Water vapor permeability of bag materials used for corn storage

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Abstract: Polypropylene and jute bags are widely used for grain storage across the developing world. The permeability of clear polypropylene bags (PP-C), opaque polypropylene bags (PP-O) and jute bags were determined using the ASTM E96 Standard Test Methods under three temperature and relative humidity combinations (25°C / 65%, 28°C / 75% and 30°C / 80%) that resulted in three vapor pressure deficits of 1.11, 0.95, and 0.85 kPa. The water vapor transfer rate (WVTR) and the interaction between water vapor permeability (WVP) of the materials were determined. WVTR ranged from 216 g m^{-2} day^{-1} for opaque polypropylene (PP-O) exposed to air conditions of 30°C / 80% to 478 g m^{-2} day^{-1} for jute exposed to air at 25°C / 65% WVTR decreased with vapor pressure deficit for all materials. There was no significant difference in the WVTR between the polypropylene bags (PP-C and PP-O). WVP values ranged from 4.7×10^{-5} g $(m\ day\ Pa)^{-1}$ to 6.4×10^{-4} g $(m\ day\ Pa)^{-1}$ at 25°C / 65% for PP-O and jute, respectively. WVP of PP-C and PP-O decreased slightly as the vapor pressure deficit increased. The permeability of jute was significantly different from both polypropylene bags under these test conditions (p<0.05). The change in corn moisture content with initial moisture at 10% and 12% (wb) were investigated using mini bags constructed from the three materials. Environmental condition, initial grain moisture, and the interaction among the parameters, had a large impact on the moisture change. There was a weak positive interaction between WVP of bag materials and change in corn moisture. This study demonstrates that environmental condition affects moisture redistribution in grain stored in woven bags, thus adequate monitoring is required to maintain grain quality during storage.
Keywords: bagged grain; moisture migration; postharvest losses; storage.

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1 Introduction

Corn (Zea mays) is an important crop for meeting the daily food requirement in many developing countries. Starch-based grains, primarily corn, are the basis for food security in Africa providing over 20% of total calories in human diets in 21 countries and over 30% in 12 countries (Yakubu et al., 2011). Effective grain storage is an important aspect of reducing postharvest losses, especially in countries where food losses are high (30% or more), and reduced losses contribute to increased food security without bringing more land area under cultivation (Kumar and Kalita, 2017). The shortage of effective storage infrastructure in developing countries has been identified as a crucial factor in reducing post-harvest losses (Hodges et al., 2010; Sheahan and Barrett, 2017). The use of polypropylene and jute bags for grain storage has been an age-long practice in much of the world and will likely remain a common practice in much of the developing world at the farm and market level.

Bag storage (typically 50 or 100 kg each) is popular in much of the developing world because of its numerous

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advantages in handling, transportation, and storage for relatively small quantities of grain. Bulk handling of grain is limited by road infrastructure, availability of trucks, and local constraints to grain marketing. Furthermore, most of the grain is produced by subsistence farmers with small land holdings who store grain on-farm or in their houses, thus large bulk storage facilities are not readily available. Polypropylene bags, which typically hold 100 kg of grain, has become a standard unit for handling, transportation, and marketing of grains at all levels in the developing world. Even though several works have suggested that polypropylene bags do not offer barriers to moisture transfer or insect and mold infestation (Ognakossan et al., 2013) there are indications that the practice will continue for the foreseeable future.

Previous research has indicated that improved handling and storage practices, such as the use of metal or plastic silos (~1 mt capacity) and hermetically sealed bags (70 to 100 kg) can reduce postharvest losses of grain at the household and farm level. The Purdue Improved Cowpea Storage (PICS) bags (Amadou et al., 2016; Baoua et al., 2014; Williams et al., 2017). The PICS system uses a double layer of sealed plastic bags to create hermetic conditions that is placed inside a woven polypropylene bag to protect the plastic bags during handling. Issues identified with PICS bags compared to polypropylene bags are its small size (holding about 70 kg which is less than the standard 100 kg), the cost of the PICS bag is about ten-fold higher than polypropylene bags, and skilled-labor is required to tie the bags which makes it less attractive to grain aggregators and processors dealing with thousands of bags (Nouhoheflin et al., 2017). ZeroFly storage bags which are insecticide-incorporated polypropylene bags have also been used for grain storage in Africa. The advantage of the bag is that it prevents insect attacks on the stored grain and can easily be sewed using either a handheld bag closer or traditionally with needles and twine (Paudyal et al., 2017).

