BIOMECHANICS OF BIOENERGY *SORGHUM*

[*Sorghum bicolor* (L.) MOENCH]

A Thesis

by

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ABSTRACT

Stem lodging is a complex and is a limiting factor on bioenergy sorghum yield worldwide. Stem lodging is defined as mechanical failure at the stem caused by external forces due to wind or rain. Current lodging ratings are frequently unreliable because various factors that cause lodging and there is uncertainty about which factors are responsible. Temporal and spatial unpredictability has also hindered progress on the systematic research on this issue. As a result, stem lodging resistance is considered as one of the highest priorities for a bioenergy sorghum breeding program. In this study, a three-point bending (3PBT) test was used to quantify the biomechanical properties of bioenergy sorghum with different lodging ratings. The 3PBT was able to detect significant statistical differences among genotypes and within their stems. Significant genetic effect and variability was identified for a group of 15 bioenergy sorghum genotypes that may allow to identify quantitative trait loci (QTL) related to these geometric, shape, and biomechanical properties toward applying marker assisted recurrent selection (MAS). Geometry, shape, and biomechanical properties are influenced by maturity and developmental stages of a growing sorghum plant. Plant height, internode length, volume and flexural stiffness are particular important traits that that may serve to select for lodging resistance in plants. Future studies should focus on composition, rind thickness and computerized tomography (CT) scan in sorghum stems to develop a better model of the sorghum stem. This will allow sorghum breeders to select for important traits that infer lodging resistance in a bioenergy sorghum breeding program to improve germplasm with lodging resistance characteristics.

DEDICATION

This thesis is dedicated to Maria and Francisco, my parents, who supported me in every way possible and gave me the freedom and joy of understanding the world; to my sister Maria for her guidance; to Alicia my partner in life in the vastness of space and immensity of time, it is my joy to share a planet and an epoch with you; with gratitude, admiration and love.

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NOMENCLATURE

N	Newton [kg ms^{-2}] (1 Newton = 1 kg ms^{-2})
3PBT	Three point bending test
MPa	Mega Pascal
E	Young's Modulus of Elasticity [MPa]
I	Axial second moment of an area of a cross section [m^4]
σ_{max}	Strength [MPa]
E*I	Flexural Stiffness or rigidity [N m^2]
CS	College Station, TX
CSE	College Station Early, TX
CSL	College Station Late, TX
WE	Weslaco, TX
PI	Photoperiod insensitive
MPS	Moderate photoperiod sensitive
PS	Photoperiod sensitive
TAMU	Texas A&M University

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CHAPTER I

INTRODUCTION TO PLANT BIOMECHANICS

Nature uses only the longest threads to weave her patterns, so that each small piece of her fabric reveals the organization of the entire tapestry.

Richard P. Feynman

Plants in the environment are subjected to mechanical factors like gravity, wind, water flow, and friction, changes in temperature, pressure, and humidity. Plant biomechanics measures the mechanical response of plants and their building blocks to these mechanical factors and in reverse plant biomechanics explains how mechanical factors influence growth and development of plants (Rusin and Kojs 2011).

Biomechanics play a critical role in cereal agriculture, as standability is a required agronomic trait (Farquhar, Zhou and Wood 2002). A common phenomena limiting yield in most cereal crops is "lodging". Lodging, is defined as plants uprooting, breaking, or otherwise mechanically deforming from the ground due to the effect of wind, rain, or hail on their stems and leaves (K. J. Niklas 1992). Thus, it can either occur through stem lodging or displacement of the roots within the soil (Berry, Spink, et al. 2003). As a result stem lodging resistance in tall high biomass bioenergy sorghum [*Sorghum bicolor (*L.*)* Moench] is considered as one of the highest priorities in a bioenergy sorghum breeding program.

Through the incidence of lodging in cereal crops, several methods have been developed to select for lodging resistance, perhaps the most valuable of these has been genetic improvement of lodging resistance through plant breeding. However, many of these efforts have been focused in grain sorghum and very few in bioenergy sorghum. As a result, relatively little information is known about the plant characters which confer stem lodging resistance in bioenergy sorghum.

Two studies were designed to use a biomechanical approach to identify traits which are important to improve our understanding of lodging in sorghum, so that sorghum breeders may have better criteria in selecting lodging resistant germplasm. The first study addressed the problem by applying a three-point bending test (3PBT) to determine the effect of genotype on the biomechanical properties within a selected group of sorghum genotypes, while relating them to other important traits. The second study applied the same 3PBT to determine the effect of genotype and environment, maturity on the biomechanical properties of a diverse set of bioenergy sorghum genotypes from the TAMU Sorghum Breeding Program.

CHAPTER II
LITERATURE REVIEW ON PLANT BIOMECHANICS

'Physics-envy is the curse of biology'

Joel Cohen

Plant Biomechanics can be defined as the study of the structures and functions of biological systems from the phylum *Plantae* by making use of concepts and methods from mechanics (Moulia 2013). Thus, the sorghum plant may be studied from a biomechanical perspective which can extend our fundamental understanding of the plants adaptation to its physical environment and address problems such as lodging.

Lodging is a common problem in most cereals including wheat (*Triticum aestivaum*), barley (*Hordeum vulgare*), oats (*Avena sativa*; (Mulder 1954); (Pinthus 1973), corn (*Zea mays*); (Minami and Ujihara 1991), and sorghum (*Sorghum bicolor*); (Larson 1977, Worley, et al. 1991). Lodging is a term agronomist use to describe uprooting, breaking, or other forms of mechanical deformation causing stems to fail (K. J. Niklas 1992). Lodging can result either from buckling of any part of the stem (stem-lodging) or failure of the root soil anchorage system (root-lodging) (Berry, Sterlinger and Mooney 2006).

Stem lodging results from weak stalks which are either genetically inherited or caused by biotic and abiotic factors including pathogens, insects, and externally applied mechanical forces that exceed the load capacity of the stems (Pinthus 1973) (K. J. Niklas 1992) (Flint-Garcia, et al. 2003). A limiting factor decreasing yield in the C_4 bioenergy grass sweet sorghum [*Sorghum bicolor* (L.) Moench] is stem lodging, therefore the primary breeding objective for sorghum energy breeders is to diminish stem lodging (Rooney, Blumenthal, et al. 2007).

Lodging in sorghum has been addressed mostly in grain types through the deployment of dwarfing genes to reduce both lodging and ease of mechanical harvesting (Quinby 1974). Selection on traits such as stalk rot resistance, increased stem diameter, and thicker rind were improved to reduce stem lodging (Sleper and Poehlman 2006). However, bioenergy sorghums are tall and most hybrids are photoperiod sensitive. Photoperiod sensitivity in sorghum indirectly affects plant height. The longer the plants remain vegetative the more nodes and leaves it produces thus increasing plant height. There is an inherent assumption that tall plants lodge more often and that increased stem diameter increases strength. Regardless, of the vast research to minimize lodging in grain sorghum few studies have addressed the link between geometry, shape, and biomechanical properties in order to minimize the likelihood of stem lodging in tall bioenergy sorghum.

Ultimately, lodging can be characterized by the biomechanical forces required to cause stem failure. These biomechanical factors play a critical role in grain crops and good stem lodging resistance is a desirable agronomic trait (Farquhar, Zhou and Wood 2002). A review by (Foulkes, et al. 2011) stated that increasing lodging resistance was an important component toward increasing yield in wheat, but to do so, plant breeders must increase stem diameter and material strength of the stem, at the same time as reducing the width of the stem wall. Plants are composite materials composed of heterogeneous materials, which are greatly influenced by their geometry and shape. (K. J. Niklas 1992) described mechanical stability as a function of the material properties of tissues and the geometry of plant organs, and is defined by the environment and by the loadings applied to plant stems. Therefore, the design factor of a plant is dependent on the likelihood of it undergoing several types of loadings, as well as the frequency of their duration and magnitude (K. J. Niklas 1992). Knowledge is increasing regarding the importance of biomechanical properties and the effect of geometry of individual organs of herbaceous plant stems on lodging (K. J. Niklas 1992) (Spatz, Kohler and Speck 1998) (Niklas and Speck 2001) (Moulia, Coutan and Lenne 2006) (Niklas and Spatz 2012). But, little to no studies have addressed the link between material properties of sorghum and their geometry.

Current stem lodging ratings strongly depend on the environmental conditions for evaluations. Since environments are highly variable, selection is often impossible or ineffective (Thompson 1963) (Hu, Liu, et al. 2013). As a consequence, several methods to measure stalk strength in cereal crops have been developed in hope of identifying an effective system to select for stem lodging resistance (Zuber and Grogan 1961). For example, stalk crushing strength was measured to select for stronger stalks in maize (*Zea mays* spp. *mays* L.) (Zuber and Grogan 1961). Another approach, the rind penetrometer (RPR) collects data on the force required for a spike to penetrate the stalk rind and has been used in genome wide selection studies (GWAS) and quantitative trait loci (QTL) mapping in maize (Peiffer, et al. 2013) (Hu, Meng, et al. 2012). Pederson and Toy (1999) did not detect a relationship between RPR and lodging in sorghum, thus concluding that RPR scores were not reliable predictors of lodging resistance (Pedersen and Toy 1999). Another method used in plant biomechanics to explore the mechanical properties of plant specimens, or segments thereof, is a three-point bending test (3PBT) (Niklas and Spatz 2012).

In most cases in grass stems nodes are stronger at the nodes than internodes (K. J. Niklas 1989) (Robertson, et al. 2015). This results in most stem failures occurring at the internode just above the restraining node. Stem lodging in bioenergy sorghum has been observed to occur more frequently around internodes three to six usually just above the node. This is similar to maize where observations have concluded that the fourth internode is more susceptible to lodging (Hu, Liu, et al. 2013).

Sorghum stem tissues are biologically active and react to both genotype and environmental factors which can change their material properties as they age or as a function of their immediate physiological condition (i.e. hydrated tissues) (K. J. Niklas 1992). Simple solid material, whose properties are unaffected by geometry, are very different than those of a composite material (i.e., a sorghum stem) and are profoundly influenced by geometry (K. J. Niklas 1992). This is because the materials within the sorghum stem influence the material properties of the composite as a whole. Thus, it is critical when addressing the materials properties of a sorghum stem to refer to the geometry of that stem (i.e., shape and size of the stem or stem section).

Stem lodging depends on the complex interactions between the mechanical properties of the stems, geometry, shape, development, and maturation. Accordingly, it is the material properties, geometry, shape, development and maturity of the plant stem that contribute to their mechanical behavior and dynamic loadings (K. J. Niklas 1992). Therefore, dissecting biomechanical, geometric, and shape at the weakest section of the sorghum stem (internode 3 to 6) may help us understand important characteristics that may aid in our goal to minimize stem lodging.

The present studies in sorghum were undertaken to apply a biomechanical approach to determine the mechanical properties of stems and how this may influence lodging tendencies. The first objective of this research was to assess the value of the 3PBT to detect variation for biomechanical properties among genotypes. The second objective of this study was to compare the bending moment on nodes and internodes to determine which stem part is more resistant to bending. The third objective was to associate these traits with stem lodging resistance to allow more effective selection against stem failure. Finally, the fourth of objective was to assess relative genetic, genotype x environment, and maturity effects. This study aims to improve understanding of lodging resistance in bioenergy sorghum and formulate recommendations on selection criteria which will be useful in breeding programs engaged in the improvement of lodging resistance research.

CHAPTER III

ELUCIDATING FACTORS INFLUENCING STEM LODGING IN ENERGY SORGHUM

Introduction & Literature Review

Minimizing stem lodging in the C_4 bioenergy grass sweet sorghum [*Sorghum bicolor* (L.) Moench] is a primary breeding objective (Rooney, Blumenthal, et al. 2007) (Mullet, et al. 2014) (Worley, et al. 1991). Stem lodging is the biomechanical failure and permanent displacement of the stem, and it results from genetically weak stalks or from biotic and abiotic factors including pathogens, insects, and externally applied mechanical forces that exceed the load capacity of the stems (Pinthus 1973) (K. J. Niklas 1992) (Flint-Garcia, et al. 2003). An example of genetically weaker stems are the brown midrib mutants which reduce lignin concentration and increase stem lodging. *Macrophomina phaseolina* and *Fusarium moniliforme sensu lato* are common fungal pathogens that cause stalk rot, thus reducing the strength of the stalk and increasing susceptibility to lodging (Tuinstra, et al. 2002) (W. L. Rooney 2000) (Frederiksen 2000). Insect pests that increase stalk stem lodging in sorghum in the U.S. include the sugarcane borer (*Diatraea saccarilis* Fabricius), neotropical borer (*Diatraea lineolatus* Walker), southwestern corn borer (*Diatraea grandiosella* Dyar), and the Mexican rice borer (*Eoreuma loftini* Dyar) (Teetes and Pendleton 2000). Increased conditions of high plant populations (close spacing) as well as high fertility, often lead to taller, thinner stems, which are more susceptible to stalk lodging (Worley, et al. 1991).

Ultimately, stem lodging can be characterized by the biomechanical forces required to cause stem failure. These biomechanical factors play a critical role in grain crops and good stem lodging resistance is a desirable agronomic trait (Farquhar, Zhou and Wood 2002). A review by (Foulkes, et al. 2011) stated that increasing lodging resistance was an important component toward increasing yield in wheat, but to do so, plant breeders must increase stem diameter and material strength of the stem, at the same time as reducing the width of the stem wall. Plant are composite materials composed of heterogeneous materials, which are greatly influenced by their geometry and shape. Niklas (1992) described mechanical stability as a function of the material properties of tissues and the geometry of plant organs, and is defined by the environment and by the loadings applied to plant stems. Therefore, the design factor of a plant is dependent on the likelihood of it undergoing several types of loadings, as well as the frequency of their duration and magnitude (K. J. Niklas 1992). Knowledge is increasing regarding the importance of biomechanical properties and the effect of geometry of individual organs of herbaceous plant stems on lodging (K. J. Niklas 1992) (Spatz, Kohler and Speck 1998) (Niklas and Speck 2001) (Moulia, Coutan and Lenne 2006) (Niklas and Spatz 2012). But, little to no studies have addressed the link between material properties of sorghum and their geometry.

Current stem lodging ratings strongly depend on the environmental conditions for evaluations. Since environments are highly variable, selection is often impossible or ineffective (Thompson 1963) (Hu, Liu, et al. 2013). As a consequence, several methods to measure stalk strength in cereal crops have been developed in hope of identifying an effective system to select for stem lodging resistance (Zuber and Grogan 1961). For example, stalk crushing strength was measured to select for stronger stalks in maize (*Zea mays* spp. *mays* L.) (Zuber and Grogan 1961). Another approach, the rind penetrometer (RPR) collects data on the force required for a spike to penetrate the stalk rind and has been used in genome wide selection studies (GWAS) and quantitative trait loci (QTL) mapping in maize (Peiffer, et al. 2013) (Hu, Meng, et al. 2012). Pederson and Toy (1999) did not detect a relationship between RPR and lodging in sorghum, thus concluding that RPR scores were not reliable predictors of lodging resistance. Another method used in plant biomechanics to explore the mechanical properties of plant specimens, or segments thereof, is a three-point bending test (3PBT) (Niklas and Spatz 2012).

The 3PBT determines the plants biomechanical properties under compression as plant stems are both heterogeneous and highly anisotropic material, therefore the bending should be applied for compressive failure of the stem subjected to loads causing bending (Schulgasser and Witztum 1997). In maize, (Hu, Liu, et al. 2013) used 3PBT to identify morphological traits associated with stem strength. (Robertson, et al. 2014) in maize used 3PBT and found a higher bending moment when load was applied at the node rather than the internode of the stem. Bashford in 1976 used an Instron Testing Machine with a two-point beam in grain sorghum and found that the biomechanical properties of lodging resistant types were generally shorter and stockier than more lodging susceptible types (Bashford 1976).

The focus of this research is to apply a biomechanical approach to determine the mechanical properties of stems and how this may influence lodging tendencies. The first objective of this research is to assess the value of the 3PBT to detect variation for biomechanical properties among genotypes. The second objective of this study is to compare the bending moment on nodes and internodes to determine which organ is more resistant to bending. The third objective is to associate these traits that with stem lodging resistance to allow more effective selection against stem failure.

Materials and Methods

Plant Materials

Six sorghum genotypes were selected based on previous reports of lodging, maturity, and other phenotypic characteristics. These selected genotypes were of similar maturity and were known for differences in their tendency to lodge with a plant height >2.5 m. (Table 1).

Table 1. Sorghum genotypes used in this study and grown at Weslaco Texas during the 2013 season.

	Genotype	Lodging Rating (1-9)[/1]	Stem Characteristics	Utilization	Cultivar Type
1	R.09109	7	Juicy	Biofuel	Line
2	Rio	5	Juicy	Biofuel	Line
3	M81E	5	Juicy	Sweet	Line
4	EJX 7285	7	Juicy	Biofuel	Hybrid
5	EJX 7J906	1	Juicy	Biofuel	Hybrid
6	EJX 7J907	1	Juicy	Biofuel	Hybrid

/1 Lodging rating: 1=Lodging resistant 5=moderate lodging 9=Susceptible

Experimental Design and Field Management

Seed was planted in February 12, 2013 at Weslaco, TX (WE) in a randomized complete block design with four replications. Standard sorghum agronomic practices from the Texas A&M Sorghum Breeding Program were used including irrigation as needed to maintain normal growth and development. Seed was planted in 40-inch rows (101cm) apart with a plot length of 17 ft. (5.2m). Seedlings in each plot were thinned 3-5’’ inches apart (7-13 cm). The soil type where the experiment was conducted is Ships clay loam.

Data Collection and Analysis

Because this location is planted when day lengths are less than twelve hours, all genotypes flowered in May. All phenotypic data were collected ~147 days after planting and all entries were in the hard dough stage of maturity (GS8 of the sorghum growth stage scale) (Vanderlip 1993). At harvest, four random plants in the middle of the plot were cut at the base, tagged, bundled and immediately phenotyped using several plant architecture, geometric, shape, and biomechanical parameters (Table 2).

Morphological and Anatomical Measurements

All leaves and leaf sheaths were removed from each stem. The number of internodes (No. of Internodes) was counted starting at the first internode above the ground to the last internode below the peduncle. Plant height was measured as the length (cm) of the plant from the base of the plant to the tip of the panicle. Internode length (cm) was measured as the distance between nodes from the base of the plant to the top. Internode diameter (mm) was measured at the center of each internode using a digital caliper. Internode volume (ml) was measured by submerging an internode in a cylinder and measuring the water displacement (Table 2).

Table 2. Trait description measured in six bioenergy sorghum genotypes at Weslaco Texas during the 2013 season.

	Variable	Type of Variable	Description
1	No. of internodes/plant	Architecture	Total number of internodes from the ground to below peduncle
2	Plant height (PHT)	Geometry	Plant height was measured as the length of the plant from the base to the tip of the panicle (cm)
3	Internode length	Geometry	Internode length was measured from node to node using a ruler (cm)
4	Internode diameter	Geometry	Internode diameter was measured using a digital caliper at the center of each internode (cm)
5	B1	Physical	Bending distance of internode/dual internode before fracture occurs (mm) using a digital caliper
6	F1	Physical	Force recorded at internode/dual internode B1 (N) before fracture using a force gauge with a cylinder attached
7	B2	Physical	Bending distance of internode/dual internode after fracture occurs (mm) using a digital caliper
8	F2	Physical	Force recorded at internode/dual internode at B2 (N) using a force gauge with a cylinder attached

Three-point Bending Test

The 3PBT was engineered (Figure 1) to measure the loading force (measured in Newton's, *N*) required to bend *B* (in millimeters, mm) and fracture individual sorghum internodes.

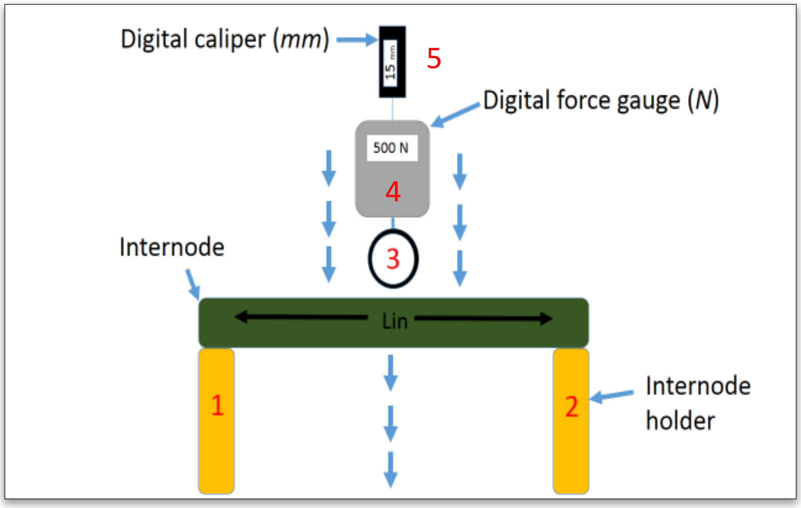


Figure 1. Schematic view of the three-point bending device (3PBT) used to load sorghum stems consists of: (1) and (2) are the two adjustable vertical supports to hold stem samples; (3) is the central point that applies force in the center of the two supports; (4) is the digital force gauge used to measure force applied to stem at each interval;, and (5) is a modified digital caliper above the force gauge that measures distance traveled by the bending stem.

The 3PBT device consists of five identifiable parts (Fig. 1). Plant stem samples were loaded so that the central point (force gauge) will be above the center of the span of each individual sample. At the third central point a force gauge (MARK-10 ®) recorded the force (F) and a modified digital caliper measured the bending displacement (B). The 3PBT was used to estimate four parameters. The F1 parameter is the force required to bend but not damage or fracture the stem sample at B1. The B1 parameter is the distance (mm) traveled without damaging the structural integrity of the stem sample. Similarly, the F2 parameter is the force required to fracture the stem at B2. The B2 parameter is the distance (mm) traveled to break stem. Stem fracture was defined when the stem fails upon the third central loading point. Under 3PBT, the maximum stress (tension and compression) is located at the surface while the center experiences zero tensile and compression bending stresses (Muliana 2015).

Figure 2. Two different loading configuration on a three-point bending device: (a) loading at individual internode, and (b) loading at the node.

