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ARTICLE

Diminished Strength of Peanut Pod Hulls from Rainfall on Windrowed Peanuts

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ABSTRACT

Peanut pods after digging are placed in windrows, which can be exposed to rainfall while awaiting harvest. Peanut pod exposure to rainfall after digging can reduce peanut grade quality. Effects of rainfall exposure on pod hull strength were investigated for harvest years 2021 to 2024 from irrigated experimental plots of runner peanuts, Georgia 06G cultivar. Experimental peanut plots were managed at four irrigation levels 0% (dry land), 33%, 66%, and 100% of the recommended irrigation. Peanuts were left in windrows and exposed to simulated rainfall in amounts relative to the irrigation level and then harvested one week after each rainfall using an experimental peanut combine and dried to below 10% moisture. Pod hull strength was measured by compressing 3,599 sample pods in a universal mechanical testing machine to record the force and displacement required to reach rupture stress on the pod suture or seam. Dryland (0% irrigated) peanut pods showed no statistically significant difference in the stress on the pod suture at rupture between the unexposed pods and those exposed to any amount of simulated rainfall. Irrigated peanut pod suture stress at rupture significantly decreased after a single rainfall exposure at all irrigation levels. Pod integrity was not significantly further reduced with subsequent rainfall exposure. When the force needed to rupture pod sutures is reduced, the number of loose shelled kernels at grading may be increased which reduces the value of the peanuts. Peanut farmers should schedule digging peanuts when rainfall is not expected to maintain pod hull strength. If peanuts are exposed to rainfall while inverted in windrows, handling peanuts before shelling should be minimized to reduce the likelihood of increasing loose-shelled kernels.

INTRODUCTION

The first operation in peanut harvesting is digging. Using a digger-shaker-inverter pulled by a tractor, the peanut plants have the roots cut below the peanut pod level, the plant foliage and pods lifted from the soil, clinging dirt shaken off, the plants inverted so the pods are placed uppermost, and the plants collected into windrows. The windrows are typically left in the field to dry for four to six days until the moisture in the peanut kernels decreases from 50-60% to 25-30% before collecting the dried peanuts (harvesting) with a combine (Young, Person, et al. 1982).

Windrow drying initially reduces losses of peanuts in the field, but keeping the peanuts in windrows past 3-5 days increases in-field losses, loose shelled kernels (LSK), sound splits (SS), and damaged seed (Young, Person, et al. 1982). Extended windrow drying does reduce energy costs for forced air drying, but the savings do not compensate for the value losses due to in-field peanut losses and quality reduction. Longer periods spent in windrows increase the likelihood of rainfall exposure for the peanut pods which adds moisture to the pods (Young 1977).

As plant materials, the physical and mechanical properties of peanut pods and kernels are dependent on many factors such as moisture content, microbial degradation, and genetics. The geometric and mechanical properties of peanut pods and kernels have been shown to be dependent on moisture content. To investigate the effects of moisture content on peanut pod geometric and mechanical properties, dried peanut pods and kernels were rehydrated to 5.7%, 15.3%, and 24.2% wet basis moisture content (Aydin 2007). The volume of the pods and kernels increased with moisture content. The rupture strength of the peanut pod hull loaded across the pod-long-axis decreased from 105 N to 45 N with increasing moisture (Aydin 2007).

Ince et al. (2009) measured the rupture resistance of peanut pods at various moisture content levels on the pod-long-axis of the peanut, on the pod split plane (pod suture plane), and perpendicular to the split plane. The measurements were made using a material testing machine that recorded force and displacement at the point a pod ruptured. The pods were tested by compressing them between two flat steel plates. Ince found that the force required to rupture peanut pods was greatest for pods loaded perpendicular to the split plane. The force decreased for loading parallel to the split plane and was the least for loading along the pod-long-axis. Increasing the moisture content of the peanut pods reduced the force required to rupture the pods. The relation of rupture force to loading direction relative to the pod suture plane was also reported by Bagheri et al. (2011).

When peanuts are harvested and placed in transport or storage containers, they must be dried to under 10% w.b. moisture within 2 to 3 days to prevent quality losses from biological degradation (Young, Person, et al. 1982). Peanut pod hulls can be degraded by fungus, mold, and bacteria if the moisture levels are sufficient to allow growth (Kerr, et al. 1986). Using electron microscopy, peanut pod hulls were observed to be extensively degraded after exposure to microorganisms *C. versicolor, P. placenta, T. reesei,* and *Arthrobacter* sp. KB-I. The peanut pod hulls were seen to lose 21% of the initial mass when cultured for 90 days with the natural flora existing on the hulls and water, but lost 55% when the water was supplemented with a 10% solution of ammonium nitrate.

The genetic contribution to shell strength (pod hull strength) was investigated using a penetrator pushing through one half of a pod hull going from the inside surface to exterior and into a hole in the support plate (Israel, et al. 2024). The penetration method of measuring shell strength showed the most statistically significant difference between the two peanut varieties under investigation. The penetrator method also showed good correlation with observed pod breakage levels for mechanical harvesting of the two varieties, with higher shell strength associated with lower pod breakage. Genetic analysis identified both major and minor quantitative trait loci significantly associated with shell strength. Higher shell strength appeared to be more associated with shell density than thickness, with accumulation of lignin, cellulose, and crude fiber influencing shell strength (Israel, et al. 2024).

The present study investigated the effect of rainfall exposure on the pod hull strength of peanut pods awaiting harvest in windrows. If rainfall exposure reduces the pod hull strength, the amount of LSK and damaged seed generated during harvesting with a combine, transporting, drying, and storage of the peanut pods could increase, thus reducing the graded quality of the peanuts. Reduced pod hull strength will also alter the performance of peanut shelling equipment, requiring adjustment of the shelling line to maintain product quality.

MATERIALS AND METHODS

Peanut Crop Management and Rainfall Exposure

To study the effect of rainfall exposure on peanut pod hull strength of windrowed peanuts, samples were collected from the harvested peanuts in an ongoing study conducted by Bucior, et al. (2025) at the Shellman Multi-crop Irrigated Research Farm (Shellman, GA; 31°44'44''N 84°36'42''W). Peanuts were grown with a minimum 3-year rotation with corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.). The peanuts were irrigated using a linear overhead irrigation system set to provide 33%, 66%, and 100% recommended irrigation. The Shellman Research Farm has Greenville type soil and 2% slope so 100% irrigation was 19 mm of water per application (Lamb, et al. 2011). The study plots were 16.5 m wide by 30.5 m long in a field with unplanted 6-m strips between test strips. Irrigation was triggered when a soil-water potential of -60 kPa was reached, with IrrigatorPro (an irrigation management software) used as a backup (Butts, Sorensen and Lamb 2020). A randomized complete block design within each irrigation treatment was used to plan cropping sequences of peanuts, cotton, and corn with conventional tillage being used to prepare the plot soil (Lamb, et al. 2011). Peanuts were planted 20 seeds/m in six rows spaced at 0.91 m. Peanuts were dug at the recommended pod maturity (Williams and Drexler 1981) using a traditional inverter. The rainfall control (no exposure) samples were collected 2-3 days after digging depending on weather, but before any rainfall occurred. Peanuts were gathered from 15 m of windrow and threshed using a small plot picker (Bucior, et al. 2025).

