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Research article

Evaluation of a small-scale desiccant-based drying system to control corn dryness during storage

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Abstract: Approximately 4.5 billion people worldwide are negatively affected by mycotoxins, especially small-scale farmers in regions that do not have access to energy efficient and appropriately designed drying systems. Mycotoxins are produced by fungi tainting durable commodities (e.g. corn and rice), which have been inadequately dehydrated and stored. Controlling produce dryness to below 0.6 water activity (A_w) is an imperative factor to maintain their safety and quality. Unfortunately, there is a lack of inexpensive, small-scale (<15 kg) technologies to adequately dry and store durable commodities. A potential solution is to utilize small-scale desiccant-based drying systems to reduce and then maintain the optimum A_w and dry basis moisture content (M_D). Desiccants, like hygroscopic salts and DryBeads^{TM}, can be used to remove the moisture from surrounding commodities and potentially maintain conditions during storage. For small-scale applications, it is important to keep the design low-cost and energy efficient. Utilizing corn (*Zea mays*) as a model product, the current study aims to evaluate a small-scale desiccant drying system consisting of two stacked 18.9 L (5 gallon) buckets equipped with a centered 51 mm diameter acrylonitrile-butadiene-styrene (ABS) pipe to support a fan (102 mm × 102 mm × 25 mm) to circulate air (mean air-flow = 0.015 m^3-s^{-1}, 31.8 cfm). Potassium carbonate (K_2CO_3), magnesium chloride ($MgCl_2$), sodium iodide (NaI), and DryBeads^{TM} were compared against an untreated control in their ability to reduce the A_w below 0.6 and hold it over 14 days of storage without over-drying the corn. The small-scale desiccant system combined 0.73 kg of each desiccant and 9 kg of corn with an initial M_D of 19.6% (dry basis). Twelve 50 g corn samples contained in mesh bags were distributed at three levels (top, middle, and bottom) within each bucket to later infer the corn's final M_D and A_w. In addition, temperature (T), and relative humidity (RH) at the three levels were recorded each hour with T/RH sensors. Results indicated that all of the evaluated desiccants significantly ($p \leq 0.05$) reduced the corn's A_w below 0.6, in comparison to the untreated control, after 14 days of drying/storage.

Keywords: hygroscopic; desiccation; storage; relative humidity; temperature

Abbreviations: ABS: Acrylonitrile-butadiene-styrene; A_W: Water activity; ERH: Equilibrium relative humidity; K_2CO_3: Potassium carbonate; kWh: Kilowatt-hours; LAN: Local-area network; MT: Metric tons; M_D: Dry basis moisture content; $MgCl_2$: Magnesium chloride; NaI: Sodium iodide; LiCl: Lithium Chloride; RH: Relative humidity; sd: Standard deviation; T: Temperature; USD: United States dollars; VDC: Direct current voltage

1. Introduction

Improper postharvest preservation and storage of agricultural commodities is one of the leading causes of global food loss, particularly in developing countries. In Africa and India alone, postharvest losses account for about 30% of food loss [1]. Food loss in dry produce, such as pulses, tree nuts, and grains, is caused mainly by fungal contamination, including *Aspergillus spp.*, *Penicillium*, *Cladosporium*, and *Alternaria*. In addition, these fungi produce mycotoxins like aflatoxin and fumonisin, which can cause a variety of birth defects and human diseases [2].

Currently, it is estimated that around 4.5 billion people suffer from illnesses caused by mycotoxins, especially in regions where the ambient Relative Humidity (RH) during drying and storage is high (>85%), and there is no availability of appropriately scaled drying systems [2]. To prevent detrimental fungal growth on produce, reduction of moisture content via drying after harvest and prior to storage is critical and best achieved when water activity (A_w) [3] is reduced to and maintained at 0.6 or lower [4]. RH is the ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water at a given temperature expressed as a percentage, while A_w is the headspace RH, expressed as a decimal, within a commodity or a hygroscopic material. A_w is also known as the Equilibrium Relative Humidity (ERH) [5]. Controlling the ambient RH within the drying and storage systems is essential because this will influence the ERH and therefore a commodity's A_w [2]. Unfortunately, in many countries and among small-scale farmers, this can be difficult to achieve with the technology available to them.

Several methods are used to dry agricultural commodities, ranging in sophistication. Farmers with limited resources often utilize the direct sun drying by spreading a thin layer of produce directly on the ground or on tarps. This drying method may be sufficient in temperate climates but is less effective in climates with a high ambient temperature and relative humidity, such as the humid tropics. More advanced drying methods use heated air dryers; however, these methods are inaccessible to some farmers, especially in developing countries, due to the high cost and energy demand of inappropriately sized drying systems, as these are designed for typical trailer load increments of 12 to 13 metric tones (MT). In addition, most heated-air drying systems rely on fossil fuels (mainly natural gas or propane), which may not be available or affordable. Many of these advanced drying systems were developed with limited knowledge of the energy and financial constraints in developing countries, and small-scale farmers typically do not have access to efficient systems with an adequate design to properly dry produce [6]. To maintain the quality and safety of the agricultural produce after drying, it must be immediately stored in a dry, low-oxygen environment. In practice, woven plastic bags with hermetic liner bags are used to reduce and prevent fungal growth during storage; however, if moisture enters the packaging, fungal growth and mycotoxin production can occur [2].

