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EFFECTS OF SPLITS CONTENT ON DRY MATTER LOSS RATES OF SOYBEANS MEASURED USING A STATIC GRAIN RESPIRATION MEASUREMENT SYSTEM

Ana B. Gatsakos¹, Thomas B. Scatolini², Mary-Grace C. Danao³, Richard S. Gates⁴, Kent D. Rausch^{1,*}

Highlights

- Respiration rate increased with percentage of split beans.
- Splits multiplier for soybeans appears to be more sensitive than the corn damage multiplier.
- Relationship between split percentage and splits multiplier for soybeans is approximately linear.
- Value for splits multiplier for beans at 18% moisture content soybeans stored at 35°C is provided.

ABSTRACT. *The objectives of this study were to compare effects of 0-16% (w/w) splits content (x_s) of soybeans stored at 35°C and 18% moisture content (w.b.) on dry matter loss rates (v_{DML}), and to determine a splits multiplier (M_S) for soybeans stored at these conditions, similar to the damage multiplier (M_D) utilized in ASABE Standard D535 for shelled corn. Effects of percentage by weight splits (x_s) on M_S and safe storage time are expected to be greater than M_D for corn because soybeans are prone to cracking and splitting, lipid oxidation, and protein degradation – all of which lead to grain dry matter and quality losses. Results indicated v_{DML} increased with increasing x_s and mean v_{DML} for samples with 16% splits was 1.5 times greater than that for samples with 4% splits. M_S for soybeans was linearly correlated with x_s , decreasing from 1.0 to 0.60 for 0% to 16% splits, respectively. Soybeans appeared to be more sensitive to percent by weight splits than was corn to the presence of damaged kernels. M_D for corn only decreased from 1.0 to 0.8 when percent (w/w) damaged kernels content increased from 30% to 40%. In comparison, it should be noted that damage to soybeans was defined differently from damage to corn. This research is useful in defining M_S for 18% moisture content soybeans stored at 35°C under hermetic conditions. The*

procedures outlined in this paper may be used in the future to more formally define a soybean M_S that covers a wider range of moisture contents, storage conditions and possibly a M_D based on other factors included in the USDA definitions of damaged soybean kernels.

Keywords. *allowable storage time, grain quality, splits multiplier*

INTRODUCTION

Different cereal grains and oilseeds start deteriorating from the time of harvest. During storage, two factors influence deterioration rates and, ultimately, grain dry matter and quality losses. The first factor is the presence of spoilage organisms, such as mites, molds, insects, and mycotoxins. The second factor is unfavorable storage conditions, such as high temperature, low oxygen levels, and high moisture in the grain and surrounding air (Coker, 1994). However, even in the absence of spoilage organisms and with favorable storage conditions, grain will continue to respire, albeit at rates so low that they are practically negligible, and the grain can be safely stored indefinitely. Storage of shelled corn has been studied extensively and it has been found that increases in storage temperature (T), moisture content (w), or total damaged kernels (D) can decrease dramatically the safe storage time (t_s); alternatively, increases in fungal resistance from either hybrid traits or fungicide application can increase t_s .

To estimate shelled corn storage time for 0.5% dry matter loss (*DML*), ASABE Standard D535 (R2019) provides an equation for t_s :

$$t_s = 9.583 M_T M_w M_D M_H M_F \quad (1)$$

where M_T , M_w , M_D , M_H , and M_F are temperature, moisture, damage, hybrid resistance, and fungicide multipliers, respectively. For shelled corn, these multipliers are all equal to unity for a generic hybrid without fungicide treatment, held at 25% (w.b.) moisture content and 15.6°C, and assuming 30% (w/w) of kernels have been damaged during mechanical harvest. Effects of w and T on t_s are laid out in a table

in the standard and have been a useful guide for those who are storing corn in bins or holding corn in transport vessels. Equation 1 and t_s values in the standard were based on several studies that measured carbon dioxide production of different hybrids of shelled corn at different T , M , D , and fungicide treatments to develop individual equations for these multipliers.

To attain a better understanding of the effects of temperature, moisture content, and damage on t_s , their corresponding multipliers (M_T , M_w , M_D) were first plotted as shown in figure 1 and then applied to the following example. Suppose shelled corn at 16% moisture content is stored at 15.6°C. Using ASABE Standard D535 (R2019), for this set of conditions, M_T and M_w are equal to 0.993 and 15.8, respectively. Assuming M_D , M_H , and M_F are all equal to unity, this corn can be stored safely for up to 151 days from the time of harvest according to equation 1. If storage T is increased to 26.7°C, M_T changes to 0.312 and t_s decreases to 47.3 days. If instead the 15.6°C corn gains moisture and reaches 20%, M_w decreases to 2.945 and t_s decreases to 28.1 days. If T increases from 15.6°C to 26.7°C and w increases from 16% to 20% moisture content, the net effect is a decrease in t_s to 8.8 days.