The simulated rainfall study was conducted for four years during the 2021-2024 peanut growing seasons. The 2021-2023 crops included all three irrigation levels. The 2024 crop pods available for mechanical testing were grown at 100% irrigation level. To simulate rainfall exposure on the windrowed peanuts an irrigation system was utilized. The 100% irrigated peanuts received 25 mm of simulated rainfall per treatment, the 66% irrigated peanuts received 17 mm, the 33% irrigated peanuts received 9 mm, and the dry land (0%) peanuts did not receive any simulated rainfall. Pods of each irrigation level were thus exposed to rainfalls at the same rate and amount as their irrigation treatments. Natural rainfall was recorded and added to the total rainfall exposure (Bucior, et al. 2025). Peanuts were gathered and threshed one week after each simulated rainfall. Rainfall simulations done during the study exposed the peanut pods at each irrigation level after being windrowed to four rainfall events. Peanut pod rainfall treatments were exposure to one rainfall (100% irrigation 25 mm, 66% irrigation 17mm, 33% irrigation 9mm of rainfall), two rainfalls (total rainfall by irrigation level respectively 50 mm, 34 mm, 18mm), three rainfalls (total rainfall by irrigation level respectively 75 mm, 51 mm, 27 mm), and four rainfalls (total rainfall by irrigation level respectively 100 mm, 68 mm, 36 mm). After each threshing, the peanuts were dried and graded. Three repetitions of each irrigation level and rainfall exposure were conducted during the study.

Peanuts were dried to below 10% w.b. moisture of the kernels using heated forced air and graded following the USDA Agricultural Marketing Service standard for farmers' stock peanuts at an Alabama Federal-State Inspection Service facility (USDA Agricultural Marketing Service 2019). The peanut pods from each year were then stored in zip lock bags in a walk-in cooler maintained at 4°C. In preparation for mechanical testing peanut pods were allowed to reach equilibrium with the laboratory temperature.

Peanut Pod Hull Rupture Force Testing

Peanut pods from each combination of irrigation level, rainfall exposure, and repetition were inspected for defects. Defect-free pods approximately 3 cm in length with a two-kernel ellipsoid shape were selected for testing (Agrawal, et al. 1973). Twenty pods from each combination of irrigation level, rainfall exposure, and available replications from the 2021-2023 harvests were selected for mechanical testing. From the 2024 harvest, 40 pods were selected for mechanical testing meeting new pod testing standards. Over the four harvest years, a total of 3,599 pods were selected for mechanical testing. A total of lo600 pods from the 2021 crop, 1200 pods from the 2022 crop, 1199 from the 2023 crop, and 600 from the 2024 crop were selected for mechanical testing.

Pod hull rupture force testing of the peanut pods was done using a Universal Testing Machine (Lloyd Instruments LD5 Dual Column Test Stand, AMETEK GB Ltd., West Sussex, United Kingdom). The Universal Testing Machine (UTM) had a load capacity of 5 kN and was equipped with a 5 kN load cell (Lloyd Instruments XLC-5000). The UTM position encoder has a resolution of 1.21×10^{-4} micron per count with tool position recorded to 0.1 µm (10^{-4} mm). The load cell accuracy is ±0.5% of reading, with force measurements recorded up to 1 mN (10^{-3} N). Two 96 mm diameter hardened steel compression plates were affixed to the UTM tool holders. Control of the UTM and data recording was done on a personal computer using the Nexygen*Plus* 4 software package (Lloyd Instruments).

The peanuts selected for testing were photographed on a contrasting background next to a photographic reference scale with a tag listing identification number and barcode. The resulting images were loaded into the ImageJ software to measure the projected area of the pod and the perimeter of the pod (Schneider, Rasband and Eliceiri 2012). Pod hull thickness at a suture for runner-type peanuts grown at Shellman Experimental Farm was measured to be 0.7 mm on average with a standard deviation of 0.11 in previous research. The previously measured average pod hull thickness was used to calculate stress to reduce experimental steps and time per pod measurement. As perimeter length and force at pod failure have greater variation in value than pod hull thickness, effect on results was expected to be minimal.

Peanut pod hull rupture force testing began with the pod identification barcode being scanned into the UTM data collection software. Pods were then placed in the center of the lower compression plate in the UTM with the suture in contact with the plate and plane of the suture perpendicular to the plate, as shown in Figure 1. The pod shape is such that most pods are stable on the plate in this orientation. Pods that were not stable were held in the orientation using two rectangular cross-section wooden dowels (7 mm x 11mm x 55 mm) on either side of the pod. All pods were taller than the dowels and mechanical tests were completed before the top compression plate contacted the dowels.

Figure 1. Peanut pod placed in position on lower compression plate for hull rupture testing.

Once the pod was in place on the lower compression plate, the pod hull rupture test sequence was initiated. The UTM crosshead lowered the top compression plate down to contact the pod. Once pod contact was detected through the loadcell, the crosshead speed was reduced to 5 mm min^{-1}. Force applied to the pod, displacement of the top plate, and strain of the pod were then recorded until the control program detected a decrease in the applied force to 80% of the maximum recorded. The drop in force to 80% of maximum was considered to occur due to rupture of the pod hull. The minimum force threshold for automatic rupture detection was set at 25 N. Strain recorded by the UTM software was produced by dividing the displacement of the crosshead after contact with the pod by the height of the pod above the lower plate at contact. The crosshead returned to its starting position after rupture detection. The pod was then removed from the lower compression plate.

Using the recorded force, suture area, and projected area, the stress in the pod hull for each pod at rupture was calculated. The stress computed using the suture area was designated the suture stress and computed using,

$$\boldsymbol{\sigma_{suture}} = \frac{\boldsymbol{F_{rupture}}}{\boldsymbol{P_{pod}} \times \boldsymbol{t_{hull}}} \qquad \text{Eq. 1}$$

where, $F_{rupture}$ is the maximum force recorded for the pod, P_{pod} is the perimeter of the pod as measured from the images, and

t_{hull} is the thickness of the pod hull at the seam. The stress computed using the projected area was designated the projected area stress,

$$\sigma_{area} = \frac{F_{rupture}}{A_{pod}} \quad \text{Eq. 2}$$

where, A_{pod} is the cross-sectional area of the pod viewed from above. From the computed stresses and recorded strain of pod hulls, the suture modulus at rupture and the projected area modulus at rupture were calculated for each pod tested using

$$Modulus = \frac{\sigma_{rupture}}{\epsilon_{rupture}} \quad \text{Eq. 3}$$

where, $\sigma_{rupture}$ is the stress at pod rupture and ϵrupture is the compressive strain of the pod measured from plate contact to rupture. Each modulus is the instantaneous modulus at the point of pod rupture.

Statistical Analysis of Pod Hull Strength

Statistical analysis of the pod hull strength results was conducted using R Statistical Software version 4.5.0 (R Core Team 2025a). Results were analyzed by fitting a linear mixed-effects model to the data using the lme4 R package version 1.1.37 (Bates, et al. 2015). Cleaning and plotting the data was done with the tidyverse R package version 2.0.0 (Wickham, et al. 2019). Model output diagnostics was performed using easystats R package version 0.7.4 (Lüdecke, et al. 2022). ANOVA tables were produced using lmerTest R package version 3.1.3 (Kuznetsova, et al. 2017). Post hoc comparisons between the treatment groups and harvest years were done using emmeans R package version 1.11.1 (Lenth, et al. 2025).

Histograms were used to investigate the distribution and magnitude of the values of the pod hull stresses and moduli. The histograms would indicate which response variable is most likely to represent the effects of the experimental treatments. The histograms will also indicate outliers and indicate if further data processing is required to eliminate distortions in the data.

The linear mixed model used in the study estimated fixed effects for irrigation treatment, exposure treatment, year, and the interaction between irrigation and exposure treatment on the log of the response variable. The response variables investigated here are suture stress and projected area stress. A random intercept term was included in the model for replication nested within harvest year. The random intercept accounts for the possibility that there is some systematic difference in the "average" peanut by repetition, due to otherwise uncontrolled environmental variation that may have existed between repetitions.

