Engineered Jute Bags for Storing Food Grains within Harrington's Safe Zone of Seed Moisture Content

Kennedy Odokonyero, Adair Gallo Jr., and Himanshu Mishra *

Water Desalination and Reuse Center, Division of Biological and Environmental Sciences and Engineering, King Abdullah University of Science and Technology (KAUST),

Thuwal 23955 - 6900 Saudi Arabia,

Emails Addresses: kennedy.odokonyero@kaust.edu.sa; adair.gallojunior@kaust.edu.sa; himanshu.mishra@kaust.edu.sa

*Corresponding Author: himanshu.mishra@kaust.edu.sa

Abstract

Harrington's thumb rule states that for every 1% increase in seed moisture content (SMC), seed lifetime decreases by $\leq 50\%$. Thus, to avoid post-harvest grain losses, stored seeds must be insulated from water. Although the jute bags typically used to store grains afford an ecofriendly, durable, and low-cost storage solution, their hydrophilic nature makes them vulnerable to wetting from airborne humidity and precipitation events. To address this issue, we treated jute fabrics with alkali and wax to render them water-repellent. A 2-month seed storage experiment revealed that wax-coated jute bags (WCJBs) outperformed control jute bags (CJBs) at safeguarding wheat (*Triticum aestivum*) grains exposed to 55%–98% relative humidity. Specifically, grains stored in WCJBs exhibited 15%–50% less SMC than grains stored in CJBs, which led to a 21%–66% enhancement in the germination efficacy of WCJB-stored seeds. This engineering solution could enhance the potential of jute bags to reduce post-harvest losses.

24 **Keywords:** Harrington's rule; seed storage; post-harvest losses; jute bags; biomimetics; relative
25 humidity; seed germination; *Triticum aestivum*.

26

27

INTRODUCTION

In 2020, the Nobel Peace Prize was awarded to the World Food Programme; this is a testimony to the complete dependence of humans on our food supply¹. According to the United Nation's Food and Agricultural Organization, developing sustainable agricultural practices that can feed $\sim 10^{10}$ humans in 2050 is the mega-challenge of our time²⁻⁴. To meet the increasing demand for food, annual global food production must increase by around 70%⁵. Grain crops, such as cereals, oil seeds, and pulses, form the basis of global food security⁶⁻⁸, with two billion tons of grains currently produced annually^{7,9}. By 2050, global grain production is projected to increase by >33% to meet food and animal feed needs^{3,10}. Increasing crop yields beyond current levels is likely to be difficult given the effects of climate change, deforestation, rising groundwater depletion, and overstressed energy resources¹¹⁻¹⁴. This emerging food security scenario will demand a highly efficient food supply chain from farms to consumption⁸.

At present, $\sim 25\%$ – 33% of the total grain produced annually is lost between harvest and consumption through “post-harvest losses” (PHLs)^{6,15}, which entail quantitative and qualitative food losses within the interconnected post-harvest chain from harvest through to storage, processing, marketing, and finally consumption¹⁶⁻¹⁸. Alarming, in developing countries, up to 50%–60% of cereals may be lost during storage due to poor storage infrastructure¹⁶⁻¹⁸, slower adoption of modern technologies¹⁹, and fragmented information sharing²⁰. Conversely, in developed countries, grain losses can be as low as 1%–2% because of better post-harvest handling and improved hermetic storage technologies^{9,20}. Nevertheless, total food waste at the consumer level in developed countries is >40% (~ 222 million tons); thus, the magnitude of food losses in these countries is comparable to that in developing countries and similar to the net food production of sub-Saharan Africa (~ 230 million tons)⁶. PHLs can be in form of spoilage, seed

viability loss, grain depletion, and nutritional loss²¹ resulting from biotic (e.g., insects, rodents, and fungi) or abiotic (e.g., temperature and air-moisture/humidity) factors⁹. Fungal infection and mycotoxin contamination are major causes of PHL during seed/grain/cereal storage, accounting for 25%–40% of losses²².

In the context of seed deterioration, Harrington's thumb rule states that for every 1% increase in seed moisture content (SMC), the storage life of the seed is reduced by half²³⁻²⁴. This empirical rule underscores the importance of insulating stored grains from water in liquid and vapor forms. Typically, seeds are dried to achieve a SMC of ~13% before storage¹⁵⁻¹⁶; when SMC reaches ~16%, Harrington's rule becomes relevant and seeds begin to deteriorate in an accelerated manner²³. Therefore, to avoid increased SMC, it is important to carefully consider storage structures, packaging materials, storage duration, and relative humidity (RH).¹⁵ Issues arise when moisture-absorbing storage bags facilitate the diffusion of moisture to dry grains and thereby increase SMC. In developing countries, including those in the Indian subcontinent and sub-Saharan Africa, farmers exploit jute bags for grain storage because of their low-cost, mechanical durability, and traditional usage over millenia^{9, 19, 25}. However, jute is hydrophilic and therefore absorbs water due to its chemical components, which include cellulose (~60%), hemicellulose (~20), lignin (~10%), pectin, and water-soluble substances²⁶⁻²⁸. Consequently, jute bags are vulnerable to environmental water, e.g., precipitation, RH, and soil moisture, which interacts with conventional storage systems. Indeed, water accumulation and/or vapor transport through jute bags increases SMC and causes fungal infections; the resultant seed deterioration affects seed germination capacity²⁹⁻³¹. In India, about 60%–70% of grains are stored in traditional structures in which 36.0% and 33.5% of total PHLs are encountered for rice and wheat, respectively³². In sub-Saharan Africa, PHLs of 59% are estimated for maize grains after a

90-day storage period in traditional storage structures (granary/polypropylene bags)³³. Thus, low-cost surface modifications that create water-repellant jute bags are required to reduce PHLs during storage.