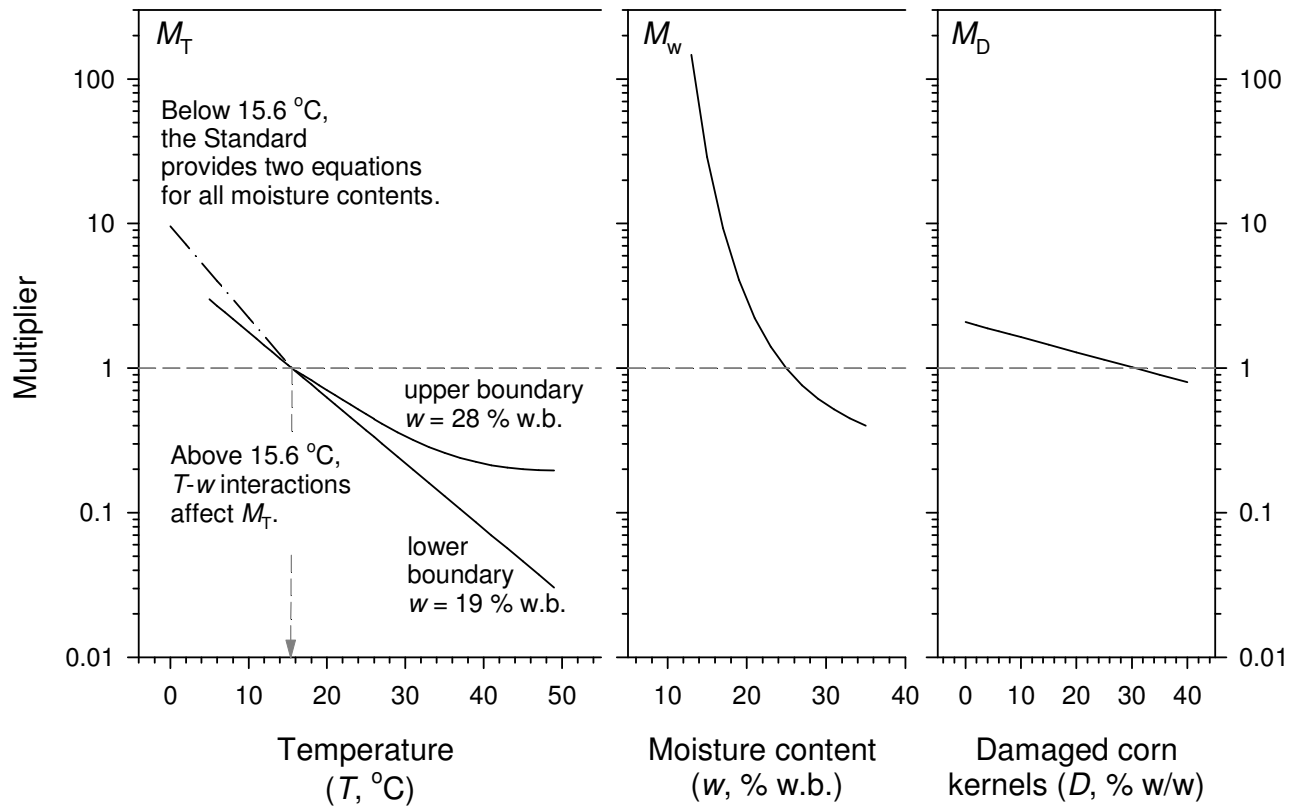


Figure 1. Multipliers (M) for temperature (T, °C), moisture (w, % w.b.), and damage level (D, % w/w) defined in the ASABE Standard D535 (R2019) for shelled corn. At conditions T = 15.6°C, w = 25% w.b. and D = 30% w/w, M_T , M_w , and M_D have a value of unity.

Note that the concept of safe storage time or maximum allowable storage time is cumulative, meaning, the amount of time that the corn was stored in the first set of storage conditions must be accounted for when determining the remaining amount of time it can be stored in subsequent storage conditions. For example, if 18% moisture corn was harvested and transported at 35°C for 2 days, 89% equilibrium relative humidity (ERH), approximately 2 days of the 8 days maximum allowable (25%) of its “shelf-life” or safe storage time towards 0.5% DML has occurred. Then, if it is subsequently dried and stored at 16% moisture content and 26.7°C, it has 75% of its shelf-life remaining, which is 0.75×47 days = 35 days.

Of these three factors, the effect of damage on t_s is not as dramatic as those of temperature and moisture content, i.e., the M_D curve in figure 1 is not as steep as the M_T and M_w curves. In other parts of the world

such as Brazil, corn harvest can begin as soon as the grain moisture content decreases to 30% moisture content, but ideal harvest conditions are typically when corn is at 20-25% moisture content grain. Cracked or broken kernels result when the combine is poorly adjusted such that more beating, shearing, or pinching of grain occurs. During drying, stress cracks can form if drying temperature is too high, or if the grain is rapidly cooled after heating in the dryer (Fortes & Okos, 1980; Steele, 1967). Hence, ASABE Standard D535 (R2019) assumes a D of 3% (w/w) for hand-shelled corn, 30% (w/w) for mechanically harvested corn under typical conditions, and 40% for corn that is heavily damaged during harvest. These D levels correspond to damage multiplier (M_D) of 2.0, 1.0, and 0.8, respectively (fig. 1) meaning hand-shelled corn can be safely stored for twice as long as mechanically harvested corn under typical conditions at the same T and w . However, a 10% increase in D decreases t_s by 20%.