The 3PBT was performed under two different loading configurations (Fig. 2). For each genotype, two plants were cut at individual internodes to measure the biomechanical properties individual internodes. The other two plants were at every other internode leaving a node in between two internodes and the 3PBT was applied at the node.

Stem Shape and Geometrical Parameters

After harvest, data was collected and bending tests were performed. These data were used to estimate geometric and biomechanical properties for each sample.

Slenderness Ratio- λ

Shape of each sampled whole plant stem an individual internodes was measured in terms of the slenderness ratio as follows:

$$\text{Slenderness Ratio} \qquad \lambda = \frac{L}{D} \qquad [3.1]$$

where L is the total length of the plant, or the total length of each internode, and *D* is an average diameter of the plant or internode (Table 2). The slenderness ratio is a dimensionless parameter that represents the aspect ratio between the length and the average cross section. In our case, the length refers to either the whole plant stem or the internode stem section under study. Plants with a high slenderness ratio are easily bent or deformed compared to the ones with low a slenderness ratio (stocky plants).

Second Moment of an Area- I

The second moment of an area (I) is a geometric property that quantifies the distribution of an area in each cross section with respect to the centroid of the cross section. I is the integral of the product of each elemental cross-sectional area and the square of the distance of each elemental cross-sectional area from the centroid axis (K. J. Niklas 1992). Assuming the sorghum stalk has a solid circular cross-section of diameter D (or radius r), the second moment of an area is given by the formula:

Second Moment of an Area $$I = \frac{\pi D^4}{64} \qquad [3.2]$$

where π = 3.1416, and *D* is the diameter of the stem.

E-Young's Elastic Modulus- E

The Young's elastic modulus *E*, (also known as the elastic modulus *E*), is measured in MPa and is the proportionality constant that relates normal stress to normal strain throughout the linear elastic range of the behavior of a material (K. J. Niklas 1992). It is a measure of material stiffness. For a slender bar under a 3PBT, *E* is calculated using the Euler-Bernoulli beam model (Muliana 2015), as represented in the following formula:

E-Young's Elastic Modulus $$E = \frac{\frac{F1 {L_{in}}^3}{48I}}{B1} \qquad [3.3]$$

where B1 is the first deflection before an internode breaks measured in millimeters (mm). F1 is the first force before internode breaks measured Newton (N), and L_{in} is the internode length (mm). I is the second moment of an area described in equation (3.2).

Strength- σ_{max}

Stem strength measured in MPa is the load (breaking load) or limit of the stem to withstand stresses that will cause the stem to fail (K. J. Niklas 1992). It is calculated as:

Strength $$\sigma_{max} = \frac{\frac{(F2)L_{in}}{4}}{I} * \frac{D}{2} \qquad [3.4]$$

where F2 is the final F at failure at the sorghum stem either internode or node. L_{in} is internode length (cm), D is internode diameter (mm), and I is second moment of an area.

Flexural Stiffness- EI

Flexural stiffness or flexural rigidity symbolized as EI measures the ability of a stem to resist bending. It is calculated in Nm^2 as:

$$\text{Flexural Stiffness} \quad E * I \qquad [3.5]$$

where E is E-Young's modulus and I is second moment of an area.

Data analysis

All data was subjected to outlier analysis using the jackknife technique available from JMP® Pro 11.1 (SAS Institute, 2013) and obvious outliers were removed from the data set. Missing observations were estimated using the Restriction Maximum Likelihood (REML) method, and the estimated values were imputed in the missing data cells. Biomechanical traits were log-transformed to meet normality assumption.

General Linear Models and Analysis of Variance

Cleaned data was analyzed using General Linear Mixed Models available from JMP®Pro 11.1 (SAS Institute, 2013). Several general linear models were constructed to obtain the best estimate of error and to test for significant effects. In all models, replicates were considered random and all other sources of variation were considered fixed. Least square means (LSMeans) were estimated using REML method and were compared using Tukey-Kramer Honest Significant Differences (HSD) method at (α=0.05).

Model 1 was fitted to the whole plant traits as a function of genotypes and replication as follows:

$$\text{Model 1} \quad y_{ij} = \mu + \beta_i + \tau_j + \epsilon_{ij} \qquad [3.6]$$

where

y_{ij} = any response of j^{th} genotype from the i^{th} replication
μ = overall mean of the experiment
β_i = random effect due to the i^{th} replication
τ_j = fixed effect due to the j^{th} sorghum genotype
ϵ_{ij} = random error term

with the assumptions of

$\beta_i \sim$ NI random distributed $(0, \sigma_i^2)$; where $i = 1 \ldots 4$

$\sum_{1}^{j} \tau_j = 0$; where $j = 1 \ldots 6$

$\varepsilon_{ij} \sim$ NI random distributed $(0, \sigma_{ij}^2)$;

Model 2 fitted geometrical, shape, and biomechanical properties as a function of genotypes, internode-node position within the plant and replicates.

Model 2 $$y_{ijk(j)} = \mu + \beta_i + \tau_j + \gamma(\tau)_{k(j)} + \varepsilon_{ikj(k)} \qquad [3.7]$$

where

y_{ijk}	=	any response of k[th] internode (node) No. from the j[th] genotype and the i[th] replication
μ	=	overall mean of the experiment
β_i	=	random effect due to the i[th] replication
τ_j	=	fixed effect due to the j[th] sorghum genotype
$\gamma(\tau)_{k(j)}$	=	fixed effect of the k[th] internode (node) No. within the j[th] sorghum genotype
ϵ_{ijkj}	=	random error term

with the assumptions of

β_i	~	NI random distributed $(0, \sigma_i^2)$;	where	i = 1… 4
$\sum_1^j \tau_j$	=	0;	where	j = 1… 6
$\sum_1^j \sum_1^k \gamma(\tau)_{k(j)}$	=	0;	where	k = 1 …n
ϵ_{ijk}	~	NI random distributed $(0, \sigma_{ijk}^2)$		

Model 3fitted geometrical, shape, and biomechanical properties as a function of internode-node position within the plant and replicates by each individual genotype in order to understand the interaction effect ($\gamma(\tau)_{k(j)}$).

Model 3 $$y_{ij} = \mu + \beta_i + \tau_j + \epsilon_{ij} \qquad [3.8]$$

where

y_{ij}	=	the response of j[th] internode from the i[th] replication
μ	=	the overall mean of the experiment
β_i	=	the random effect due to the i[th] replication
τ_j	=	fixed effect due to the j[th] internode # (Internode-Node)
ϵ_{ij}	=	an random error term

with the assumptions of

β_i	~	NI random distributed $(0, \sigma_i^2)$;	where	i = 1… 4
$\sum_1^j \tau_j$	=	0;	where	j = 1… n
ϵ_{ij}	~	NI random distributed$(0, \sigma_{ij}^2)$		

Correlations

Pair-wise Pearson Product-Moment correlation were estimated among all traits to measure the strength of the linear relationship between variables. The JMP® Pro 11.1 (SAS Institute, 2013) multivariate platform was used for this task.

Results

Whole Plant Architecture, and Geometry

Model 1-ANOVA for all traits analyzed were highly significant (P<0.0001) (Table 3). The model fit for plant height was high (r^2 = 0.71) and moderate for plant diameter, plant slenderness ratio and No. of Internodes/plant.

Table 3. Model 1-ANOVA for whole plant architecture and geometry traits in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

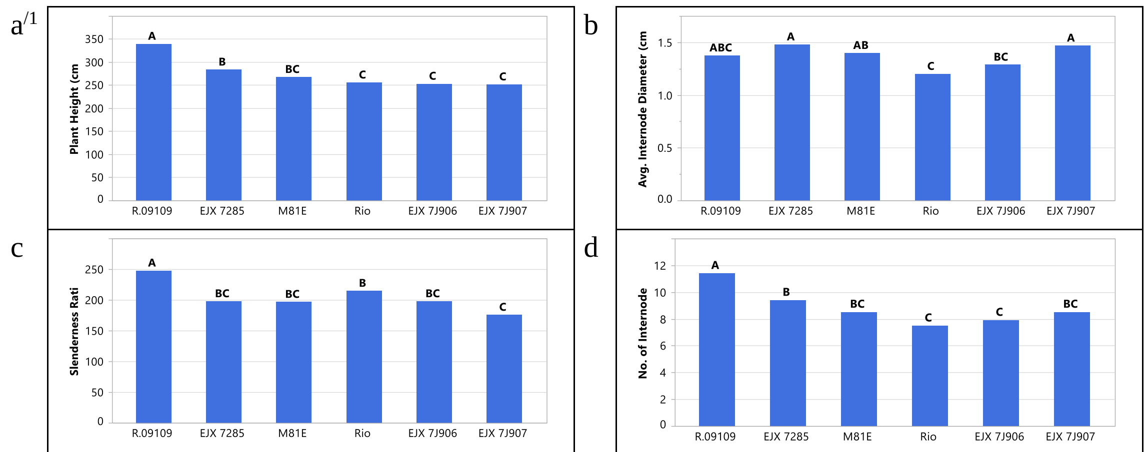
Source of variation	DF	Plant Height	Avg. Plant Diameter	Plant Slenderness Ratio	No. of Internodes / Plant
Model	8	<0.0001[/1]	<0.0001	<0.0001	<0.0001
Replicate	3	0.3102	<0.0001	0.0064	0.0015
Genotype	5	<0.0001	<0.0001	<0.0001	<0.0001
Error	87				
C. Total	95				
RSquare (R^2)		0.71	0.40	0.45	0.53
CV %		7.43	12.92	13.85	15.61

/1: P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

Table 4. LSMeans for whole plant architecture and geometry traits in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Genotypes	Lodging Rating[1]	Plant Height	Avg. Plant Diameter	Plant Slenderness Ratio	No. of Internodes / Plant
	(1-9)	cm	cm		n°/plant
R.09109	7	340 A[2]	1.38 ABC	248 A	11.4 A
EJX 7285	7	284 B	1.48 A	198 BC	9.4 B
M81E	5	268 BC	1.40 AB	197 BC	8.6 BC
Rio	5	256 C	1.20 C	215 B	7.5 C
EJX 7J906	1	253 C	1.29 BC	198 BC	7.9 C
EJX 7J907	1	252 C	1.47 A	176 C	8.6 BC
Average		276	1.37	205	8.9

/1 Lodging rating: 1: Lodging resistant; 5: Moderate Lodging; 7: Lodging Susceptible.
/2 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.



/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.

Figure 3. LSMeans for whole plant architecture and geometry traits a) plant height, b) average stem diameter, c) slenderness ratio, d) no. internodes/plant in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Average Internode Architecture, Shape, and Geometry

Model 2-ANOVA for all traits under study were highly significant ($P<0.0001$) (Table 5). Internode length has the best fit overall ($r^2=0.79$) and the rest of the variables showed a range of r^2's from 0.60 to 0.70, explaining a large portion of the variation for these properties. The CV (%) for all traits ranged from 12-19%, indicating very good precision in data collection. The significant effect of Internode No. within genotype indicates that these energy sorghum genotypes showed that individual internode position within the plant had an effect on the architecture, shape, and geometry parameters and may account for differences observed in biomechanical properties which can lead to differences in stem lodging.

Table 5. Model 2-ANOVA for individual internode architecture and geometry traits in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Sources of Variation	DF	Internode Length	Internode Diameter	Internode Volume	Internode Slenderness Ratio
Model	72	<.0001[/1]	<.0001	<.0001	<.0001
Replicate	3	<.0001	<.0001	<.0001	<.0001
Genotype	5	<.0001	<.0001	<.0001	<.0001
Internode Number (Genotype)	64	<.0001	<.0001	<.0001	<.0001
Error	791	.	.	.	.
C. Total	863	.	.	.	.
RSquare		0.79	0.60	0.69	0.70
CV%		11.78	13.66	17.38	18.89

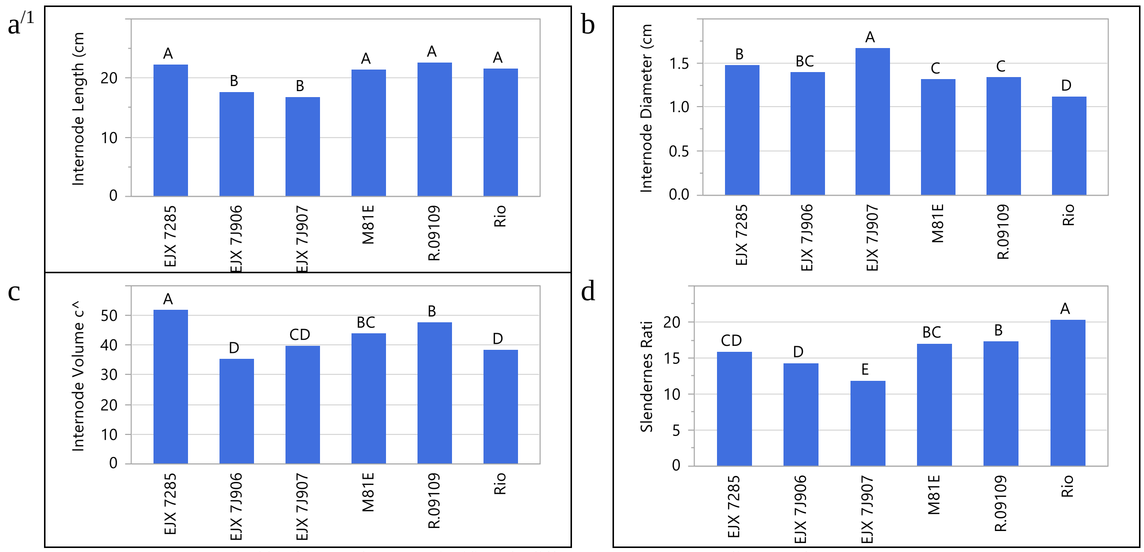
/1: P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant

Rio had the highest slenderness ratio, while EJX 7907 had the lowest (Table 6 and Fig. 5 a, b, d). The lodging resistant genotypes EJX J7906 and EJX 7J907 had the shortest internode length than any other genotypes (Table 6, Fig. 5 a)

Table 6. LSMeans and Tukey's HSD at (α= 0.05) for the average internode length, diameter, volume, and slenderness ratio of six bioenergy sorghum genotypes used in this study grown in Weslaco TX 2013.

Genotypes	Lodging rating[/1]	Internode Length	Internode Diameter	Internode Volume	Internode Slenderness Ratio
	(1-9)	cm	cm	cm^3	
R.09109	7	22.59 A[/2]	1.34 C	47.73 B	17.34 B
EJX7285	7	22.26 A	1.48 B	51.67 A	15.89 CD
M81E	5	21.38 A	1.31 C	43.90 BC	16.99 BC
Rio	5	21.68 A	1.13 D	38.28 D	20.25 A
EJX7J906	1	17.65 B	1.39 BC	35.14 D	14.32 D
EJX7J907	1	16.82 B	1.67 A	39.65 CD	11.89 E
Average		20.40	1.39	42.73	16.11

/1 Lodging rating: 1: Lodging resistant; 5: Moderate Lodging; 7: Lodging Susceptible
/2 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.



/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.

Figure 4. LSMeans and Tukey's HSD at (α= 0.05) for a) average internode length, b) average internode diameter, c) average internode volume, and d) slenderness ratio of individual internode of six bioenergy sorghum genotypes used in this study grown in Weslaco TX 2013.

Average Internode Biomechanical Properties

The effect of genotype and internode No. within genotype were all highly significant ($P<0.0001$), and the model fit was low to moderate for all biomechanical properties variables (Table 7-8 and Fig. 6).

Rio and M81E had significantly stronger stems than the other genotypes (Table 8, Fig. 6 b. E-Young's Modulus LSMeans were very similar among genotypes. EJX7907 showed lower E-Young's modulus than the other genotypes (Table 8, Fig. 6 a). Flexural stiffness LSMean was the highest in the genotype EJX 7285, which tends to lodge more often (Table 8, Fig. 6 c).

Table 7. Model 2-ANOVA for two biomechanical properties and one geometrical property in six bioenergy sorghum genotypes evaluated at Weslaco during the 2013 season.

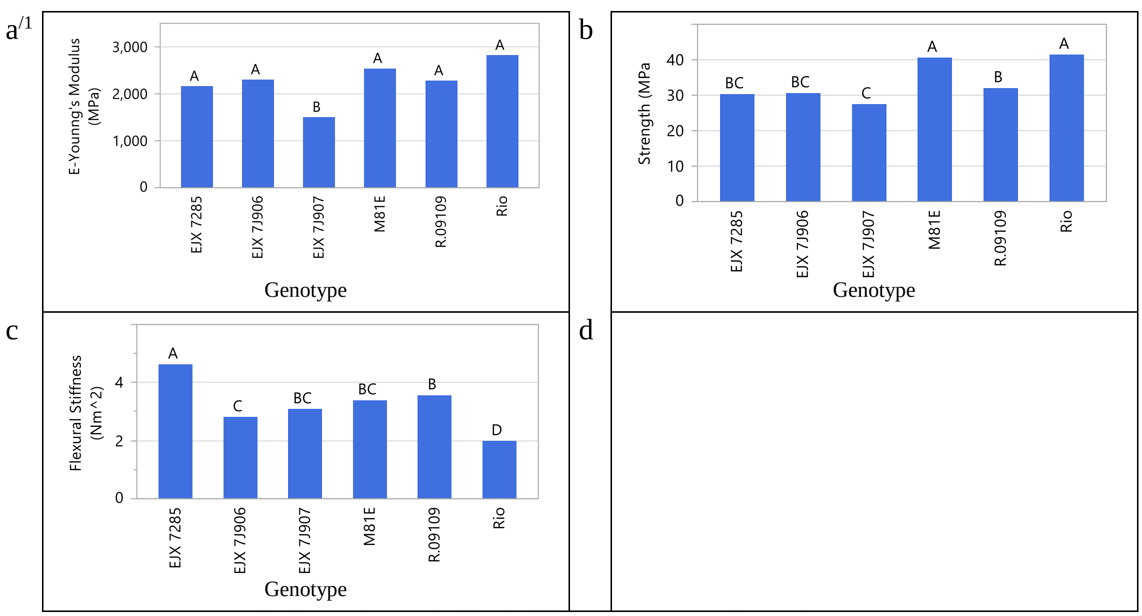
	E-Young's Module		Strength		Flexural Stiffness	
Source	DF	Prob > F	DF	Prob > F	DF	Prob > F
Model	61	<.0001[/1]	62	<.0001	61	<.0001
Replicate	3	<.0001	3	<.0001	3	<.0001
Genotype	5	<.0001	5	<.0001	5	<.0001
Internode #[Genotype]	53	<.0001	54	<.0001	53	<.0001
Error	781	.	782	.	781	.
C. Total	842	.	844	.	842	.
RSquare		0.42		0.31		0.63
CV(%)		8.60		11.50		36.60

/1: P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant

Table 8. LSMeans and Tukey's HSD at alpha = 0.05, for two biomechanical properties and one geometrical property in six bioenergy sorghum genotypes evaluated at Weslaco during the 2013 season.

	Lodging rating[/2]	E-Young's Module		Strength		Flexural Stiffness	
Genotype	(1-9)	MPa		MPa		Nm2	
R.09109	7[2]	2,530	A[/1]	31.95	B	3.57	B
EJX7285	7	2,303	A	30.28	BC	4.63	A
M81E	5	2,271	A	40.70	A	3.40	BC
Rio	5	2,828	A	41.29	A	2.00	D
EJX7J906	1	2,161	A	30.51	BC	2.80	C
EJX7J907	1	1,500	B	27.56	C	3.10	BC
Average		2,266		33.72		3.25	

/1 Genotypes not connected by same letter are significantly different according to Tukey's HSD at alpha=0.05.
/2 Lodging rating: 1: Lodging resistant; 5: Moderate Lodging; 7: Lodging Susceptible



/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.

Figure 5. LSMeans and Tukey's HSD at (α = 0.05), for two biomechanical and one identity a) E-Young's modulus, b) strength, c) flexural stiffness in six bioenergy sorghum genotypes evaluated at Weslaco during the 2013 season.

Individual Internode Architecture, Shape, and Geometry

Model 3-ANOVA showed a high fit (r^2) for all traits (Table 9). The CV (%) ranged from (6.8% to 26.8%), indicating good precision for most of the collected data for each trait in this experiment.

For each genotypes, internodes were longer and more uniform in the middle of the stem (Table 10, Fig.7), specifically, internodes 3 to 6, Lower internodes were significantly shorter (Table 10, Fig. 7). As is typical in sorghum, the bottom first internodes were thicker than internodes higher up the plant decrease slightly in diameter (Table 11, Fig. 8). The longer internode length in the middle of the stem resulted in a greater internode slenderness ratio for internodes 3 to 6 compared to lower internodes (Table 13, Fig. 10). Internode volume (cm^3) for individual internodes tended to be greater in these positions as well (Table 12, Fig.9).