Permeability to water vapor and oxygen is an important indicator of the barrier properties of a packaging material because it provides information on the shelf life of products held within (Bedane et al., 2012). Permeation is a measure of the penetration of a permeate (i.e. water vapor) through the bag material that contains grain. Permeation depends on the material properties and the environmental conditions under which the materials are used. Thus, it is important to examine the influence of ambient conditions on the permeability of grain bags (Siracusa, 2012). Laboratory experiments are usually the most reliable approach for determining the permeability of the barrier materials. Measurement of permeation of packaging materials to oxygen, water vapor, and other compounds are well documented in the literature (Galić and Ciković, 2001; Hülsmann et al., 2009; Turan, 2019; Rubino et al., 2001), where materials are tested using standard methods. In these experiments, the materials are tested keeping the temperature constant while varying the relative humidity or vice versa. The approach enables the dependency of the transport properties of packaging materials on temperature and or relative humidity to be evaluated. However, conditions encountered in grain storage are such that the two factors are changing simultaneously. The effects of storage environment on the permeability of silo bags for carbon dioxide and oxygen have also been reported (Chelladurai et al., 2016).

Grain is typically stored from three to twelve months depending on region and market demands. However, the effect of environmental conditions during storage and the influence of the bag material to moisture changes needs to be investigated. The rate of spoilage in the bag storage system will be influenced by the moisture transport through the bag material into the grain. Quantifying the moisture transport through the bag material will aid in developing effective management strategies to limit spoilage that negatively impacts the end products such as food and feed.

Therefore, this research aims to determine the water vapor transmission rate (WVTR) of polypropylene and jute bags typically used for grain storage and to evaluate the effect of their permeability on potential moisture changes in stored corn.

2 Materials and methods

2.1 Grain storage bag materials and test dishes

Jumbo size (100 kg capacity) clear polypropylene bags (produced by Nigerian Bag Manufacturing (BAGCO), Lagos Nigeria) and jute bags were obtained from a grain merchant in the Bodija market, Ibadan, Nigeria. White, polypropylene bags with a capacity of 25 kg were obtained from a local feed store in Kentucky from an unknown manufacturer. The polypropylene and bags had a thickness of 0.20 mm and the jute bag had a thickness of 1.5 mm. Fifteen units of glass dishes (Pyrex dish 4 cup/950 mL, 14.2 cm × 6.3 cm) with a surface area of 158.4 cm^2 were utilized. Samples were cut from the bags to fit the glass dishes and used as test films.

2.2 Water vapor transmission rate and permeability

The wet cup method described by ASTM E96/E96M-16 (ASTM Standards, 2016) was used to measure the WVTR of the three bag materials. The method, which provides for measuring permeance through a film utilizes low humidity on one side of the film and high humidity on the other side. The low humidity side was controlled using an environmental chamber and the high humidity side was inside the glass dish filled with distilled water and covered with test films. The wet cup test method was chosen due to its suitability for measuring WVTR through materials that act as poor barrier materials. Test films with an approximate area of 182 cm^2 were cut from the bag materials and their thickness obtained with a digital Vernier caliper. Distilled water (500 mL) was added to the dishes using a graduated cylinder. An air gap of 3.0 cm was left between the water level and the surface of the bag materials to provide space for water vapor exchange. The film was attached to the top of the glass dishes with the aid of a silicone sealant. The manufacturer supplied plastic lids were sealed using silicone to the top of the dishes for the positive control, while the dishes for the negative control were left completely open. The silicone sealant was allowed to dry for approximately an hour before the dishes were transferred into the environmental chamber (Parameter Generation & Control, Black Mountain, NC) and measurements began. Set points utilized for the experiments were the following combinations of temperature and relative humidity: 25°C / 65%, 28°C / 75% and 30°C / 80% that resulted in three vapor pressure deficits of 1.11, 0.95, and 0.85 kPa determined from ASAE D271.2 (ASABE Standards, 2014). These temperatures and relative humidity are typical conditions experienced in Nigeria. The experimental set up is shown in Figure 1. The sample dishes were weighed using a digital balance (OHAUS, Precision Advanced; 2,100 g ± 0.01 g) at an interval of 24 hours. WVTR was determined over 20 days under each environmental condition and the standard deviation was estimated.