The type of damage to soybeans and other legumes is different from types of damage inflicted on corn. A corn kernel has an outer shell (pericarp) protecting its endosperm which does not readily separate, but a soybean seed has a moderately fragile thin seed coat that cracks, revealing two cotyledons that readily split to expose interior surfaces and embryo to fungal attack and oxidation. Therefore, it is expected that splitting of cotyledons will have a significant effect on quality loss in soybeans and other legumes. At optimum harvest moisture contents of 13% to 15% for soybeans for maximum weight and minimum field losses, soybean seeds are prone to cracking after impacting metal surfaces in the combine and as a result of impacts with other seeds and surfaces during harvest and handling (Bern et al., 1999). According to Paulsen et al. (1981), soybeans' germination decreased with increase in harvest damage even when stored at a minimum moisture content. Soybean is susceptible to hydrolysis of triglycerides and protein degradation, leading to elevated levels of free fatty acids (FFA) and decreased protein content during storage (Alencar et al., 2010; Bern et al., 1999; Kong & Chang, 2013). Elevated levels of FFA in split soybeans have been correlated to poor oil quality (Mustakas et al., 1969) and refining losses during

soybean oil processing (Carr, 1976). Thus, while effects of T and moisture content on t_s for corn and soybeans may be comparable, effects of damaged and percentage of split beans (x_s) on t_s and dry matter loss rate (v_{DML}) are expected to be significant and must be quantified. Effects of storage moisture content, temperature, and other factors on quality attributes, such as oil and protein degradation, will need to be quantified for eventual development of a mathematical model to estimate maximum allowable storage time of soybeans.

Objectives of this study were to (1) compare v_{DML} of 18% moisture content soybeans with 0% to 16% (w/w) split beans content stored at 35°C, and (2) to use these results to determine a splits multiplier (M_s) for soybeans stored at these conditions, similar to multipliers utilized in ASABE Standard D535 (R2019) for corn. Storage conditions chosen in this paper are typical for soybean harvest and initial storage conditions in low latitude regions. In these regions, it is difficult to harvest and store soybeans at optimum moisture; a harvest moisture of 18% is frequently encountered. For example, while harvesting soybeans in Mato Grosso, Brazil, moisture contents often range from 10.8 to 25.7%, average ambient temperatures range from 19.7 to 35.1°C and the period of time required to transport beans to a drying facility ranges from 1 to 16 h (Danao et al., 2015).

MATERIALS AND METHODS

SOYBEANS AND SAMPLE PREPARATION

Soybeans (28T33R, DuPont Pioneer, Johnston, IA, USA) were combine harvested at approximately 15% moisture content from the Crop Sciences Research and Education Farm of the University of Illinois at Urbana-Champaign in October 2016. The soybeans were dried at ambient conditions to 12% to 13% moisture content and placed in a bin equipped with a fan at outdoor environmental temperatures, ranging from 12°C to -1.6°C. Moisture migration was prevented with cycles of aeration in the bin. On 19 January 2017, approximately 327 kg were removed from storage, placed in plastic containers (68 L capacity), and

stored at 4°C until testing, September 2017.

A batch of split soybeans was initially prepared by retrieving 3 kg from cold storage and screening them with Sieve 1, a slotted sieve with 3.97 mm by 19 mm (10/64" by 3/4") openings (Grainman, Miami, FL, USA) to remove small impurities and split beans (fig. 2). Larger impurities and damaged beans were handpicked from the remaining whole soybeans. To generate split beans for later use, the cleaned sample was passed through a custom-fabricated laboratory corn degerminator (Rausch et al., 2009; Somavat et al., 2017) and screened using Sieve 1 and also Sieve 2, a USA Standard No 8, which has circular openings with a diameter of 2.360 mm (Dual Manufacturing Co., Franklin Park, IL, USA). Samples were separated into 700 g aliquots, which were placed in sealed plastic bags prior to storing at 4°C.

Before each respiration test, four glass desiccators (10 L capacity each) were placed in an incubator (Model No 3033, Steri-Culti 200, Forma Scientific, Inc., Marietta, OH, USA) set at 35°C to acclimatize. A single 700 g aliquot of split soybeans was removed from cold storage and spread onto a tray to acclimate at room temperature (approximately 23°C) for 30 min to 40 min. In the same fashion, a 3 kg sample of whole soybeans was removed from cold storage and acclimated on a separate tray. Split and whole soybean moisture contents were estimated using a portable moisture meter (Model No SW16060, John Deere, Moline, IL, USA). These moisture measurements were used to estimate the amounts of water to be