An alternative to the described advanced systems is a drying system that utilizes desiccants like hygroscopic salts or other hygroscopic materials, such as DryBeads™, which are substances that have the potential to absorb moisture from the air. One potential benefit of desiccant drying is avoiding thermal-stress to heat susceptible produce, while achieving a cost-effective drying rate that is potentially equivalent to that of a heated-air dryer [7]. For example, the recommended maximum drying air temperature for English walnuts (*Juglans regia*) is 43.3 ℃ at a range of 0.007 m^3-s^{-1} (15 cfm) to 0.012 m^3-s^{-1} (25 cfm) for up to 40 h (depending on the incoming moisture), as long-term exposure to higher temperatures will lead to rancid walnuts [8]. Bentonite clay and zeolites have been used to dehydrate petroleum products because of their low cost and global abundance [9], and silica gel has been used as an adsorbent for the dehydration of soybean seeds since they are effective at room temperature (~25 ℃) and can be regenerated (re-dried) at low temperatures (120 ℃ for 1 to 2 h) [10]. Unfortunately, silica gel's water-retaining capacity is reduced when it is heated for regeneration [1], and its cost is high ($345/kg) (Sigma-Aldrich). Moisture in the air is typically forced through these desiccants until equilibrium is reached, providing a low-humidity environment in which produce is dried. This lowers the ERH; therefore, the A_w of the produce is reduced to levels where fungi cannot grow. Since this type of drying system protects the produce from high relative humidity conditions, it can also be used for product storage after drying. To ensure the desiccants do not come into contact with the food or feed commodities, as this might represent a remote toxicity concern (Table 1), the salts or beads can be placed in a separate compartment connected to the storage container, and desiccants can later be removed and regenerated [11].

Table 1. Desiccant properties at 25 ℃ and 75% ambient Relative humidity (RH).

Desiccant	Equilibrium Relative Humidity (ERH), %	Maximum H_2O absorption capacity (w/w, %)	Acute toxicity (LD50 oral ingestion in rats, mg-kg^{-1})
NaI [20,21]	38.17 ± 0.50	30	4340
K_2CO_3[20,22]	43.16 ± 0.33	28	2000
$MgCl_2$ [20,23]	32.78 ± 0.16	33	2000 (female), and 5000 (males)
DryBeads[20,24,25][1]	13.80 ± 2.0	3 to 22	No acute toxicity information is available for this product.

[1] Depends on bead dryness, structure, size and integrity.

The goal of this research was to develop and test the effectiveness of a small-scale desiccant system that utilizes hygroscopic materials (desiccants) as sorbents to dry agricultural commodities. Using corn (*Zea mays*) as a model, the desiccant system was tested in its ability to remove corn's moisture to achieve an A_w level below 0.6 and maintain it for 14 days. This drying system was tested with multiple desiccants including magnesium chloride ($MgCl_2$), potassium carbonate (K_2CO_3), sodium iodide (NaI), DryBeads™, and compared to an untreated control. By keeping this system small-scale, inexpensive to build and operate, and energy efficient, it is suitable and accessible to food producers around the world, especially for small-scale producers, farmers, or consumers.

2. Materials and Methods

Steps used to develop and test the effectiveness of the proposed small-scale desiccant system applying hygroscopic materials as sorbents to dry agricultural produce, using corn as a model, are illustrated in Figure 1.