Table 9. Model 3-ANOVA for four traits in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

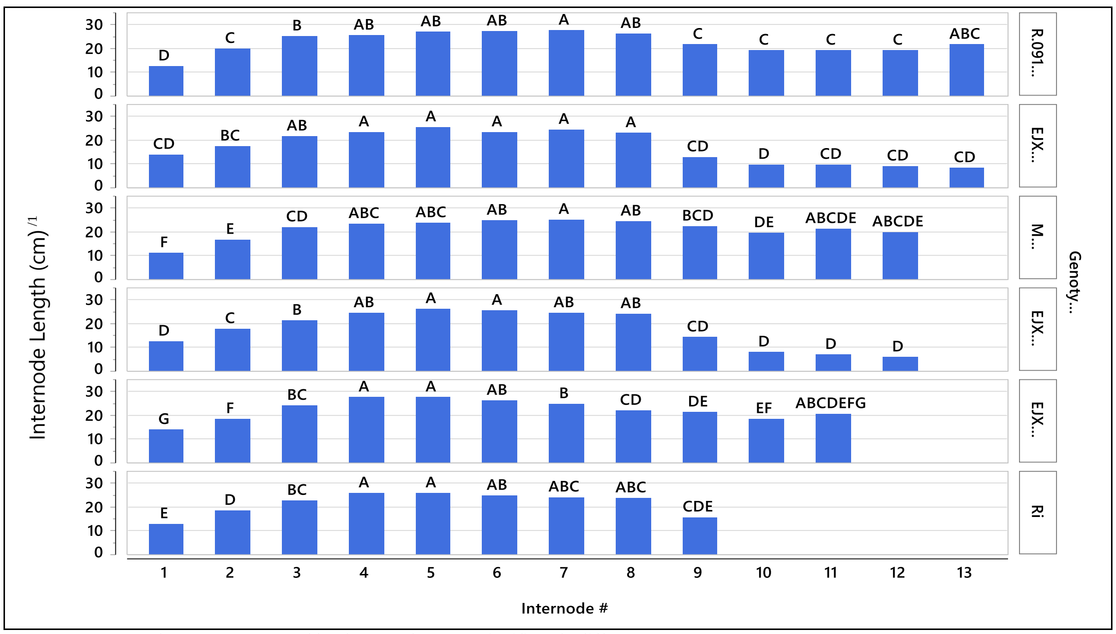
		Genotype											
		EJX 7285		EJX 7J906		EJX 7J907		M81E		R.09109		Rio	
Trait	Source	DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F
Length (cm)	Model	13	<.0001[/1]	14	<.0001	15	<.0001	14	<.0001	15	<.0001	11	<.0001
	Replicate	3	0.0549	3	0.0242	3	<.0001	3	0.3412	3	0.2606	3	0.0003
	Internode No.	10	<.0001	11	<.0001	12	<.0001	11	<.0001	12	<.0001	8	<.0001
	Error	137		112		121		131		167		108	
	C. Total	150		126	.	136		145		182		119	
	RSquare		0.83		0.79		0.72		0.87		0.83		0.75
	CV%		9.10		12.90		17.50		8.20		9.30		12.00
Diameter (cm)	Model	13	<.0001	14	<.0001	15	<.0001	14	<.0001	15	<.0001	11	<.0001
	Replicate	3	<.0001	3	0.1940	3	<.0001	3	<.0001	3	<.0001	3	<.0001
	Internode No.	10	<.0001	11	<.0001	12	<.0001	11	<.0001	12	<.0001	8	<.0001
	Error	137		112		121		131		167		108	
	C. Total	150		126		136		145		182		119	
	RSquare		0.83		0.57		0.69		0.63		0.86		0.66
	CV%		9.70		10.00		12.00		12.10		6.80		10.90
Slenderness Ratio	Model	13	<.0001	14	<.0001	15	<.0001	14	<.0001	15	<.0001	11	<.0001
	Replicate	3	<.0001	3	0.0613	3	<.0001	3	<.0001	3	<.0001	3	0.0001
	Internode No.	10	<.0001	11	<.0001	12	<.0001	11	<.0001	12	<.0001	8	<.0001
	Error	137		112		121		131		167		108	
	C. Total	150		126		136		145		182		119	
	RSquare		0.80		0.77		0.67		0.80		0.83		0.79
	CV%		15.40		16.60		26.80		14.10		10.40		14.80
Volume (cm^3)	Model	13	<.0001	14	<.0001	15	<.0001	14	<.0001	15	<.0001	11	<.0001
	Replicate	3	<.0001	3	0.0293	3	<.0001	3	<.0001	3	0.0375	3	<.0001
	Internode No.	10	<.0001	11	<.0001	12	<.0001	11	<.0001	12	<.0001	8	<.0001
	Error	137		112		121		131		167		108	
	C. Total	150		126		136		145		182		119	
	RSquare		0.82		0.64		0.68		0.72		0.84		0.61
	CV%		14.10		16.90		15.30		15.20		12.10		18.10

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant

Table 10. LSMeans and Tukey's HSD at (α= 0.05), for individual Internode Length (cm) in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Internode	Genotype					
No.	R.09109	EJX 7J907	EJX 7J906	M81E	EJX 7285	Rio
	(cm)					
1	12.59 D[/1]	14.18 CD[/1]	12.53 D	11.32 F	14.00 G	13.11 E
2	19.80 C	17.57 BC	17.69 C	16.76 E	18.58 F	18.51 D
3	25.07 B	21.62 AB	21.43 B	21.88 CD	24.07 BC	22.70 BC
4	25.55 AB	23.61 A	24.51 AB	23.52 ABC	27.63 A	26.02 A
5	26.82 AB	25.40 A	26.12 A	23.85 ABC	27.73 A	26.06 A
6	27.23 AB	23.54 A	25.42 A	24.68 AB	26.21 AB	24.84 AB
7	27.77 A	24.66 A	24.58 AB	25.35 A	24.95 B	24.06 ABC
8	26.37 AB	23.11 A	24.19 AB	24.64 AB	21.91 CD	23.79 ABC
9	21.71 C	12.95 CD	14.34 CD	22.53 BCD	21.42 DE	15.76 CDE
10	19.39 C	9.89 D	7.98 D	19.54 DE	18.45 EF	
11	19.26 C	9.63 CD	7.08 D	21.24 ABCDE	20.78 ABCDEFG	
12	19.36 C	9.13 CD	5.88 D	20.04 ABCDE		
13	21.79 ABC	8.53 CD				

/1 Internode No. not connected by the same letter are significantly different at (α=0.05)



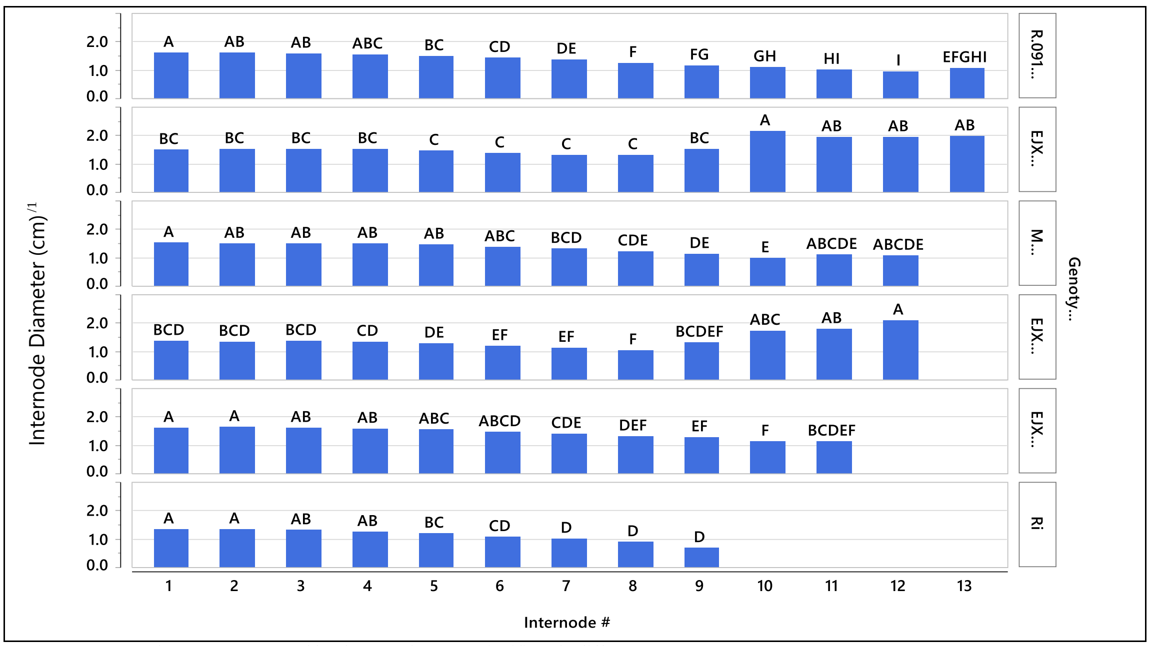
/1 Internode No. not connected by the same letter are significantly different at (α=0.05)

Figure 6. LSMeans and Tukey's HSD at (α=0.05), for individual internode length (cm) in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Table 11. LSMeans for individual Internode Diameter (cm) in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Internode No.	Genotype					
	R.09109	EJX 7J907	EJX 7J906	M81E	EJX 7285	Rio
	(cm)					
1	1.63 A[/1]	1.51 BC	1.37 BCD	1.54 A	1.63 A	1.35 A
2	1.61 AB	1.52 BC	1.36 BCD	1.51 AB	1.65 A	1.35 A
3	1.60 AB	1.53 BC	1.37 BCD	1.51 AB	1.61 AB	1.33 AB
4	1.56 ABC	1.52 BC	1.36 CD	1.51 AB	1.58 AB	1.27 AB
5	1.50 BC	1.46 C	1.28 DE	1.46 AB	1.55 ABC	1.19 BC
6	1.45 CD	1.39 C	1.20 EF	1.39 ABC	1.48 ABCD	1.07 CD
7	1.38 DE	1.32 C	1.14 EF	1.33 BCD	1.41 CDE	1.01 D
8	1.26 F	1.33 C	1.06 F	1.24 CDE	1.33 DEF	0.89 D
9	1.17 FG	1.54 BC	1.33 BCDEF	1.15 DE	1.28 EF	0.69 D
10	1.11 GH	2.16 A	1.73 ABC	0.99 E	1.15 F	
11	1.01 HI	1.94 AB	1.81 AB	1.12 ABCDE	1.13 BCDEF	
12	0.95 I	1.96 AB	2.09 A	1.07 ABCDE		
13	1.08 EFGHI	1.97 AB				

/1 Internode No. not connected by the same letter are significantly different at (α=0.05)



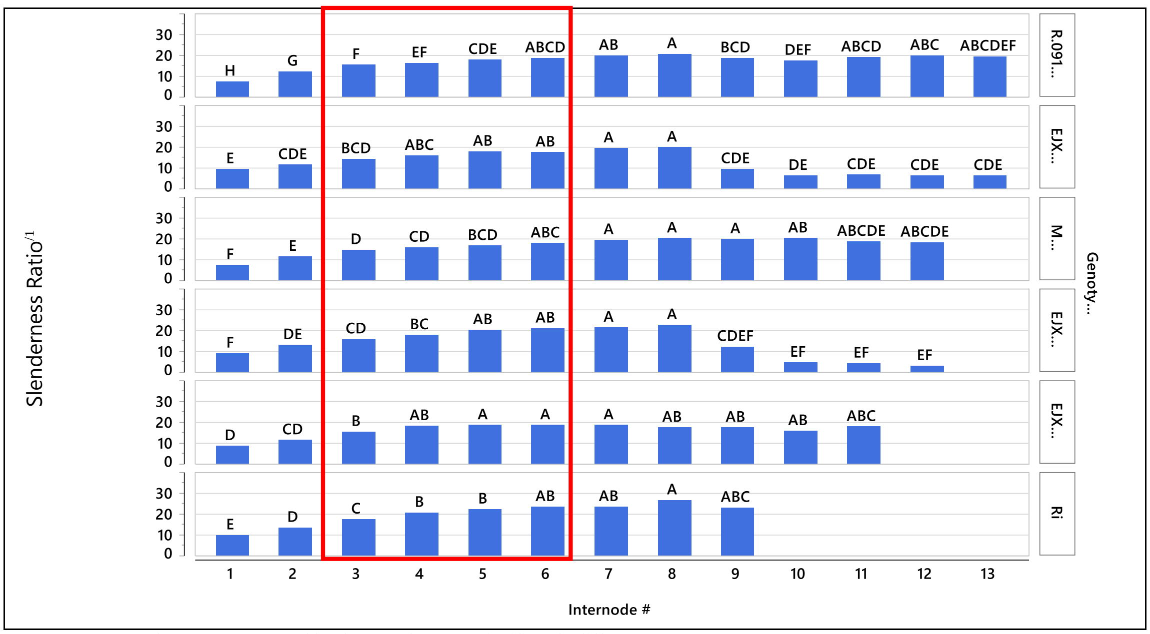
/1 Internode No. not connected by the same letter are significantly different at (α=0.05)

Figure 7. LSMeans and Tukey's HSD at (α=0.05), for individual internode diameter in six energy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Table 12. LSMeans for individual internode Slenderness Ratio for each genotypes grown in Weslaco TX during the 2013 season.

	Genotype					
Internode No.	R.09109	EJX 7J907	EJX 7J906	M81E	EJX 7285	Rio
	(cm)					
1	7.80 H[/1]	9.43 E	9.17 F	7.57 F	8.98 D	9.87 E
2	12.40 G	11.68 CDE	13.15 DE	11.45 E	11.77 CD	13.76 D
3	15.79 F	14.41 BCD	15.80 CD	14.84 D	15.76 B	17.42 C
4	16.47 EF	15.90 ABC	18.05 BC	15.94 CD	18.33 AB	20.94 B
5	17.94 CDE	17.87 AB	20.59 AB	16.64 BCD	18.78 A	22.28 B
6	18.90 ABCD	17.65 AB	21.37 AB	18.14 ABC	18.66 A	23.42 AB
7	20.13 AB	19.61 A	21.78 A	19.46 A	18.76 A	23.77 AB
8	20.99 A	19.88 A	22.98 A	20.28 A	17.40 AB	27.00 A
9	18.62 BCD	9.56 CDE	12.24 CDEF	20.20 A	17.75 AB	23.24 ABC
10	17.45 DEF	6.27 DE	4.97 EF	20.22 AB	16.18 AB	
11	19.01 ABCD	6.86 CDE	4.29 EF	18.71 ABCDE	17.84 ABC	
12	20.19 ABC	6.58 CDE	3.24 EF	18.43 ABCDE		
13	19.67 ABCDEF	6.33 CDE				

/1 Internode No. not connected by the same letter are significantly different at (α=0.05)



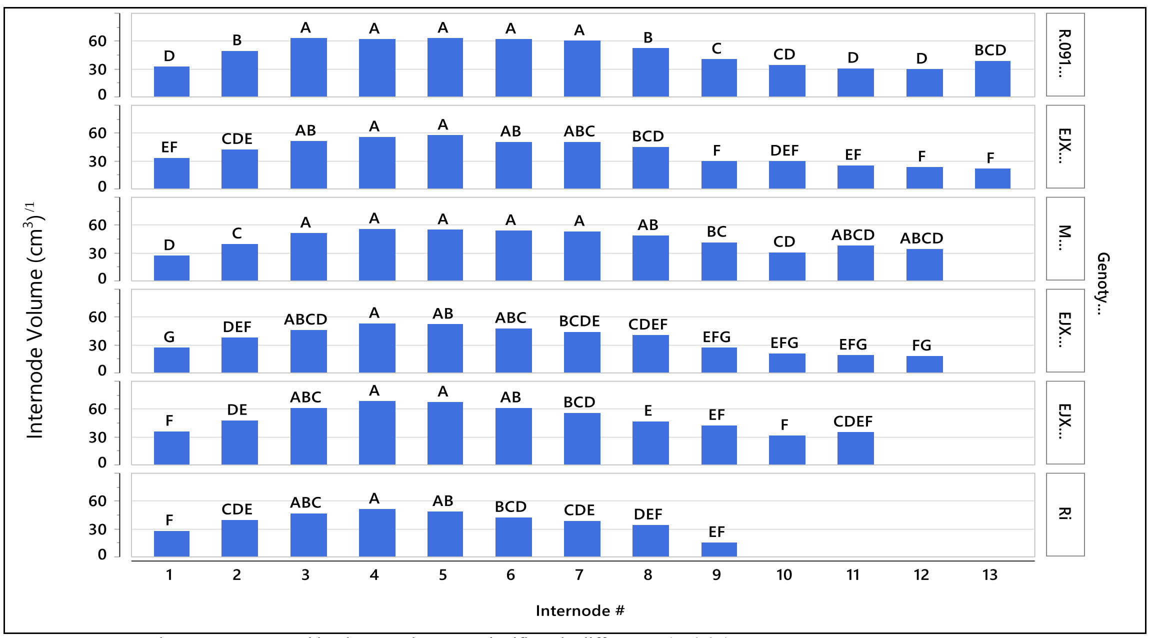
/1 Internode No. not connected by the same letter are significantly different at (α=0.05)

Figure 8. LSMeans and Tukey's HSD at (α=0.05), for slenderness ratio in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Table 13. LSMeans for individual Internode Volume (cm^3) in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Internode No.	Genotype					
	R.09109	EJX 7J907	EJX 7J906	M81E	EJX 7285	Rio
	(cm)					
1	32.24 D[/1]	33.73 EF	27.03 G	27.24 D	35.91 F	27.70 F
2	49.95 B	41.95 CDE	37.75 DEF	39.34 C	48.09 DE	39.35 CDE
3	62.81 A	51.49 AB	46.09 ABCD	51.67 A	60.85 ABC	47.17 ABC
4	62.52 A	55.76 A	52.66 A	55.75 A	68.27 A	51.73 A
5	63.29 A	57.79 A	52.56 AB	54.81 A	67.72 A	48.96 AB
6	61.86 A	50.84 AB	48.01 ABC	54.01 A	61.22 AB	42.16 BCD
7	60.30 A	50.16 ABC	44.03 BCDE	53.21 A	55.79 BCD	38.89 CDE
8	52.60 B	44.66 BCD	40.16 CDEF	48.33 AB	46.56 E	33.78 DEF
9	40.10 C	29.36 F	27.43 EFG	41.15 BC	42.65 EF	15.39 EF
10	34.14 CD	29.32 DEF	20.65 EFG	30.53 CD	31.67 F	
11	30.80 D	24.87 EF	19.00 EFG	38.20 ABCD	35.40 CDEF	
12	29.33 D	23.37 F	17.90 FG	34.37 ABCD		
13	38.49 BCD	21.48 F				

/1 Internode No. not connected by the same letter are significantly different at (α=0.05)



/1 Internode No. not connected by the same letter are significantly different at (α=0.05)

Figure 9. LSMeans and Tukey's HSD at (α= 0.05), internode volume in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Individual Internode Biomechanical Properties

Model 3-ANOVA revealed significant differences (P <0.001 & 0.05) for individual internodes within a genotype for all three biomechanical properties (Table 14), except for internode strength in EJX 7285 and E-Young's Modulus for EJX 7J907 were not significant (Table 14).

In general, internodes in the middle of the stem 3-6 had greater E-Young's Modulus values than lower internodes (Table 15 and Fig. 11). Paradoxically, these internodes are also where most of the stem failures occur. Bottom internodes 1 to 2 had higher strength values than internodes 3 to 6 (Table 16 and Fig.12). Internode 4 of EJX 7J907 and Rio was significantly weaker than their first internode and internode 4 is site in the stem where lodging often occurs (Table 16 and Fig.12). Internodes strength values dropped after internode 3 and in some genotypes the strength in the area between internodes 3 to 6 was statistically lower than bottom internodes (Table 16, Fig.12). Flexural stiffness was lower at internodes closer to the ground, and increased in the region of internodes 3-6 (Table 17 and Fig. 13).

Table 14. Model 3-ANOVA for three biomechanical properties for individual internodes in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

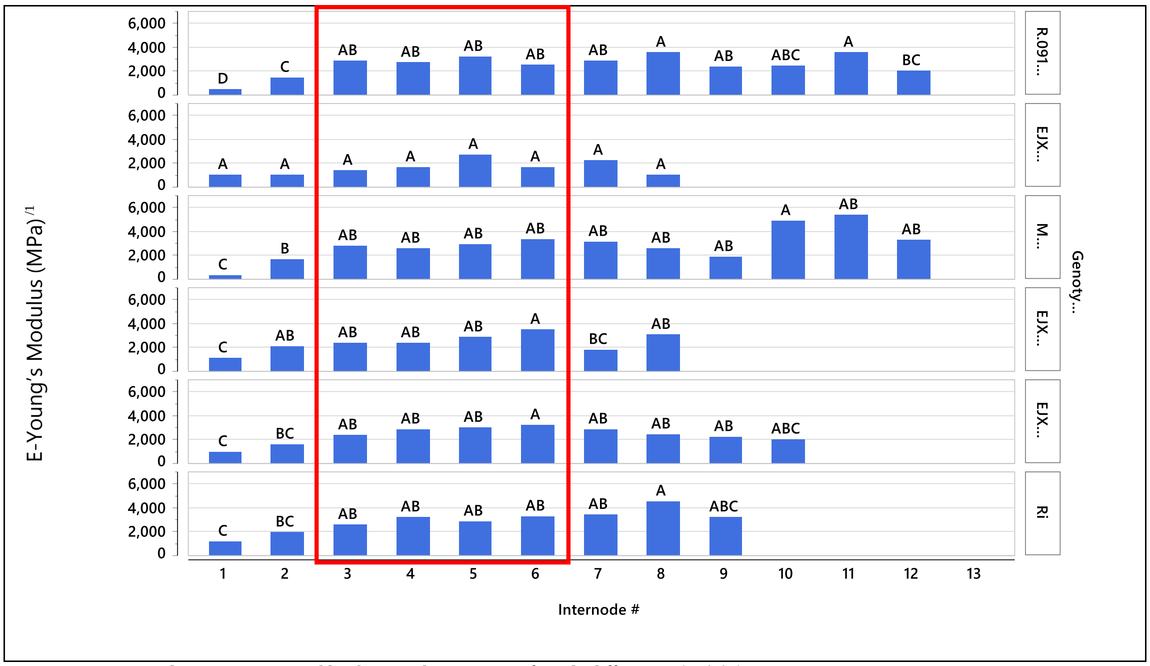
		Genotype											
		EJX7285		EJX7J906		EJX7J907		M81E		R.09109		Rio	
Property	Source	DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F
E-Young's Modulus (MPa	Model	12	<.0001/1	10	<.0001	10	<.0001	14	<.0001	14	<.0001	11	<.0001
	Replicate	3	<.0001	3	0.2085	3	<.0001	3	<.0001	3	0.0191	3	<.0001
	Internode No.	9	<.0001	7	<.0001	7	0.0225	11	<.0001	11	<.0001	8	<.0001
	Error	137		111		112		131		167		108	
	C. Total	149		121		122		145		181		119	
	RSquare		0.65		0.34		0.34		0.65		0.67		0.46
	CV		7.10		6.60		12.20		8.20		5.10		6.30
Strength (MPa)	Model	12	<.0001	11	<.0001	10	<.0001	14	<.0001	14	<.0001	11	<.0001
	Replicate	3	<.0001	3	0.1196	3	<.0001	3	<.0001	3	<.0001	3	<.0001
	Internode No.	9	0.2428	8	<.0001	7	<.0001	11	0.0002	11	<.0001	8	0.0001
	Error	137		112		112		131		167		108	
	C. Total	149		123		122		145			181	119	
	RSquare		0.59		0.45		0.44		0.43		0.38		0.37
	CV		11.60		8.80		14.80		9.30		6.30		8.20
Flexural Stiffness (Nm^2	Model	12	<.0001	10	<.0001	10	<.0001	14	<.0001	14	<.0001	11	<.0001
	Replicate	3	<.0001	3	0.0006	3	0.1413	3	0.8986	3	0.0101	3	<.0001
	Internode No.	9	<.0001	7	<.0001	7	<.0001	11	<.0001	11	<.0001	8	<.0001
	Error	137		111		112		131		167		108	
	C. Total	149		121		122		145		181		119	
	RSquare		0.65		0.53		0.32		0.69		0.79		0.52
	CV		23.60		37.50		51.90		34.00		28.30		48.80

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant

Table 15**.** LSMeans for individual internode E-Young's Modulus (MPa) for six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Internode N	Genotype					
	R.09109	EJX7J907	EJX7J906	M81E	EJX7285	Rio
	(MPa)					
1	494 D[/1]	1,076 A	1,094 C	320 C	971 C	1,195 C
2	1,500 C	1,054 A	2,104 AB	1,651 B	2,355 AB	1,948 BC
3	2,850 AB	1,434 A	2,370 AB	2,811 AB	2,876 AB	2,583 AB
4	2,743 AB	1,675 A	2,393 AB	2,611 AB	2,996 AB	3,220 AB
5	3,252 AB	2,700 A	2,854 AB	2,941 AB	3,191 A	2,891 AB
6	2,523 AB	1,693 A	3,479 A	3,332 AB	2,901 AB	3,260 AB
7	2,902 AB	2,214 A	1,818 BC	3,173 AB	2,420 AB	3,399 AB
8	3,576 A	1,029 A	3,060 AB	2,621 AB	2,237 AB	4,556 A
9	2,414 AB			1,923 AB	2,061 ABC	3,238 ABC
10	2,420 ABC			4,877 A	1,622 BC	
11	3,563 A			5,422 AB		
12	2,016 BC			3,259 AB		
13						

/1 Internode No. not connected by the same letter are significantly different at (α=0.05).