Figure 1 Experimental set up with glass containers in a random array with open dishes and those covered with plastic lids and bag materials (Left to right first row: PP-C, jute, covered dish, PP-O, covered dish, open dish, PP-O, and jute)

Mass of water loss was plotted against elapsed time and the WVTR was calculated from the slope of the straight line that fits the curve (ASTM Standards, 2016). WVTR was calculated using Equation 1:

$$WVTR=(G/t)/A \quad (1)$$

Where:

WVTR = water vapor transmission rate, g m^{-2} day^{-1}

G= cumulative mass of water lost over the measurement period, g

t = time during which mass change occurred, day

A= Area of material (film area), m^2

G/t = slope of the straight line, g day^{-1}

The permeance (g m^{-2} day^{-1} Pa^{-1}) of the bag materials was determined using Equation 2:

$$Permeance = \frac{WVTR}{\Delta p} = \frac{WVTR}{S(R_1 - R_2)} \quad (2)$$

Where:

Δp = vapor pressure difference, Pa

S = saturation vapor pressure at test temperature, Pa

R_1 = relative humidity in the dish, decimal value

R_2 = relative humidity in the environmental chamber, decimal value

The water vapor permeability (*WVP*) was determined using Equation 3 as described by Hu et al. (2001).

$$WVP = \frac{WVTR\ x\ t}{S\ x\ \Delta RH} \quad (3)$$

where;

WVP = water vapor permeability, g Pa^{-1} day^{-1} m^{-1}

S = saturation vapor pressure, Pa

t = thickness of the material, m

ΔRH=relative humidity differential between environmental chamber and inside dish, decimal value

The relative humidity differential assumed a relative humidity of 100% between the film and water surface in the glass dish and the relative humidity set using a recently calibrated environmental control chamber outside the container. The temperature of the water and temperature of the environmental chamber were assumed to be equal.

Evaporation from the negative control, open dish with no film, was compared to evaporation from an undisturbed indoor swimming pool using Equation 4 as described by Shah (2014).

$$E_0=0.00005(p_w-p_r) \quad (4)$$

where;

E_0 = evaporation rate, kg m^{-2} h^{-1}

p_r = the partial pressure of water vapor in the air at reference temperature and humidity, Pa

p_w=saturation vapor pressure at water surface temperature, Pa

2.3 Moisture changes in mini-bags

Mini-bags with an average dimension of 200 mm by 135 mm were made from the previously described bag materials. Medium-density polyethylene (MDPE) 0.2 mm thickness was procured from Asake polyethylene company (Asake poly, Ilorin Nigeria) and was used as a control. The mini-bags had a surface area of 0.054 m^2. Corn harvested from the University of Kentucky research farm was dried to 10% and 12.5% after harvest and stored under refrigeration at 5°C for approximately one week. The stored samples were taken to the laboratory and left to equilibrate with the room temperature. Samples were drawn and passed through a grain divider (Boerner divider, Seedburo Equipment Company, IL, USA) to ensure proper mixing of samples to be bagged. Triplicate samples were taken during each run for initial moisture content determination. Each mini-bag was filled with 700 g of yellow corn and stored in an environmental chamber maintained at a temperature of 25°C ± 0.5°C and relative humidity of and 65% ± 1% (EMC = 13.3%)(EMC as averaged from the Modified Chung-Pfost and Modified Henderson equations for yellow corn (ASABE Standards, 2007).). The bags were weighed weekly for 35 days. At the end of the storage period, the change in moisture content was calculated based on the mass gain in addition to the measurement of the final moisture content using the oven drying method (ASABE Standards, 2017) and the standard deviation of the values was estimated. The procedure was repeated with storage conditions maintained at a temperature of 28°C ± 0.5°C and 75% ± 1% relative humidity (EMC = 14.7%), and 30°C ±

0.5°C and 80% ± 1% relative humidity (EMC = 15.6%). The experimental set up with the mini-bags is shown in Figure 2.

To prevent variation that may result from the movement of the dishes and the bags into varying environmental conditions, the weighing balance was stationed in the environmental chamber throughout the experiment.

The experiments were carried out in the laboratory of Biosystems and Agricultural Engineering department of the University of Kentucky, Lexington KY, USA (38.0263° N and 84.5097° W).

Figure 2 Experimental set up showing corn in mini-bags made with jute, polypropylene, and polyethylene (From left to right first row: PP-O, PE, jute, PP-C, PE, PP-O, jute, and PP-C).

2.4 Experimental design

The experiment was set up in a completely randomized design. The set up for the WVTR consisted of three replicates of clear polypropylene bag material from Nigeria (PP-C), opaque polypropylene bag material from the US (PP-O) and the jute bag (J) and two controls (an open dish and dish covered with manufacturer's plastic cover). The mini-bag experiments consisted of three replicates of PP-C, PP-O, Jute and Polyethylene (control).

2.5 Data analysis

Statistical analysis was performed using SAS (version 9.4, SAS Institute, 2013). PROC GLM was used to determine the effects of the bag type and environmental condition on WVTR and WVP of the bag materials. PROC GLM was used to evaluate the average mass change and the final moisture content of corn stored in the min-bags. Significance differences in the means were determined using LSMEANS at $p < 0.05$.