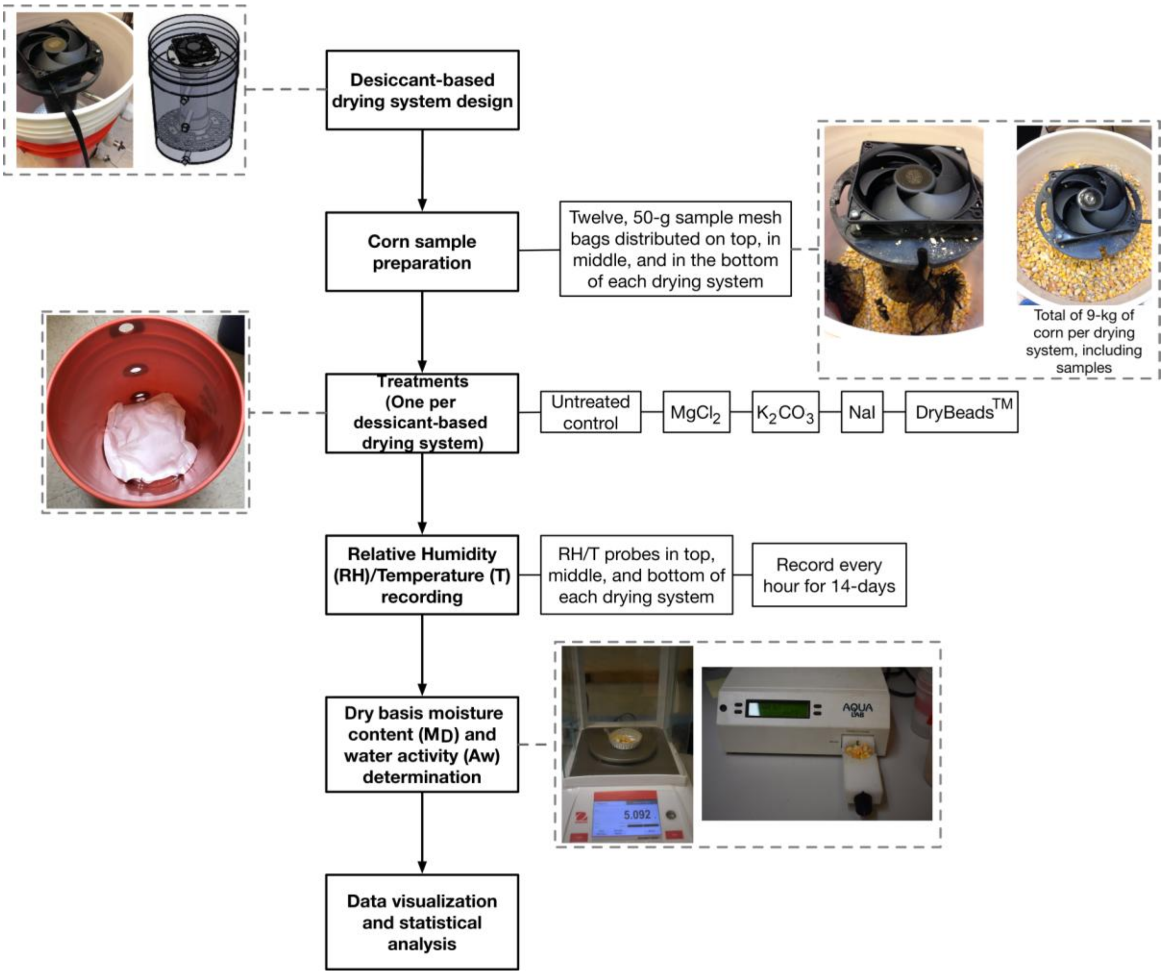

Figure 1. Schematic representation of experimental procedure used to evaluate the effectiveness of the small-scale desiccant-based drying system, during 14 days of corn dehydration and storage.

2.1. Desiccant-based drying system design

To assemble each of the desiccant-based drying systems, two 18.9 L (5 gallon) buckets were stacked, as seen in Figure 2, and circular holes (diameter = 2.54 cm) for the T/RH sensors (ZSeries Wireless Probes, Omega Engineering, Inc.) were drilled at 2 cm, 15 cm, and 29 cm height from the bottom of the bottom bucket. Additional holes of 2.54 cm diameter were drilled in the bottom of the top bucket at heights of 10 cm and 23 cm from the bottom of the top bucket. The two holes in the top bucket were lined up with the top two holes in the bottom bucket for the placement of the top two T/RH sensors. The third sensor was placed inside the bottom hole in the bottom bucket. To promote ventilation between the two buckets, as illustrated in Figure 2b, a hole of diameter 6.35 cm was drilled into the center of the bottom of the top bucket and surrounded by four holes of diameter 2.54 cm, spaced 1.7 cm apart from the center hole. Eight holes of diameter 1.5 cm were drilled in a circular pattern 3.8 cm outside the circle of 2.54 cm diameter holes. To prevent the corn from entering the space between the stacked buckets, a circular piece of perforated aluminum mesh (diameter 25 cm), with perforations of 0.64 cm diameter, was attached to the bottom of the top bucket. A flange of 17.8 cm outer diameter (Flanged Socket-Connect Reducing Adapter Standard-Wall ABS Pipe for Chemical Waste, Part No. 1608T183, McMaster Carr), with wedges cut out from its base so that 50% of the rim was remaining (to enable airflow), was attached to the center of the mesh. This flange was used to secure an ABS pipe of diameter 9 cm and length of 23 cm at one end. The outer rim of the ABS was flush with the inner rim of the flange, thus securing the ABS pipe with the flanges at either end. The bottom flange and metal mesh were attached to the bottom of the top bucket with two nylon insert nuts and screws. The opposite end of the ABS pipe was attached to another flange with a fan (Silencio FP120 PWM 2000, 120 mm cooling fan, Whisper-Quiet Cooling Performance, CoolerMaster), which was secured with four screws that attached the flange to the fan through existing holes in both components. To control and prevent excess moisture from entering the desiccant system and air leakage from the system, the stacked buckets were pressure sealed using a bucket lid.

2.2. Corn sample preparation

Commercially available whole dry yellow corn (Producer's Pride, Tractor Supply Co., Brentwood, TN, USA) was purchased for this study. To achieve typical in-field corn harvest dry basis moisture content (M_D), corn was re-humidified to around 20% M_D [12]. To ensure corn moisture uniformity, initial corn M_D was assessed using the air-oven method [2]. Since the corn's original M_D was measured to be approximately 18%, the water-to-corn ratio was determined to be 0.5 mL of water to 20 g corn. Therefore, to increase the moisture content of the corn to the desired in-field level, 20 g of corn was placed in a re-sealable plastic bag with 0.5 mL of distilled water and thoroughly mixed. The mixed sample was left to equilibrate for 24 h before experimentation. After equilibrium was reached, three 50 g randomized corn samples were assessed for their M_D following the moisture content by the air-oven method for industrial testing [13], yielding a mean M_D ± standard deviation (sd) equal to 19.6 + 0.31%. Enough corn was re-humidified to fill sixty corn sample mesh bags, each containing 50 g of corn.

2.3. Desiccant-based drying treatments and experimental design

A unique desiccant treatment sachet (Table 1) was used within a different desiccant-based drying system. To prepare each of the desiccant treatments, two 0.254 m × 0.254 m sheets of Tyvek were cut and sealed at 3 edges with a 20.3 cm tabletop impulse heat sealer (Model No. H-163, Uline, Pleasant Prairie, WI, USA). Thereafter, 0.73 kg of each desiccant was introduced into each sachet. Once the desiccant was added, the fourth edge was sealed with the tabletop impulse heat sealer, and the sachet was labeled with its corresponding desiccant (treatment). The control was similarly prepared, but corn was placed into the sachets instead of the desiccants. This will account for potential drying due to air-leakage and additional drying, mainly due to heat (e.g. heat generated by the fan). The treatment sachet was placed in the space between the two buckets within a unique desiccant-based drying system, and the three RH/T sensors were aligned in each of the drying systems prior to adding the corn samples.