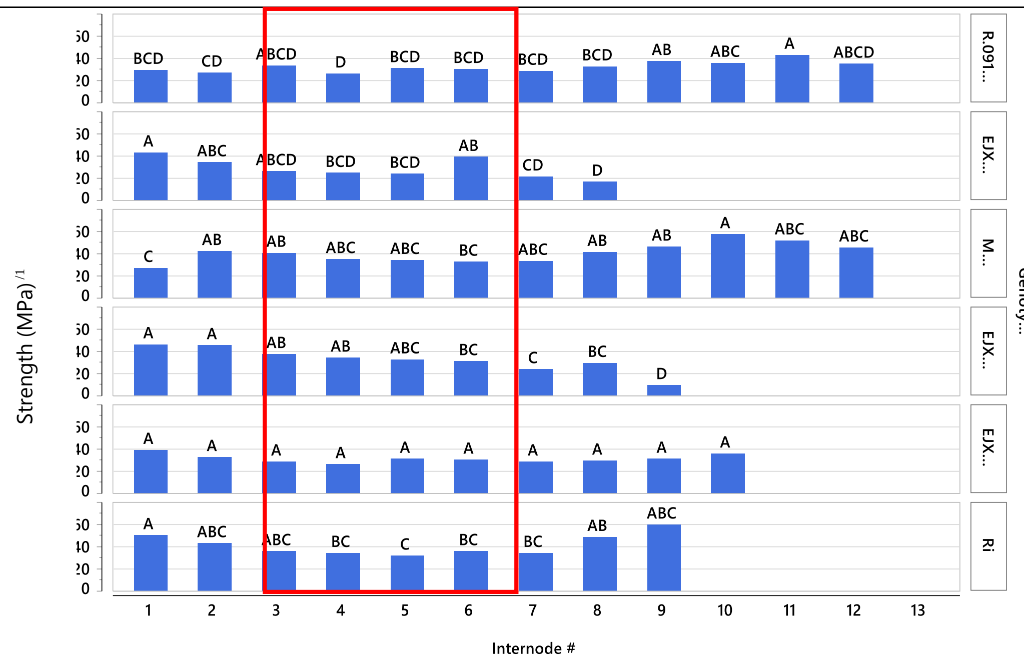
/1 Internode No. not connected by the same letter are significantly different at (α=0.05).

Figure 10. LSMeans and Tukey's HSD at (α= 0.05), for *E*-Young's modulus (MPa) for individual internodes in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Table 16. LSMeans for individual internode strength (MPa) for six genotypes grown in Weslaco TX during the spring of 2013.

Internode N	Genotype					
	R.09109	EJX 7J907	EJX 7J906	M81E	EJX 7285	Rio
	(MPa)					
1	29.30 BCD[/1]	43.54 A	46.26 A	27.22 C	39.25 A	50.15 A
2	27.55 CD	34.30 ABC	45.68 A	42.37 AB	32.84 A	43.00 ABC
3	33.70 ABCD	26.73 ABCD	37.61 AB	40.49 AB	29.02 A	36.15 ABC
4	26.49 D	24.99 BCD	34.33 AB	34.85 ABC	26.11 A	34.01 BC
5	31.09 BCD	23.92 BCD	33.13 ABC	34.61 ABC	31.10 A	32.05 C
6	30.48 BCD	39.27 AB	31.27 BC	32.63 BC	30.22 A	35.82 BC
7	28.90 BCD	21.80 CD	29.48 BC	33.94 ABC	28.86 A	34.58 BC
8	32.41 BCD	17.14 D	23.79 C	41.47 AB	29.27 A	48.86 AB
9	37.24 AB		9.39 D	46.73 AB	31.39 A	60.35 ABC
10	35.92 ABC			57.64 A	35.93 A	
11	42.85 A			52.35 ABC		
12	35.17 ABCD			45.74 ABC		
13						

/1 Internode No. not connected by the same letter are significantly different at (α=0.05).



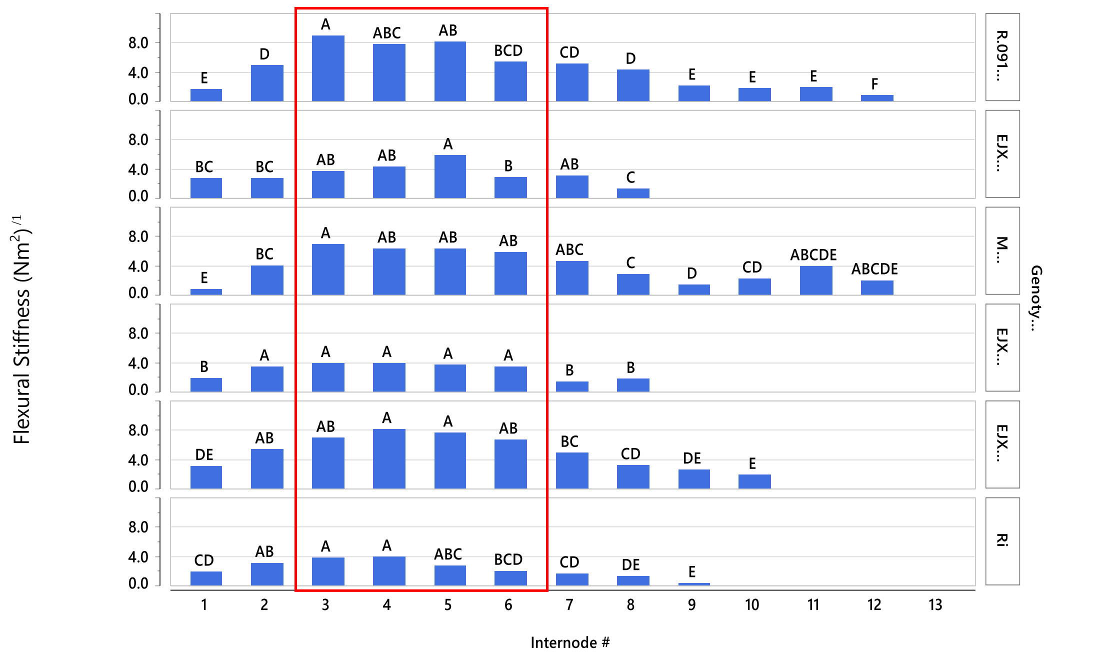
/1 Internode No. not connected by the same letter are significantly different at (α=0.05).

Figure 11. LSMeans and Tukey's HSD at (α = 0.05), for stem strength in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Table 17. LSMeans for individual internode Flexural Stiffness (Nm^2) for six genotypes grown in Weslaco TX during the spring of 2013.

Internode N°	Genotype					
	R.09109	EJX 7J907	M81E	EJX 7J906	EJX 7285	Rio
	Nm^2					
1	1.69 E[/1]	2.71 BC	1.87 B	0.84 E	3.11 DE	1.90 CD
2	4.94 D	2.70 BC	3.51 A	4.08 BC	5.36 AB	3.18 AB
3	9.01 A	3.78 AB	3.99 A	6.93 A	6.98 AB	3.80 A
4	7.85 ABC	4.32 AB	3.95 A	6.33 AB	8.14 A	3.94 A
5	8.11 AB	5.83 A	3.68 A	6.34 AB	7.63 A	2.74 ABC
6	5.40 BCD	2.93 B	3.48 A	5.84 AB	6.77 AB	2.00 BCD
7	5.18 CD	3.07 AB	1.49 B	4.65 ABC	4.94 BC	1.71 CD
8	4.38 D	1.34 C	1.83 B	2.89 C	3.27 CD	1.37 DE
9	2.21 E			1.50 D	2.67 DE	0.38 E
10	1.83 E			2.30 CD	1.89 E	
11	1.86 E			3.95 ABCDE		
12	0.84 F			2.00 ABCDE		
13						

/1 Internode No. not connected by the same letter are significantly different at (α=0.05).



/1 Internode No. not connected by the same letter are significantly different at (α=0.05).

Figure 12. LSMeans and Tukey's HSD at (α= 0.05), for flexural stiffness (Nm^2) for individual internodes in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Average Node Biomechanics for Six Sorghum Genotypes

Model 2-ANOVA for the node's related variables showed that genotype and node position within genotype were highly significant (P<0.0001). Moderate fits of Model 2 for biomechanical properties were observed, which were similar to those found for similar analyses for the internodes (Table 18). The susceptible lodging genotype R.09109 showed the largest E-young's modulus (12,157 MPa), strength (74 MPa), and flexural stiffness (19 Nm^2) at the node level (Table 19). The low-lodging rated genotypes EJX J7J906 and EJX 7J907 were among the lowest for E-young's modulus (4,107 & 5,039 MPa), low to moderate strength (53.12 & 47.54 MPa), and a low to large flexural stiffness (6.86 & 13.16 Nm^2) (Table 19). Even though EJX7285 expressed similar E-Young's modulus with EJX7J906 and EJX7J907, they are extremely different with regards to lodging ratings (7 & 1 respectively) (Table 1 & 19). Similarly the same was observed with strength (Table 1 & 19).

Table 18. Summary of analyses of variance for nodes estimated with EMS for three biomechanical properties of six sorghum genotypes grown in Weslaco TX 2013 season.

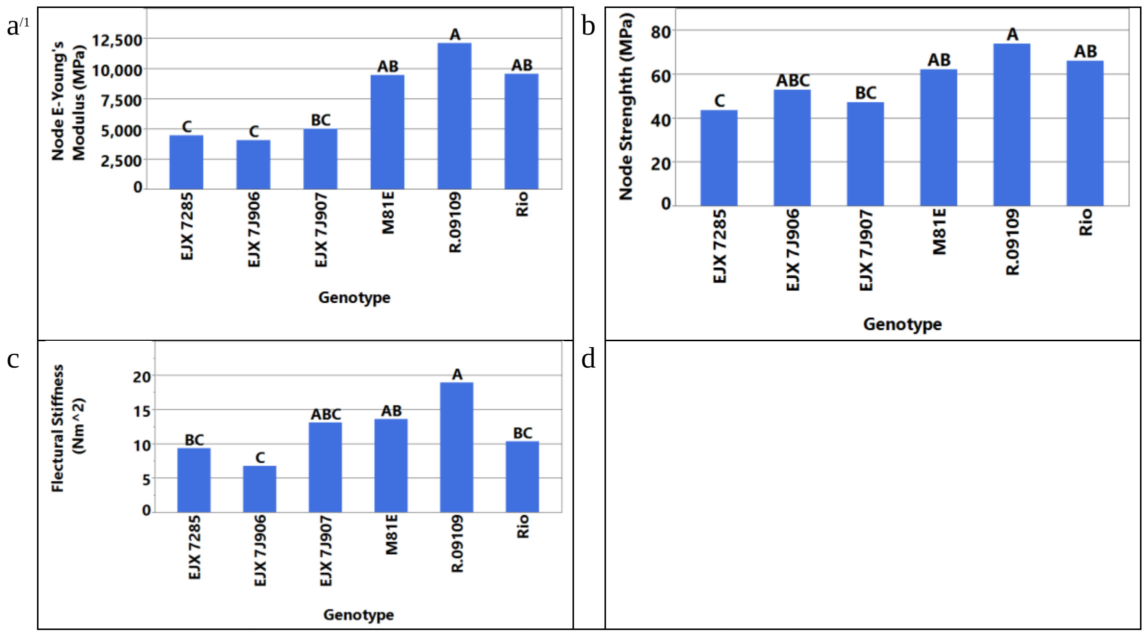
	E-Young's Modulus		Strength		Flexural Stiffness	
Source	DF	Prob > F	DF	Prob > F	DF	Prob > F
Model	33	<.0001[/1]	33	<.0001	33	<.0001
Replicate	3	0.0005	3	<.0001	3	0.0009
Genotype	5	<.0001	5	<.0001	5	<.0001
Node #[Genotype]	25	<.0001	25	<.0001	25	<.0001
Error	150	.	155	.	150	.
C. Total	183	.	188	.	183	.
RSquare	0.50		0.49		0.63	
CV	8.72		9.42		23.99	

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant

Table 19. LSMeans of three biomechanical properties estimated with REML for six genotypes of sorghum grown in Weslaco TX during the spring of 2013.

Genotype	Lodging rating (1-9)	E-Young's Modulus (MPa)	Strength (MPa)	Flexural Stiffness Nm^2
R.09109	7	12,157 A[/1]	74.04 A	18.97 A
EJX7285	7	4,516 C	43.79 C	9.40 BC
M81E	5	9,507 AB	62.33 AB	13.69 AB
Rio	5	9,578 AB	66.39 AB	10.40 BC
EJX7J906	1	4,107 C	53.12 ABC	6.86 C
EJX7J907	1	5,039 BC	47.54 BC	13.16 ABC

/1 Genotype not connected by the same letter are significantly different at (α=0.05)



/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.

Figure 13. LSMeans and Tukey's HSD at (α= 0.05), for three biomechanical properties a) E-Young's modulus, b) strength, c) flexural stiffness in six bioenergy sorghum genotypes evaluated at Weslaco during the 2013 season.

Individual Node Biomechanical Properties

Model 3-ANOVA detected significant differences for node effect within each genotype for all three biomechanical properties, with exceptions in Rio for E-Young's modulus; R.09109, EJX 7J907 and Rio for strength; and Rio for flexural stiffness (Table 20). E-Young's modulus for node 3 was significantly greater than node 1 for M81E and EJX 7285 (Table 21, Fig.15). Flexural stiffness was significantly greater at node 3 than node 1 for M81E and EJX 7285 (Table 23 and Fig.17).

Table 20. Model 3-ANOVA for three biomechanical properties for nodes in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

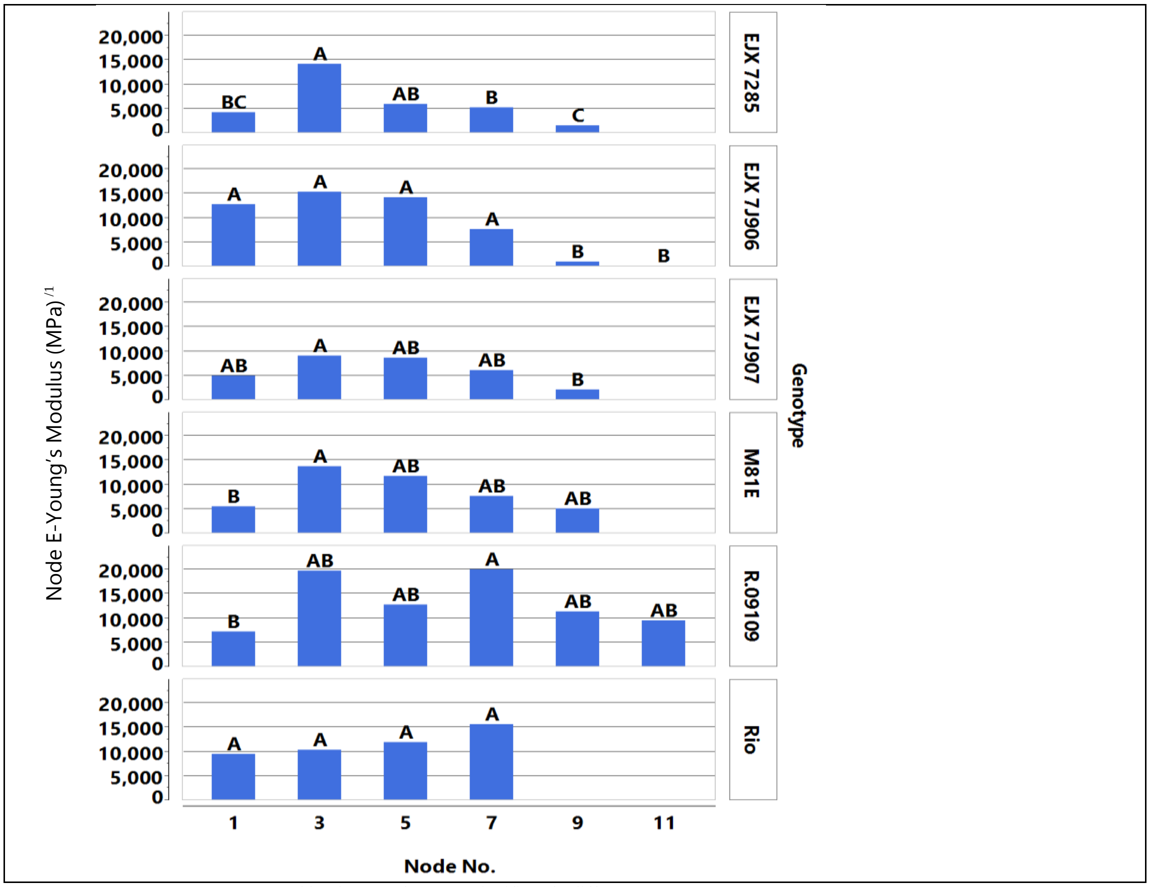
		E-Young's Modulus		Strength		Flexural Stiffness	
Genotype	Source	DF	Prob > F	DF	Prob > F	DF	Prob > F
EJX 7285	Model	7	<.0001[/1]	7	<.0001	7	<.0001
	Replicate	3	<.0001	3	<.0001	3	0.0023
	Node	4	0.0002	4	0.0002	4	<.0001
	Error	28		26		28	
	C. Total	35		33		35	
	RSquare		0.76		0.75		0.76
	CV		7.23		6.75		24.08
EJX 7J906	Model	8	<.0001	8	<.0001	8	<.0001
	Replicate	3	<.0001	3	<.0001	3	0.0015
	Node	5	<.0001	5	<.0001	5	<.0001
	Error	20	.	21	.	20	.
	C. Total	28	.	29	.	28	.
	RSquare		0.90		0.84		0.86
	CV%		4.77		5.63		15.47
EJX 7J907	Model	6	0.0001	7	0.0037	6	0.0150
	Replicate	2	<.0001	3	0.0355	2	0.5753
	Node	4	0.0260	4	0.0358	4	0.0099
	Error	16		21		16	.
	C. Total	22		28		22	.
	RSquare		0.79		0.58		0.49
	CV%		4.91		9.16		18.12
M81E	Model	7	<.0001	7	<.0001	7	<.0001
	Replicate	3	<.0001	3	<.0001	3	0.0874
	Node	4	0.0157	4	<.0001	4	<.0001
	Error	23		24		23	
	C. Total	30		31		30	
	RSquare	0.70		0.78		0.69	
	CV%	5.90		6.00		16.91	
R.09109	Model	8	0.0025	8	<.0001	8	<.0001
	Replicate	3	0.0076	3	<.0001	3	0.0349
	Node	5	0.0375	5	0.0902	5	<.0001
	Error	30		27		30	
	C. Total	38		35		38	
	RSquare		0.51	8	0.68		0.67
	CV%		6.68	6.00	6.00		20.71
Rio	Model	6	0.0027	6	0.0186	6	<.0001
	Replicate	3	0.0004	3	0.0116	3	<.0001
	Node	3	0.6544	3	0.3875	3	0.3875
	Error	19		21		19	
	C. Total	25		27		25	
	RSquare		0.61		0.47		0.77
	CV%		7.87		8.79		24.79

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant

Table 21. LSMeans for E-Young's modulus at the nodes in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Node No.	Genotype					
	R.09109	EJX 7J906	M81E	EJX 7J907	EJX 7285	Rio
	(MPa)					
1	7,223 A[/1]	12,772 A	5,473 B	4,960 AB	4,320 BC	9,476 A
2	19,727 AB	15,372 A	13,750 A	9,029 A	14,220 A	10,339 A
3	12,846 AB	14,193 A	11,856 AB	8,618 AB	5,903 AB	11,920 A
4	20,050 A	7,628 A	7,713 AB	6,066 AB	5,294 B	15,608 A
5	11,369 AB	960 A	5,140 AB	2,064 B	1.563 C	.
6	9,505 AB	159 B	.	.	.	.