3 Results and discussion

3.1 Effects of ambient condition on WVTR and WVP of grain storage bags

The water loss profile of the three bag materials and the control (open dish) under the three test conditions are shown in Figures 3-5. Water loss from the dishes covered with the manufacturers' lids was negligible throughout the measurement period so this data was not included in the results. The water in the control dish in Figure 3 (at 25°C and 65% that represented the highest vapor pressure deficit (VPD) of 1.11 kPa, was completely evaporated after 11 days.

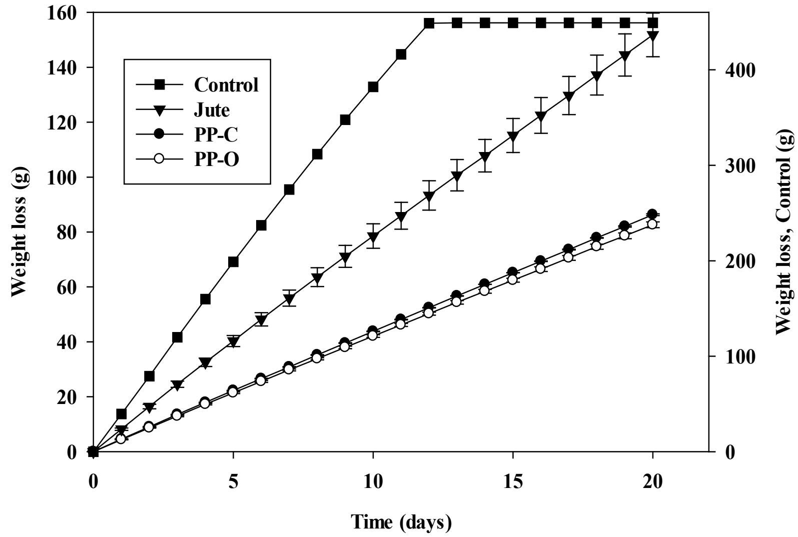

Figure 3 Average mass loss of from glass dishes covered with three bag materials (jute and two types of polypropylene bags, PP-C and PP-O) and control (open dish) at 25°C and 65% relative humidity (VPD of 1.11 kPa)

Note: Error bars are one standard deviation with three replications

The slope of the curve for the control (open dish) was very steep compared to the bag materials. This was expected as water freely evaporates from the dish without restriction thus an evaporation rate of 37 g of water per day was recorded. This was followed by the jute bag with an average water loss of 7.5 g day^{-1}. PP-C and PP-O bags have a lower slope with average water loss 4.3 and 4.1 g day^{-1}, respectively.

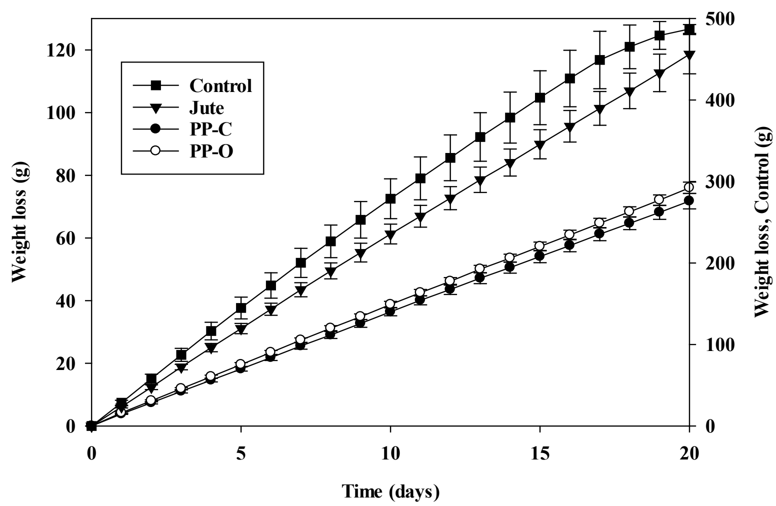

Figure 4 Average mass loss of from glass dishes covered with three bag materials (jute and two types of polypropylene bags, PP-C and PP-O) and control (open dish) at 28°C and 75% relative humidity (VPD of 0.95 kPa)

Note: Error bars are one standard deviation with three replications

As vapor pressure deficit decreased, the average water loss rate decreased. When the condition was changed to 28°C and 75% the slope declined due to the decrease in VPD (Figure 4). The average water loss reduced to 26, 6.0, 3.6 and 3.8 g day^{-1} for control, jute, PP-C and, PP-O, respectively. A further reduction in slope was observed under 30°C and 80%, the lowest VPD level tested, with an average water loss of 24, 5.3, 3.5 and 3.6 g day^{-1} respectively (Figure 5).