Once the sensors were in place within all of the desiccant-based drying systems (treatments), four 50 g mesh bag corn samples (section 2.2) were randomly placed in the bottom of the top bucket, throughout all of the desiccant-based drying systems. Loose corn was poured on top of these sample mesh-bags until the top of the corn was level with the sensor located in the middle level of the desiccant-based drying system. This same procedure was repeated in the middle and top sections of the desiccant-based drying system, yielding a total of twelve 50 g corn samples per treatment. A total of 8.4 kg of corn was ultimately added to each desiccant-based drying system (treatments), so that each held 9 kg of corn. A completely randomized design was used to compare the effect of each desiccant-based drying system (treatment) to the corn sample M_D and A_w, within different drying system levels (top, middle, and bottom), as samples were randomized through the desiccant-based drying systems (treatments). During the experiments, desiccant-drying systems were placed inside a temperature-controlled laboratory at a constant temperature equal to 25 ℃.

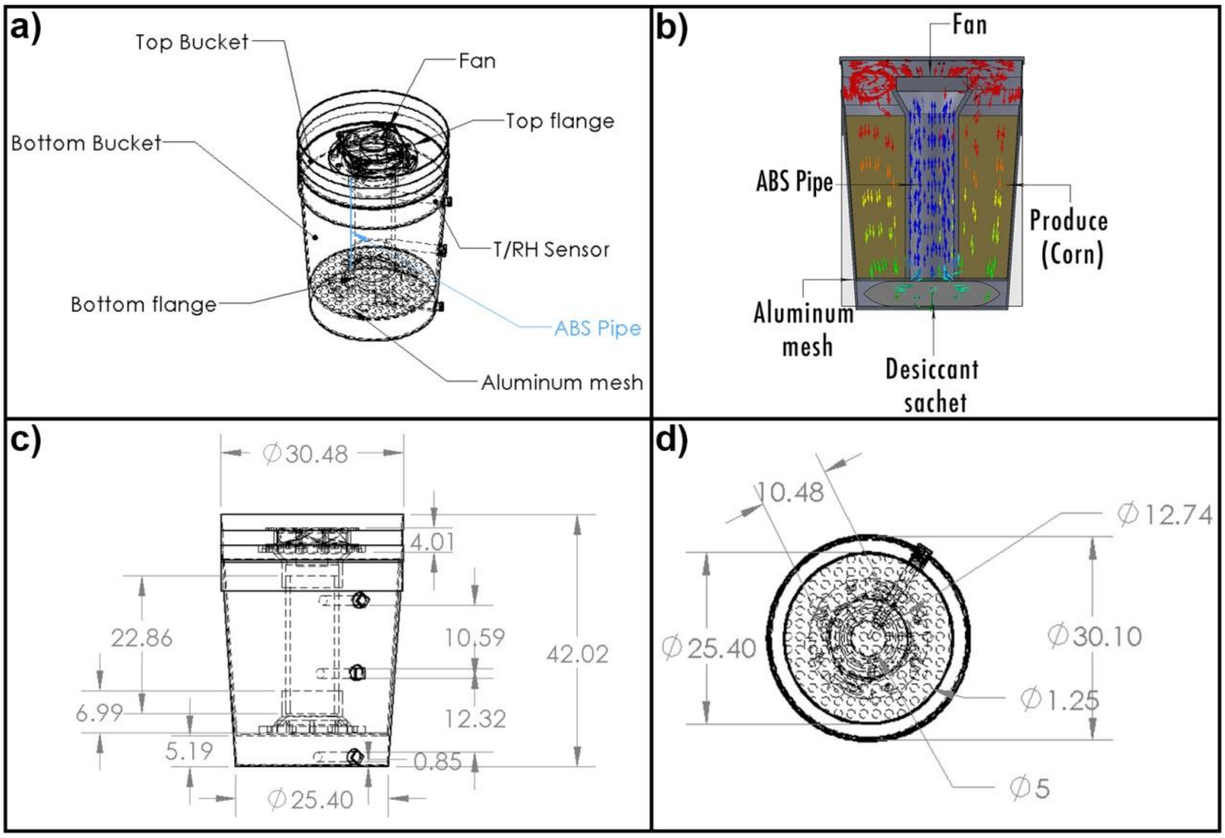

Figure 2. Desiccant-based drying system schematic representation (SolidWorks 2017, Dassault Systèmes SolidWorks Corporation, MA) of (a) three-dimensional labeled view, (b) side labeled view with arrows simulating the flow of air through the drying system (c) side view, and (d) top view. All measurements are in centimeters.

2.4. Relative humidity (RH) and temperature (T) recording

During the 14 days of the experiment, ambient and desiccant-based drying system RH and T were recorded on an hourly basis onto a Dell desktop computer (Dell, Round Rock, TX), using Windows 10 software, which was wirelessly connected to the RH/T sensors (ZSeries Wireless Probes, Omega Engineering, Inc.) and saved as a .csv file. The RH/T data acquisition system used active web pages to display real time readings and virtual data charts.