In more formal statistical notation, the model for peanut pod i in irrigation treatment j, exposure treatment k, year l, and repetition m can be written as:

$$\log y_{ijklm} = \beta_0 + \beta_{Irr,j} + \beta_{Exp,k} + \beta_{Year,l} + \beta_{Irr:Exp,jk} + \beta_{Irr:Year,jl} + \beta_{Exp:Year,kl} + \beta_{Irr:Exp:Year,jkl} + u_{lm} + \epsilon_{ijklm};\ u \sim Normal(0, \sigma_u);\ \epsilon \sim Normal(0, \sigma) \quad \text{Eq. 4}$$

The measured value for a given peanut is a function of the intercept (β_0) plus the parameters (β_{Irr}, β_{Exp}, $\beta_{Irr:Exp}$…) corresponding to the irrigation treatment, exposure treatment, year, and combinations thereof that the peanut pod is from, plus a random intercept u_{lm} for what repetition and year combination it is from, plus a residual error ϵ_{ikjlm} which is a random noise term for the individual variation that every peanut pod possesses. The random intercepts for repetitions are normally distributed, so an estimate of the σ_u parameter is used, as well as an overall σ for the model residuals.

Estimated marginal means were produced for irrigation, for exposure, and for exposure within each irrigation level using the linear mixed model excluding the secondary peak. Estimated marginal means were produced for each year separately, then averaged across years. Pairwise contrasts were taken and adjusted with the conservative Sidak multiple comparisons correction. Multiple comparison letters were generated to summarize the significant contrasts.

RESULTS AND DISCUSSION

Data Investigation

The distribution in the values of the suture stress, projected area stress, suture modulus at rupture, and projected area modulus at rupture was investigated by evaluating histograms. The peanut pod suture stress at rupture histogram shows a large primary peak centered on 1 MPa and a small secondary peak at 3.5 MPa stress, Figure 2. The projected area stress histogram also shows two peaks with a primary peak at 125 kPa and a secondary peak at 600 kPa, Figure 3.

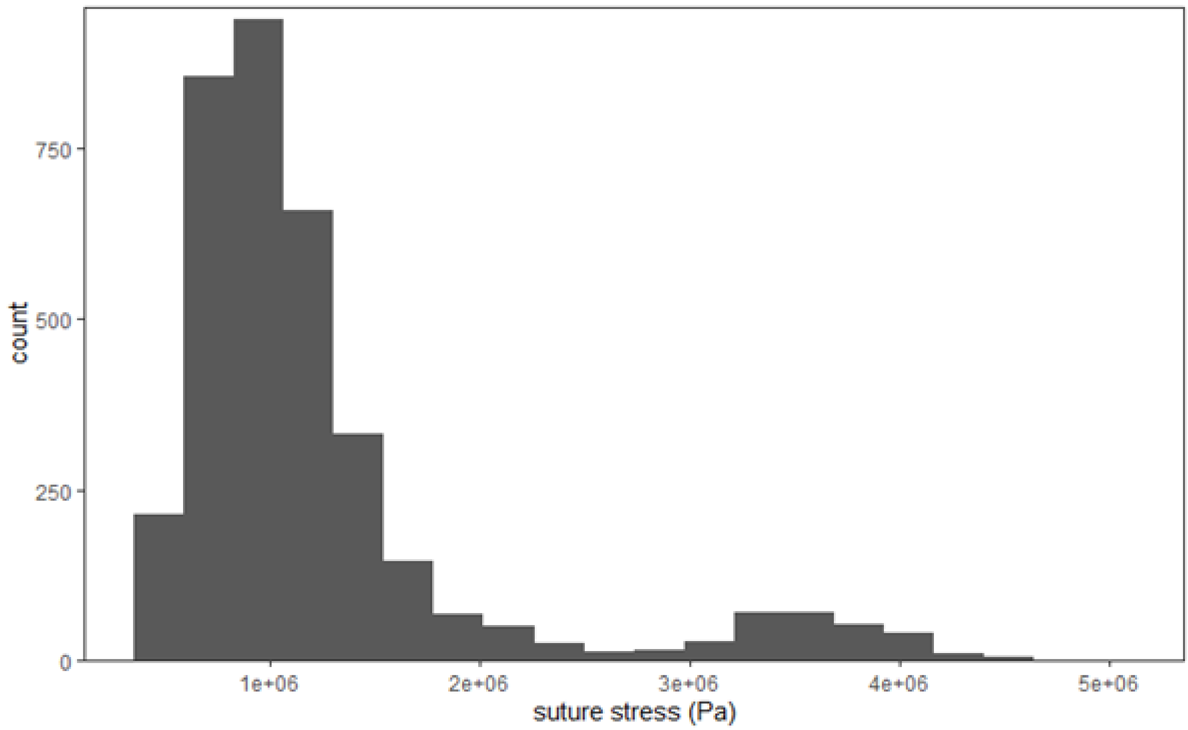

Figure 2. Histogram of pod suture stress.

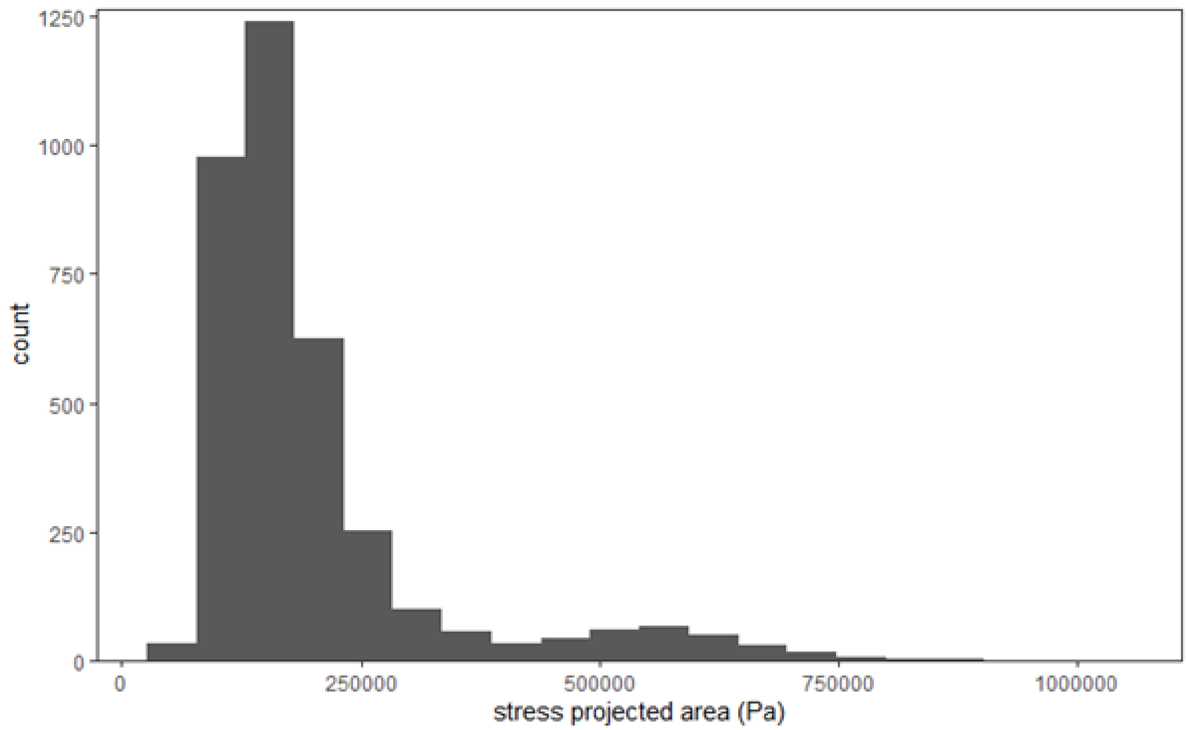

Figure 3. Histogram of projected pod area stress.