To address this problem, we took inspiration from the numerous plants and animals that have developed water-repellency by combining hydrophobic waxy coatings with micro/nanoscale surface roughness. Examples include lotus leaves (*Nelumbo nucifera*)³⁴, the bodies of sea-skaters (*Halobates germanus*)³⁵⁻³⁶, the cuticles of springtails (Collembola)³⁷, as well as certain desert plants³⁸ and insects³⁹ among others⁴⁰. Researchers have already developed bioinspired technologies for drag reduction⁴¹, separation and purification⁴²⁻⁴³, cavitation mitigation⁴⁴, coating-free entrapment of air underwater^{37, 42, 45}, and producing super-water-repellent cotton⁴⁶. Thus, there is a growing expectation for new agrotechnologies to be inspired by nature⁴⁷⁻⁴⁸.

Herein, we present a bioinspired surface treatment for jute bags that enhances their robustness for improved grain storage. Specifically, jute fabrics were treated with alkalis and then coated with paraffin wax to produce water repellence. The seed storage efficacy of these wax-coated jute bags (WCJBs) was compared with that of control jute bags (CJBs, i.e., untreated jute bags) under controlled humidity conditions during a 2-month storage experiment. This was followed by a germination study in which the viability of seeds stored in WCJBs and CJBs was comparably assessed. The low cost, eco-friendly, and simple treatment process reported here has the potential to substantially reduce PHLs, particularly in developing countries currently reliant on regular jute bags for grain storage.

MATERIAL AND METHODS

Materials and apparatus. Paraffin wax was obtained from common white candles manufactured by IKEA (Sweden); hexane and ethanol were purchased from VWR International S.A.S (Fontenay-Sous-Bois, France); ammonium acetate, glacial acetic acid, and calcium nitrate tetrahydrate ($\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$) were purchased from Sigma Aldrich (St. Louis, MO, USA); sodium chloride, potassium sulfate, and sodium hydroxide were purchased from Fisher Scientific (New Jersey, USA). All chemicals were used as received from suppliers. Jute packaging sacks (*Indian Sela Basmati Rice*, 50 kg) were obtained from the *Al Jawahir* Company (Saudi Arabia). A Quanta 600 scanning electron microscope system was used for scanning electron microscopy. A Quorum Q150 TS sputter coater was used to coat jute bags (CJBs and WCJBs) with a 3 nm-thick platinum layer to avoid electrical charging during electron microscopy. A DSA100E contact angle goniometer (Kruss, Germany) was used to characterize the wettability of surfaces. Wheat grains (*T. aestivum* L.) were harvested from a field at King Abdulaziz University's Agricultural Research Station in Hada Al-Sham (which extends between 39°30' and 40°15' East and 21°45' and 22°10' North, in Makkah, Saudi Arabia).

Surface treatment of jute. Jute sacks were cut into 14 × 7 cm pieces and hand-sewn to produce jute storage bags. First, the bags were cleaned by immersion in water (10 min) and then 70% ethanol (20 min), before being dried in a thermal convection oven at 80°C (30 min). Cleaned bags were then immersed in 0.5-M ammonium acetate solution (adjusted to pH 5 using 1.0% glacial acetic acid) for 30 min. After further oven-drying at 80°C (30 min), the bags were immersed in 5% (m/v) NaOH solution (1.25 M and pH ~14) for 2 h. These alkali-treated bags were washed with deionized water and again oven-dried at 80°C (30 min). Subsequently, the bags were immersed in solutions of paraffin wax dissolved in hexane (6 g/L), during which they

were turned upside-down several times to facilitate uniform coating. After 30 min of this treatment, the bags were left to dry overnight in a solvent hood at $21.6^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$.

Wettability tests. Deionized water droplets with and without food coloring and the DSA100E contact angle goniometer were used to characterize the wettability of bag surfaces. WCJBs and CJBs were also exposed to simulated rainfall for ~1 min: they were placed at an angle of $\sim 30^{\circ}$ and the simulated raindrops were applied by releasing water droplets (~2 mL) from a syringe placed ~5 cm above the bags. The moisture absorption of WCJBs and CJBs was estimated by measuring their mass.