2.5. Dry basis moisture content (M_D) and water activity (Aw) determination (response variables)

From each of the twelve 50 g bags of corn in each treatment, a subsample of 10 g was used to measure M_D and $A_{w.}$ M_D was determined following the method described in section 2.2 (corn sample preparation). A_w was measured with an AquaLab A_w meter (Model: Series 3 TE, Decagon Devices, Inc., WA, USA), following the manufacturer's procedure.

2.6. Data visualization and statistical analysis

To visualize changes in RH and T, data was averaged for each day and graphed against time for each bucket level (top, middle, and bottom).

Two-way analysis of variance was used to determine the statistical differences of the means of the M_D and A_w after 14 days of storage. The two independent variables (factors) in the two-way ANOVA are the different desiccant treatments and the desiccant system levels. Significance between each desiccant mean (for each treatment) within all levels in comparison to the untreated control was determined using the Dunnett's test post-hoc multiple comparisons of means with adjusted family-wise confidence level ($p \leq 0.05$), based on the single step method. In addition, significance between means within each level and treatments including the control was determined using the Tukey post-hoc multiple comparisons of means test at the 95% family-wise confidence level ($p = 0.05$) [14]. Calculations were performed using the statistical package "R V 3.3.1: A language and environment for statistical computing" (R Development Core Team, 2007) (https://cran.r-project.org/).

3. Results and Discussion

To assess the effectiveness of each desiccant after 14 days of drying, the M_D and A_w data were compared amongst the treatments at the different levels, as seen in Figure 3. While the M_D relates to the A_w data, M_D cannot be used on its own to determine the desiccants' effectiveness, because M_D thresholds depend on the type of commodity and its intrinsic properties [2]. On the other hand, a A_w of 0.6 is the limit to prevent microbial growth for all types of dried products; therefore, a desiccant is considered effective if it lowers a commodity's A_w to 0.6 or below without over drying the product. Over-drying reduces saleable product weight and potential revenue [4].

The two-way ANOVA showed that the treatment effects were significant for M_D (F(4,45) = 276.75, p-value ≤ 0.05), and A_w (F(4,45) = 230.07, p-value ≤ 0.05). Post hoc analysis using the Dunnett's test indicated that the average M_D and A_w from all desiccant treatments, after 14 days within all levels, were significantly lower than the untreated control at a p-value < 0.01. In addition, post hoc analyses using the Tukey honest significant difference test indicated that the average M_D and A_w, after 14 days, was significantly lower in the $MgCl_2$ (M_D: mean = 15.3, sd = 0.20; A_w: mean = 0.49, sd = 0.007), DryBeads (mean = 15.9, SD = 0.30; A_w: mean = 0.51 , sd = 0.004), and NaI (mean = 16.02, SD = 0.18; A_w: mean = 0.50 , sd = 0.004) desiccants, in comparison to the K_2CO_3 (M_D: mean = 17.1, sd = 0.18; A_w: mean = 0.54, sd = 0.004), and the control (M_D: mean = 18.8, sd = 0.44; A_w: mean = 0.64, sd = 0.027). The latter finding was consistent in all three levels of the desiccant system, as summarized in Figure 3, yielding A_w values below the 0.6 threshold in all of the desiccant treatments. In addition, the fact that there was a reduction in M_D, and A_w in the control indicated that the desiccant treatment drying was not just caused by water adsorbed by the desiccants, but it may have been caused by sensible heat added by the fan and air-leakage from the test containers.