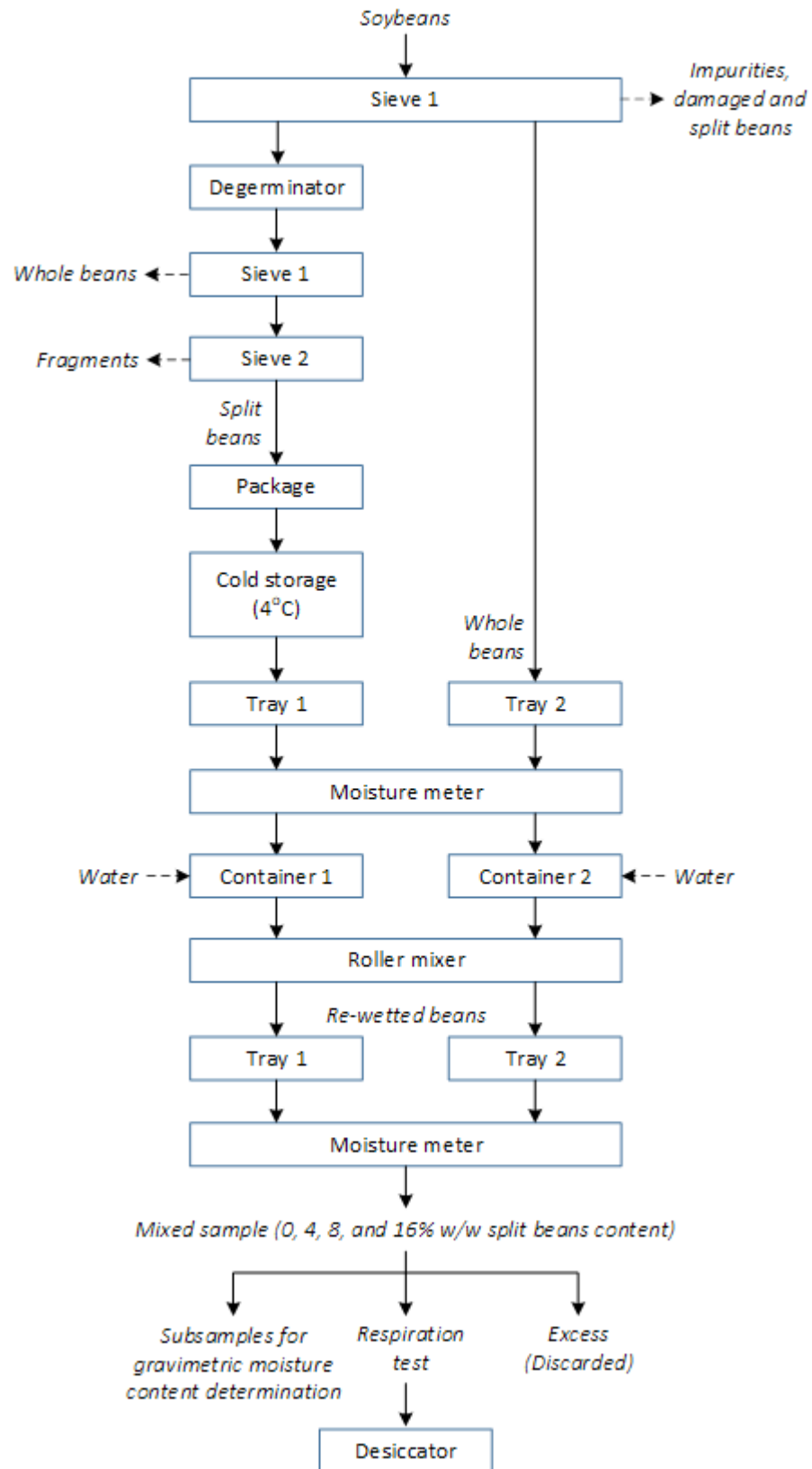


Figure 2. Soybean sample preparation.

added to reach the desired 18% moisture content for testing. Whole and split soybeans were placed in separate containers and slowly rehydrated over a 60 min interval by adding the required amount of water (plus 10 mL of excess water) every 10 min. Between water additions, the containers were placed on roller mixers (Model No MX-T6-S, Scilogex, Rocky Hill, CT, USA) set to 60 rpm.

After 60 min of re-wetting, the moisture content of both batches was estimated using the portable moisture meter. Then, whole and split soybeans were spread into thin layers on separate trays to facilitate the evaporation of excess moisture at room temperature for 30 min to 40 min. Every 5 min, the moisture content of both batches were estimated using the portable moisture meter. Once 18% moisture content was reached, split beans were mixed with whole soybeans to yield four levels of x_s (0, 4, 8, and 16% w/w), where 0% (w/w) splits served as a control sample. Each mixture weighed approximately 500 g. From the remaining split beans and whole soybeans, three subsamples (30 g each) were set aside for gravimetric moisture content measurement following ASABE Standard S352.2(R2017). Each 500 g of mixed sample was placed in an acclimated desiccator (10 L capacity) equipped with a sensor package with a built-in datalogger (Model K33-BLG, CO2Meter, Inc., Ormond Beach, FL, USA) and sealed hermetically with vacuum grease (fig. 3). All filled desiccators were placed in the 35°C incubator.

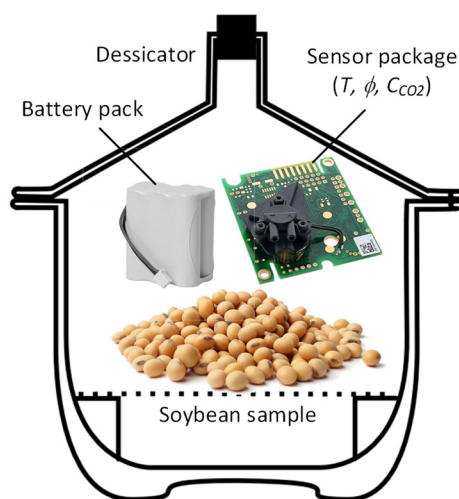


Figure 3. Components of static grain respiration measurement system (S-GRMS).