Seed storage experiments. Clean and healthy *T. aestivum* grains, devoid of any physical damage, were selected and placed inside paper bags for initial weight measurement. These grains were then dried in an oven at 80°C for 72 h, after which their mass did not change further; thus, SMC in the initial state was calculated as follows: $SMC = (W_1 - W_2)/W_1$, where W_1 is the initial weight of grains and W_2 is their final weight after drying. Subsequently, wheat grains were packaged in WCJBs and CJBs, and the bags were placed in airtight plastic containers with the following RHs: 55%, 75%, and 98%. The air humidity level was controlled in confined spaces by equilibrating it with supersaturated salt solutions of $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$, NaCl, and K_2SO_4 ⁴⁹⁻⁵⁰. Specifically, to obtain 55% RH, 50 g of $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ was dissolved in 100 mL of deionized water by stirring; more salt was added until a saturated solution was formed with a salt:water ratio of 3:1 (w/w). This procedure was repeated to obtain 75% RH using NaCl (but with a 2:1 salt:water ratio) and 98% RH using K_2SO_4 (at a ~3:1 salt:water ratio). The saturated salt solutions were then poured into the lower compartment of the airtight plastic containers, which were integrated with humidity and temperature sensors (Fig. 1). The bags containing wheat grains were then placed on a plastic mesh tray (barrier) above the saturated salt solutions;

therefore, they were exposed to air with well-controlled humidity. Experiments were carried out in triplicate; therefore, nine containers with WCJBs or CJBs were randomly placed and monitored for 2 months. Moisture absorption was determined by weighing each jute bag every 3 days. Total moisture absorbed was calculated in grams per gram of jute bag plus stored seed combined.

Figure 1 Moisture absorption setup for wheat grains stored in jute bags under variable relative humidity (RH) conditions. (A) Schematic of a moisture box containing one control jute bag (CJB) and one wax-coated jute bag (WCJB) in each storage chamber. Each bag contained 130 g of oven-dried wheat grains. The saturated salt solution at the bottom of the box allowed for precise control of air RH. (B) Photograph of the experimental setup showing the three different RH conditions (50%, 75% and 98% RH) replicated in triplicate.

Seed moisture content and post-storage germination/viability. After two months of seed storage, seed groups were combined based on RH treatment during storage. From these larger groups, ~130 g of seeds was withdrawn into paper bags, weighed, and then oven-dried at 80°C

for 72 h to determine post-storage SMC. To evaluate the germination viability of post-storage seeds, 30 seeds from each storage bag were germinated in Petri dishes containing Whatman filter paper soaked in deionized water. These dishes were maintained in a dark incubator and allowed to germinate at $21.6^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$. The germination patterns of seeds were monitored from the first day after sowing until the seventh day, after which the experiment was discontinued.

Statistical analysis. The seed storage experiment involved a completely randomized factorial design, which was used to investigate the effect of jute storage bags and RH on moisture absorption, SMC, and seed germination percentage. For analysis of data including triplicate samples per treatment, we used Origin Pro software to perform a two-way ANOVA, with Tukey's test applied for multiple comparisons of means; $p < 0.05$ was set as the level of statistical significance⁵¹.

RESULTS AND DISCUSSION

Water repellency. Alkali treatment of cellulosic fibers, also known as mercerization, has been exploited to tune various characteristics, such as elastic moduli, brittleness, surface roughness, and readiness for surface coating, of jute and cotton^{27, 46, 52-54}. In the current study, the alkali treatment (Fig. 2) of jute enhanced the surface roughness of fibers, presumably due to the dissolution of the hemicellulose content (Fig. 3). Previously, alkali treatment has been reported to dissolve hemicellulose and other fiber components, thereby rearranging them, which results in the swelling and constriction of pores in jute fabrics^{27, 55-57}.

Figure 2. Schematic of the jute surface treatment process (Credit: Xavier Pita, KAUST).

Figure 3. Representative scanning electron micrographs of jute fiber surface morphologies from control jute bags (CJBs) and wax-coated jute bags (WCJBs). Fibers from CJBs (**A**, **B**, and **C**) show lower surface roughness in comparison to WCJB fibers (**D**, **E**, and **F**). Wax deposits are also indicated with arrows.

We chose an alkali concentration of 5% and treatment duration of 2 h because they enhance the surface roughness of fibers without significantly depleting their mechanical

strength^{27, 55}. For instance, Wang et al.⁵⁸ demonstrated that mechanical properties, such as tensile strength, flexural strength, tensile modulus, and flexural modulus, were superior for 6% NaOH-treated jute fabric reinforced composites relative to the mechanical properties of jute fabrics treated at higher alkali concentrations (>6%). High alkali concentrations not only remove lignin and hemicellulose but also change the native cellulose I to cellulose II^{27, 59}. Such concentrations can also cause excessive peeling of the fiber surface, which reduces the strength and toughness of fibers⁵⁸. In our further analyses, as the alkali-treated fabrics were coated with paraffin wax, the combination of surface roughness and the hydrophobicity of the wax produced robust water repellence^{43, 60}. The intrinsic hydrophobicity of the paraffin wax is characterized by the apparent contact angles of water droplets on smooth wax-coated surfaces: $\theta_o \approx 105^\circ$. When a rough surface is coated with a hydrophobic coating, the resulting water-repellence is enhanced by the entrapment of air inside the surface asperities, which also prevent the penetration of water into the microtexture. After wax coating, the gaps between the WCJB fibers reduced in comparison to the gaps between the CJB fibers (Fig. 3A–C).