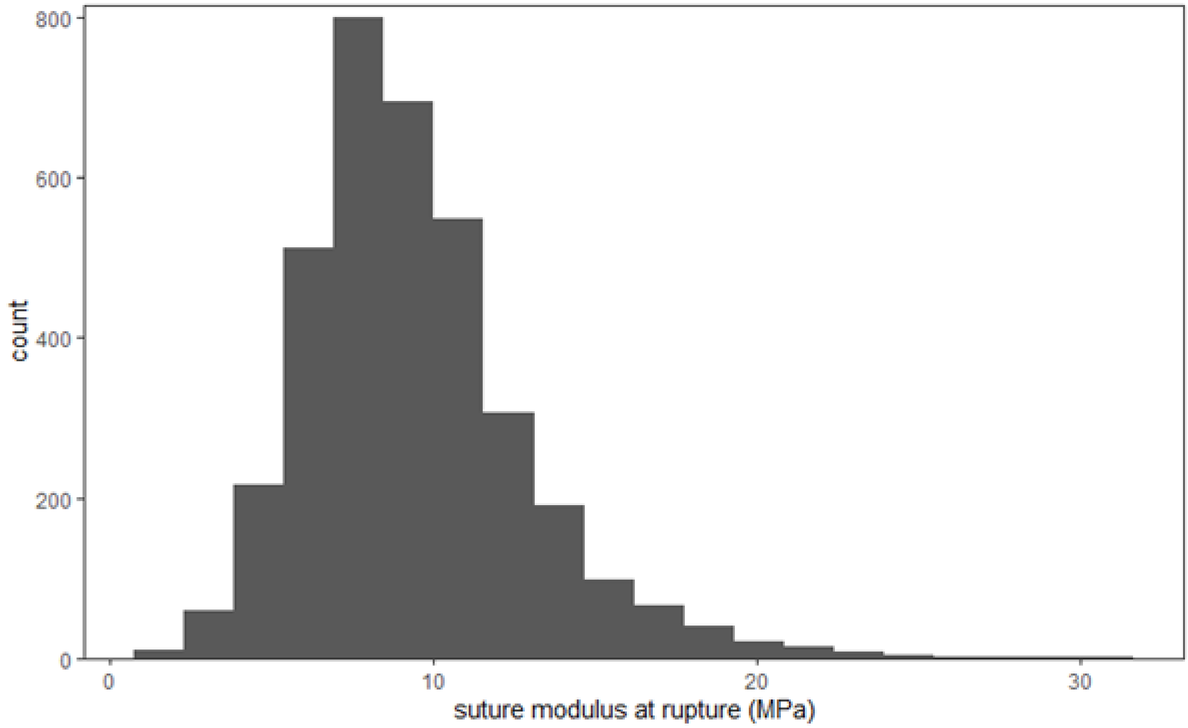

Figure 4. Histogram of suture modulus at rupture values.

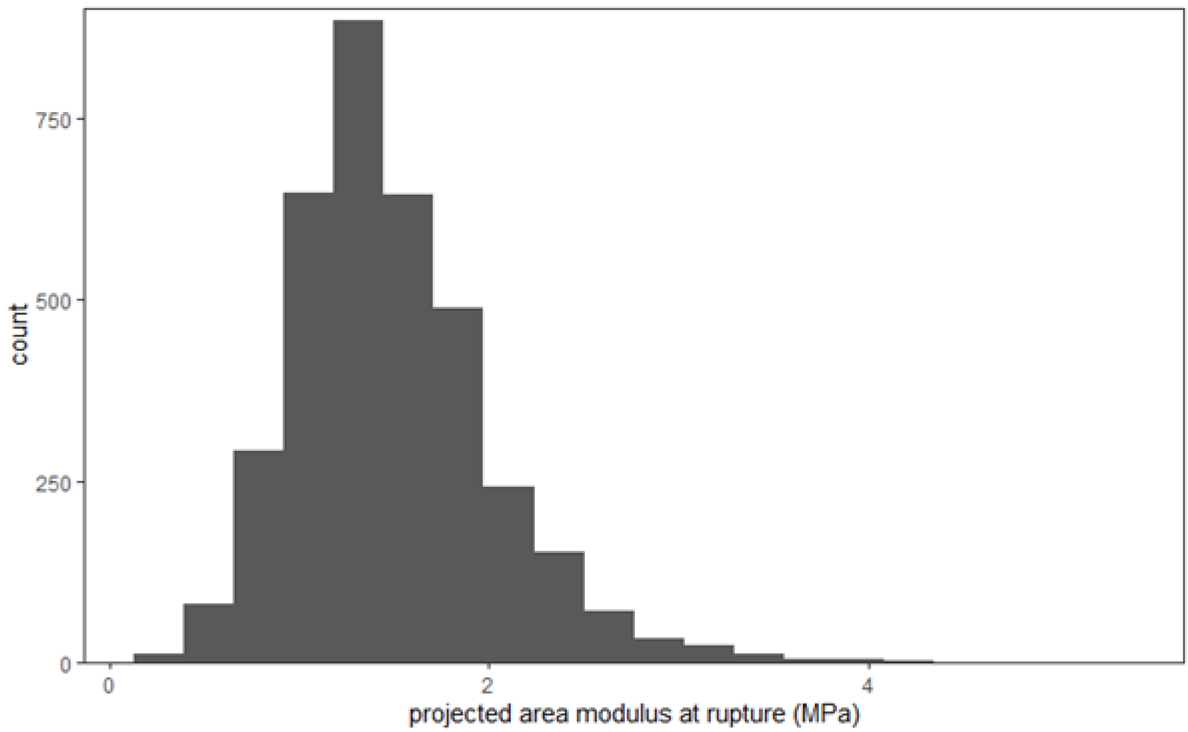

Figure 5. Histogram of projected area modulus at rupture values.

The statistical model does not account for the effect of location of load application on the pod. To gain insight into the importance of the bimodal distribution in the values of the suture stress and projected area stress, the statistical analysis was done twice. The first analysis includes all the stress data, and the second analysis removes the data points producing the second peak.

The suture stress using all the data is plotted with replicates shown as separate box plots to see whether there are any systematic differences in the replicants (reps), then with replicates combined to simplify the graph (Figure 6). Box colors in the graph legend indicate the rainfall exposure and drying treatments. Rectangular box sizes in the graph span the first to third quartiles of the data values, the whisker lines extend to encompass data values 1.5 times the inter-quartile range or distance between the first and third quartiles. Data values beyond the whiskers are given as individual points. The median of the data is shown by the line crossing the rectangular boxes (R Core Team 2025b). Figure 7 presents a box plot of suture stress data with secondary peak suture data removed.

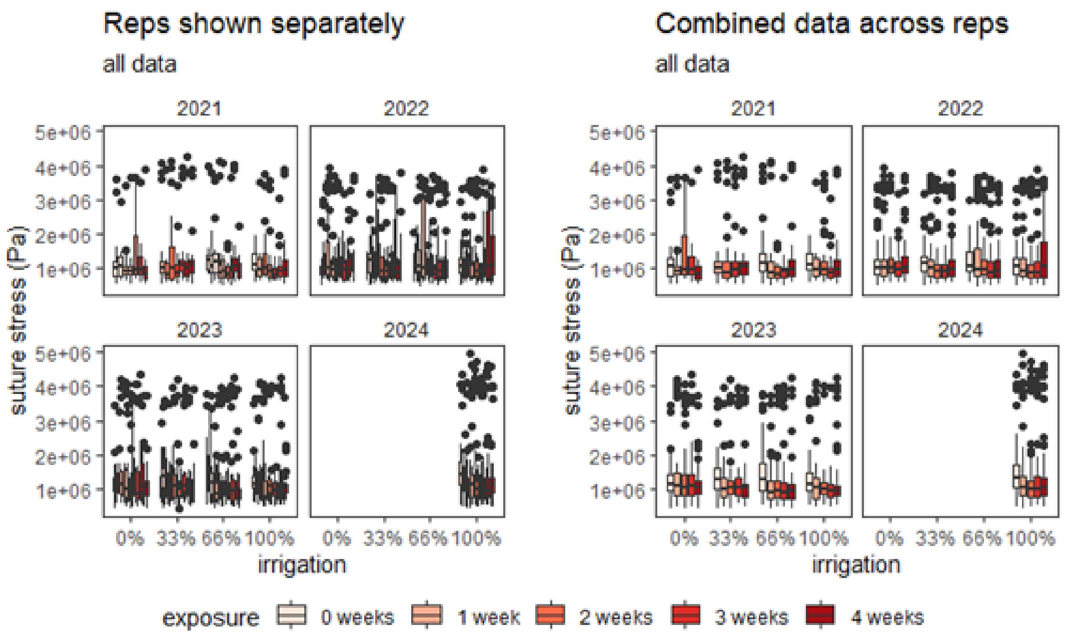

Figure 6. Box plots of all suture stress data by year, irrigation level, and rain exposure.