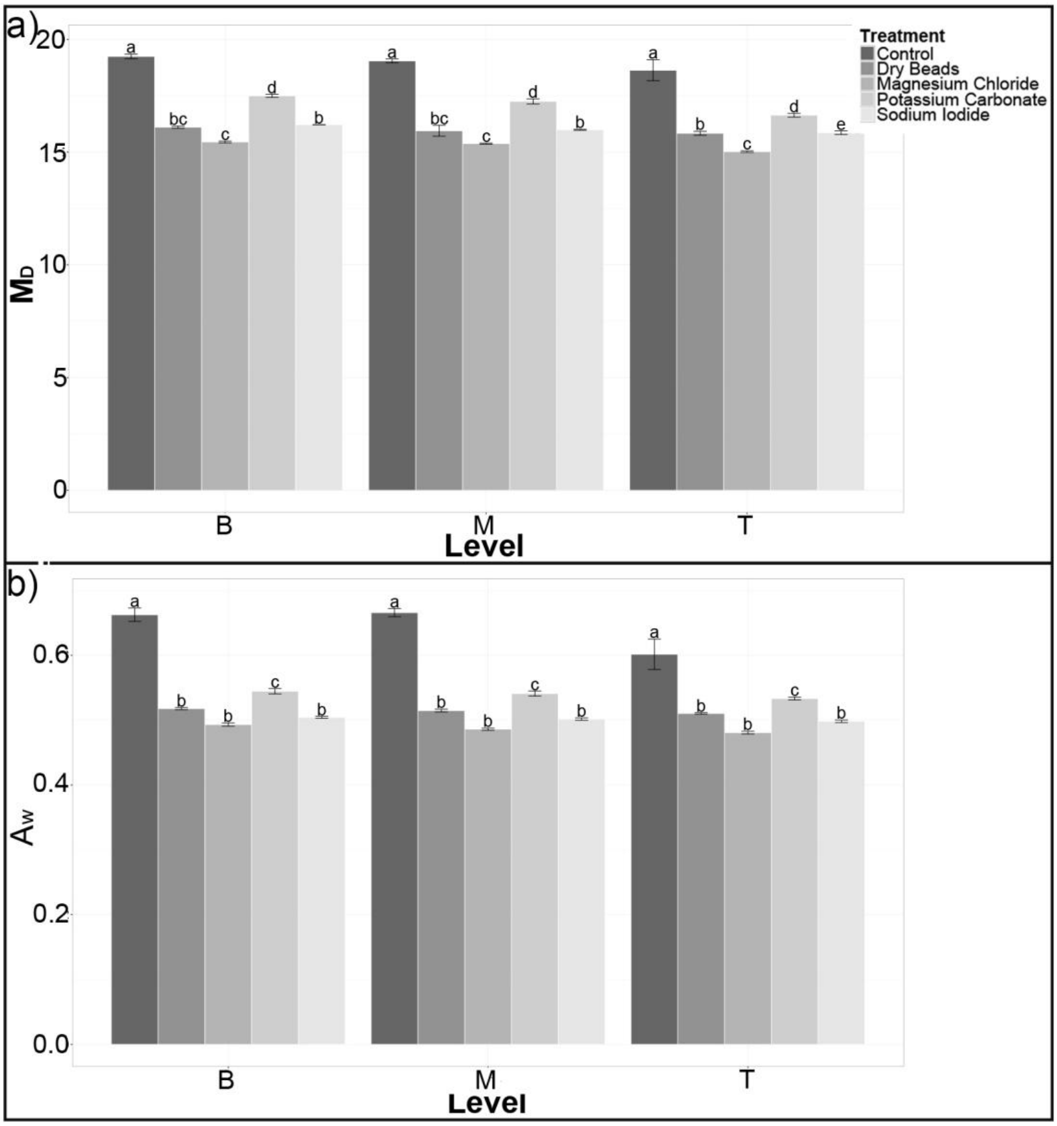

Figure 3. (a) Mean dry basis moisture content (M_D), and (b) A_w of corn samples per treatment, after 14 days dehydration and storage in the small-scale desiccant-based drying system. Values followed by the same letter within organisms are not significantly different at $p < 0.05$ (ANOVA) (Tukey multiple comparison of means). Error bars indicate standard deviation.

$MgCl_2$ had the lowest overall M_D (mean = 15.02 , sd = 0.07) and A_w (mean = 0.48 , sd = 0.004) in the top level of the desiccant system throughout the 14 day period. The RH/T graphs support the A_w and M_D data, as $MgCl_2$ yielded the lowest RH (%) in the top and middle levels, along with the highest T throughout the 14 day period in all 3 levels of the desiccant-drying systems (Figure 4), and different in comparison to the recorded ambient T (mean = 24.8, sd = 1.8) and RH (mean = 62.4, sd = 3.7). In addition, these findings are supported by the intrinsic characteristics of the desiccants, as summarized in Table 1. Overall, the untreated control consistently showed the highest RH in all three levels in comparison to all of the desiccant treatments, and the highest M_D (mean = 18.8, sd = 0.44) and A_w (mean = 0.64, sd = 0.027). Most importantly, K_2CO_3 was the only desiccant treatment that reduced the Aw to below 0.6 (mean = 0.54, sd = 0.004), but without over drying the corn, yielding a mean ± sd M_D equal to 17.1 ± 0.18. This finding is important, as over drying 320 kg of corn—which is equivalent to the world per capita grain consumption [15]—to a mean 15.02% M_D as observed in the $MgCl_2$ desiccant treatment instead of a higher M_D as observed in the K_2CO_3 desiccant treatment (17.1%), would translate to a loss of 6.6 kg of moisture (potential revenue, and nutrient availability).