When water droplets of $\sim 8 \mu\text{L}$ were placed onto CJBs, they gradually penetrated into the fibers in ≤ 2 min (Figure 4A, C, and E). In contrast, this volume of water droplets placed onto WCJBs did not penetrate into the fibers due to the entrapment of air in the microtexture; the drops exhibited apparent contact angles of $\theta_r \approx 130^\circ$ and remained in their sessile position (pinned and θ_r decreasing) until they evaporated (Figure 4B, D, and F). These air-trapped wetting states are described by the Cassie–Baxter model⁶¹, which connects the macroscopic apparent contact angles on the rough surface, θ_r , with θ_o and the area fractions of liquid–solid (ϕ_{LS}) and liquid–vapor (ϕ_{LV}) fractions underneath the drop as $\cos \theta_r = \phi_{\text{LS}} \times \cos \theta_o - \phi_{\text{LV}}$.

Figure 4. Photographic images of the time-dependent wetting of a control jute bag (CJB) and wax-coated jute bag (WCJB) with colored water droplets placed on the jute surfaces. At 30 s, the water droplets began to rapidly seep through the CJB, whereas the droplets remained suspended on the WCJB (A and B). In only 1 min, the CJB showed significant wetting; in contrast, the water droplets remained stable on the WCJB (C and D). From 2 min onwards, the water droplets were completely absorbed by the CJB, whereas the droplets on the WCJB were stable and remained standing for >3 h (E and F).

The WCJBs and CJBs were also exposed to simulated rainfall. The CJBs were wetted by the impact of water droplets, which they accumulated (Movie 1); however, the simulated raindrops simply rolled-off the WCJBs, thereby preventing water accumulation (Movie 2). In comparison to the CJBs, therefore, the WCJBs showed the potential for superior protection of stored grains against humid air.

Seed storage experiments. We investigated the potential of WCJBs to enhance the shelf-life and viability of wheat grains (*T. aestivum*) stored at 50%–98% RH for 2 months by comparing their

performance with that of CJBs (Fig. 1). The SMC of the wheat prior to storage was 7.1%, which was well within Harrington's safe zone (6%–16%)²⁴. Wheat grains were stored in WCJBs and CJBs (as controls) at $21.6^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ under three different air humidity conditions: 55%, 75%, and 98% RH. During the 2-month-long storage experiment, we examined the moisture absorption and mold growth on jute bags and stored grains every 3 days (Fig. 5). For the 55% RH treatment, there were no significant differences in moisture absorption between the WCJBs and CJBs and the grains stored within these bags (Fig. 5A and D). Consequently, at the end of the storage period, the grains had not suffered from fungal growth. Similarly, for the 75% RH treatment, the WCJBs and their stored grains did not exhibit moisture absorption or mold growth; however, the CJBs and their stored grains showed dampness and fungal growth (Fig. 5B and E). For the 98% RH treatment, both the CJBs and WCJBs and their stored grains exhibited dampness and fungal growth (Fig. 5C and F). Nevertheless, although the water droplets condensed and grew on the WCJBs, they rolled off along the surface because of bags' water repellence (Fig. 5F, inset); consequently, fungal proliferation on wheat grains stored in WCJBs at 98% RH was less prominent than that on wheat grains stored in CJBs.

Figure 5. Photographs of wax-coated jute bags (WCJBs) and untreated control jute bags (CJBs) with stored wheat grains after 8 weeks of storage in different relative humidity (RH) conditions. CJBs and wheat grains stored at 55% RH (A), 75% RH (B), and 98% RH (C); WCJBs and wheat grains stored at 55% RH (D), 75% RH (E), and 98% RH (F). Red arrows indicate fungal (mold) growth. At 55% RH, neither WCJBs nor CJBs suffered from dampness or fungal growth, although seed moisture content increased from 7.1% to 7.5% and 14.9% in WCJBs and CJBs, respectively. WCJBs also performed well at 75% RH; however, grains stored in CJBs at 75% RH showed signs of fungal growth. At 98% RH, both WCJBs and CJBs and their stored grains exhibited dampness and fungal growth (dark grey patches). The inset photograph in (F) shows the accumulation of moisture on WCJBs in the third week of storage.

The amount of moisture absorbed by the bags containing stored grains and the grains' SMCs were also quantified at the end of the storage period (Figure 6). At 55% RH, the total moisture absorbed through the WCJBs was 46% lower than that absorbed through the CJBs (Fig. 6A); the SMC of grains stored in the WCJBs increased from 7.1% to 7.5%, which remained well within Harrington's safe zone, whereas the SMC of grains in the CJBs increased to 14.9%

(Figure 6B). CJBs absorbed twelve times the moisture absorbed by WCJBs; thus, they acted as reservoirs for moisture influx into stored grains. At 75% RH, the total moisture absorbed through the WCJBs was 32% lower than that absorbed through the CJBs; the SMC of grains stored in WCJBs increased from 7.1% to 11%, whereas the SMC of grains increased to 17% in the CJBs, i.e., the latter SMC violated Harrington's rule leading to fungal infestation. At an RH of 98%, the total moisture absorbed through the WCJBs was 45% lower than that absorbed through the CJBs; the SMC of grains stored in WCJBs increased to 26%, whereas the SMC of grains in CJBs increased to 32%. Thus, at 95% RH, both storage media failed to safeguard grains. Notwithstanding, significant differences were found between WCJBs and CJBs for both total moisture absorbed and SMC ($p < 0.05$) at all RHs.