/1 Node No. within each genotypes not connected by the same letter are significantly different at (α=0.05)



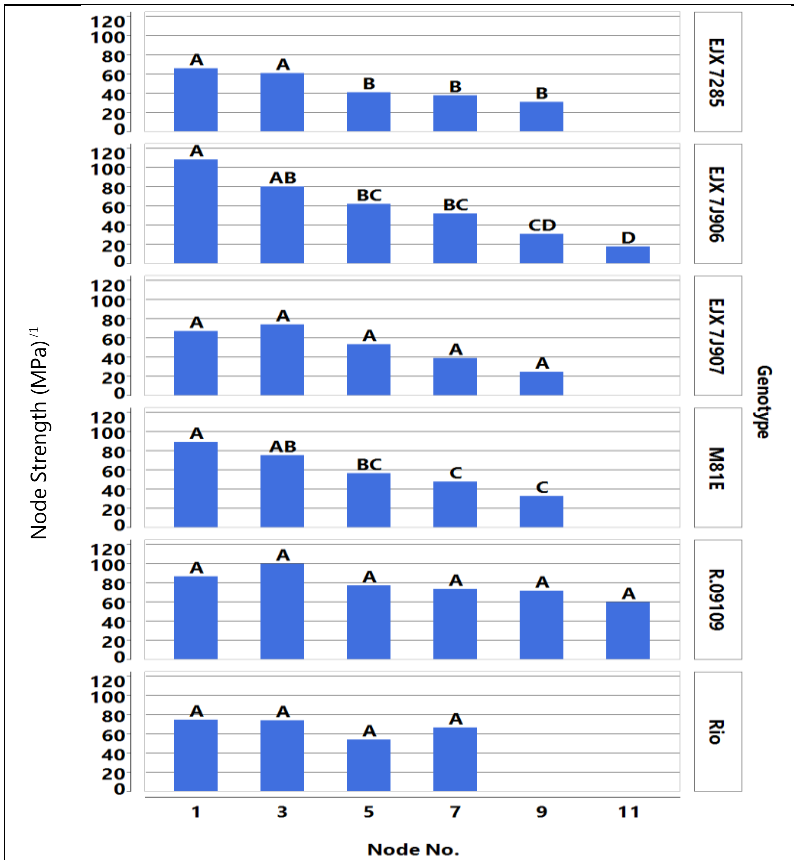
/1 Genotypes not connected by the same letter are significantly different at (α=0.05)

Figure 14. LSMeans and Tukey's HSD at (α= 0.05), for E-Young's modulus in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Table 22. LSMeans for strength at the nodes in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Node No.	Genotype					
	R.09109	EJX 7J906	M81E	EJX 7J907	EJX 7285	Rio
	(MPa)					
1	86.57 A[/1]	108.98 A	89.20 A	67.50 A	66.39 A	75.12 A
2	100.09 A	80.44 AB	75.85 AB	74.43 A	61.24 A	74.40 A
3	77.63 A	62.31 BC	56.88 BC	54.02 A	41.31 B	54.29 A
4	73.98 A	52.23 BC	48.16 C	39.52 A	38.39 B	66.63 A
5	72.16 A	31.36 CD	33.18 C	25.09 A	31.08 B	.
6	60.15 A	17.82 D	.	.	.	.

/1 Node No. within each genotypes not connected by the same letter are significantly different at (α=0.05)



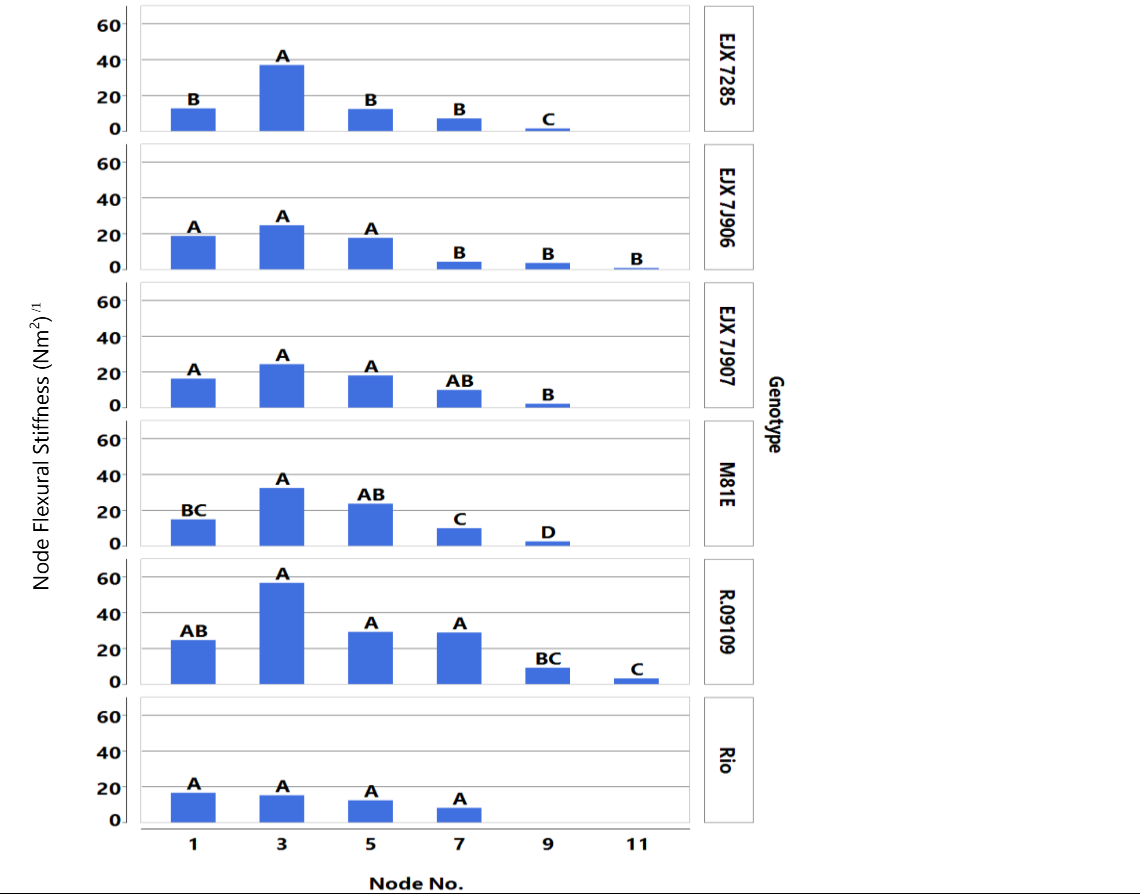
/1 Node No. within each genotypes not connected by the same letter are significantly different at (α=0.05)

Figure 15. LSMeans and Tukey's HSD at (α= 0.05), for strength at the nodes in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Table 23. LSMeans for flexural stiffness at the nodes in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Node No.	Genotype					
	R.09109	EJX 7J906	M81E	EJX 7J907	EJX 7285	Rio
	(MPa)					
1	24.85 AB[/1]	18.79 A	14.90 BC	16.47 A	13.04 B	16.82 A
2	56.84 A	24.98 A	32.67 A	24.36 A	37.26 A	15.51 A
3	29.55 A	17.69 A	23.89 AB	54.02 A	12.47 B	12.44 A
4	28.94 A	4.72 B	10.02 C	39.52 AB	7.22 B	8.41 A
5	9.30 BC	3.73 B	2.96 D	25.09 B	1.61 C	
6	3.62 C	1.14 B				

/1 Node No. within each genotypes not connected by the same letter are significantly different at (α=0.05)



/1 Node No. within each genotypes not connected by the same letter are significantly different at (α=0.05)

Figure 16. LSMeans and Tukey's HSD at (α= 0.05), for node flexural stiffness in six bioenergy sorghum genotypes evaluated at Weslaco during the 2013 season.

Internode vs Node Biomechanics

For all genotypes the biomechanical properties of nodes were significantly higher values for E-young's modulus, strength, and flexural stiffness than internodes (Table 24 and Fig. 18: a, b, c).

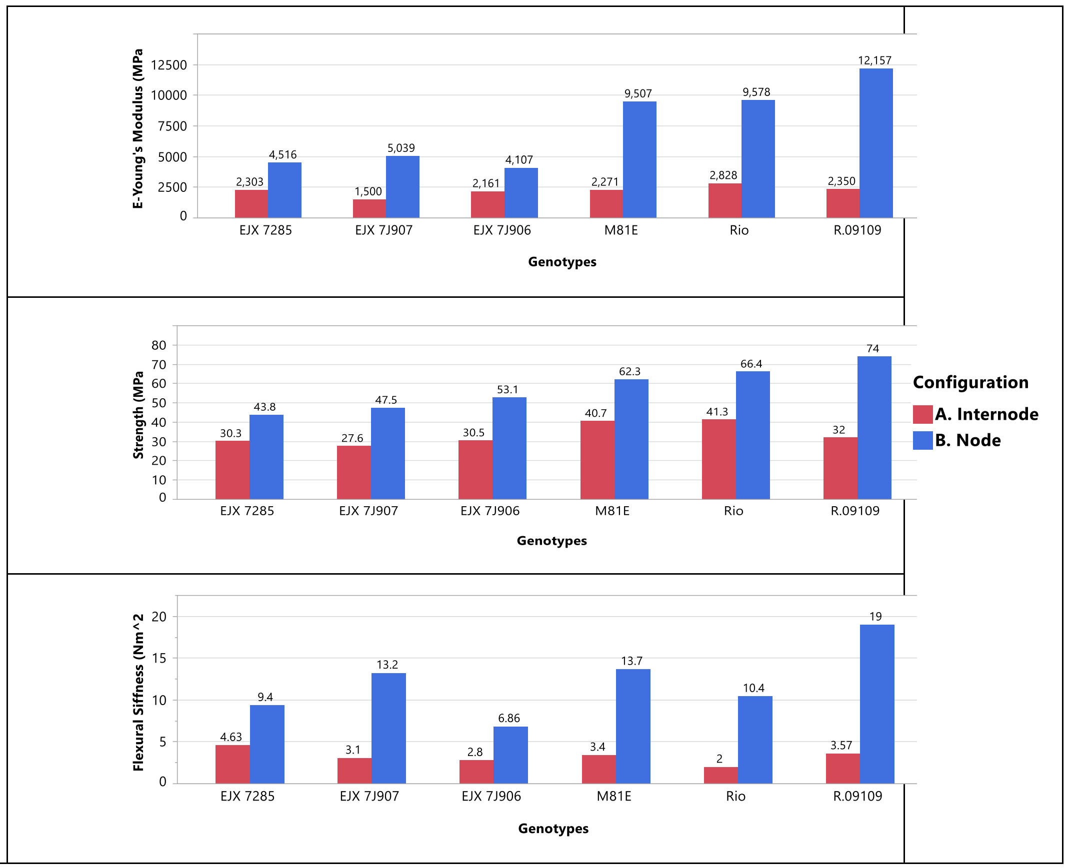


Figure 17. Comparison for biomechanical properties at the node and internode for in six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

Table 24. Match pair comparison for biomechanical properties comparing nodes and internodes for six bioenergy sorghum genotypes evaluated at Weslaco TX during the 2013 season.

	E-Young's Modulus (MPa)	Strength (MPa)	Flexural Stiffness (Nm^2)
Std Error	1291.35	3.91539	1.70053
Prob > |t|	0.0097[/1]	0.0016	0.0035

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant

Table 25. LSMeans for biomechanical properties at the nodes in six bioenergy sorghum genotypes evaluated at Weslaco during the 2013 season.

Property	Genotypes	Configuration A Internode	Configuration B Node	Difference	Percentage Over %
E-Young's Modulus (MPa)	EJX 7285	2,303	4,516	2,213	51.00
	EJX 7J907	1,500	5,039	3,539	29.77
	EJX 7J906	2,161	4,107	1,946	52.62
	M81E	2,271	9,507	7,236	23.89
	Rio	2,828	9,578	6,750	29.53
	R.09109	2,350	12,157	9,807	19.33
	Avg.	2,236	7,484	5,248	34.35
Strength (MPa)	EJX 7285	30.30	43.80	13.50	69.18
	EJX 7J907	27.60	47.50	19.90	58.11
	EJX 7J906	30.50	53.10	22.60	57.44
	M81E	40.70	62.30	21.60	65.33
	Rio	41.30	66.40	25.10	62.20
	R.09109	32.00	74.00	42.00	43.24
	Avg.	33.73	57.85	24.12	59.25
Flexural Stiffness (Nm^2)	EJX 7285	4.63	9.40	4.77	49.26
	EJX 7J907	3.10	13.20	10.10	23.48
	EJX 7J906	2.80	6.86	4.06	40.82
	M81E	3.40	13.70	10.30	24.82
	Rio	2.00	10.40	8.40	19.23
	R.09109	3.57	19.00	15.43	18.79
	Avg.	3.25	12.09	8.84	29.40

Correlation among Traits

Tables 26 provide pairwise correlation for whole plant and individual architecture, geometry, shape, and biomechanical properties. Plant slenderness ratio and plant height were positively, with a low-moderate (0.57) correlation and significant (Table 26). E-young's modulus and internode slenderness ratio exhibited a positive, moderate-high (0.79) and significant correlation. (Table 26). Flexural stiffness was positively, moderate-high (0.76) and significantly correlated with internode volume (Table 26). Interestingly, internode strength and E-Young's modulus exhibited a negative, moderate-high (-0.63) and significant correlation with internode diameter (Table 26). Pairwise comparison for each genotype by whole and individual internode architecture, geometry, shape, and biomechanical properties can be found in Table (A3 1) at APPENDIX under Chapter III.

Table 26. Selected pairwise correlations among geometry, shape, and biomechanical properties of six bioenergy sorghum genotypes frown at Weslaco during the 2013 season.

Type Variable	Variable	Type by Variable	by Variable	Correlation	Lower 95%	Upper 95%	Signif Prob
Plant Geometry	No. of Internodes/ Plant	Plant Geometry	Plant Height	0.63	0.59	0.67	<.0001[/1]
Plant Geometry	Plant Slenderness Ratio	Plant Geometry	Plant Height	0.57	0.41	0.69	<.0001
Plant Geometry	Plant Slenderness Ratio	Plant Geometry	Plant Diameter	-0.73	-0.81	-0.62	<.0001
Internode Geometry	Internode Diameter	Plant Geometry	Plant Diameter	0.85	0.78	0.90	<.0001
Internode Geometry	Internode Slenderness Ratio	Internode Geometry	Internode Length	0.77	0.75	0.80	<.0001
Internode Geometry	Internode Volume	Internode Geometry	Internode Length	0.75	0.72	0.78	<.0001
Internode Geometry	Internode Volume	Plant Geometry	Plant Diameter	0.57	0.42	0.69	<.0001
Internode Geometry	Internode Volume	Internode Geometry	Internode Diameter	0.45	0.40	0.50	<.0001
Internode Geometry	Internode Diameter	Plant Geometry	Plant Slenderness Ratio	-0.41	-0.56	-0.22	<.0001
Internode Geometry	Internode Slenderness Ratio	Plant Geometry	Plant Diameter	-0.46	-0.61	-0.29	<.0001
Internode Geometry	Internode Slenderness Ratio	Internode Geometry	Internode Diameter	-0.75	-0.77	-0.72	<.0001
Biomechanics	Internode Strength	Biomechanics	Internode Strength	0.92	0.91	0.93	<.0001
Biomechanics	E-Young's Modulus	Internode Geometry	Internode Slenderness Ratio	0.79	0.76	0.82	<.0001
Biomechanics	Flexural Stiffness	Internode Geometry	Internode Volume	0.76	0.73	0.79	<.0001
Biomechanics	Internode Strength	Biomechanics	E-Young's Module	0.64	0.60	0.68	<.0001
Biomechanics	E-Young's Modulus	Internode Geometry	Internode Length	0.61	0.57	0.65	<.0001
Biomechanics	E-Young's Modulus	Biomechanics	Internode Strength	0.58	0.53	0.62	<.0001
Biomechanics	Flexural Stiffness	Internode Geometry	Internode Length	0.58	0.54	0.62	<.0001
Biomechanics	Flexural Stiffness	Biomechanics	E-Young's Module	0.47	0.41	0.52	<.0001
Biomechanics	Internode Strength	Internode Geometry	Internode Volume	-0.42	-0.47	-0.36	<.0001
Biomechanics	E-Young's Modulus	Plant Geometry	Plant Diameter	-0.5	-0.64	-0.33	<.0001
Biomechanics	E-Young's Modulus	Internode Geometry	Internode Diameter	-0.63	-0.67	-0.59	<.0001
Biomechanics	Internode Strength	Internode Geometry	Internode Diameter	-0.63	-0.67	-0.59	<.0001
Biomechanics	Internode Strength	Plant Geometry	Plant Diameter	-0.65	-0.75	-0.51	<.0001

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant

Discussion

In this study, mechanical methods were applied to stems of six bioenergy sorghum genotypes to quantify their variation, and assess any association with lodging. These properties are commonly used in material science and are applicable to biological materials (sorghum). Sorghum stem tissues are biologically active and react to both genotype and environmental factors which can change their material properties as they age or as a function of their immediate physiological condition (i.e. hydrated tissues) (K. J. Niklas 1992). Simple solid material, whose properties are unaffected by geometry, are very different than those of a composite material (i.e., a sorghum stem) and are profoundly influenced by their geometry (K. J. Niklas 1992). This is because the materials within the sorghum stem influence the material properties of the composite as a whole. Thus, it is critical when addressing the materials properties of a sorghum stem to refer to the geometry of that stem (i.e., shape and size of the stem or stem section).

In this study, six sorghum bioenergy genotypes with a history of differential lodging tendencies (Table 1) were grown in Weslaco, TX during 2013 season. To characterize the geometry of each genotype, basic traits previously associated with lodging were quantified (internode diameter, length and volume) and a new one (slenderness ratio) was introduced. For instance, bioenergy sorghums have a high slenderness ratio as compared to grain sorghums, which have low a slenderness ratio because they are short in stature and have a thick diameter.

The biomechanical properties that were quantified using a 3PBT were E-Young's modulus, strength, and flexural stiffness. E-young's modulus describes the relationship between stress and strain within the proportional (elastic) limit of loading of a material or a composite material. Strength is the dimensionless parameter that measured the sorghum plant-internode limit to withstand stresses under compression in natural environments, for example wind or rain could exert force that would cause the stem to fail. Flexural stiffness is the product of E-Young's modulus and second moment of an area (I) which gives the plant-internode resistance to bending, and can be attributed to the materials property (E) or geometry (I) or both. The flexural stiffness of plants provides a measure of the stem's resistance to bending (K. J. Niklas 1990). Hence, in some instances this may reflect the susceptibility of a cultivar to stem lodging.

Highly significant differences among all whole plant and internode geometry, shape and biomechanical properties among genotypes ($P<0.001$) were detected (Table 3, 5). This indicates that genotypes differed in all properties considered and may contribute to explain their lodging rating.

The more lodging susceptible genotypes, (R09109 and EJX 7285) were among the tallest, had moderately thicker plant diameter and had greater internode No./plant. Interestingly, both genotypes differed in internode diameter. These genotypes also differed significantly for plant slenderness ratio and internode slenderness ratio, had a high E-young's modulus; a moderate strength (32 & 30.3 MPa); and finally, both genotypes differed for their average flexural stiffness (Table 4, 6, 8).

In contrast, the more lodging resistant genotypes, (EJX J907 and EJX J906) were shorter and had fewer internodes per plant. Interestingly, both lodging resistance genotypes differed significantly in average stem plant diameter (1.5 & 1.3 cm), and individual internode diameter (1.7 & 1.4 cm). These genotypes also significantly differed in plant slenderness ratio (176 & 198) and internode slenderness ratio (11.9 & 14.3) (Table 4); showed moderate E-Young's modulus (1,500 & 2,161 MPa); strength (27.6 & 30.5 MPa); and a low to moderate flexural stiffness (3.10 & 2.8 Nm^2) (Table 4, 6, 8).

By contrasting the geometric and biomechanical characteristics of the susceptible and resistant to lodging genotypes, it was evident that plant height and whole plant slenderness ratio are important differentiating traits (Rooney, 2015). While increasing plant height in these bioenergy sorghum genotypes appears to increase lodging, this is not always the case. Godoy and Tesso (2013) found that lodging scores were not always consistent with the general expectation that tall stature is associated with increases susceptibility of lodging, where tall high biomass hybrids had better standability than their tall parents. Furthermore, stem diameter was not important in this instance to differentiate between lodging susceptible and resistant genotypes. The average strength value did not account for differences in the current lodging ratings as well. Interestingly, the genotype EJX 7285 which had the higher average strength among all genotypes has a larger tendency to lodge presumably due to other potential modes of failure (K. J. Niklas 1992, Sindhu, et al. 2007).

Another contributing factor to lodging tendencies could be differences within each genotype for their geometry and biomechanical properties of each internode within the stem. Herein, the internode characteristics differed based on position, with the exception of strength for genotype EJX 7285 (Tables 9 & 14). Internodes in the middle of the stem tended toward having a greater E-Young's modulus, greater flexural stiffness, and weaker internodes but statistical differences were not always detected (Tables 15, 16, 17). It has been long known that internodes are longest and most uniform in the middle of the stalk and shortest at the base

(Artschwager 1948). Internode length is a factor in the estimation of the biomechanical properties, thus affecting the mechanical behavior of the stem and possible lodging performance.

In general, most sorghum genotypes typically exhibited numerically weaker internodes between internodes three and six but not all were statistically different from first two internodes were stem lodging is rarely observed (Table 16). For example, in the lodging resistant genotype EJX J907 and the moderate lodging resistant genotype Rio internodes were significantly weaker than the first two bottom internodes (Table 16). Similarly, most genotypes had a higher E-Young's Modulus between internodes three and six (Table 15) with the exception to the lodging resistance genotype EJX 7J907 (Table 15). Genotypes also had a greater flexural stiffness between internodes three and six compared to the first two bottom internodes (Table 17). However, there was a significant increase in slenderness ratio from bottom to top internodes across the stem, and leveling off around internodes six (Table 12). This indicates that the geometry of the stems between internodes three and six tends to bend more easily and the materials properties at the regions are weaker and stiffer. While the interaction between the materials properties and geometry results in a more rigid and more resistant to bending region of the stem compared than the first two bottom internodes were little stem lodging has been observed to occur. This is the result of the specific stem architecture the plant is in at a particular growth stage and its specific environment. Therefore, the results indicate that there was a significant internode effect for each genotypes for their biomechanical properties and geometry that may result in the likelihood of stem failure. These results may also suggest that the higher frequency of field observations for stem lodging usually between internodes three and six may be due to weaker internodes. In addition, these results are similar to reports in maize where the fourth internode is the breakpoint in most stem lodging observations (Hu, Liu, et al. 2013).

Differences among genotypes and nodes within genotypes were detected for all three biomechanical properties (Table 18), but there no specific patterns in lodging tendencies were apparent. For example, genotypes with similar lodging rating had different biomechanical properties. R.09109 had almost three times the flexural stiffness at the nodes than EJX 7J906 (Table 19). This may be a result of being the tallest plant with the greatest No internodes/plant, the nodes were stiffer, and had a good strength, thus resisted more to bending which allowed to be the plant to be taller. However, factors contributing to making this genotype to lodge at a higher frequency are still unknown.