RESPIRATION DATA COLLECTION AND ANALYSIS

Respiration tests

Prior to a respiration test, each desiccator/sensor package was assigned to a single x_s level and calibrated according to procedures described in Pereira Da Silva (2018) with a two-point method using N₂ gas (for zero) and certified calibration gas for span. The sensor packages' built-in data loggers were set to record T (°C), relative humidity (ϕ , %RH), and carbon dioxide concentration (C_{CO_2} , %) inside each desiccator every 10 min for 10 days.

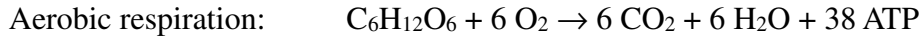
The experiment was a completely randomized design with replication. Each set of respiration tests consisted of one each of the four x_s levels, randomly assigned to one of the four desiccators; the set of respiration tests was replicated five times with new soybean samples. At the end of each respiration test, three subsamples (30 g each) previously set aside from each desiccator were used to determine moisture content according to ASABE Standard S352.2 (R2017). Each 30 g sample was transferred to a metal container and heated in a forced convection oven at 103°C for 72 h. Moisture content was determined from the difference in sample weight before and after oven drying. Initial and final moisture content measurements for each test were within $\pm 1\%$ of the equilibrium moisture content, corresponding to measured relative humidity of 88% RH ($\pm 5\%$) and temperature of 35°C ($\pm 1^\circ\text{C}$) inside each of the desiccators. Results of oven moisture tests confirmed accuracy of the moisture meter being used to monitor addition of moisture to the samples.

Conversion of respired CO₂ to DML estimate

The start of a respiration test (t_0) was designated as the time when the temperature in the desiccator reached $35 \pm 1^\circ\text{C}$. C_{CO_2} readings were corrected using the appropriate calibration equation and by subtracting the C_{CO_2} at t_0 . Using the ideal gas law, corrected C_{CO_2} readings were converted to accumulated mass of respired CO₂ inside the desiccator (eq. 2), which, after normalizing to the mass of dry matter of the mixed soybean sample (m_{dm}), was subsequently converted to *DML* (eq. 3), according to the

stoichiometric relationship between CO₂ and glucose during respiration:

$$\Sigma m_{CO_2} = C_{CO_2} \left(\frac{P V M_{CO_2}}{R T} \right) \quad (2)$$



$$DML = \left(\frac{\Sigma m_{CO_2}}{m_{dm}} \right) \left(\frac{1 \text{ mol } C_6H_{12}O_6}{6 \text{ mol } CO_2} \right) \left(\frac{M_{C_6H_{12}O_6}}{M_{CO_2}} \right) \quad (3)$$

where Σm_{CO_2} is the accumulated mass of respired CO₂ (g), P is the pressure inside the desiccator (1 atm), V is the desiccator volume (10 L), R is the ideal gas constant (0.08205 L atm K⁻¹ mol⁻¹), T is the temperature (K), and $M_{C_6H_{12}O_6}$ and M_{CO_2} are the molar masses of glucose (180.16 g mol⁻¹) and carbon dioxide (44 g mol⁻¹), respectively.

Rate of dry matter loss

Time series *DML* estimates showed an initial lag period and curvilinear shape until about 0.05% *DML* was reached followed by a steady increase in *DML* at a constant rate (fig.4). The time at which *DML* reached 0.05% ($t_{0.05}$) was considered the start time of grain *DML*. v_{DML} was estimated by taking the slope of the best-fit line from $t_{0.05}$ until the experiment end using the linear regression option of the Data Analysis ToolPak in MS Excel (Office 365, Microsoft Corporation, Redmond, WA, USA). *DML* rates for samples with splits were normalized by dividing the rate for a given percent splits, v_{DML,x_s} by $v_{DML,x_s} = 0$ to yield a ratio, R_{x_s} , which provided the relative rates of *DML*.

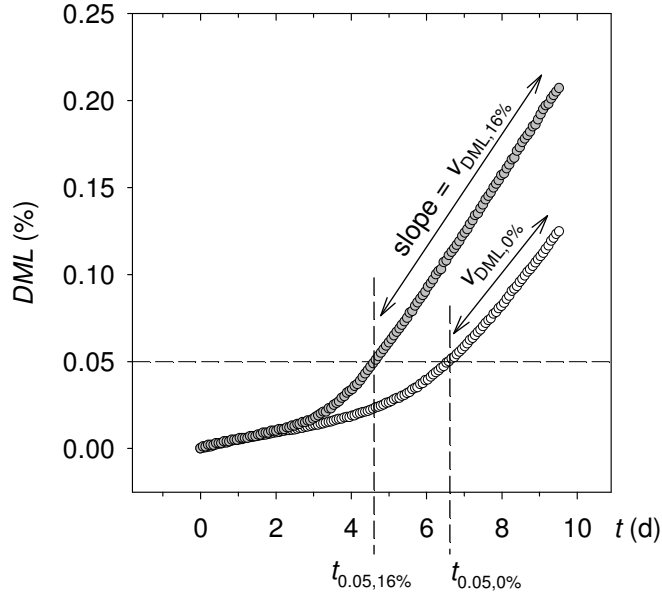


Figure 4. Rates of dry matter loss (v_{DML,x_s} , % d-1) were initially low and did not reach steady-state until after about 0.05% *DML* was reached. Rate of *DML* was estimated as slope of the steady-state increase in *DML* after this time. The two curves show typical accumulated *DML* for a sample with 16% splits and another control with 0%.