Evaporation rate from the open dishes under the selected environmental conditions are comparable to available data from the evaporation of water from an undisturbed indoor pool with the obtained values showing very marginal differences at 28°C / 75% and 30°C / 80%

This suggests that the observed trends are due to the properties of the materials. Water evaporation rates from the open dishes were: 0.08, 0.07 and 0.06 kg m^{-2} h^{-1} at 25°C / 65%, 28°C / 75% and 30°C / 80%, respectively, and follows the expected trend with vapor pressure deficit. The evaporation rate decreased with a decrease in vapor pressure deficit.

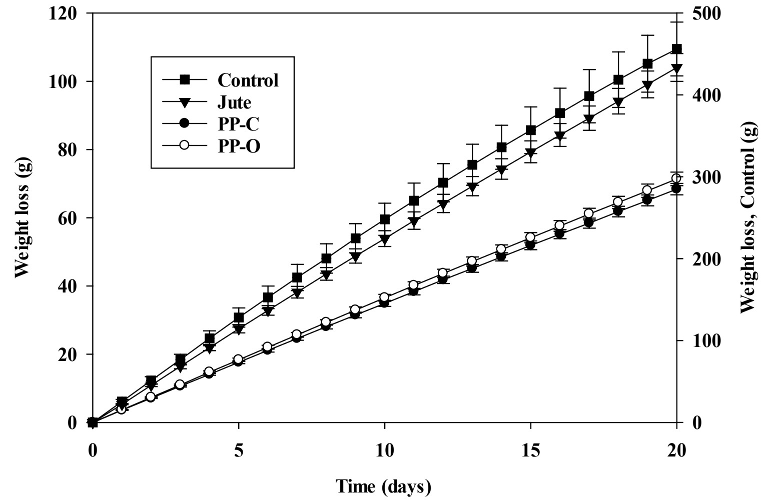

Figure 5 Average mass loss of from glass dishes covered with three bag materials (jute and two types of polypropylene bags, PP-C and PP-O) and control (open dish) at 30°C and 80% relative humidity (VPD of 0.85 kPa)

Note: Error bars are standard deviations with three replications

The effect of environmental conditions on the calculated WVTR, permeance and WVP of the grain storage bags is shown in Table 1. WVTR of the woven PP-C and PP-O were statistically the same but significantly different (p<0.0001) from that of jute bag. Environmental conditions, or vapor pressure deficit, had a significant effect (p<0.0001) on the WVTR of the bag materials. A significant interaction (p<0.0001) also existed between bag type and environmental conditions.

WVP values are the same for PP-C and PP-O bags but significantly different from that of jute bag (p<0.001). WVP values of PP-C and PP-O were not significantly affected (p<0.08) by the environmental condition. However, WVP values of jute bags were significantly affected by the environmental condition (p<0.02). In contrast, the published value of WVP for polypropylene (not woven) is 4.5×10^{-8} g (m day Pa)$^{-1}$ at 38°C and 0%-90% (Morillon et al., 2002).

Table 1 Effect of ambient conditions on the water vapor transmission rate and permeability of bag materials

Material Description	Condition (Temp °C/ %)	VPD (kPa)	WVTR (g m^{-2} day^{-1})	Permeance (g m^{-2} day^{-1} Pa^{-1})	WVP (g m^{-1} day^{-1} Pa^{-1})
	25 / 65	1.11	272±1 ^{d}	0.24 ±0.00 ^{c}	4.9±0.0 x 10^{-5} ^{c}
PP-C	28 / 75	0.95	233±5 ^{e}	0.25±0.05 ^{c}	4.9±0.1 x 10^{-5} ^{c}
	30 / 80	0.85	216±3 ^{e}	0.26±0.03 ^{c}	5.1±0.1 x 10^{-5} ^{c}
	25 / 65	1.11	261±2 ^{d}	0.23±0.01 ^{c}	4.7±0.0 x 10^{-5} ^{c}
PP-O	28 / 75	0.95	239±2 ^{e}	0.25±0.03 ^{c}	5.1±0.1 x 10^{-5} ^{c}
	30 / 80	0.85	226±3 ^{e}	0.26±0.04 ^{c}	5.3±0.1 x 10^{-5} ^{c}
	25 / 65	1.11	478±12 ^{a}	0.43±0.11 ^{a}	6.4±0.2 x 10^{-4} ^{a}
Jute bag	28 / 75	0.95	374±9 ^{b}	0.40±0.10 ^{b}	5.9±0.2 x 10^{-4} ^{b}
	30 / 80	0.85	324±6 ^{c}	0.39±0.07 ^{b}	5.8±0.1 x 10^{-4} ^{b}

Note: [a]Values within columns sharing the same superscript letter are not significantly different (p < 0.05; n= 27). Values are the mean ± standard deviation.