Figure 6. Moisture absorption through jute bags and the moisture content of wheat grains after 2 months of storage. (A) Total moisture absorbed through control jute bags (CJBs: unfilled shapes) and wax-coated jute bags (WCJBs: filled shapes) over the seed-storage period. Total moisture absorbed was taken as the sum of moisture uptake by jute bags and stored grains; the average combined mass of the storage bag plus seed was ~170 g/bag. (B) Post-storage seed moisture content (SMC) of stored wheat grains at different relative humidity (RH) conditions. Horizontally-dotted line (SMC_0) represents initial SMC (7.1%) before storage; error bars represent the standard errors ($\pm SE$) of means from three replicates.

Seed viability after storage. The germination capacity of seeds, or seed viability, is affected by increasing SMC and fungal molds²⁹. For example, the germination capacity of soybean (*Glycine max*), sorghum (*Sorghum bicolor*), red clover (*Trifolium pratense*), and Timothy grass (*Phleum pratense*) seeds reduces substantially during 6–12 months of storage at 30°C and 75% RH²⁹. To investigate the full potential of WCJBs as a reliable seed storage medium, we studied the germination of the stored grains using the following formula: $SG = \frac{\text{Number of germinated seeds}}{\text{Total number of seeds sown}} \times 100\%$. Overall, we found that germination was significantly higher for wheat grains stored in WCJBs than for wheat grains stored in CJBs ($p < 0.05$). Specifically, at 55%, 75%, and 98% RH, storage in WCJBs resulted in 32%, 35%, and 12% improved germination capacity, respectively (Fig. 7).

Figure 7. Seed germination on Petri dishes of wheat grains stored for 8 weeks in control jute bags and wax-coated jute bags (WCJBs) at different relative humidity (RH) conditions. (A) Seed germination patterns monitored for 7 days after sowing and (B) seed germination of seeds stored in control jute bags and WCJBs at 55%, 75%, and 98% RH. The percentage seed germination of wheat grains stored in WCJBs was higher than that of wheat grains stored in control bags under all RHs. Error bars represent the standard error ($\pm$ SE) of means from 100 seeds.

Taken together, our results demonstrate the efficacy of WCJBs. This bioinspired engineering solution can enhance the shelf-life of grains by maintaining their SMC within the limits of Harrington's safe zone. In Fig. 8, we illustrate the comparative seed storage potential of CJBs and WCJBs. Naturally, a question arises: what are the factors and mechanisms that underlie the superior performance of WCJBs over CJBs? Firstly, the water repellence of WCJBs reduces the accumulation of water from precipitation or condensation because drops of certain momentum and mass roll off the enhanced bags; with fewer sessile drops on a porous surface, absorption and mass transfer are also reduced. Secondly, we noticed that the fibers of WCJBs were somewhat swollen in contrast to those of CJBs (Fig. 4). This likely led to partial pore clogging of the treated-jute layer and reduced the flux of water vapor through the pores. In addition, enhanced surface roughness due to the removal of surface impurities and other fiber components by alkali could have increased the contact area between the jute fibers and wax matrix⁶⁰. Consequently, paraffin wax seeping through pores from both surfaces could eventually clog some pores. This hypothesis is consistent with the findings of Ghosh et al.⁶², who studied the durability of jute geotextiles in soil; they noticed that impregnation of nonwoven jute samples with bitumen reduced jute pore sizes because of the formation of a superimposing bitumen binder layer on the surface of both sides of the jute fabric. Additional studies on the efficacy of this approach, in which different seed types, storage durations, and temperatures are applied, as well as on the exposure of WCJBs to running water (time-dependent changes in wetting)⁶⁰, are required to explore strengths and weaknesses of this approach. The mechanical strength of WCJBs also needs to be compared against CJBs to ensure that they will not start physically deteriorating after loading.

Figure 8. Schematic showing the surface treatments of jute bags with alkali and wax coating, the seed storage experiment, and the germination experiment for stored wheat grains. Conventional (control) jute bag, CJB; hydrophobic (wax-coated) jute bag, WCJB. On the WCJB, water droplets accumulate and roll off the surface. Seeds from hydrophobic jute bags are more likely to germinate than seeds from conventional jute bags. Credit: Xavier Pita, KAUST.

In summary, WCJBs have the potential to alleviate PHLs due to seed deterioration in regions with a humid climate, e.g., the Indian subcontinent and sub-Saharan Africa. Farmers in these regions extensively exploit conventional jute bags to store grains; these bags are stacked in traditional storage structures or outdoor stockpiles covered with tarpaulin^{9, 19}. Thus, the stored grains are often exposed to high humidity, especially in the event of precipitation or increased RH, which elevates SMC, accelerates the deterioration of seeds, and reduces germination capacity. In the present study, wheat grains stored in WCJBs for over 2 months experienced small deviations in SMC, i.e., 7.1%–7.5% at 55% RH and 7.1%–11% at 75% RH that were well within Harrington’s limits. In contrast, wheat grains stored in CJBs over the same duration experienced much higher SMC, i.e., 7.1%-14.9% at 55% RH and 7.1%-17% at 75% RH. Consequently, WCJBs improved the germination capacity of stored grains by 32%–35% in comparison with the germination capacity of grains stored in CJBs under identical conditions.