Significant differences were detected within nodes for all genotypes for all biomechanical properties except for the genotype Rio and R.09109 for Strength (Table 20). M81E and EJX 7285 had a higher E-Young's modulus and flexural stiffness for node 3 (Table 21) but statistical differences were not detected. This implies that node 3 will be stiffer and more resistant to bending. In addition, upper nodes of EJX 7J906, M81E and EJX 7285 were weaker (Table 22).

Another possible explanation for the inconsistency of data for nodes and lodging could be that nodes are not a stem breakpoint because they are consistently stronger than the internode. Nodes have significantly higher E-Young's modulus, strength, and flexural stiffness than internodes (Table 24). On average, node values for E-young's modulus, strength, and flexural stiffness were 34%, 60% and 29% higher, respectively than in the internode (Table 25). Thus, the stem section more likely to fail is the internode and relative values at the node are not subject to stress. This observation is corroborated in maize (*Zea May*s), bamboo (*Phyllostachys aurea*), giant reed (*Arundo donax*), and scouring rush (*Equisteum hyemale*) (K. J. Niklas 1989) (Robertson, et al. 2014) (Robertson, et al. 2015) This may suggest that the solid stem of the sweet sorghum bicolor nodes can act as support and joints for the stem depending on internode length (K. J. Niklas 1989) (K. J. Niklas 1997) (K. J. Niklas 1997). Furthermore this is highly congruent to what Niklas (1992) found that when node are stiff and inflexible, most of the bending strains are predicted to occur at the internode most distance from restraining nodes.

Identification of any association among traits under study would be highly desirable from the breeding stand point. For these genotypes, overall correlations varied from low to high. While not unexpected, there was not a single correlation that definitively related a trait with lodging. It was apparent that increasing diameter does not increase the material properties strength and E-Young's modulus *per se* in a genotype. This contradicts that increasing stem diameter makes stems stronger, which is inconsistent with the traditional belief in sorghum breeding that increasing stem diameter also increases stem strength (Sleper and Poehlman 2006). Thus increasing stem diameter does not reduce strength as such, but the stress that is distributed/felt by the stem is reduced. Strength is a specific material property which indicates the maximum stress that can be sustained by the stem (Muliana 2015). Strength by definition is the magnitude of force (*F*) reduced by the increase in the diameter d of a sorghum stem. Niklas and Speck (2001) explains that from a theoretical perspective, it is clear that plant height cannot increase without having mechanical failure unless stem diameter or tissue stiffness (E- Young's

Modulus) increases. Even a small increase in diameter will drastically elevate the mechanical stability of a vertical plant stem by increasing exponentially the second moment of an area (which is the measure of the attributes from size, shape, and geometry make to the ability of the stem to resist bending) which is a function of diameter (Niklas and Speck 2001) (K. J. Niklas 1992). Thus, there are mechanical advantages of stem diameter and this explains why plant height correlates very well with stem diameter across a broad taxa in other plant species (Niklas and Speck 2001).

Several factors in this study may affect actual biomechanical properties. First, the removal of the leaf sheaf may affect precise biomechanical properties, as in other monocot species they are expected to function as an external cylindrical brace which contribute to the overall bending stiffness and structurally reinforce growing and mature stem internodes (K. J. Niklas 1990, K. J. Niklas 1992, K. J. Niklas 1998). We do not expect that our inferences were affected by the removal of the leaf sheaf as sorghum genotypes harvested in our study were at hard dough and leaf sheaf at most of the bottom internodes had senesced. A second factor that can affect precise biomechanical properties is turgor pressure, as it can affect the tensile stresses generated within cell walls and the mechanical stiffness of thin-walled cells and thin walled tissues, such as parenchyma (K. J. Niklas 1992). For example E-Young’s modulus of dry cellulose is higher than that of wet cellulose (K. J. Niklas 1992). To reduce the environmental variability (i.e. turgor pressure) in our results, all specimens were harvested in the early morning and phenotyped on the same day.

The biomechanical variation plants exhibit throughout their stem not only has to do with inherited factors but with the environment which sorghum stem inhabit in the field. These plants must compete for light with their neighboring plants to carry on photosynthesis and at the same time withstand mechanical forces due to rain or wind. Thus, the plant must establish a competitive balance for light (taller) with standability (resistance to lodging). The evaluation of these biomechanical properties were on plants in normal planting density and the results provide a better understanding how these plants manage these factors. In addition, the history of the genotypes evaluated may give an indication on how selection affected their biomechanical properties. For example the Texas A&M Sorghum Conversion Program have converted tall exotic germplasm into dwarf genotypes without regarding of maintaining their biomechanical properties that may contribute to a desirable standability.

This study reveals the highly complex nature of stem lodging, where one trait or two traits do not necessarily infer stem lodging resistance. This complexity is similar to grain mold resistance in sorghum; where an array of screening and selection methodologies have been developed; however numerous traits have been found associated with increased grain mold resistance, but none of them confer complete resistance. (Rooney, Collins, et al. 2002). Therefore, to further elucidate the phenotypic complexity of stem lodging, and relate it to the sorghums stem genetics a need of further studies on this topic is necessary.

Conclusions

This study provides the first insight into the usefulness of a 3PBT to detect significant variation for biomechanical properties which are highly effected by geometry to characterize six bioenergy sorghum genotypes. Moreover, with the 3PBT this study was able to identify the weakest section of the stem that is most likely to fail (internodes 3-6); and nodes enhance the biomechanical properties of the stem to withstand failure. The 3PBT allowed to associate biomechanical properties with stem geometry and elucidate traditional beliefs to increase stem strength in sorghum, in order to reduce the likelihood of stem lodging. It is recommended to continue using the 3PBT to evaluate a more diverse sorghum germplasm, and validate findings to this study, and further demonstrate that improving biomechanical properties is of paramount importance in enhancing stem lodging performance. However, stem lodging continues to be a very complex phenomena and future studies should address the sorghums stems composition to identify the material properties which attribute to the stems biomechanics. Rind thickness are factors that would be expected can contribute to stem biomechanics. Future research should focus on the section of the sorghum stem were plants are weaker (internodes 3-6) to improve its mechanical stability. It would also be important for other experiments to do replicated test on multiple environments in order to determine genotype x environment interactions as well as genetic and environmental variances attributed to biomechanical parameters. All these factors will allow us to elucidate the complex nature of stem lodging and address the limiting factor reducing yield in bioenergy sorghum.

CHAPTER IV

GEOMETRY, SHAPE, AND BIOMECHANICAL PROPERTIES OF 15 BIOENERGY SORGHUM GENOTYPES EVALUATED IN THREE TEXAS ENVIRONMENTS

Introduction and Literature Review

Stem lodging is a complex and common problem in most cereal crops, and is a limiting factor on yield worldwide. Lodging, is defined as plants uprooting, breaking, or otherwise mechanically deforming from the ground due to the effect of wind, rain, or hail on their stems and leaves (K. J. Niklas 1992). Thus, it can either occur through stem lodging or displacement of the roots within the soil (Berry, Spink, et al. 2003). Stem lodging results from weak stalks which are either genetically inherited or caused by biotic and abiotic factors including pathogens, insects, and externally applied mechanical forces that exceed the load capacity of the stems (Pinthus 1973), (K. J. Niklas 1992), (Flint-Garcia, et al. 2003). Stem lodging is a significant limiting factor decreasing yield in the C4 bioenergy grass sweet sorghum [Sorghum bicolor (L.) Moench] and as such, reducing it is a primary breeding objective for sorghum bioenergy breeders (Rooney, Blumenthal, et al. 2007).

Lodging in sorghum has been addressed mostly in grain types through the deployment of dwarfing genes to reduce both lodging and ease of mechanical harvesting (Quinby 1974). Selection on other traits such as stalk rot resistance, increased stem diameter, and thicker rind also contributed to the reduction of stem lodging (Sleper and Poehlman 2006). Compared to grain sorghums, bioenergy sorghums are tall and most hybrids are photoperiod sensitive which means different approaches to mitigating lodging must be used. There is an inherent assumption that tall plants lodge more often and that increased stem diameter increases strength. Initial results from this study (Chapter III) found that while increasing stem diameter may increase mechanical stability it does not necessarily increase stem strength, as it was found that stem strength was negatively correlated with stem diameter. This is because sorghum stems are composite materials composed of heterogeneous tissue arrangement, thus are deeply affected by their geometry. Another study confirmed that tall stature genotypes in bioenergy sorghum did necessarily increase susceptibility to lodging over other tall genotypes (Godoy and Tesso 2013). Regardless, of the vast research to minimize lodging in grain sorghum few studies have addressed the link between geometry, shape, and biomechanical properties in order to minimize the likelihood of stem lodging in tall bioenergy sorghum.

Initial results from this study (Chapter III) corroborated the notion that in most cases grass stems are stronger at the nodes than at internodes (K. J. Niklas 1989) (Robertson, et al. 2015). This results in most stem failures occurring at the internode just above the restraining node. Stem lodging in bioenergy sorghums has been observed to occur more frequently around internodes three to six, usually just above the node. Previous results from this study outlined that that internodes three to six tended to be weaker. This is similar to maize where observations have concluded that the fourth internode is more susceptible to lodging (Hu, Liu, et al. 2013).

Stem lodging depends on complex interactions between the mechanical properties of the stems, geometry, shape, development, and maturation. Accordingly, it is the material properties, geometry, shape, development, and maturity of the plant stem that contribute to their mechanical behavior and dynamic loadings (K. J. Niklas 1992). Therefore, dissecting biomechanical, geometric, and shape at the weakest section of the sorghum stem (internode 3 to 6) may help us understand important characteristics that may aid in our goal to minimize stem lodging.

The unpredictable occurrence of stem lodging across time and space is a crucial factor influencing stem lodging. Therefore, this study seeks to dissect the effects of important quantitative traits under different environments which are important in determining our understanding of the stem lodging phenomenon in bioenergy sorghum, so that better selection criteria for lodging resistant germplasm may be introduced in plant breeding programs. Therefore, the objectives of this study were to 1) characterize 15 genotypes with different maturity response and lodging characteristics at the weakest section of the stem (internode 3-6) for geometry, shape and biomechanical properties using a 3PBT; 2) asses relative genetic, genotype x environment, and maturity effects 4) identify traits associated with lodging susceptibility

Materials and Methods

Plant Materials

Fifteen sorghum genotypes from the TAMU Sorghum Breeding Program were selected based on their prior history with regards to lodging tendencies (L. W. Rooney 2015). Genotypes were divided in three groups, based on relative level of photoperiod sensitivity (Table 27).

Table 27. Sorghum genotypes used in this study and grown at three environments in TX during the 2014 season.

Genotype	Maturity/1	Lodging Rating (1-9)/2	Type
Della	PI	7	Inbred line
R.07007	PI	7	Inbred line
SOR2014	PI	1	Inbred line
EJX 7285	MPS	7	Hybrid
EJX 7J906	MPS	1	Hybrid
EJX 7J907	MPS	1	Hybrid
M81E	MPS	5	Inbred line
Rio	MPS	5	Inbred line
ATx623/R07007	PS	3	Hybrid
ATx645/SOR2014	PS	1	Hybrid
GRASSL	PS	7	Inbred line
R.10030	PS	5	Inbred line
R.10135	PS	5	Inbred line
R.11434	PS	5	Inbred line
R.11438	PS	5	Inbred line

/1 PI = Photoperiod sensitive, MPS = Moderate photoperiod sensitive, PS = Photoperiod sensitive
/2 lodging rating: 1 = Lodging resistant, 5 = moderate lodging, 9: lodging susceptible

Experimental Design and Field Management

All genotypes were evaluated under three environmental conditions during 2014 (Table 28 and Figure 18. Experiments were established using a randomized complete block design (RCBD) with four replications. Standard sorghum agronomic practices from the Texas A&M Sorghum Breeding Program were used. At 15 days after emergence, the plants were manually thinned to 15 cm spacing between plants.

Table 28. Sorghum growing environments in Texas for this study.

Planting Location	DMS[1]	Planting Date	Day Length at Planting (h:m)	No. of Days at harvest (dap)	Day Length at harvest (h:m)	Plot:Row distance: (m)
Weslaco (WE) TX	26°10'49.32"N 97°59'19.39"W	Feb. 18, 2014	11:22	92	13:41	5:1.02
College Station (CSE), TX	30°39'14.25"N	April 21, 2014	13:05	100	13:40	4.6:0.76
College Station (CSL) TX	96°20'40.89"W	May 22, 2014	13:50	98	12:55	

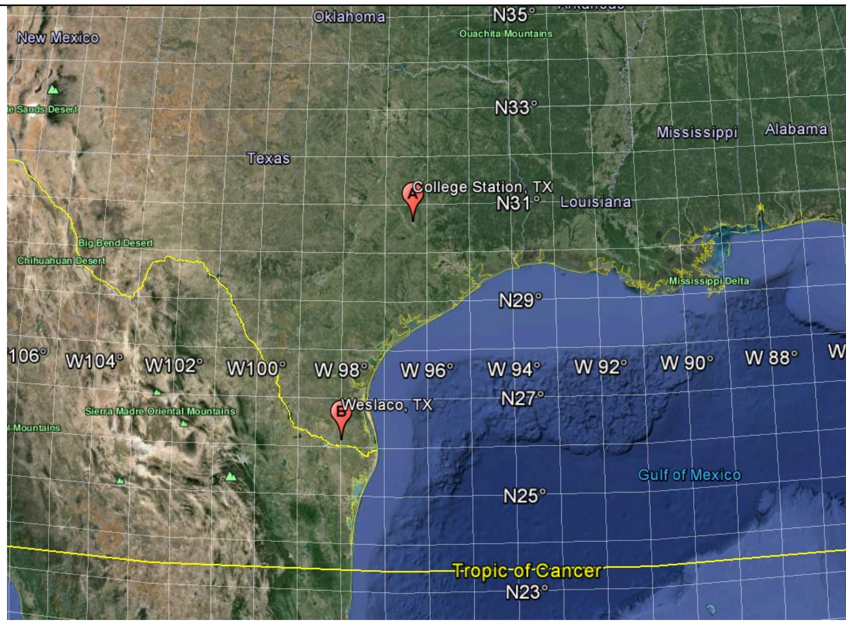


Figure 18. DMS information where were experiments were conducted in Texas 2014. A) College Station, TX. B) Weslaco, TX. Estimated distance ~630 km from point A to point B. (https://sites.google.com/a/tas.tw/mscitation/how/ge)

Data Collection

Specifically, data were collected when the photoperiod insensitive group was at hard dough stage of maturity (GS8 of the sorghum growth stage scale), thus the moderate and photoperiod sensitive varied for their growth stage in each location (Vanderlip 1993) (Table 29).

Table 29. Vanderlip's growth stage for each maturity group at each location when harvested.

Maturity response	Environment	Vanderlip growth stage
Photoperiod insensitive	College station early	7.9
Photoperiod insensitive	College station late	7.8
Photoperiod insensitive	Weslaco	7.6
Moderate photoperiod sensitive	College station early	5.5
Moderate photoperiod sensitive	College station late	4.3
Moderate photoperiod sensitive	Weslaco	7.5
Photoperiod sensitive	College station early	2.3
Photoperiod sensitive	College station late	2.2
Photoperiod sensitive	Weslaco	6.2

At sampling, four random plants in the middle of the plot were cut at the base, tagged, bundled, and immediately characterized using several plant geometric, shape, and biomechanical parameters (Table 30).

Table 30. Traits description measured in 15 bioenergy sorghum genotypes at three environments in TX during the 2014 season.

	Variable	Type of Variable	Description
1	Plant height	Geometry	Plant height was measured as the length of the plant from the base to the tip of the panicle (cm)
2	Internode length	Geometry	Internode length was measured from node to node using a ruler (cm)
3	Internode diameter	Geometry	Internode diameter was measured using a digital caliper at the center of each internode (cm)
5	B1	Physical	Bending distance of internode/dual internode before fracture occurs (mm) using a digital caliper
6	F1	Physical	Force recorded at internode/dual internode B1 (N) before fracture using a force gauge with a cylinder attached
7	B2	Physical	Bending distance of internode/dual internode after fracture occurs (mm) using a digital caliper
8	F2	Physical	Force recorded at internode/dual internode at B2 (N) using a force gauge with a cylinder attached

Morphological and Anatomical Measurements

For each stem sample measured, all leaf sheaths were removed from stem segments. Plant height was measured as the length (cm) of the plant from the base to the tip of the panicle. Internode length (cm) for internodes 3 to 6 was measured using a ruler from the lower node of an internode to the bottom of the next node of the following internode. Internode diameter (mm) was measured for internodes 3 to 6 and the last internode before the peduncle at the center of each internode using a digital caliper (Table 30.). An additional internode diameter measurement was collected at the uppermost internode and used to estimate the whole plant diameter Figure 19 describes, in a general sense, the phenotyping process for these traits.

Three-point bending test

A 3PBT test was performed on individual internodes to measure the loading force (*N*) required to bend *B* (mm) and fracture individual sorghum internodes.

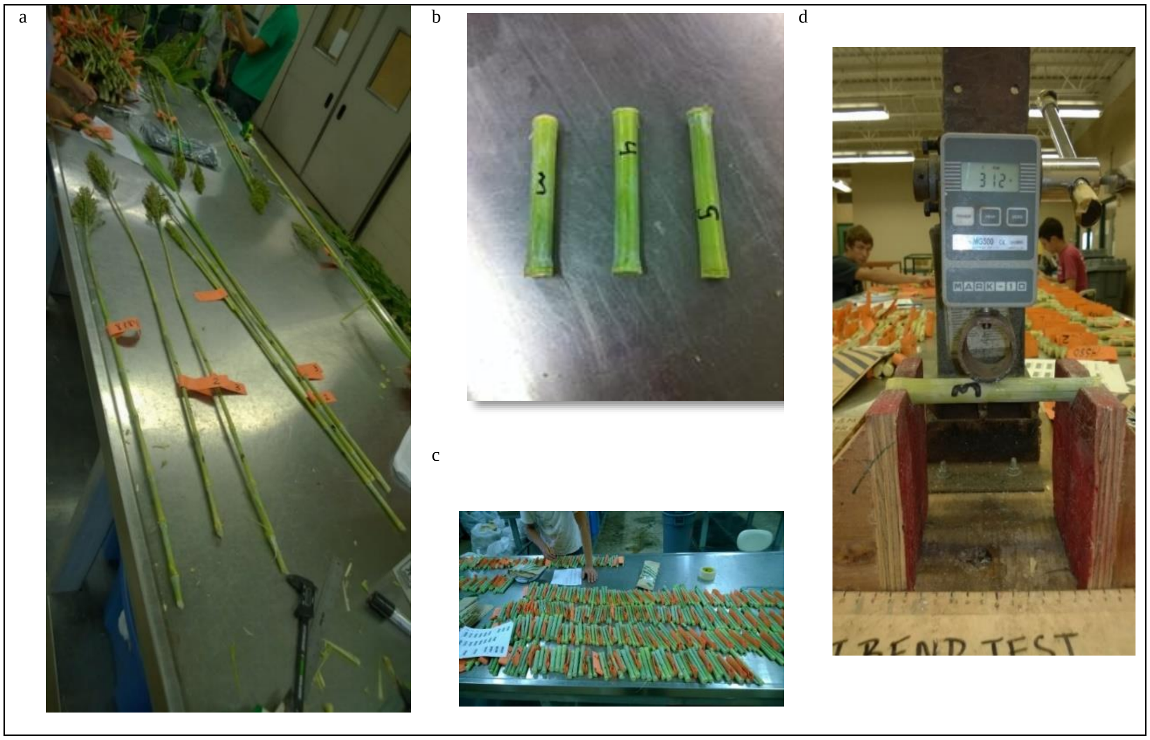


Figure 19. Schematic phenotyping process: a) whole plant measurements, b) individual internode measurements, c) internode organization by genotype, d) applying a 3PBT

Stem Shape and Geometrical Parameters

Geometric and biomechanical properties were computed using the formulas following described below:

Slenderness Ratio λ

Slenderness for whole plant and individual internode ratio as follows:

Slenderness ratio $$\lambda = \frac{L}{D}$$ [4.1]

where L is the total length of the plant, or the total length of each internode, and D is an average diameter of the plant or internode (Table 3). The slenderness ratio is a dimensionless parameter and plants with a high slenderness ratio are easily bent or deformed compared to the ones with low a slenderness ratio (stocky plants).

Second Moment of an Area I

The second moment of an area is a geometric property that quantifies the distribution of an area in each cross section with respect to the centroid of the cross section, and is symbolized by I; it is the integral of the product of each elemental cross-sectional area and the square of the distance of each elemental cross-sectional area from the centroid axis (K. J. Niklas 1992). The stalk is assumed to have a solid circular cross-section of diameter D (or radius r), the second moment of an area is given by the formula.

Second moment of an area $$I = \frac{\pi D^4}{64} \qquad [4.2]$$

where π = 3.1416, and D is the diameter of the stem.

Stem Biomechanical Properties

Data from the bending test and geometry were used to calculate the following stem biomechanical properties.

E-Young's Modulus- E

The Young's elastic modulus E, also known as the elastic modulus E, is measured in (MPa) and is the proportionality constant relating normal stress to normal strain throughout the linear elastic range of the behavior of a material (K. J. Niklas 1992). It is a measure of material stiffness. For a slender bar under 3PBT, E is calculated using the Euler-Bernoulli beam model (Muliana 2015) As follows:

E-Young's Modulus $$E = \frac{\frac{F1{L_{in}}^3}{48I}}{B1} \qquad [4.3]$$

where B1 (bending) is the first deflection before an internode breaks measured in millimeters (mm). F1 is the first force before internode breaks measured Newton's (N), and L_{in} is the internode length (mm). I is the second moment of an area described in equation (4.2).

Strength- σ_{max}

Stem strength measured in (MPa) is the load (breaking load) or limit of the stem to withstand stresses that will cause the stem to fail (K. J. Niklas 1992). It is calculated as:

Strength $$\sigma_{max} = \frac{\frac{(F2)L_{in}}{4}}{I} * \frac{D}{2} \qquad [4.4]$$

where F2 is the final F at failure at the sorghum stem either internode or node. L_{in} is internode length (cm), D is internode diameter (mm), and I is second moment of an area.