The observed differences in the magnitude of water loss are related to the bag materials. Jute fiber bags are visually porous and not as tightly woven as polypropylene bags thus having higher water loss rate at equivalent environmental conditions. The observed trend is consistent with those reported in previous studies where moisture gain increased linearly with time through polyurethane and polymeric packing materials (Schwartz et al., 1989; Turan, 2019; Zeman and Kubík, 2007). Similar trends have also observed in polylactic acid and chitosan blends films where the moisture loss was linear with time (Teo and Chow, 2014). Water vapor transmission rate has also been reported to increase as the temperature increases under constant relative humidity in polymer packages made from edible coatings (Othman et al., 2017)

3.2 Effects of VPD on WVTR of the bag materials

Significant differences were observed in the WVTR from jute bags. At all three VPD levels, the WVTR was significantly higher than the WVTR from the polypropylene bags. Decreasing the VPD from 1.11 to 0.95 kPa reduced the WVTR from 478 to 374 g m^{-2} day^{-1}, a decrease of 21.8%. A further reduction in the VPD from 0.95 to 0.85 kPa resulted in a 13.4% decrease in the WVTR. The WVTR decreased linearly with the decrease in VPD (Figure 6) with r^2 values of 0.992, 0.999 and 0.995 for PP-C, PP-O and jute, respectively. For 1 kPa increase in vapor pressure deficit, the WVTR increased by 597, 218 and 135 g m^{-2} day^{-1} for jute, PP-C and PP-O, respectively. The PP-C and PP-O have intercepts of 28.58 and 111.16 g m^{-2} day^{-1}, respectively while jute bag has a negative intercept of 187.74 g m^{-2} day^{-1}. This is in contrast to the findings of Chen et al. (2014), who reported that WVTR of BOPP materials tested at a 10°C to 40°C increased linearly with increase in relative humidity but the values increased exponentially as the temperature increased. While the linear relationship can be attributed to the influence of relative humidity on vapor pressure deficit the decrease in values cannot be attributed to either of the two parameters due to their main effects and interaction effects on barrier properties of the tested materials.

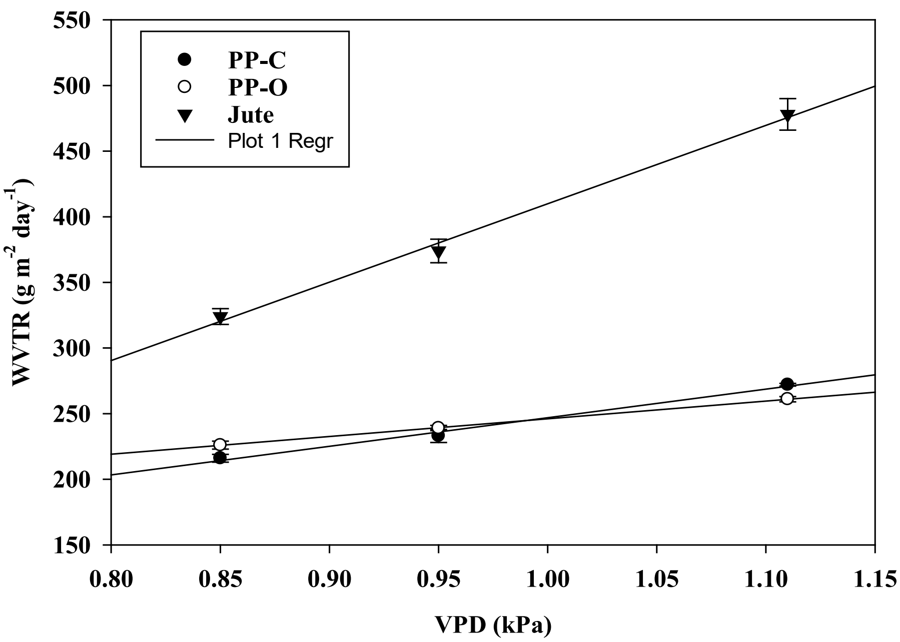

Figure 6 Effect of vapor pressure deficit on water vapor transmission rate values of three bag materials (jute and two types of polypropylene bags, PP-C and PP-O)

Note: Error bars are standard deviations with three replications

Jute bag can be considered a highly permeable film and there are potential measurement errors in WVTR in highly permeable films. High water vapor fluxes can lead to a relative humidity less than saturation leading to an underestimation as of the WVTR in highly permeable films (Hu et al., 2001). There is a dependency of permeability on temperature and relative humidity that has also been reported by Togashi and Hara (2011), where an increase in the coefficient of permeability of polypropylene film was observed as temperature and relative humidity increased.