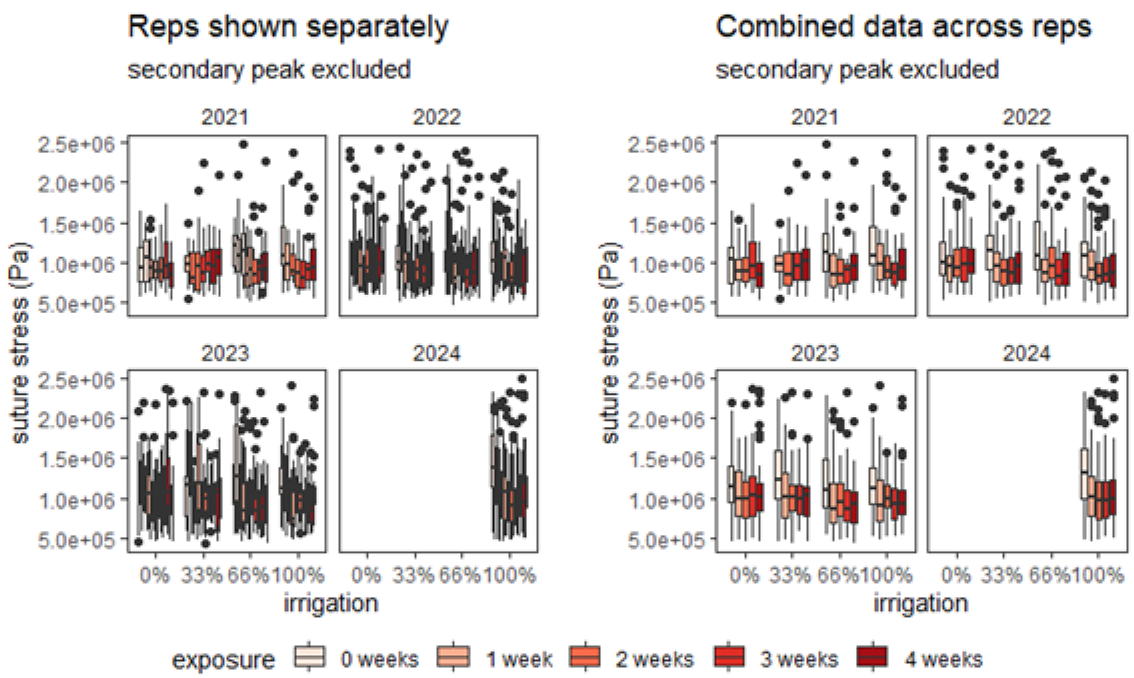

Figure 7. Box plots of suture stress data with secondary peak excluded by year, irrigation level, and rainfall exposure.

Figure 6 and Figure 7 show that there may be some effect of the treatments on pod suture stress at rupture. As rainfall exposure increases to 3 or 4 weeks, the stresses seem to slightly reduce. Slight reductions may only occur at high levels of irrigation, but the figures don't provide a definite indication. The figures indicate that there does not appear to be a systematic difference between the replications. Also, including or excluding data points with abnormally high suture stress does not materially affect results. Both the full and secondary peak excluded data will be used to fit the linear mixed models to properly account for replication effects. Data patterns are very similar for results from 2022 and 2023, so results were averaged for those years.

Linear mixed models were fitted to both the full data and the data excluding the secondary peaks. To check the accuracy of the models, diagnostic tests of the model residuals, (difference between model predictions and data) were conducted. The residual diagnostic for the model fitted to the full data indicates a relatively poor fit as the homogeneity of variance reference line is curved and tilted from the horizontal, Figure 8. The normality of the residuals plot is an S-shaped curve instead of following closely to the zero line. The divergence from the zero line also indicates a poor fit between the model and the data.

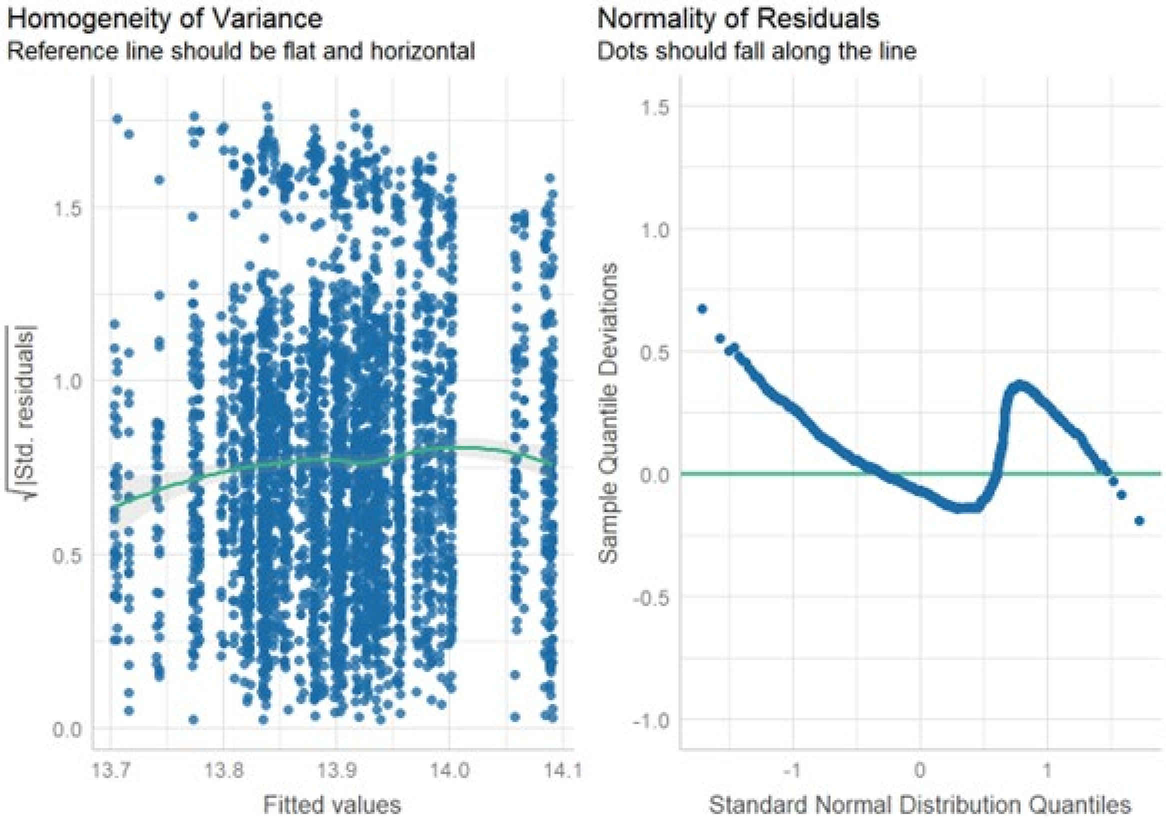

Figure 8. Residual diagnostic for linear mixed model fitted to full suture stress data.

The residual diagnostic for the model fitted to the data excluding the secondary peak shows noticeably improved model fit, Figure 9. The homogeneity of variance reference line has a flatter curve and is closer to horizontal. The normality of residuals plot is flat in the middle with curves limited to the ends and follows closely to the zero line. The diagnostics indicate that the linear mixed model with full data does not produce a valid result. The exclusion of the higher stress levels seen in secondary peak of the histograms from the data produces a linear mixed model with valid results. As the high stress outliers are a small fraction of the total stress measurements, their exclusion was not considered to have removed valid data from the model.