Therefore, WCJBs have the potential to substantially extend the shelf-life of seeds under low RH conditions and they facilitate increased resilience under higher RH conditions. Importantly, grains stored in WCJBs remain within Harrington's safe zone for SMC; thus, PHLs due to seed deterioration are prevented. The low cost, eco-friendliness, and availability of jute fabrics, alkalis, and paraffin wax, along with the simplicity of the treatment process, gives wax-coated jute fabrics great potential for use in agro-technologies and other applications.

Abbreviations used: PHL: post-harvest losses; CJBs: control jute bags; WCJBs: wax-coated jute bags; SMC: seed moisture content; RH: relative humidity.

Acknowledgements: The coauthors thank Mr. Sankara Arunachalam (KAUST) for his assistance with the scanning electron microscopy of jute bags; Mr. Xavier Pita, Senior Scientific illustrator, KAUST, for creating the graphical abstract and Figs. 2 and 8; Dr. Nishan MA for sourcing and preparing the jute bags; Mrs. Juliet Aber for sewing the jute bags used in the seed storage experiment; Prof. Magdi Mousa of the King Abdulaziz University, Jeddah, for providing the wheat grains used in this study; and Mr. Firas Atef Baba (KAUST) for providing the jute bags.

Conflict of interest: HM and KO have filed a provisional patent (USPTO Serial No. 63/141,104).

Author contributions: HM conceived the idea and led this research project. KO designed and performed the experiments, including the surface treatments and materials characterization, seed storage study, and germination study. AGJ assisted with the experimental design, data analysis, and the wetting model. KO wrote the manuscript, which HM and AGJ revised.

Funding source: The research reported in this publication was supported by funding from King Abdullah University of Science and Technology under award number **BAS/1/1070-01-01**.

Graphical Abstract

Synopsis. This paper broadens the utilization of paraffin wax, a benign bi-product of petroleum, to engineer hydrophobic seed storage jute bags.

378 REFERENCES:

- 379 1. World-Food-Programme, Hunger, Conflict, and Improving the Prospects for Peace.
380 United Nations World Food Programme: Rome, Italy, October 2020.
- 381 2. United-Nations *World Population Prospects: The 2017 Revision*; United Nations,
382 Department of Economic and Social Affairs, Population Division: New York, NY, USA, 2017.
- 383 3. Alexandratos, N.; Bruinsma, J. *World Agriculture Towards 2030/2050: The 2012*
384 *Revision ESA Working paper No. 12-03. Rome, FAO.*; FAO: Rome, 2012.
- 385 4. FAO *The future of food and agriculture: Trends and challenges*; Food and Agriculture
386 Organization of the United Nations 2017.
- 387 5. FAO *Global agriculture towards 2050*; Food and Agriculture Organization: Rome, 2009;
388 pp 1-4.
- 389 6. FAO *Global food losses and food waste: extent, causes and prevention*; Food and
390 Agriculture Organization: Rome, 2011; p 37.
- 391 7. Gustavsson, J. C., C.; Sonesson, U.; and Emanuelsson, A *The methodology of the FAO*
392 *study: "Global Food Losses and Food Waste - extent, causes and prevention"*- FAO, 2011;
393 2013.
- 394 8. Mesterhazy, A.; Olah, J.; Popp, J., Losses in the Grain Supply Chain: Causes and
395 Solutions. *Sustainability* **2020**, *12* (6).
- 396 9. Jayas, D. S., Storing Grains for Food Security and Sustainability. *Agricultural Research*
397 **2012**, *1*, 21-24.
- 398 10. Lal, R., Feeding 11 billion on 0.5 billion hectare of area under cereal crops. *Food and*
399 *Energy Security* **2016**, *5* (4), 239-251.
- 400 11. Rodell, M.; Velicogna, I.; Famiglietti, J. S., Satellite-based estimates of groundwater
401 depletion in India. *Nature* **2009**, *460* (7258), 999-U80.
- 402 12. Solander, K. C.; Reager, J. T.; Wada, Y.; Famiglietti, J. S.; Middleton, R. S., GRACE
403 satellite observations reveal the severity of recent water over-consumption in the United States.
404 *Scientific Reports* **2017**, *7*.
- 405 13. Scanlon, B. R.; Longuevergne, L.; Long, D., Ground referencing GRACE satellite
406 estimates of groundwater storage changes in the California Central Valley, USA. *Water*
407 *Resources Research* **2012**, *48*.
- 408 14. Famiglietti, J. S., The global groundwater crisis. *Nature Climate Change* **2014**, *4* (11),
409 945-948.
- 410 15. FAO *Seeds toolkit*; Rome, 2018; p 112 pp.
- 411 16. Sawicka, B., Post-harvest Losses of Agricultural Produce BT - Zero Hunger. Leal Filho,
412 W.; Azul, A. M.; Brandli, L.; Özuyar, P. G.; Wall, T., Eds. Springer International Publishing:
413 Cham, 2019; pp 1-16.
- 414 17. DE LUCIA, M. A., D *Agricultural Engineering in Development: Post-harvest*
415 *Operations and Management of Foodgrains*; FAO Agricultural Services
416 : Rome 1994.
- 417 18. Hodges, R. J.; Buzby, J. C.; Bennett, B., Postharvest losses and waste in developed and
418 less developed countries: opportunities to improve resource use. *Journal of Agricultural Science*
419 **2011**, *149*, 37-45.
- 420 19. Tesfaye, W.; Tirivayi, N., The impacts of postharvest storage innovations on food
421 security and welfare in Ethiopia. *Food Policy* **2018**, *75* (February), 52-67.