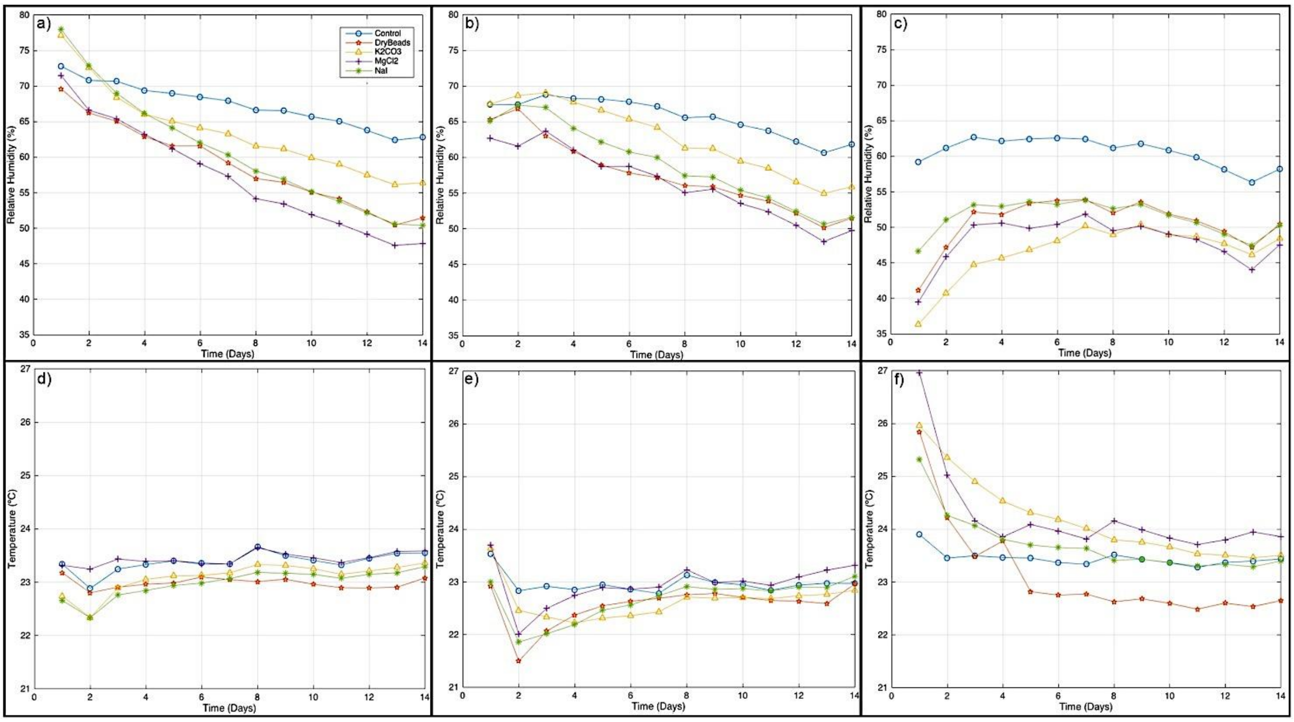

Figure 4. Daily mean relative humidity (RH) for (a) top, (b) middle, and (c) bottom sections; and daily average temperature (T) for (d) top, (e) middle, and [2] bottom sections during 14days corn dehydration and storage in the small-scale desiccant-based drying system.

Based on these findings, it is recommended that K_2CO_3 be used as the primary desiccant in the small-scale drying system. Local price and desiccant availability can also influence this selection. Currently, there is no evidence that salts can be utilized several times or effectively regenerated (dehumidified) after dehydrating agricultural products, and future studies are required to address this. However, evidence exists that supports that successive regeneration cycles have been possible in other applications, such as the low temperature (40 ℃) [16] and solar regeneration [17] of lithium chloride (LiCl), which is used as a desiccant in air-conditioning systems.

The design of the desiccant system includes a fan and holes drilled in the bottom of the top bucket to promote heat and mass (moisture) transfer between the corn and the dehumidified ambient air. Preliminary experiments (results not included) indicated that if the desiccant system did not contain a fan, it was unlikely that moisture reduction would be uniform in the corn throughout the desiccant system. Heat and moisture transfer proved to be effective in the desiccant system containing a fan, as the two-way ANOVA showed that the treatment and level interaction effect were not significant for M_D ($F(8,45) = 0.76$, p-value $= 0.64$), and A_w ($F(8,45) = 1.39$, p-value ≤ 0.47). This indicated that no statistically significant difference was observed between the different M_D levels in the desiccant system within each treatment. Heat transfer occurred in two main processes: convection of heat from the air inside the desiccant system to the surface of the corn and conduction of heat from the surface of the corn to the interior of the corn. Mass transfer of water (moisture) is carried out through diffusion from the interior of the corn to the corn's surface, followed by convection from the corn's surface to the air within the desiccant system [3].

To dry 9 kg of corn and maintain its dryness for 14 days, the fan used in this system required 0.12 kWh, based on the manufacturer's performance specifications. If electricity costs $0.19 US$/kWh, the energy expenditure would be US$0.08 to dry 9 kg of corn for 14 days [18]. The approximate cost for additional materials to build the small-scale desiccant-type system in the United States can be found in Table 2. The cost of the desiccant system will vary depending on the geographical location and availability.

Table 2. Approximate system and operational cost to dry 9 kg of corn for 14 days.

Category	Cost (US$)/Unit	Quantity	Cost for System (US$)
Electricity (operational cost)	0.12/kWh	0.645 kWh	0.08
Fan	10.50	1	10.50
Bucket	3.48	2	6.96
Flange	8.13	2	16.26
ABS pipe	44.69/20 ft	0.75 ft	1.68
Aluminum mesh	51.64/8361 cm^2	490.87 cm^2	3.03
Total			38.51
Desiccants (Does not assume regeneration)			
$MgCl_2$	1.32/kg	0.730 kg	0.96
NaI	3.60/kg		2.63
K_2CO_3	3.85/kg		2.81
DryBeads™	20/kg		14.60

The desiccant drying process using K_2CO_3 removed a total of 0.34 kg of moisture from the corn during 14 days of storage. This included the potential moisture loss due to sensible heat added by the fan, other sources (e.g. increase of ambient temperature) and air-leakage from the desiccant system that accounted for around 0.09 kg of moisture loss, as inferred by the control. This resulted in an energy use efficiency of 358 Wh per kg of water removed. This compares with the combined electricity and gas use efficiency of commercially-used grain dryers which ranges from approximately 600 to 1800 Wh per kg [6,19]. Even though this system is for small-scale drying applications, desiccant drying will prove to be energy efficient and applicable if the energy required to produce and transport the desiccants to the dryer originally and the energy needed to regenerate the desiccants does not increase the total energy use above that of existing commercial dryers.

4. Conclusions

There is a necessity for efficient desiccation systems that dehydrate and store agricultural produce. Without such systems in place, harvested produce can develop microbial growth that release mycotoxins and lead to food waste and food-borne illness. The goal of this research was to design a desiccant system and test the effectiveness of various hygroscopic salts as desiccants, using corn as the model produce. The different treatments were compared on a basis of M_D and A_w of the corn, along with the RH and T within the three different levels in the desiccant systems.