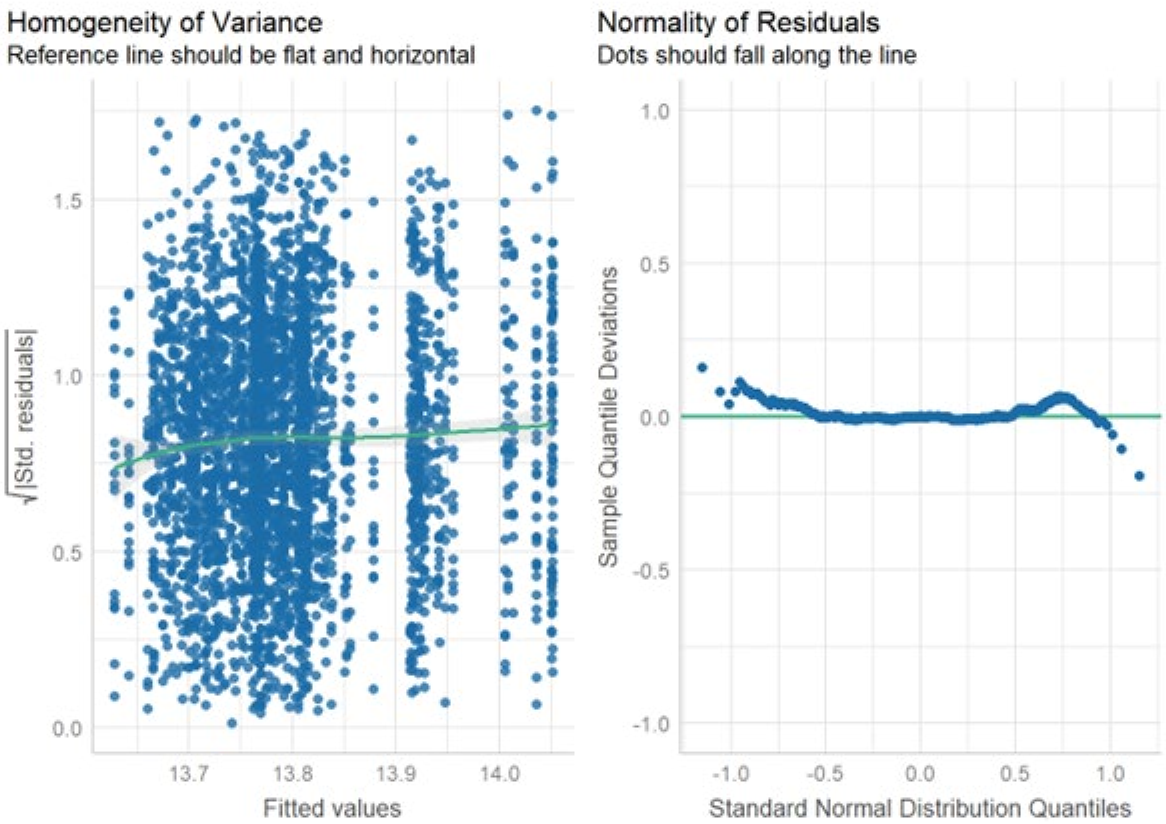

Figure 9. Residual diagnostic for linear mixed model fitted to suture stress data excluding secondary peak.

Statistical Analysis of Treatment Effects

The statistical analysis of the treatment effects on the suture stress was begun by performing an Analysis of Variance (ANOVA) test of the data, Table 1. Two of the treatments indicate statistically significant effects, p-value ≤ 0.05. The effect of rainfall exposure on suture stress at rupture was the most significant effect with an F-statistic of 34.59 and a p-value of $<10^{-6}$. Harvest year has a smaller significant effect with an F-statistic of 4.07 and a p-value of 0.043. Since the harvest year was found to have a significant effect, comparisons were made both separately by year and averaged across years. Within-year averages and the across years/overall averages were investigated to compare the magnitude and trends of the effect of harvest year on suture stress.

Table 1. Analysis of Variance (ANOVA) for suture stress versus irrigation, rainfall exposure, and harvest year. Notation A:B is interaction of treatments.

Treatments	sum of squares	mean square	numerator d.f.	denominator d.f.	F-statistic	p-value
Irrigation	0.61	0.20	3	453.92	1.95	0.121
Rainfall exposure	14.41	3.60	4	3,061.35	34.59	< 1 × 10-6
Harvest year	1.28	0.43	3	9.23	4.07	0.043
Irrigation: Rainfall exposure	2.10	0.17	12	3,128.16	1.68	0.065
Irrigation: Harvest year	0.94	0.16	6	650.92	1.51	0.174
Rainfall exposure: Harvest year	0.82	0.07	12	3,153.98	0.66	0.793
Irrigation: Rainfall exposure: Harvest year	1.57	0.07	23	3,155.91	0.66	0.890

The yearly estimated marginal means for irrigation and rainfall exposure are given in Table 2. When compared across all rainfall exposures, the amount of irrigation did not indicate any significant differences in suture stress at rupture. When the effect of rainfall exposure was compared across all irrigation treatments, a significant difference was seen in suture stress at rupture between no rainfall exposure and the first rainfall exposure. The suture stress at rupture decreases by over 100 kPa with one rainfall exposure. Subsequent rainfall exposures, however, do not significantly affect the suture stress at rupture.

Table 2. Effects of Irrigation Level and Rainfall Exposure on pod suture stress at rupture by year.

Year	Irrigation Level	Suture Stress at Rupture (Pa)[a]		Rainfall Exposure	Suture Stress at Rupture (Pa)[b]	
2021	0%	918,700	a	0	1,060,000	a
	33%	945,500	a	1	923,600	b
	66%	932,600	a	2	915,000	b
	100%	974,200	a	3	917,800	b
				4	930,700	b
2022	0%	988,100	a	0	1,077,000	a
	33%	954,700	a	1	934,800	b
	66%	951,900	a	2	924,200	b
	100%	926,400	a	3	916,800	b
				4	931,200	b
2023	0%	1,015,000	ab	0	1,141,000	a
	33%	1,023,000	a	1	959,100	b
	66%	947,600	b	2	963,100	b
	100%	974,700	ab	3	951,900	b
				4	946,500	b
2024	0%	—		0	1,258,000	a
	33%	—		1	985,800	b
	66%	—		2	949,700	b
	100%	1,020,000	a	3	946,600	b
				4	991,100	b

[a] Suture stress at rupture averaged across all rainfall exposures. Means followed by the same letter within same year are not significantly different at α=0.05.
[b] Suture stress at rupture averaged across irrigation levels. Means within the same year followed by the same letter are not significantly different at α=0.05.

The effect of irrigation level on suture stress at rupture is shown over the four years of the study in Figure 10. Irrigation level changes do not show a consistent effect on pod suture stress at rupture over the harvest years of the study. Pods harvested in 2021 show an increase in the mean suture stress with irrigation amount with large overlaps in the confidence intervals. Pods harvested in 2022 indicate a decrease in mean suture stress with irrigation level. Irrigation level changes are related to statistically significant differences in suture stress for just one harvest year, 2023. The pods grown with 66% of the recommended irrigation level have reduced maximum suture stress at rupture. The 95% confidence bars of all irrigation levels show significant overlap. During the 2024 harvest year, the irrigation level was 100% for all pods with a mean pod suture stress similar to the high value of suture stress observed during harvest year 2023 at the 33% irrigation level. When averaged over all the harvest years, a slight decrease in the mean pod suture stress is seen with increasing irrigation level but not at a statistically significant level.