20. Kumar, D.; Kalita, P., Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries. *Foods* **2017**, *6* (1), 8-8.
21. Boxall, R. A., Post harvest losses to insects-A world view. *International Biodeterioration and Biodegradation* 2001; Vol. 48, pp 137-152.
22. Kumar, R.; Mishra, A. K.; Dubey, N. K.; Tripathi, Y. B., Evaluation of *Chenopodium ambrosioides* oil as a potential source of antifungal, antiaflatoxigenic and antioxidant activity. *International Journal of Food Microbiology* **2007**, *115* (2), 159-164.
23. Harrington, J. F., Seed storage and longevity. . In *Seed Biology*, Kozlowski, T. T., Ed. Academic Press: New York & London, 1972; Vol. III.
24. Harrington, J. F., Biochemical basis of seed longevity
. *Seed Sci. Technol.* **1973**, *1*, 453-461.
25. Gupta, M. K.; Srivastava, R. K.; Bisaria, H., Potential of Jute Fibre Reinforced Polymer Composites : A Review. *International Journal of Fiber and Textile Research* **2015**, *5* (3), 30-38.
26. Wang, W.-m.; Cai, Z.-s.; Yu, J.-y., Study on the Chemical Modification Process of Jute Fiber. *Journal of Engineered Fibers and Fabrics* **2008**, *3* (2), 155892500800300203.
27. Mwaikambo, L. Y.; Ansell, M. P., Chemical modification of hemp, sisal, jute, and kapok fibers by alkalization. *Journal of Applied Polymer Science* **2002**, *84* (12), 2222-2234.
28. Ali, A.; Shaker, K.; Nawab, Y.; Jabbar, M.; Hussain, T.; Militky, J.; Baheti, V., Hydrophobic treatment of natural fibers and their composites—A review. *Journal of Industrial Textiles* **2018**, *47* (8), 2153-2183.
29. Delouche JC, M. R., Dougherty GM, Boyd AH, Storage of seed in Sub-tropical and Tropical regions. *Seed Science and Technology* **1973**, *1*, 671-700.
30. Bradford, K. J.; Dahal, P.; Asbrouck, J. V.; Kunusoth, K.; Bello, P.; Thompson, J.; Wu, F., The dry chain : Reducing postharvest losses and improving food safety in humid climates. *Trends in Food Science & Technology* **2018**, *71* (November 2017), 84-93.
31. Manandhar, A.; Milindi, P.; Shah, A., An Overview of the Post-Harvest Grain Storage Practices of Smallholder Farmers in Developing Countries. *Agriculture* **2018**, *8* (4), 57.
32. Nagpal, M.; Kumar, A., Grain losses in India and government policies. *Quality Assurance and Safety of Crops & Foods* **2012**, *4* (3), 143-143.
33. Swai, J., Mbega, E. R., Mushongi, A., & Ndakidemi, P. A., Post-harvest losses in maize store-time and marketing model perspectives in Sub-Saharan Africa. *Journal of Stored Products and Postharvest Research* **2019**, *10* (1), 1-12.
34. Barthlott, W.; Neinhuis, C., Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta* **1997**, *202* (1), 1-8.
35. Mahadik, G. A.; Hernandez-Sanchez, J. F.; Arunachalam, S.; Gallo, A.; Cheng, L.; Farinha, A. S.; Thoroddsen, S. T.; Mishra, H.; Duarte, C. M., Superhydrophobicity and size reduction enabled *Halobates* (Insecta: Heteroptera, Gerridae) to colonize the open ocean. *Scientific Reports* **2020**, *10* (1).
36. Cheng, L., Marine and Freshwater Skaters: Differences in Surface Fine Structures. *Nature* **1973**, *242* (5393), 132-133.
37. Domingues, E. M.; Arunachalam, S.; Mishra, H., Doubly Reentrant Cavities Prevent Catastrophic Wetting Transitions on Intrinsically Wetting Surfaces. *Acs Applied Materials & Interfaces* **2017**, *9* (25), 21532-21538.
38. Pan, Z.; Pitt, W. G.; Zhang, Y.; Wu, N.; Tao, Y.; Truscott, T. T., The upside-down water collection system of *Syntrichia caninervis*. *Nature Plants* **2016**, *2* (7), 16076.