Similar results have also been reported for some high barrier plastic materials and edible films where the values of the parameters increase with temperature due to the corresponding increase in partial pressure (Othman et al., 2017; Hülsmann et al., 2009; Schwartz et al., 1989). Dependency of WVP on relative humidity has also been reported by Turan (2019), who observed that WVP of casted polyurethane films increased significantly has the relative humidity increased. The analysis presented here however, focused on VPD so the influence of temperature and relative humidity on WVTR could not be isolated.

3.3 Effect of ambient conditions on change in mass of bagged corn.

The effects of environmental condition and initial moisture content (nominal 10% wb) on changes in mass and final moisture content of bagged corn are shown in Table 2. There was a significant mass gain (p<0.0001) in all the bags as the storage conditions change across the three bags except in the control where mass gain was negligible. Consequently, the moisture content increased with the mass gain. Effects of bag type on increase in moisture content was, however, not significant. Moisture content of the corn increased significantly over the storage period.

Table 2 Effect of ambient conditions on change in mass of bagged corn initially at 10% wb moisture content after 35 days

Material Description	Condition (Temp °C/ %)	EMC (% wb)	Initial MC (% wb)	Change in MC (% wb)	Mass gain (g)
PP-C	25 / 65	13.3	9.9±0.0	1.6±0.1^{d}	12.5±0.1^{e}
	28 / 75	14.7	9.6±0.1	3.0±0.1^{c}	23.8±0.1^{d}
	30 / 80	15.6	10.0±0.1	3.6±0.1^{ab}	28.4±0.1^{b}
PP-O	25 / 65	13.3	9.8±0.1	1.6±0.1^{d}	12.6±0.1^{e}
	28 / 75	14.7	9.6±0.1	3.0±0.0^{c}	24.0±0.1^{d}
	30 / 80	15.6	10.0±0.2	3.5±0.1^{b}	27.9±0.5^{b}
Jute	25 / 65	13.3	9.9±0.1	1.6±0.1^{d}	12.8±0.1^{e}
	28 / 75	14.7	9.8±0.1	3.1±0.1^{c}	24.8±0.3^{c}
	30 / 80	15.6	9.7±0.1	3.7±0.0^{a}	29.7±0.4^{a}
Control	25 / 65	13.3	9.9±0.1	0.0±0.0^{f}	0.0±0.0^{g}
	28 / 75	14.7	10.0±0.1	0.4±0.1^{e}	3.2±0.4^{f}
	30 / 80	15.6	9.9±0.0	0.4±0.1^{e}	3.0±0.1^{f}

Note: [a]Values within columns sharing the same superscript letter are not significantly different ($p < 0.05$; n= 36).

As expected, storage environments with a higher EMC had a higher mass gain and a corresponding increase in moisture content. There was no statistically significant difference in the two polypropylene materials. With jute bags, the mass gain was like the polypropylene bags at the driest environmental condition (EMC of 13.3%) but was significantly higher than the polypropylene bags at the more humid conditions (EMC of 14.7% and 15.6%). This would be expected since the driving force for moisture addition was larger. On average, the corn moisture increased by 1.6, 3.0 and 3.6 percentage points in polypropylene bags from an initial moisture content of 10.0% while the corresponding moisture increase in jute bags was 1.6, 3.1 and 3.7 percentage points. These results consistent with the findings from previous research where the moisture content of grain stored in woven polypropylene have been reported to increase as the humidity of the storage environment increase and decrease when the relative humidity of the ambient conditions decrease (Afzal et al., 2017; Lane and Woloshuk, 2017; Likhayo et al., 2018).

In bagged corn with an initial moisture content of 12% (Table 3), the observed mass gain in the bags were significantly influenced by environmental condition and initial moisture content as well as the interaction among the treatments (p<0.0001). The increased in moisture content were significantly different for mini-bags stored under different environmental conditions but were the same across bag types. However, the condition of corn in all the bags (including control) remained unchanged with the temperature at 25°C and 65% relative humidity.