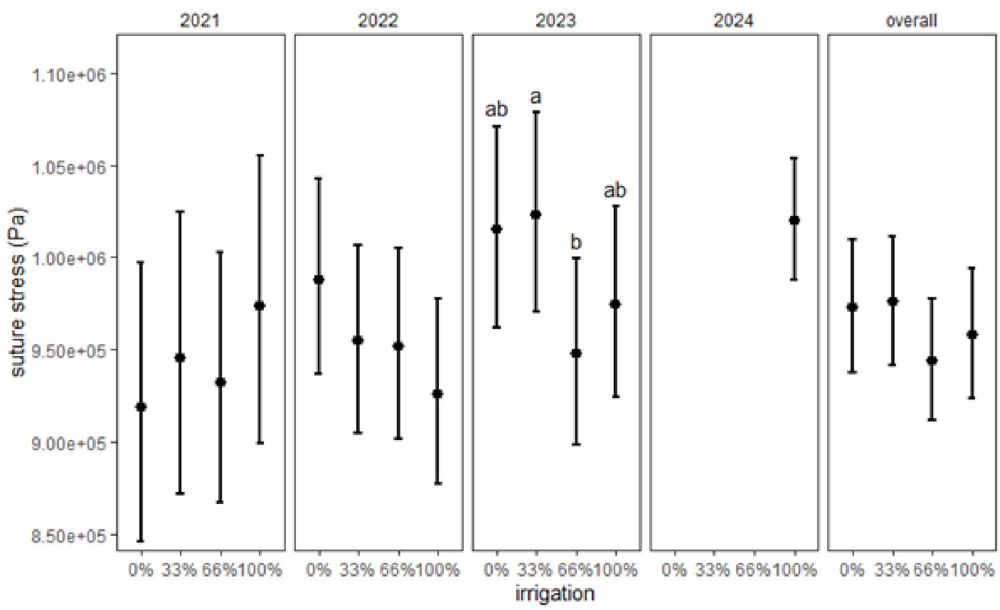

Figure 10. Effect of Irrigation Level on Pod Suture Stress at Rupture. Secondary peak excluded. Significance letter labels for single year only. If no letter above bar results are statistically similar.

The effect of rainfall exposure on the pod suture stress at rupture with all irrigation levels included and the secondary peak data excluded shows pronounced and statistically significant decrease in suture stress at rupture between pods that have not been exposed to rainfall and those that were exposed to rainfall Figure 11. The average suture stress needed to rupture the pods shows a statistically significant decrease in suture stress at rupture after the first rainfall exposure of 137 kPa in the 2021 harvest year, 143 kPa in the 2022 harvest year, 182 kPa in the 2023 harvest year. The 100% irrigated pods for the 2024 harvest year indicate the largest decrease at first rainfall exposure of 273 kPa. The overall average for all years shows a decrease of 156 kPa. All harvest years and the overall average do not show a statistically significant decrease in suture stress at rupture with further rainfall exposure. The reduction in pod hull strength occurs for the first rainfall exposure but not subsequent rainfall exposures. Peanut producers should schedule digging peanuts to avoid rainfall exposure to pods before harvesting with a combine to maintain pod hull strength and maintain crop value. The reduction in pod hull strength corresponds to the increase in loose shelled kernels that factor into grade quality of peanuts as reported by Bucior et al., (2025). The mechanism by which rainfall exposure reduces the pod hull strength will be the subject of future research.

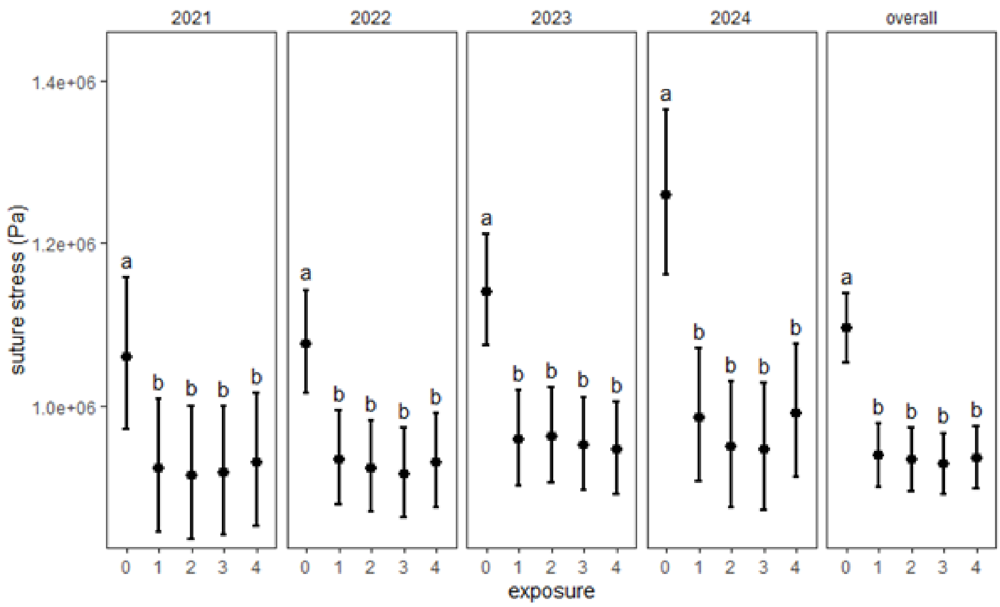

Figure 11. Effect of Rainfall Exposure on Pod Suture Stress at Rupture. Secondary peak data excluded. Significance letter labels for single year only.

When the interaction between the effects of irrigation level and rainfall exposure on pod suture stress at rupture was plotted, the effects were minor for 0% irrigation or dryland peanuts Figure 12. In harvest year 2021, significant differences in suture stress occur for the 66% irrigation level pods after the first rainfall exposure. In harvest year 2022, significant decreases in suture stress occurred after the first rainfall exposure for the 33% and 66% irrigation levels. In harvest year 2023, there was a significant decrease in suture stress after the first rainfall. Suture stress decreased for pods from the 2023 harvest year that were not exposed to rainfall from the 33% irrigation level as irrigation increases to 100%, though not by a statistically significant amount, Figure 12. When data from all the harvest years are analyzed together, a statistically significant decrease in suture stress at rupture occurs for the 33%, 66%, and 100% irrigation level pods. The average suture stress decreases with rainfall exposure for the 0% irrigation pods but not a statistically significant difference for years 2021, 2022, 2023, and overall. The combined trend is that the zero-exposure pod hull strength increases from 0% to 33% irrigation then decreases as irrigation is increased. The amount of decrease in suture stress that occurs at first rainfall exposure is reduced as irrigation is increased from 33% to 100%. Pods produced with 100% recommended irrigation would still be susceptible to significant pod hull strength degradation as the suture stress at rupture is reduced by 127 kPa after the first rainfall exposure. Reduced integrity pods will be more prone to shelling during transport and processing, leading to increased LSK. Increased LSK at grading would lead to subsequent value loss (USDA Agricultural Marketing Service 2019). A statistical analysis of the relationship between an in LSK and pod hull strength will be the subject of a future investigation.

