seeds, were placed in a sealed container above a saturated NaCl slurry in an oven at 35 °C. Temperature and humidity sensors (DHT22) were positioned in the container headspace and inside each bag among the seeds. Measurements were recorded by a microcontroller at 5-min intervals for 1 week (Fig. 8a).

Vapor sorption. Samples of control fabric, wax-coated fabric, wheat seeds, and soybean seeds were analyzed using a vapor sorption analyzer (AquaLab VSA) at 35 °C. The target RH was initially set to 10% and maintained until the mass change was less than 0.01% h^{-1}; the mass at this point was defined as the reference mass (m_0). The RH was then increased to 55%, decreased to 10%, and finally increased to 75%, with each step maintained until the same equilibrium criterion was reached. The moisture content at time t was calculated on a wet basis as $(m_t - m_0)/m_t \times 100\%$.

Salt tracing. In 2026, three years after the storage experiment ended, CJBs and WCJBs from the long-term storage experiment were retrieved for salt contamination analysis. The bags had been stored in a sealed container since April 2023. Approximately 1 g of fabric was collected from each of the upper and lower faces of each bag and placed in a Falcon tube. DI water (40 mL) was added to each tube to soak the fabric. The samples were shaken at 35 °C for 1 h to dissolve the salts, after which the electrical conductivity of each extract was measured in triplicate using a conductivity meter (Mettler Toledo).

Statistical analysis

The storage experiment followed a completely randomized factorial design, with bag type (CJB or WCJB), RH (55% or 75%), and temperature (22 or 35 °C) as fixed factors and three replicate bags per combination. Each crop was analyzed separately. Moisture gain, θ_{sf}, and G_f were analyzed using three-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) test for multiple comparisons in OriginPro 2017 (OriginLab, Northampton, MA, USA)[71]. Statistical significance was set at $p < 0.05$. was taken as significant. Germination percentages were arcsine square-root transformed before analysis. Pearson correlation coefficients between G_f and θ_{sf} were computed across the eight bag–condition means per crop.

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Data availability

The data supporting the findings of this study are available in the Supplementary Information and from the corresponding authors upon reasonable request.

Competing interests

K.O. and H.M. are inventors on patent application PCT/IB2022/050592, which relates to wax-coated jute fabrics. The other authors declare no competing interests.

Author contributions

K.O. designed and performed the surface treatments, characterized the materials, conducted the seed storage and germination experiments, collected and analyzed the data, and wrote the first draft. M.S.S. analyzed the storage data; designed and performed the transport, sorption, and wetting experiments; developed the mechanistic interpretation; and revised the manuscript. W.M.T. prepared the experimental bags and assisted with the treatment process. H.M. conceived the study, supervised the research, and wrote the manuscript with K.O. and M.S.S.

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