Table 3 Effect of ambient conditions on change in mass of bagged corn initially at 12% wb moisture content after 35 days

Material Description	Condition (Temp °C/ %)	EMC (% wb)	Initial MC (% wb)	Change in MC (% wb)	Mass gain (g)
PP-C	25 / 65	13.3	11.8±0.0	0.0±0.0^{e}	0.0±0.0^{f}
	28 / 75	14.7	11.5±0.1	1.0±0.0^{c}	8.1±0.1^{c}
	30 / 80	15.6	12.3±0.2	1.8±0.1^{b}	14.8±0.2^{b}
PP-O	25 / 65	13.3	11.9±0.1	0.0±0.0^{e}	0.0±0.0^{f}
	28 / 75	14.7	11.7±0.1	1.0±0.1^{c}	8.0±0.0^{c}
	30 / 80	15.6	12.2±0.1	1.8±0.2^{b}	14.4±0.0.8^{b}
Jute	25 / 65	13.3	11.8±0.1	0.0±0.0^{e}	0.2±0.1^{f}
	28 / 75	14.7	11.7±0.1	1.1±0.1^{c}	8.5±0.1^{c}
	30 / 80	15.6	12.2±0.1	2.0±0.1^{a}	16.3±0.3^{a}
Control	25 / 65	13.3	11.8±0.0	0.±0.0^{e}	0.0±0^{f}
	28 / 75	14.7	11.8±0.0	0.1±0.1^{d}	0.7±0.2^{e}
	30 / 80	15.6	12.4±0.1	0.2±0.0^{d}	1.6±0.1^{d}

Note: [a]Values within columns sharing the same superscript letter are not significantly different ($p < 0.05$; n= 36).

There was no mass gain in both polypropylene and polyethylene (control) bags when exposed to air at 25°C / 65% (EMC of 13.3%). In comparison, there was a marginal increase in the mass gain in jute bags at these environmental conditions, but this did not result in a measurable change in moisture content. The low magnitude of the mass gain under these conditions was due to the initial moisture content and environmental conditions being very close to equilibrium. The mass gain of corn stored in the two polypropylene bags increased significantly as the EMC increased. Interestingly, jute bags had a statistically similar mass gain to the polypropylene bags with conditions of 28°C / 75% (EMC of 14.7%), although the mass gain at 30°C / 80% (EMC of 15.6%) was statistically different from polypropylene bags at the same condition. The average moisture increase in polypropylene bags from 12.0% was 0.0, 1.0 and 1.8 percentage points when exposed to environmental conditions with an EMC of 13.3%, 14.7%, and 15.6%, respectively while the corresponding values in jute bags were 0.0, 1.1, and 2.0 percentage points, respectively. The marginal change in moisture content of corn with an initial moisture content of 12% corroborates the results reported by Angelovič et al. (2018) and Likhayo et al. (2018), where corn stored in woven polypropylene bags with similar initial moisture content were found to be stable in storage.

In contrast corn moisture in control samples (polyethylene) only increased by about 0.4% point under the most humid condition. This is expected because MDPE is a better barrier to moisture transfer than the other materials which is why polyethylene is used a liner in hermetic bags which have proven to provide stability to stored grains (Amadou et al., 2016; Williams et al., 2017). The marginal change in moisture seen in the polyethylene may be connected to the tightness of the sealing and also the fact that polymer materials do not serve as "absolute barriers" against water vapor as pointed out by Gajdoš et al. (2000).

In relating the WVP of the bags with the change in MC, the statistical analysis showed that there is a weak positive correlation (p<0.07) between the two parameters, which may be due to the interaction effect of other parameters that were considered in this study. This points to the fact that, although the permeability of the bag materials may influence moisture fluxes into the bags, the storage environment drives the magnitude of the observed changes. Jute bags are not desirable for use under very humid conditions due to the higher permeability and its tendency to absorb water vapor which can aid mold formation. However, when using polypropylene bags under high temperature and relative humidity, appropriate ventilation should be provided to prevent the buildup of hot spots within the bags which will also lead to spoilage. Although the PP-O and PP-C bags behaved similarly, there are other factors that would influence the selection of bags at the market level. Clear bags are more desirable by consumers because they can easily notice grain damage and the presence of frass, mold and/or foreign materials.

4 Conclusions

This study has shown the effect of water vapor transmission rate (WVTR) in common bag materials at three environmental conditions. The permeability of two polypropylene bag materials (PP-C and PP-C) and their performance under the test conditions were identical. This implies that the moisture change of grain stored in the two types of bags would likely behave similarly.

The permeability of the bag materials and their performance is largely affected by the ambient condition with the effects more pronounced in jute bags. This study has provided useful information on the interaction of WVTR of storage bag materials and environmental conditions on the process of moisture flux into bagged grains. A considerable amount of moisture can be transferred from the ambient air in storage warehouses to stored grain as the environmental condition changes depending on the initial moisture of the grain. The study reiterates the need for adequate monitoring bagged grain storage systems, where little or no environmental control is being practiced, to prevent quality deterioration when storing bagged grain.

It is, however, necessary to extend the investigation to cover prevailing environmental conditions typically found where grain storage in bags is being practiced and preferably using full size bags (100 kg) to match field/market conditions.

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