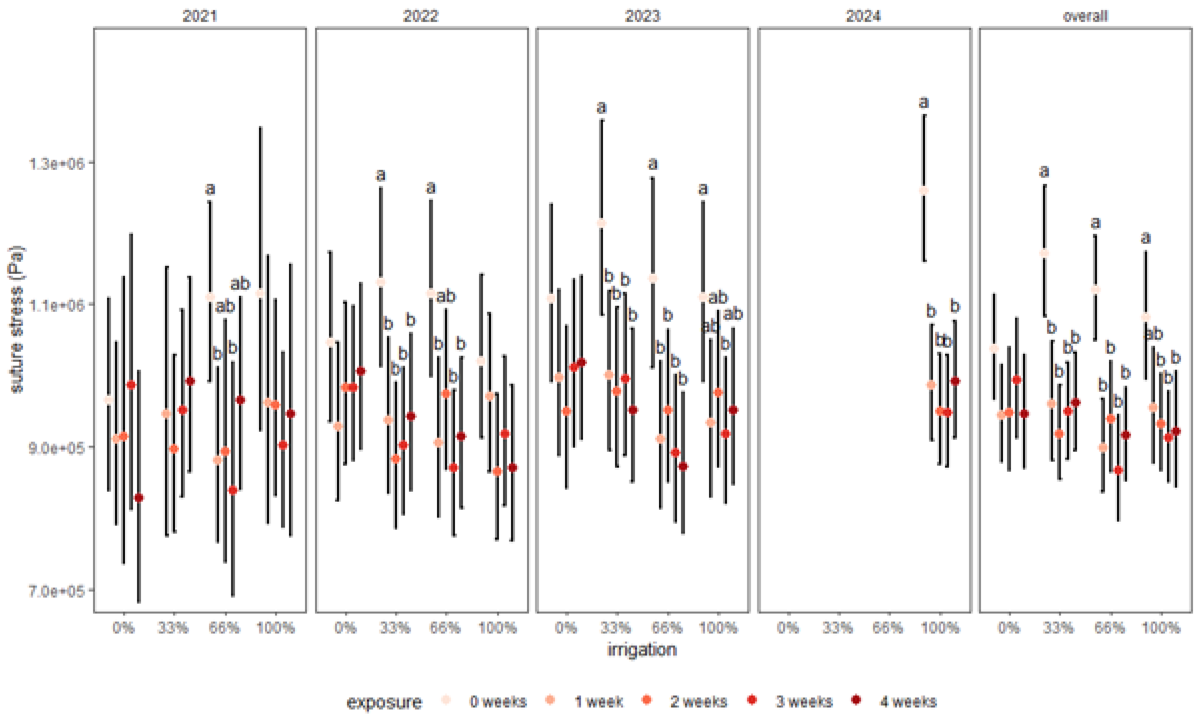

Figure 12. Effect of Irrigation Level and Rainfall Exposure on Pod Suture Stress at Rupture. Secondary peak data excluded. Significance letter labels for single year and irrigation level only. If no letter above bar results are statistically similar.

The results of this investigation showed that suture stress at rupture of peanut pods exposed to rainfall while in windrows decreases significantly at the first rainfall exposure but not for subsequent rainfall events. The significant loss of pod hull strength from exposure to a single rainfall that dried quickly enough that no degradation of the pods is observed was unexpected. The decrease in pod hull strength correlates with the increase in the number of LSK found when grading the peanuts and a decrease in harvest yield reported in Bucior, et al. (2025) versus pods that have not been exposed to rainfall. Peanut producers should schedule peanut digging when rainfall is not expected before harvest to maintain pod hull strength. If peanuts are exposed to rainfall while inverted in windrows, handling the peanuts before shelling should be minimized to reduce the likelihood of generating loose-shelled kernels.

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LITERATURE CITED

Agrawal K.K., B.L. Clary, and E.W. Schroeder. 1973. Mathematical Models of Peanut Pod Geometry. Trans. ASAE. 16 (2): 315-319. doi:10.13031/2013.37510.

Aydin C. 2007. Some engineering properties of peanut and kernel. J. Food Eng. 79: 810-816. doi:10.1016/j.jfoodeng.2006.02.045.

Bagheri I., S.H. Payman, and F. Rahimi-Ajdad. 2011. Mechanical behavior of peanut kernel under compression loading as a function of moisture contents. Elixir Agriculture (Elixir) 26: 3552-3557.

Bates D., M. Maechler, B Bolker, and S. Walker. 2015. Fitting Linear Mixed-Effects Models Using lme4. J. Statistical Software. 67 (1): 1-48. doi:10.18637/jss.v067.i01.

Bucior E.R., R.B. Sorensen, M.C. Lamb, C.L. Butts, and H.K. Abbas. 2025. Peanut Yield and Grade Response to Multiple Simulated Rainfall Events Following Inverting. J. of Sustainable Agric. and Env. 4: (e70043): 1-7. doi:10.1002/sae2.70043.

Butts C.L., R.B. Sorensen, and M.C. Lamb. 2020. Irrigatorpro: Progression of a Peanut Irrigation Scheduling Decision Support System. Applied Eng. in Agric. 36 (5): 785-795. doi: 10.13031/aea.13909.

Ince A., S. Ugurluay, E. Güzel, and M.T. Özcan. 2009. Mechanical Behavior of Hulled Peanut and Its Kernel During the Shelling Process. The Philippine Agricultural Scientist. 92 (1): 92-99.

Israel G.B., Kunta S., Mlelwa W., A. Harel, K. Gupta, Y. Levy, S. Galili, and R. Hovav. 2024. Genetic characterization and mapping of the shell strength trait in peanut. BMC Plant Biol. 24 (1047): 1-13. doi:10.1186/s12870-024-05727-9.

Kerr T.J., R. Benner, J.H. Woodward, W.E. Rigsby, and W.R. Windham. 1986. Chemical Composition and In-vitro Digestibility of Biologically Degraded Peanut Hulls. J. Sci. of Food and Agricul. 37 (7): 637-651. doi:10.1002/jsfa.2740370707.

Kuznetsova A., P.B. Brockhoff, and R.H.B. Christensen. 2017. Package: Tests in Linear Mixed Effects Models. J. Statistical Software. 82 (13): 1-26. doi:10.18637/jss.v082.i13.

Lamb M., R. Sorensen, R.C. Nuti, C.L. Butts, W.H. Faircloth, D. Eigenberg, and D. L. Rowland. 2011. Agronomic and Economic Effect of Irrigation Rate in Corn Produced in Georgia. Crop Mngmnt. 10 (1): 1-8. doi:10.1094/CM-2011-0721-02-RS.

Lenth R.V., J. Piaskowski, B. Banfai, B. Bolker, P. Buerkner, I. Giné-Vázquez, M. Hervé, M. Jung, J. Love, F. Miguez, H. Riebl, and H. Singmann. 2025. emmeans: Estimated Marginal Means, aka Least-Squares Means. CRAN. doi:10.32614/CRAN.package.emmeans.

Lüdecke D., D. Makowski, M.S. Ben-Shachar, I. Patil, B.M. Wiernik, E. Bacher, and R. Thériault. 2022. easystats: Framework for Easy Statistical Modeling, Visualization, and Reporting. CRAN. doi:10.32614/CRAN.package.easystats.

R Core Team. 2025a. R: A Language and Environment for Statistical Computing. Manual. Vienna: R Foundation for Statistical Computing. https://www.R-project.org/.

R Core Team. 2025b. Rdocumentation. https://www.rdocumentation.org/packages/ggplot2/versions/3.5.2/topics/geom_boxplot.

Schneider C.A., W.S. Rasband, and K.W. Eliceiri. 2012. NIH Image to ImageJ: 25 years of image analysis. Nature Methods. 9 (7): 671-675. doi:10.1038/nmeth.2089.

USDA Agricultural Marketing Service. 2019. Farmers' Stock Peanut Inspection Instructions. Vers. July 2019. Accessed 2025. https://www.ams.usda.gov/grades-standards/farmers-stock-peanut-inspection-instructions.

Wickham H., M. Averick, J. Bryan, W. Chang, L. D'Agostino McGowan, R. François, G. Grolemund, et al. 2019. Welcome to the tidyverse. J. Open Source Software. 4 (43): 1686. doi:10.21105/joss.01686.

Williams E.J., and J.S. Drexler. 1981. A Non-Destructive Method for Determining Peanut Pod Maturity. Peanut Sci. 8 (2): 134-141. doi:10.3146/i0095-3679-8-2-15.

Young J.H. 1977. Simulation of Peanut Drying in Inverted Windrows. Trans. ASAE. 20 (4): 782-784. doi:10.13031/2013.35648.

Young J.H., N.K. Person, J.O. Donald, and W.D. Mayfield. 1982. Harvesting, Curing and Energy Utilization. Chap. 12. pp. 458-485 in H.E. Pattee and C.T. Young (eds.), Peanut Science and Technology, Am. Peanut Res. and Educ. Soc. https://apresinc.com/images/2015/12/PST-Chapter-12.pdf.