Flexural stiffness- EI

Flexural stiffness or flexural rigidity (EI) measures the ability of a stem to resist bending, and it is calculated as:

Flexural stiffness $$EI = E * I$$ [4.5]

where E is the material property E-Young's modulus described in formula 4.3 and I is the second moment of an area described in formula 4.2.

Data Analysis

All data was previously subjected to outlier analysis using the jackknife technique available from JMP® Pro 11.1 (SAS Institute, 2013). Missing observations were estimated using the Restriction Maximum Likelihood (REML) method, and the estimated values were imputed in the missing data set cells. Biomechanical traits were transformed to meet normality.

General Linear Models and Analysis of variance

Cleaned data was further analyzed using appropriate General Linear Mixed Models available from JMP®Pro 11.1 (SAS Institute, 2013). Several linear models were constructed to obtain the best estimate of error and to test the significance of effects (Tables 31-33). First, individual environments analysis of variance were performed to test homogeneity of variances. In all model instances (Model 1-3) replicates were considered to be random, while the others sources of variation were considered fixed (i.e. genotypes, environments, internodes No. etc.). Model 4 considered all sources of variation as random in order to estimate variance components using EMS procedure available from JMP®Pro 11.1 (SAS Institute, 2013).

Least square means (LSMeans) were estimated using REML method and were compared using Tukey-Kramer Honest Significant Differences (HSD) method at (α=0.05).

Model 1 (Table 31) fitted the response variables as a function of maturity response and genotype.

Model 1 $$y_{ijkl} = \mu + \alpha_i + \beta(\alpha)_{i(j)} + \tau_{k+} + \alpha\tau_{ik} + \gamma(\tau)_{l(k)} + \varepsilon_{ijkl}$$ [4.6]

Table 31. Model 1 characteristics.

Model Term	Term Description	Level	Assumptions
y_{ijkl}	Any observation from the experiment from each variable		
μ	Overall mean parameter common to any observation		
α_i	Fixed effect arisen from the i[th] environment	i = 1, 2, 3	$\sum_{i=1}^{n=3} \alpha_i = 0$
$\beta(\alpha)_{i(j)}$	Random effect arisen from the j[th] replication at the i[th] environment	j = 1, 2, 3, 4	$\beta(\alpha)_{i(j)} \sim NI\ (0, \sigma^2_{i(j)})$
τ_k	Fixed effect from the k[th] maturity group	k = 1, 2, 3,	$\sum_{k=1}^{n=3} \tau_i = 0$
$\alpha\tau_{ik}$	Fixed interaction effect between the i[th] environment and k[th] maturity group	i = 1, 2, 3 k = 1, 2, 3	$\sum_{i=1}^{n=1} \sum_{k=1}^{n=3} \alpha\tau_{ik} = 0$
$\gamma(\tau)_{l(k)}$	Fixed effect of the l[th] genotype within the k[th] maturity group	l = 1, 2….n k = 1, 2, 3	$\sum_{l=1}^{n} \sum_{k=3}^{n=3} \text{k} = 1, 2, 3 = 0$
$\alpha\gamma(\tau)_{il(k)}$	Fixed effect of the interaction between the i[th] environment and the l[th] genotype within the k[th] maturity group	i = 1, 2, 3 l = 1, 2….n k = 1, 2,	$\sum_{i=1}^{n=3} \sum_{l=1}^{n} \sum_{k=1}^{n=3} \alpha\tau_{ik} = 0$
ε_{ijkl}	Random error term		$\varepsilon_{ijkl} \sim NI(0, \sigma^2)$

Model 2 (Table 32) fitted the response variables as a function of genotype by maturity response

Model 2 $$y_{ijkl} = \mu + \alpha_i + \beta(\alpha)_{i(j)} + \gamma_k + \alpha\gamma_{ik} + \varepsilon_{ijkl} \quad [4.7]$$

Table 32. Model 2 characteristics.

Model Term	Term Description	Level	Assumptions
y_{ijkl}	Any observation from the experiment from each variable		
μ	Overall mean parameter common to any observation		
α_i	Fixed effect arisen from the i[th] environment	i = 1, 2, 3	$\sum_{i=1}^{n=3} \alpha_i = 0$
$\beta(\alpha)_{i(j)}$	Random effect arisen from the j[th] replication at the i[th] environment	i = 1, 2, 3 j = 1, 2, 3, 4	$\beta(\alpha)_{i(j)} \sim NI\ (0, \sigma^2_{i(j)}$
γ_k	Fixed effect from the k[th] genotype	k = 1, 2, …n	$\sum_{k=1}^{n=} \gamma_k = 0$
$\alpha\gamma_{ik}$	Fixed interaction effect between the i[th] environment and k[th] genotype	i = 1, 2, 3 k = 1, 2, …n	$\sum_{i=1}^{n=3} \sum_{k=1}^{n=} \alpha\gamma_{ik} = 0$
ε_{ijkl}	Random error term		$\varepsilon_{ijkl} \sim NI(0, \sigma^2)$

Model 3 (Table 33) fitted for response variables as a function of genotype by maturity response

$$y_{ijkl} = \mu + \alpha_i + \beta(\alpha)_{i(j)} + \gamma_k + \alpha\gamma_{ik} + \delta(\gamma)_{l(k)} + \alpha\delta(\gamma)_{il(k)} + \varepsilon_{ijkl} \quad [4.8]$$

Table 33. Model 3 characteristics.

Model Term	Term Description	Level	Assumptions
y_{ijkl}	Any observation from the experiment from each variable		
μ	Overall mean parameter common to any observation		
α_i	Fixed effect arisen from the ith environment	i = 1, 2, 3	$\sum_{i=1}^{n=3} \alpha_i = 0$
$\beta(\alpha)_{i(j)}$	Random effect arisen from the jth replication at the ith environment	i = 1, 2, 3 j = 1, 2, 3, 4	$\beta(\alpha)_{i(j)} \sim NI\ (0, \sigma^2_{i(j)})$
γ_k	Fixed effect from the kth genotype	k = 1, 2, …n	$\sum_{k=1}^{n=} \gamma_k = 0$
$\alpha\gamma_{ik}$	Fixed interaction effect between the ith environment and kth genotype	i = 1, 2, 3 k = 1, 2, …n	$\sum_{i=1}^{n=3} \sum_{k=1}^{n=} \alpha\gamma_{ik} = 0$
$\delta(\gamma)_{l(k)}$	Fixed effect of the lth internode within the kth genotype	l = 1, 2, 3, 4 k = 12, …n	$\sum_{l=3}^{n=6} \sum_{k=1}^{n} \delta(\gamma)_{l(k)} = 0$
$\alpha\delta(\gamma)_{il(k)}$	Fixed interaction effect of the ith environment with the lth internode within the kth genotype	i = 1, 2, 3 k = 1, 2, …n l = 1, 2, 3,.4	$\sum_{i=1}^{n=3} \sum_{l=1}^{n=4} \sum_{k=1}^{n=} \alpha\delta(\gamma)_{il(k)} = 0$
ε_{ijkl}	Random error term		$\varepsilon_{ijkl} \sim NI(0, \sigma^2)$

Model 4 fitted the response variables as a function of genotype by maturity response, and setting all the terms as random to estimate variance components.

$$y_{ijkl} = \mu + \alpha_i + \beta(\alpha)_{i(j)} + \gamma_k + \alpha\gamma_{ik} + \delta(\gamma)_{l(k)} + \alpha\delta(\gamma)_{il(k)} + \varepsilon_{ijkl} \qquad [4.9]$$

Results

Combined Analysis of Internode Geometry, Shape and Biomechanical Properties

In the combined analysis, all main sources of variation were significant for all dependent variables that were measured except for replications within environments [Rep(Env)] (Table 34). Interactions of these main effects were also significant based on differential responses of the different maturity groups and genotypes within the maturity response [gen(mat resp)] (Table 34). Because of the significant and meaningful interactions between maturity groups and environments, further analysis was based on each maturity group (Fig. 20). This resulted in modeling (Model 2, Table 32) internode geometry, shape, and biomechanical properties by grouping the 15 genotypes according to their maturity response.

Table 34. Model 1-ANOVA for internode geometry, shape, and biomechanical properties by maturity response of 15 genotypes evaluated in three environments in Texas during the 2014 season.

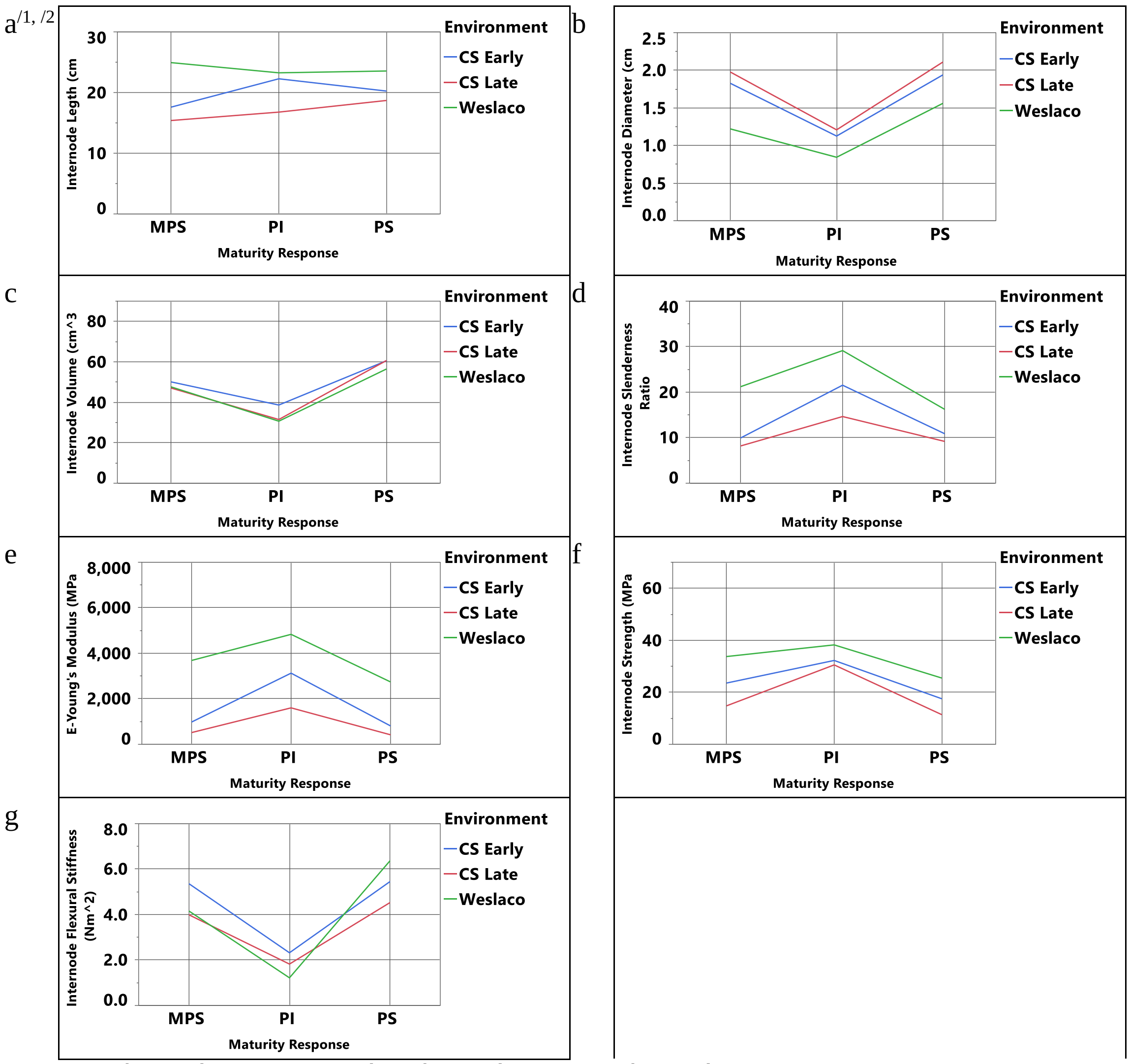
		Geometry & Shape				Biomechanical Properties		
Source[/2]	DF	Internode Length	Internode Diameter	Internode Volume	Internode Slenderness Ratio	E-Young's Modulus	Internode Strength	Flexural Stiffness
Model	53	<.0001[1]	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
env	2	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
rep(env)	9	0.5744	<.0001	0.0822	<.0001	<.0001	<.0001	0.1417
mat resp	2	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
mat resp* env.	4	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
gen(mat resp)	12	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
gen(mat resp) * env	24	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Error	4234							
C. Total	4287							
RSquare		0.51	0.67	0.63	0.72	0.71	0.61	0.62
CV		0.50	0.03	1.13	0.38	0.17	0.07	0.04

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.
/2 (env) = environment; [rep(env)] = replicate within environment; (mat resp) = maturity response; [mat resp* env] = maturity response and environment interaction; [gen(mat resp)] = genotype within maturity response; [gen(mat resp) * env] = interaction of genotype within maturity response and the environment

Table 35. LSMeans for internode geometry, shape, and biomechanical properties by maturity response of 15 genotypes evaluated in three environments in Texas during the 2014 season.

	Geometry & Shape								Biomechanical Properties					
Maturity/ Photoperiod	Length		Diameter		Volume		Slenderness Ratio		E-Young's Modulus		Strength		Flexural Stiffness	
PI	20.76	A[/1]	1.02	C	33.60	C	21.77	A	2743.25	A	32.58	A	1.67	C
MPS	19.31	A	1.57	B	48.24	B	13.11	B	859.54	B	22.05	B	3.90	B
PS	20.83	B	1.76	A	59.21	A	12.10	C	787.95	C	16.63	C	5.16	A

/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD
/2 PI = Photoperiod sensitive, MPS = Moderate photoperiod sensitive, PS = Photoperiod sensitive



/1 PI = Photoperiod sensitive, MPS = Moderate photoperiod sensitive, PS = Photoperiod sensitive
/2 CS Early = College Station Early; CS Late = College Station Late

Figure 20. Maturity x Environment interaction plots for traits collected at three environments in Texas during the 2014 season. a) internode length, b) internode diameter, c) internode volume, d) internode slenderness ratio, e) e-young's modulus, and f) strength, and g) flexural stiffness.

Whole Plant and Internode Geometry, Shape, and Biomechanics

Photoperiod Insensitive Maturity Group

All main effects and their interaction in the photoperiod insensitive genotypes were highly significant for all measured traits except the environment effect for the biomechanical property strength (Table 36). In general, the [env*int(gen] reflected the conditions during the growth and development of each internode (Figure 26 and Figure 27).

The photoperiod-insensitive genotypes were the tallest and had the highest slenderness ratio in College Station late planting (CS Late) (Table 37 and Fig. 21 a, c). The longest internode length and thinnest diameter occurred in Weslaco (WE) (Table 37 and Fig. 21 d and e). Genotypes also exhibited the highest internode slenderness ratio, E-Young's modulus, and strength at WE, but flexural stiffness was the lowest (Table 37 and Fig. 21 g, h, i, j).

Among the photoperiod insensitive genotypes (PI), R.07007 was the tallest and had the thickest stem diameter, and exhibited a moderate E-Young's modulus and strength (Table 38 and Fig. 22-23 a, b, h). R.SOR2014 had the highest plant slenderness ratio, the longest internode length, thinnest internode diameter, and smallest internode volume (Table 38 and Fig. 22-23 a, d, e, f). In addition the R.SOR2014 had the highest E-Young's modulus and strength but the lowest flexural stiffness among all the PI genotypes (Table 38 and Fig. 23 h, i, j). The genotype R.SOR2014 varied for plant height across all environments but had consistently the thinnest, more slender, stiffest, and strongest internodes among all the PI genotypes in all three environments (Figure 24-25 a, b, c, g, h, i), and had consistently the lowest flexural stiffness across all environments (Fig. 24 j).

Table 36. Model 2-ANOVA for all traits collected on a group of photoperiod insensitive sorghum genotypes evaluated in three environments in Texas during the 2014 season.

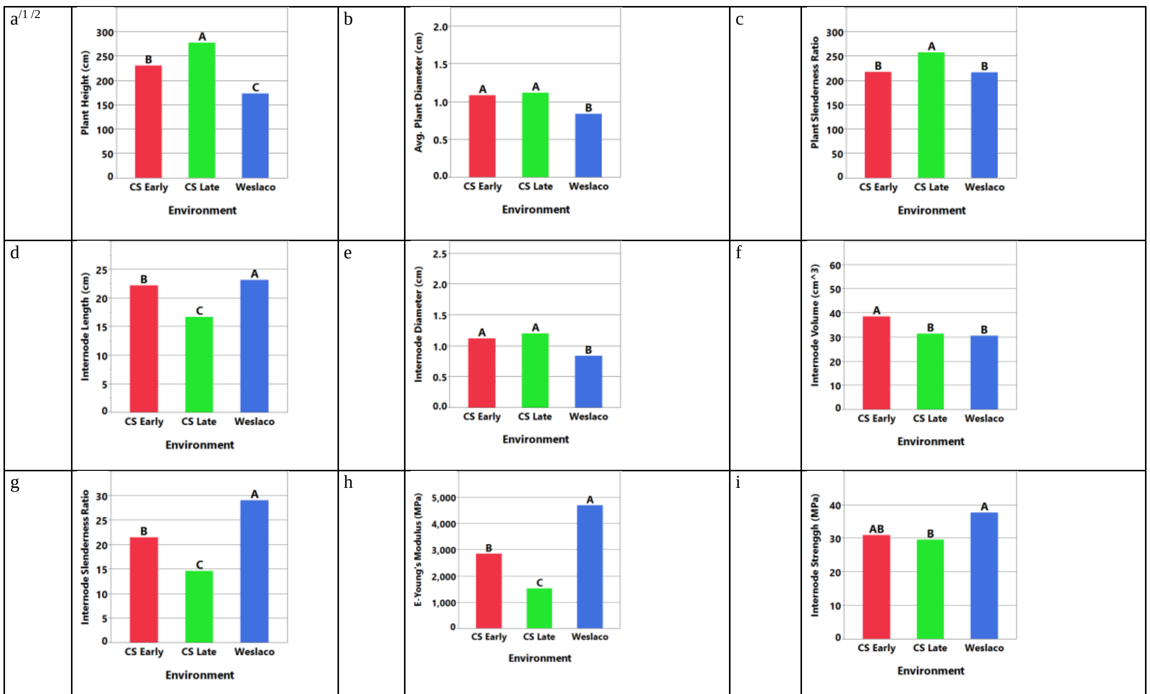
	Whole Plant Geometry (Model 2)						Internode Geometry & Shape (Model 3)					Biomechanics (Model 3)			
	Height		Avg. Diameter		Slenderness Ratio			Length	Diameter	Volume	Slenderness Ratio		E-Young's modulus	Strength	Flexural Stiffness
Source	DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F	Prob > F	Prob > F	Prob > F	DF	Prob > F	Prob > F	Prob > F
Model	17	<.0001	17	<.0001	17	<.0001	44	<.0001	<.0001	<.0001	<.0001	44	<.0001	<.0001	<.0001
Env	2	<.0001	2	<.0001	2	0.0036	2	<.0001	<.0001	<.0001	<.0001	2	<.0001	0.0732	<.0001
rep(env)	9	<.0001	9	<.0001	9	<.0001	9	0.0501	<.0001	<.0001	<.0001	9	<.0001	<.0001	<.0001
gen	2	<.0001	2	<.0001	2	<.0001	2	<.0001	<.0001	<.0001	<.0001	2	<.0001	<.0001	<.0001
env*gen	4	<.0001	4	<.0001	4	<.0001	4	<.0001	<.0001	<.0001	<.0001	4	<.0001	<.0001	<.0001
int no.(gen)							9	<.0001	<.0001	<.0001	<.0001	9	<.0001	<.0001	<.0001
env*int no(gen)							18	<.0001	<.0070	<.0001	<.0001	18	<.0001	<.0001	<.0001
Error	1,237		1,213		1,213		979		.			910	.		
C. Total	1,254		1,230		1,230		1,023		.		.	954	.	.	.
RSquare		0.98		0.84		0.81		0.81	0.84	0.77	0.81		0.61	0.46	0.79
CV%		3.41		9.90		9.86		11.5	10.6	14.2	20		6.2	8.9	14.2

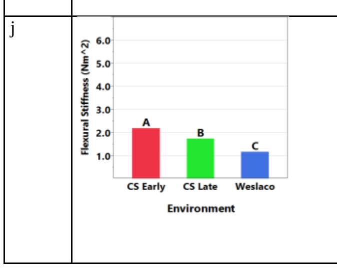
P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant

Table 37. LSMeans for all traits from a group of photoperiod insensitive sorghum genotypes evaluated in three environments in Texas during the 2014 season.