STATISTICAL ANALYSES

ANOVA with Tukey's range test

One-way analysis of variance (ANOVA) tests were conducted using the PROC ANOVA function with Tukey's range test in SAS (2017 University Edition Software, SAS Institute, Inc., Cary, NC, USA). Response variables were v_{DML} with four treatment levels of x_s (0, 4, 8 and 16% w/w), and R_{x_s} with three treatment levels of x_s (4, 8, and 16% w/w). Differences among treatment means were assumed significant at $\alpha = 0.05$. If treatment effects were significant, means were separated using the Tukey t-test option.

Developing a splits multiplier (M_s) based on R_{x_s}

By definition, storage time is inversely proportional to v_{DML} , so the safe storage time t_s for soybean samples with a given % splits (i.e. t_{s,x_s}) is proportional to t_s with 0% splits:

$$v_{DML} = \frac{\Delta DML}{\Delta t} = \frac{\Delta DML}{t_s - 0} = \frac{\Delta DML}{t_s} \quad (4)$$

$$\frac{t_{s,x_s}}{t_{s,x_s=0}} = \frac{v_{DML,x_s=0}}{v_{DML,x_s}} \quad (5)$$

Thus, the relation between t_{s,x_s} and $t_{s,x_s=0}$ is:

$$t_{s,x_s} = \left(\frac{v_{DML,x_s=0}}{v_{DML,x_s}} \right) t_{s,x_s=0} = \frac{1}{R_{x_s}} t_{s,x_s=0} = M_S t_{s,x_s=0} \quad (6)$$

which suggests that M_S for soybeans may be estimated as $1/R_{x_s}$ (eq. 6). Note that soybeans used in the control and mixed samples were harvested from a single lot, so it was assumed that the degree of mechanical damage to the seed coat of the whole and split beans were the same and that the M_S estimate incorporated effects from both mechanical damage and x_s . The relationship between M_S and x_s was fitted with linear and exponential equations (Sigmaplot Version 13, Systat Software, San Jose, CA, USA). Because the M_D equation for shelled corn in the ASABE Standard D535 (R2019) is the only available reference giving values for a damage multiplier, the regression results and overall effect of split soybeans on t_s from this paper were compared to the M_D for corn. .

RESULTS AND DISCUSSION

DRY MATTER LOSS ESTIMATES AND RATES

DML estimates over time showed initial lag periods ranging from 2.82 d to 7.21 d, decreasing as x_s increased (fig. 5). This lag period was observed by Rukunudin et al. (2004) and Trevisan (2017) in their studies, where grain respiration was measured in systems with a steady supply of airflow to the grain mass. However, Ochandio et al. (2012) and Jian et al. (2014) used hermetically sealed systems, similar to the ones used in this study, and did not report an initial lag period, due to the extremely low *DML* values they observed.

Over a 10-day respiration test, *DML* reached 0.09% to 0.16% for control samples ($x_s = 0\%$ splits). Maximum *DML* values increased with increasing x_s : 0.10% to 0.21% for 4% splits, 0.14% to 0.27% for 8% splits, and 0.19% to 0.39% for 16% splits. After 2 to 4 days of storage, soybeans started to exhibit visible mold growth, which may explain the steady increase after 0.05% on *DML*, as verified by

inspection. At the end of the tests, visible mold growth increased within splits percentage.