39. Parker, A. R.; Lawrence, C. R., Water capture by a desert beetle. *Nature* **2001**, 414 (6859), 33-34.
40. Darmanin, T.; Guittard, F., Superhydrophobic and superoleophobic properties in nature. *Materials Today* **2015**, 18 (5), 273-285.
41. Wong, T. S.; Kang, S. H.; Tang, S. K. Y.; Smythe, E. J.; Hatton, B. D.; Grinthal, A.; Aizenberg, J., Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity. *Nature* **2011**, 477 (7365), 443-447.
42. Arunachalam, S.; Das, R.; Nauruzbayeva, J.; Domingues, E. M.; Mishra, H., Assessing omniphobicity by immersion. *Journal of Colloid and Interface Science* **2019**, 534, 156-162.
43. Subramanian, N.; Qamar, A.; Alsaadi, A.; Gallo, A.; Ridwan, M. G.; Lee, J.-G.; Pillai, S.; Arunachalam, S.; Anjum, D.; Sharipov, F.; Ghaffour, N.; Mishra, H., Evaluating the potential of superhydrophobic nanoporous alumina membranes for direct contact membrane distillation. *Journal of Colloid and Interface Science* **2019**, 533, 723-732.
44. Gonzalez-Avila, S. R.; Nguyen, D. M.; Arunachalam, S.; Domingues, E. M.; Mishra, H.; Ohl, C.-D., Mitigating cavitation erosion using biomimetic gas-entrapping microtextured surfaces (GEMS). *Science Advances* **2020**, 6 (13), eaax6192.
45. Das, R.; Ahmad, Z.; Nauruzbayeva, J.; Mishra, H., Biomimetic Coating-free Superomniphobicity. *Scientific Reports* **2020**, 10 (1), 7934.
46. Chauhan, P.; Kumar, A.; Bhushan, B., Self-cleaning, stain-resistant and anti-bacterial superhydrophobic cotton fabric prepared by simple immersion technique. *J Colloid Interface Sci* **2019**, 535, 66-74.
47. Vermeulen, S. J.; Campbell, B. M.; Ingram, J. S. I., Climate Change and Food Systems. *Annual Review of Environment and Resources* **2012**, 37 (1), 195-222.
48. Jury, W. A.; Vaux, H., The role of science in solving the world's emerging water problems. *Proceedings of the National Academy of Sciences of the United States of America* **2005**, 102 (44), 15715-15720.
49. Wexler, A.; Hasegawa, S., Relative Humidity-Temperature Relationships of Some Saturated Salt Solutions in the Temperature Range 0-Degree to 50-Degrees-C. *Journal of Research of the National Bureau of Standards* **1954**, 53 (1), 19-26.
50. Suma, A.; Sreenivasan, K.; Singh, A. K.; Radhamani, J., Role of Relative Humidity in Processing and Storage of Seeds and Assessment of Variability in Storage Behaviour in Brassica spp. and Eruca sativa. *Scientific World Journal* **2013**.
51. Origin(Pro) OriginLab Corporation: Northampton, MA, USA, Version 2017.
52. Ray, D.; Sarkar, B. K.; Rana, A. K.; Bose, N. R., Effect of alkali treated jute fibres on composite properties. *Bulletin of Materials Science* **2001**, 24 (2), 129-135.
53. Bhushan, B., Biomimetics: lessons from nature--an overview. *Philos Trans A Math Phys Eng Sci* **2009**, 367 (1893), 1445-86.
54. Gassan, J.; Bledzki, A. K., Possibilities for improving the mechanical properties of jute/epoxy composites by alkali treatment of fibres. *Composites Science and Technology* **1999**, 59 (9), 1303-1309.
55. Taha, I.; Steuernagel, L.; Ziegmann, G., Optimization of the alkali treatment process of date palm fibres for polymeric composites. *Composite Interfaces* **2007**, 14 (7-9), 669-684.
56. Kuruvilla, J.; Sabu, T.; Pavithran, C.; Brahmakumar, M., Tensile properties of short sisal fiber-reinforced polyethylene composites. *Journal of Applied Polymer Science* **1993**, 47 (10), 1731-1739.

57. Chen, H.; Yu, Y.; Zhong, T. H.; Wu, Y.; Li, Y. J.; Wu, Z. H.; Fei, B. H., Effect of alkali treatment on microstructure and mechanical properties of individual bamboo fibers. *Cellulose* **2017**, *24* (1), 333-347.
58. Wang, X.; Chang, L. L.; Shi, X. L.; Wang, L. H., Effect of Hot-Alkali Treatment on the Structure Composition of Jute Fabrics and Mechanical Properties of Laminated Composites. *Materials* **2019**, *12* (9).
59. Castro, G. R.; Panilaitis, B.; Kaplan, D. L., Emulsan, a tailorable biopolymer for controlled release. *Bioresour Technol* **2008**, *99* (11), 4566-71.
60. Mishra, H.; Schrader, A. M.; Lee, D. W.; Gallo, A.; Chen, S. Y.; Kaufman, Y.; Das, S.; Israelachvili, J. N., Time-Dependent Wetting Behavior of PDMS Surfaces with Bioinspired, Hierarchical Structures. *Acs Applied Materials & Interfaces* **2016**, *8* (12), 8168-8174.
61. Cassie, A. B. D.; Baxter, S., Wettability of porous surfaces. *Transactions of the Faraday Society* **1944**, *40*, 0546-0550.
62. Ghosh, S. K.; Ray Gupta, K.; Bhattacharyya, R.; Sahu, R. B.; Mandol, S., Improvement of Life Expectancy of Jute Based Needle-punched Geotextiles Through Bitumen Treatment. *Journal of The Institution of Engineers (India): Series E* **2014**, *95* (2), 111-121.