In alignment with the projects goals, the small-scale desiccant-type drying system was designed to reduce and maintain the corn's A_w at or below 0.6, but without over-drying the corn. This was achieved most successfully with the use of K_2CO_3 as a desiccant. In addition, $MgCl_2$, NaI, and DryBeads also significantly reduced the A_w of the corn to below 0.6. The desiccant system removed moisture from the produce and maintained it throughout the duration of the experiment. Overall, the T increased and the RH decreased over a period of 14 days within the desiccant-based drying system. Since this desiccant system is small-scale and proved to effectively and safely dehydrate corn, it has the potential to be widely available to small-scale farmers and consumers to dry commodities. On a global scale, this can increase food security by creating more stable food sources and reducing cases of mycotoxin-related illnesses and loss of produce.

Acknowledgments

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Conflict of interest

All authors declare no conflict of interest in this paper.

References

1. Wilson CL, Pusey PL (1985) Potential for Biological Control of Postharvest Plant Diseases. *Plant Dis* 69: 375–378.
2. Bradford KJ, Dahal P, Asbrouck JV, et al. (2017) The dry chain: Reducing postharvest losses and improving food safety in humid climates. *Trends Food Sci Technol* 71: 84–93.
3. Agrawal SG, Methekar RN (2016) Mathematical model for heat and mass transfer during convective drying of pumpkin. *Food and Bioprod Process* 101: 68–73.

4. Beuchat LR (1983) Influence of Water Activity on Growth, Metabolic Activities and Survival of Yeasts and Molds. *J Food Prot* 46: 135–141.
5. Thompson JF, Reid MS, Felix L, et al. (2016) DryCardTM—A Low-Cost Dryness Indicator for Dried Products. *AIMS Agric Food* 2: 339–344.
6. Kudra T, Mujumdar AS (2009) Advanced Drying Technologies. 2nd Edition, Boca Raton, CRC Press.
7. Sturton SL, Bilanski WK, Menzies DR (1983) Moisture exchange between corn and the desiccant bentonite in an intimate mixture. *Can Agric Eng* 25: 139–141.
8. Rumsey T (1991) High temperature walnut drying. Sacramento, CA: Walnut Marketing Board. Research report: University of California, Davis.
9. United States Evironmental Protection Agency—Air and Raditation (2006) Replacing Glycol Dehydrators with Desiccant Dehydrators. United States Environmental Protection Agency.
10. Li Z, Kobayashi N, Watanabe F, et al. (2002) Sorption drying of soybean seeds with silica gel. *Drying Technol* 20: 223–233.
11. Nassari PJ, Keshavulu K, Rao M, et al. (2014) Post harvest drying of tomato seeds to ultra low moisture safe for storage using desiccant (Zeolite) beads and their effects on seed quality. *American J Res Commun* 2: 75–79.
12. Willcutt H (1914) Harvesting, drying, and storing corn. Extension Service of Mississippi State University, cooperating with U.S. Department of Agriculture: Mississippi State University.
13. Reeb JE, Milota MR (1999) Moisture content by the ovendry method for industrial testing. 1999 May Portland, OR. 50th. Conference of Western Dry Kiln Association, 66–74.
14. Ott LR, Longnecker M (2001) An introduction to statistical methods and data analysis. Duxbury Pacific Grove, CA.
15. Ag Professional (2012) A perspective on world grain demand. Available from: https://www.agprofessional.com/article/perspective-world-grain-demand.
16. Bouzenada S, Kaabi AN, Fraikin L, et al. (2017) Successive dehumidification/regeneration cycles by LiCL desiccant for air-conditioning system. *AIP Conf Proc* 1809: 020009.
17. Cheng Q, Zhang X (2013) Review of solar regeneration methods for liquid desiccant air-conditioning system. *Energy Build* 67: 426–433.
18. U.S. Energy Information Administration—Department of Energy (2018) Average Price of Electricity to Ultimate Customers by End-Use Sector. Electric Power Monthly. May 30, 2018 ed. Washington, DC.
19. Dyck J (2017) Reducing Energy Use in Grain Dryers. Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Available from: http://www.omafra.gov.on.ca/english/engineer/facts/17-001.htm.
20. Greenspan L (1976) Humidity fixed points in binary saturated aqueous solutions. *J Res Natl Bur Stand—A Phys Chem* 81A: 89–95.
21. Podorozhnyj AM, Korobkina NA, Safonov VV, et al. (1988) Investigation of sodium iodide hydration and dehydration in moist atmospher. *Zh Neorganicheskoj Khim* 33: 13–17.
22. Coenen K, Gallucci F, Cobden P, et al. (2018) Influence of material composition on the CO_2 and H_2O adsorption capacities and kinetics of potassium-promoted sorbents. *Chem Eng J* 334: 2115–2123.

23. Gu W, Li Y, Zhu J, et al. (2017) Investigation of water adsorption and hygroscopicity of atmospherically relevant particles using a commercial vapor sorption analyzer. *Atmos Meas Tech* 10: 3821–3832.
24. Hay FR, Thavong P, Taridno P, et al. (2012) Evaluation of zeolite seed ‘Drying Beads®’ for drying rice seeds to low moisture content prior to long-term storage. *Seed Sci Technol* 40: 374–395.
25. Hay FR, Timple S (2013) Optimum ratios of zeolite seed Drying Beads® to dry rice seeds for genebank storage. *Seed SciTechnol*: 407–419.