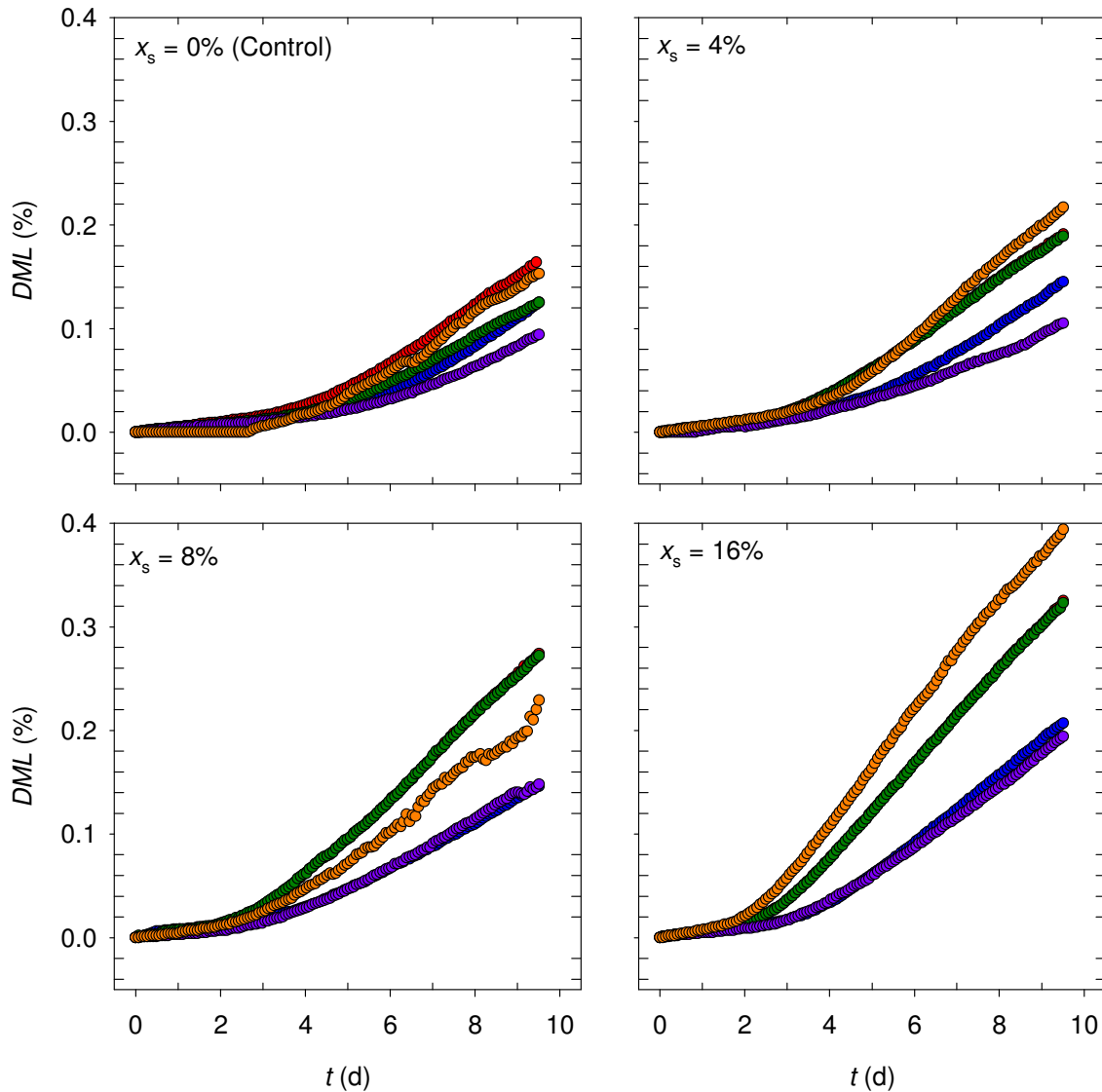


Figure 5. Dry matter loss increased with increasing splits content (x_s , % w/w). Each plot shows data from five replications. One or more replicates cannot be distinguished because data overlapped.

Mean v_{DML} for samples with 16% split beans content was greater than that of control samples but was not different from those of samples with 8% splits (table 1). Likewise, mean v_{DML} for the control sample was not different from that of samples with 4% splits. Variance of the mean v_{DML} values increased with increasing x_s and was large enough to result in overlapping treatment means. Similarly, the normalized v_{DML} comparison to that of the control showed a difference between $R_{x_s=4\%}$ and $R_{x_s=16\%}$, but neither values

were different from $R_{x_s=8\%}$ (table 2), owing to large standard deviations (σ_R) at 8% and 16% splits content.

Table 1. Dry matter loss rates of soybeans at 18% moisture content with 0-16% (w/w) splits content, stored at 35°C.

x_s (% w/w)	v_{DML} (% d-1) ^[a]					Mean and Std. Deviation	
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	$\bar{v}_{DML} \pm \sigma_{v_{DML}}$ (% d-1) ^[b]	
0	0.0245	0.0268	0.0222	0.0185	0.0266	0.0237 ± 0.0035	b
4	0.0240	0.0282	0.0281	0.0168	0.0350	0.0264 ± 0.0066	b
8	0.0215	0.0376	0.0372	0.0227	0.0300	0.0298 ± 0.0076	ab
16	0.0318	0.0450	0.0448	0.0283	0.0528	0.0405 ± 0.0101	a

^[a]Standard errors of the rate estimates were less than 0.0001% d⁻¹.

^[b]Means followed by the same letter were not different from each other ($p < 0.05$).

Table 2. Normalized dry matter loss rates of soybeans (R_{x_s}) at 18% moisture content with 4-6% (w/w) splits content, stored at 35°C and splits multipliers estimate (M_S).

x_s (% w/w)	$R_{x_s} = v_{DML,x_s} / v_{DML,x_s=0}$					Mean and Std. Deviation		$M_S = 1/R_{x_s}$
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	$\bar{R}_{x_s} \pm \sigma_R$ ^[a]		
4	0.98	1.05	1.27	0.91	1.32	1.10 ± 0.18	b	0.91
8	0.88	1.40	1.68	1.23	1.13	1.26 ± 0.30	ab	0.79
16	1.30	1.68	2.02	1.53	1.98	1.70 ± 0.31	a	0.59

^[a]Means followed by the same letter were not different from each other ($p < 0.05$).

Per ASABE Standard D535 (R2019), M_D for shelled corn ranges from 1.0 to 0.8 for mechanically harvested corn as the portion of damaged kernels increases from 30 to 40% (w/w). For soybeans, the mean M_S , estimated as the inverse of R_{x_s} (eq. 6), ranged from 1.0 to 0.6 as x_s increased from 0% to 16% (w/w) (fig. 6). While it appeared that M_S for soybeans was more sensitive to damage than M_D for corn kernels, it is important to note the difference in the definition of “damage” in this study compared to that used in the Standard. Here, the damage level was defined as x_s in mixed soybean samples tested while the Standard uses the definition from Stroshine and Yang (1990), in which damage was percent by weight of kernels in a 100 g sample with pieces of kernel broken away or with cuts or abrasion to the pericarp as determined by visual inspection without staining or magnification. Nevertheless, based on these tests, the relationship between M_S and x_s for soybeans can be described using a linear or exponential model, with a lower standard error (SE) obtained with the linear model (fig. 6).

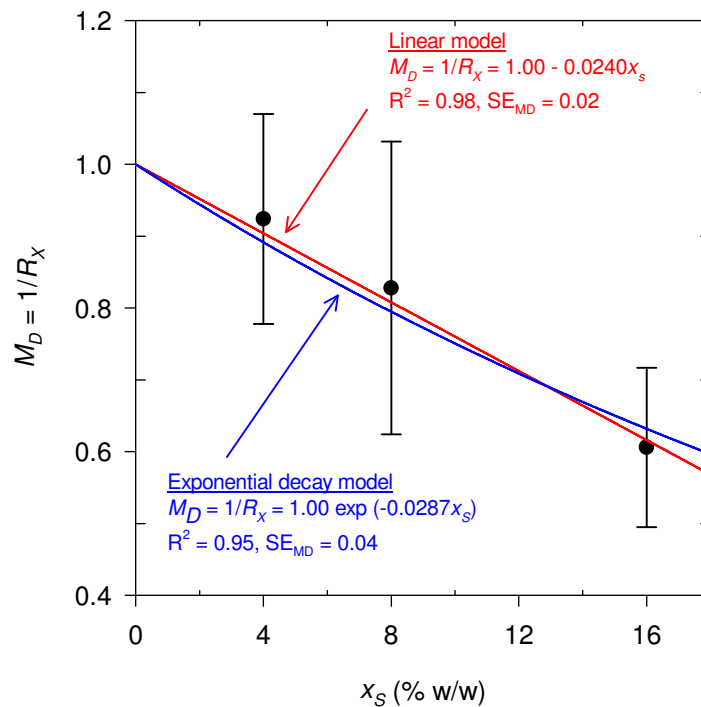


Figure 6. Linear and exponential models showing the relationship between damage multiplier (M_D) for soybeans and splits content. The linear model yielded a lower standard error (SE).

US Standard Grades for soybeans include other factors that indicate damage to seeds. These include seeds damaged on their germ or badly damaged by diseases, frost, or insect activity, along with seeds discolored by heating, or by contact with the ground or weather, or otherwise physically damaged. Factors from this list that have a significant effect on DML could be identified and appropriate multipliers could be determined for these factors. As mentioned in the introduction, lipid oxidation and protein degradation are also important quality attributes. Therefore, studies could also be conducted to determine whether there is a relationship between these two quality attributes and DML .

CONCLUSION

The rate of DML of soybeans increased modestly with increasing splits content (x_s), with a four-fold increase in split beans (from 4% to 16% w/w) resulting in 1.5 times greater v_{DML} . No significant difference in mean v_{DML} was detected between samples with 8% and 16% split beans. The same trend held true when

v_{DML} were normalized to that of control samples to yield the ratio of dry matter loss at different percentages of splits (R_{x_s}). The inverse relationship between R_{x_s} and splits multiplier (M_s) showed that the effect of increasing the percent by weight splits in soybeans from 0% to 16% was substantially greater than the change from 30% to 40% by weight damaged kernels for shelled corn. If all other factors are considered constant, it can be suggested that the presence of a high proportion of splits could substantially reduce the time required for the soybeans to reach 0.5% *DML*. This research was a useful step towards understanding the effects of split beans on safe storage time of 18% moisture content soybeans at 35°C under hermetic conditions and could be expanded in the future to cover a wider range of moisture contents and storage temperatures. More studies could also be conducted to include other damage factors on seeds and its relationship with lipid oxidation and protein degradation.

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NOMENCLATURE

Abbreviation	Definition
ANOVA	Analysis of variance
FFA	Free fatty acids
w.b.	Wet-basis

Symbol	Chemical name
ATP	Adenosine triphosphate
CO ₂	Carbon dioxide
C ₆ H ₁₂ O ₆	Glucose
H ₂ O	Water
O ₂	Oxygen

Variable	Description	Unit of measurement
Δ	Change or difference	---

Variable	Description	Unit of measurement
ϕ	Relative humidity	%RH
σ_R	Standard deviation of the ratio	---
σ_{VDML}	Standard deviation of the rate of dry matter loss	% d ⁻¹
C_{CO_2}	Concentration of carbon dioxide	%
D	Damaged kernels	% w/w
DML	Dry matter loss	% w/w
m_{dm}	Dry matter mass	g
M_{CO_2}	Molar mass of carbon dioxide	g mol ⁻¹
$M_{C_6H_{12}O_6}$	Molar mass of glucose	g mol ⁻¹
M_D	Multiplier, damage	---
M_F	Multiplier, fungicide treatment	---
M_H	Multiplier, hybrid resistance	---
M_T	Multiplier, temperature	---
M_w	Multiplier, moisture	---
Σm_{CO_2}	Mass of accumulated mass of respired carbon dioxide	g
p	Probability value	---
P	Pressure inside the desiccator	atm
R	Ideal gas constant	L atm K ⁻¹ mol ⁻¹
R_{x_s}	Ratio of dry matter loss rate at a specific splits content to that of the control (or zero splits content)	---
SE	Standard error of the damage multiplier	---
T	Temperature	°C
t_0	Onset of grain storage (i.e., "time zero")	d

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