	Whole Plant Geometry & Shape			Internode Geometry & Shape				Biomechanical Properties		
Environment	Plant Height (cm)	Avg. Plant Diameter (cm)	Plant Slenderness Ratio	Length (cm)	Diameter (cm)	Volume (cm^3)	Slenderness Ratio	E-Young's Modulus MPa	Strength MPa	Flexural Stiffness Nm^2
CSE[2]	231 B[1]	1.09 A	218 B	22.3 B	1.1 A	38.6 A	21.5 B	2,847.75 B	2,847.75 A	2.17 A
CSL	278 A	1.12 A	257 A	16.8 C	1.2 A	31.5 B	14.6 C	1,668.80 C	1,668.80 A	1.77 B
WE	173 C	0.83 B	221 B	23.2 A	0.8 B	30.7 B	29.1 A	4,438.85 A	4,438.85 A	1.12 A
Average	227	1.01	232	20.8	1.1	33.6	21.8	2,985.13	2,985.13	1.69

/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.
/2 CSE = College Station Early; CSL = College Station Late; WE = Weslaco





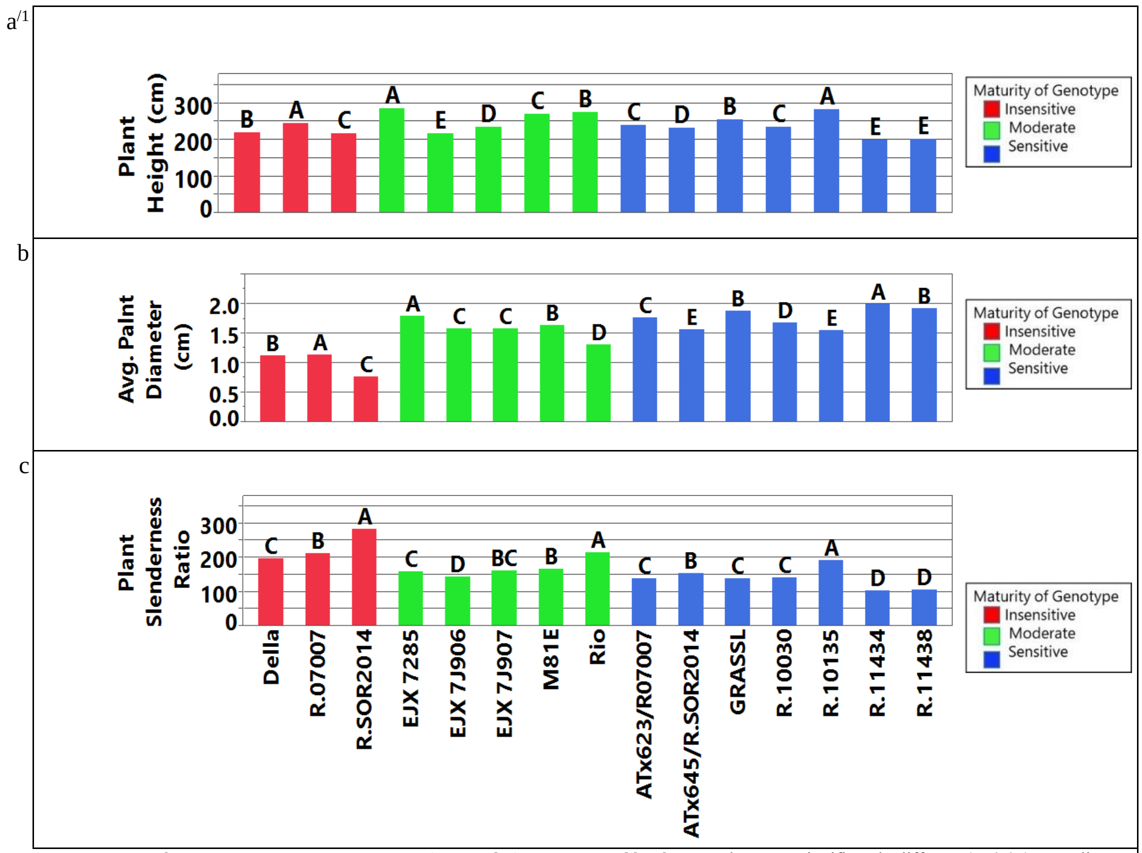
/1 Environments not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.
/2 CS Early = College Station Early; CS Late = College Station Late

Figure 21. LSmeans for whole plant and internode geometry, shape, and biomechanical properties for three photoperiod insensitive genotypes evaluated in three environment in Texas during the 2014 season a) plant height, b) avg. plant diameter, c) plant slenderness ratio, d) internode length, e) internode diameter, f) internode volume, g) slenderness ratio, h) *e*-young's modulus, i) strength, j) flexural stiffness.

Table 38. LSMeans for whole plant and internode geometry for a group of photoperiod insensitive sorghum genotypes evaluated in three environments in Texas during the 2014 season.

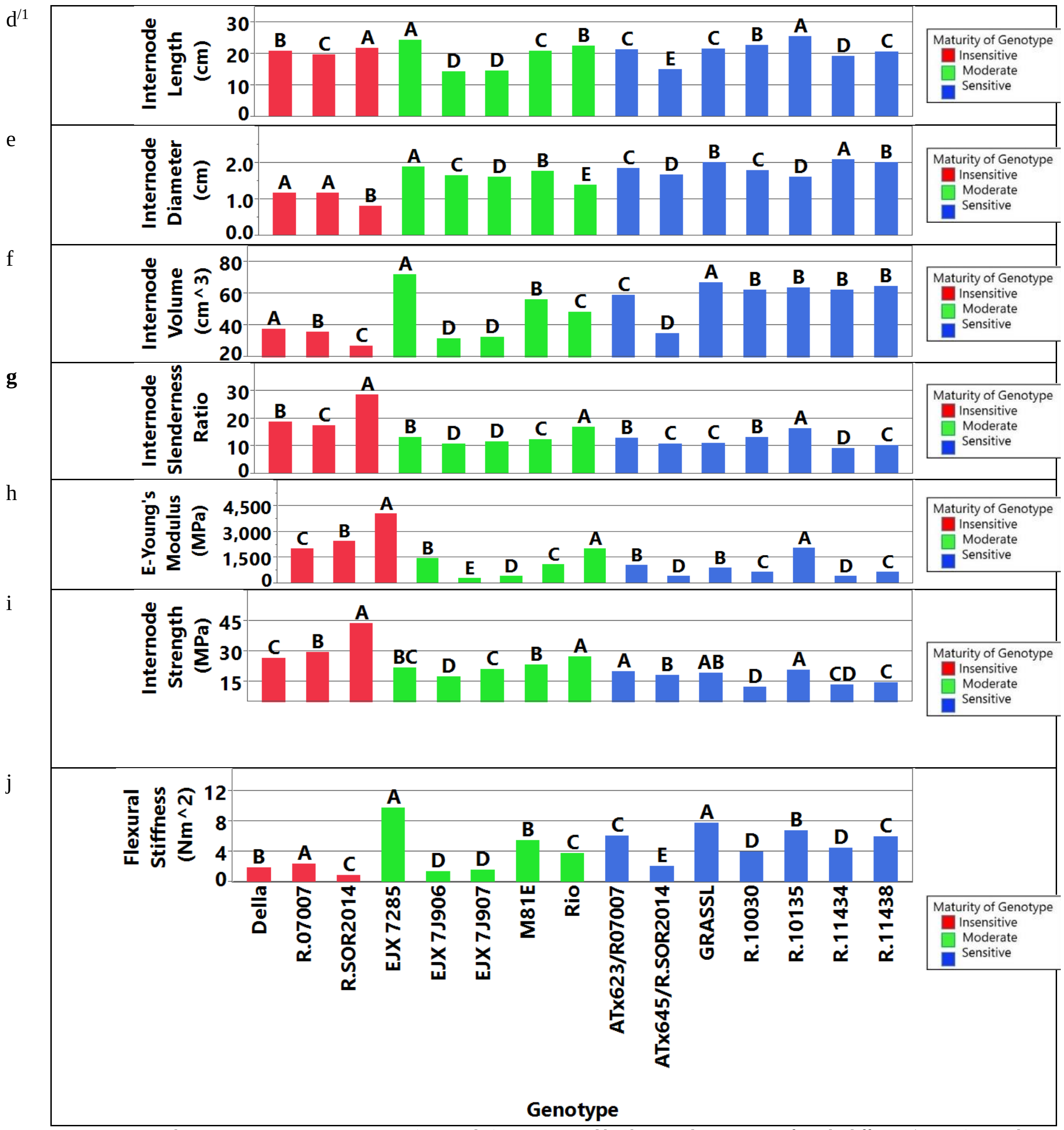
		Whole Plant Geometry & Shape			Internode Geometry & Shape				Biomechanical Properties		
Genotype	Lodging Rating 1-10	Plant Height (cm)	Avg, Plant Diameter (cm)	Plant Slenderness Ratio	Length (cm)	Diameter (cm)	Volume (cm^3)	Slenderness Ratio	E-Young's Module (MPa)	Internode Strength (MPa)	Flexural Stiffness (Nm^2)
Della	7	219 B[/1]	1.12 B	197 C	21.0 B	1.2 A	37.9 A	19.0 B	2,087 C	26.74 C	1.91 B
R.07007	7	245 A	1.15 A	213 B	19.6 C	0.8 A	36.0 B	17.6 C	2,488 B	29.81 B	2.37 A
R.SOR2014	1	217 C	0.77 C	286 A	21.7 A	1.1 B	26.9 C	28.7 A	4,062 A	44.26 A	0.88 C
Average		227	1.01	232	20.8	1.0	33.6	21.8	2,879	33.60	1.72

/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.



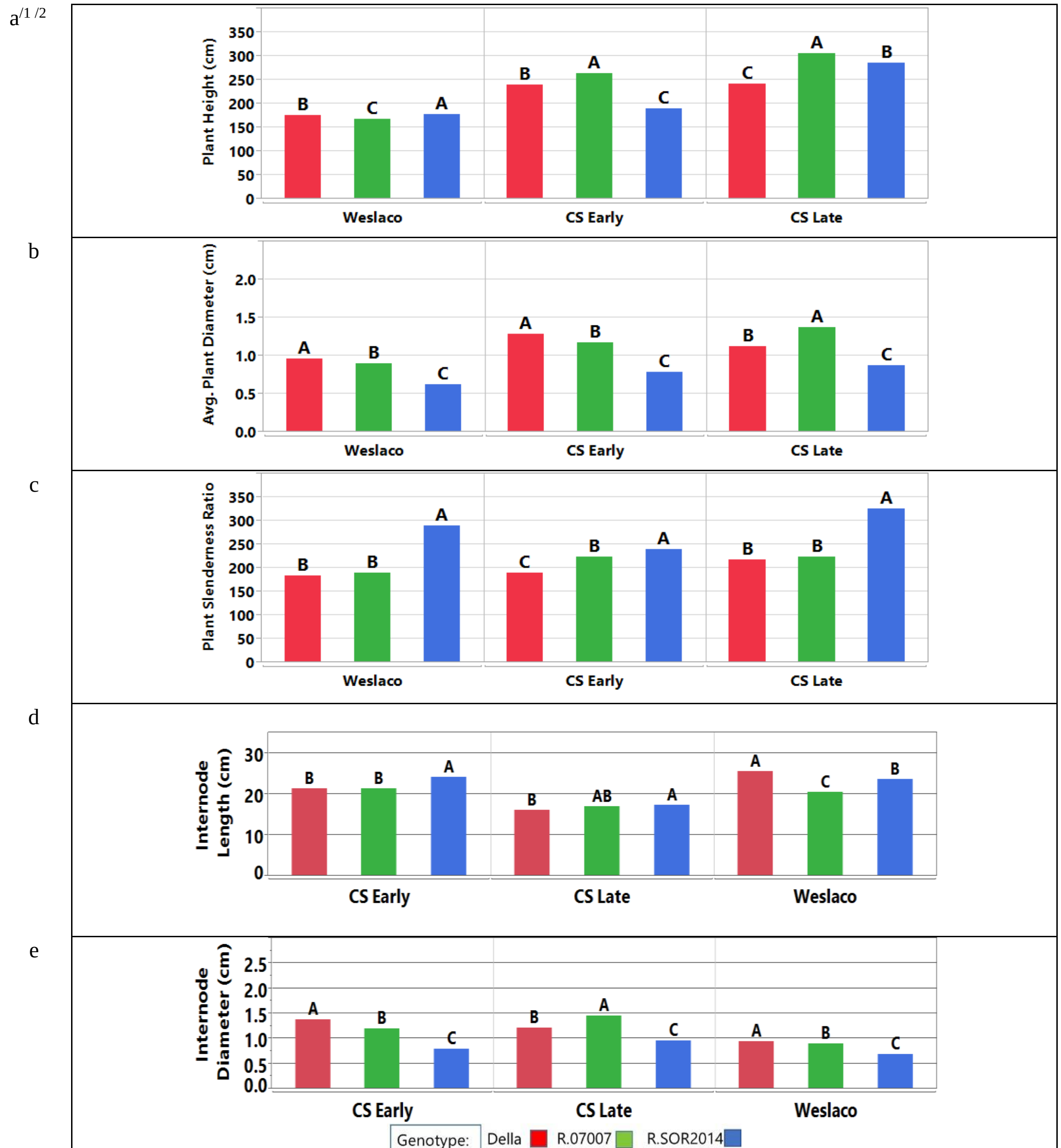
/1 Genotypes within same maturity response group (same color) not connected by the same letter are significantly different (α=0.05) according to Tukey's HSD.

Figure 22. LSMeans for whole plant geometry, shape, and biomechanical properties for a group of photoperiod insensitive (RED) sorghum genotypes evaluated in three environments in Texas during the 2014 season: a) plant height b) avg. plant diameter, c) plant slenderness ratio



/1 Genotypes within same maturity response group (same color) not connected by the same letter are significantly different (α=0.05) according to Tukey's HSD.

Figure 23. LSMeans for whole plant and internode geometry, shape, and biomechanical properties for a group of photoperiod insensitive (red) sorghum genotypes evaluated in in three environments in Texas during the 2014 season: a) plant height, b) avg. plant diameter, c) plant slenderness ratio, d) internode length e) internode diameter, f) internode slenderness ratio, g) internode volume, h) e-young's modulus i) internode strength, j)flexural stiffness



/1 Within an environment, genotypes not connected by the same letter are significantly different (α=0.05) according to Tukey's HSD.
/2 CS Early = College Station Early; CS Late = College Station Late

Figure 24. LSMeans for whole plant and internode geometry, shape, and biomechanical properties for a group of photoperiod insensitive sorghum genotypes evaluated in three environments in Texas during the 2014 season: a) plant height, b) avg. plant diameter, c) plant slenderness ratio, d) internode length, e) internode diameter

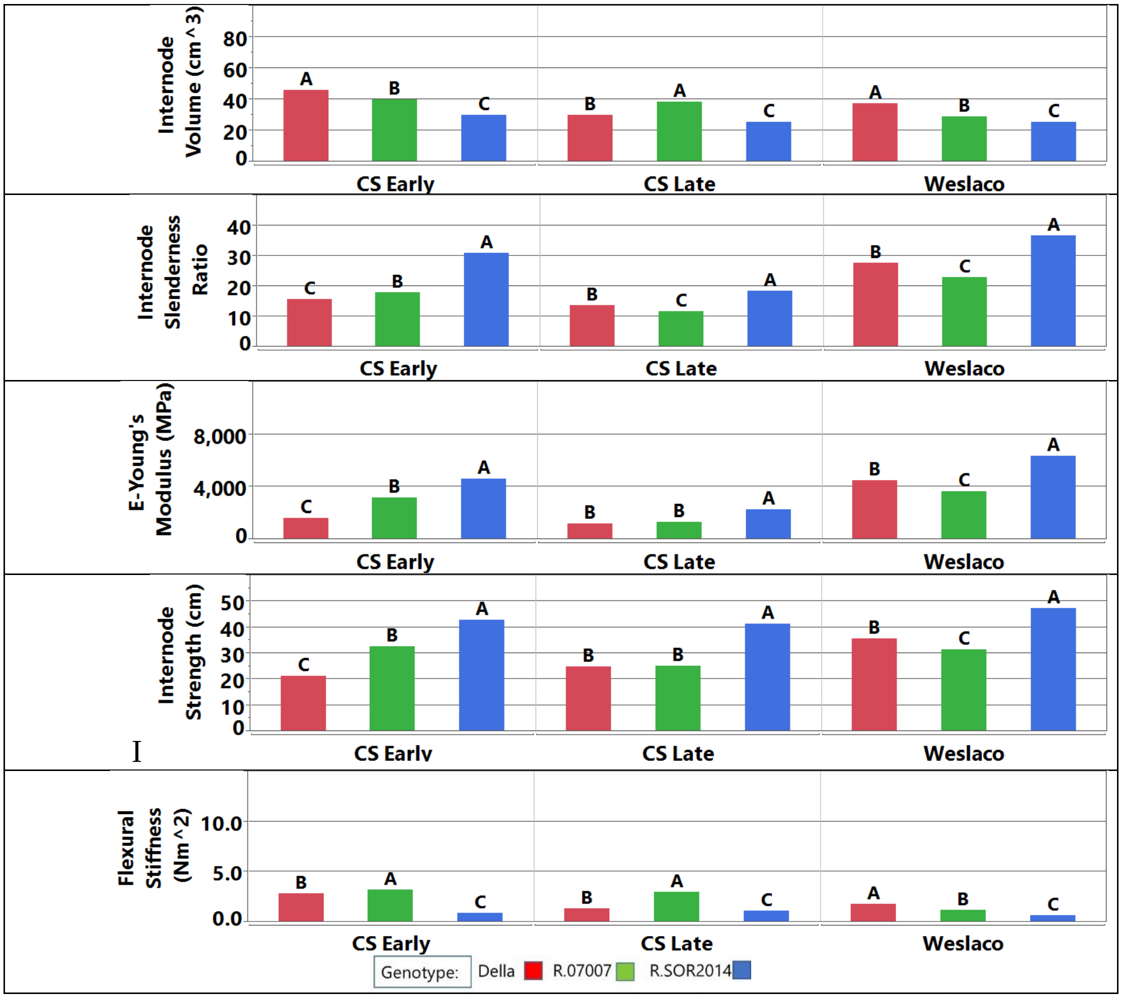
f/1/2

g

h

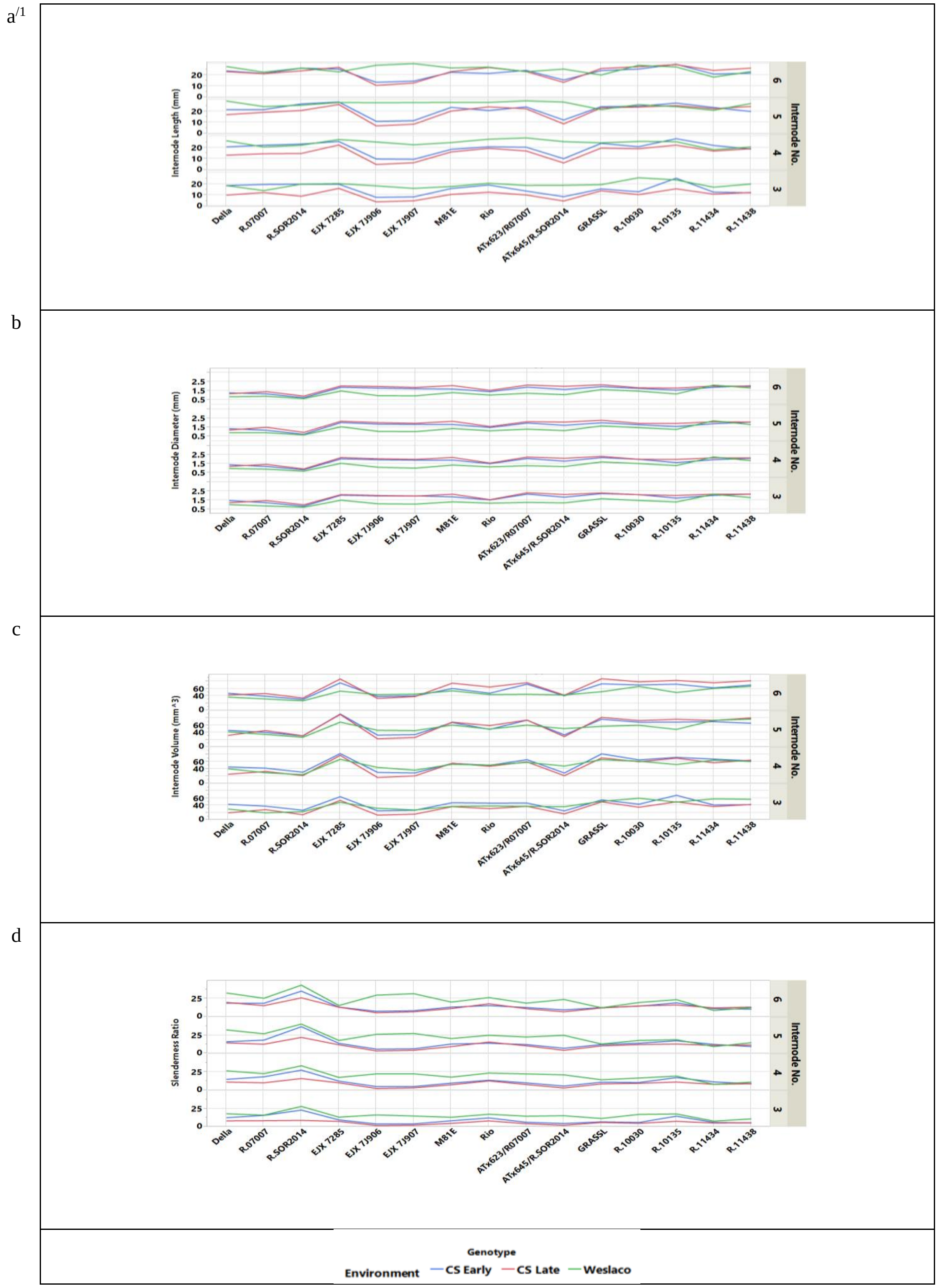
i

j



/1 Within each environmenty, genotypes not connected by the same letter are significantly different (α=0.05) according to Tukey's HSD
/2 CS Early = College Station Early; CS Late = College Station Late

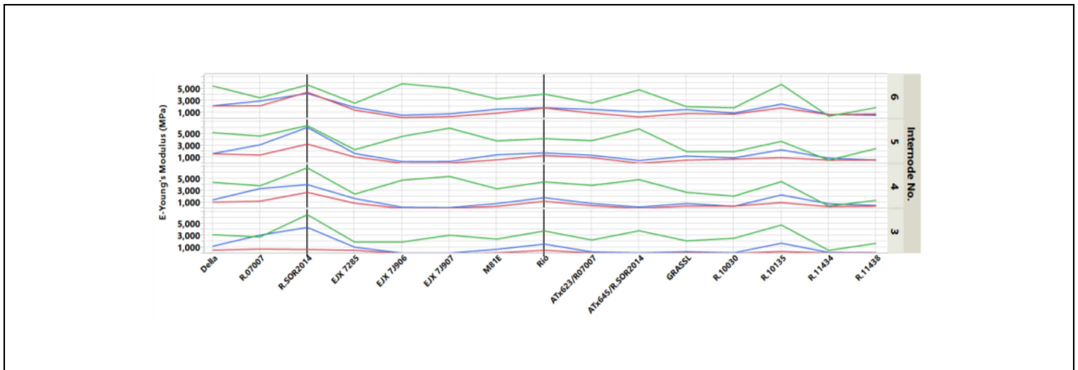
Figure 25. LSMeans for whole plant and internode geometry, shape and biomechanical properties for a group of photoperiod insensitive sorghum genotypes evaluated in three environments in Texas during the 2014 season: f) internode slenderness ratio, g) internode volume, h) E-Young's modulus, i) internode strength, and j) flexural stiffness



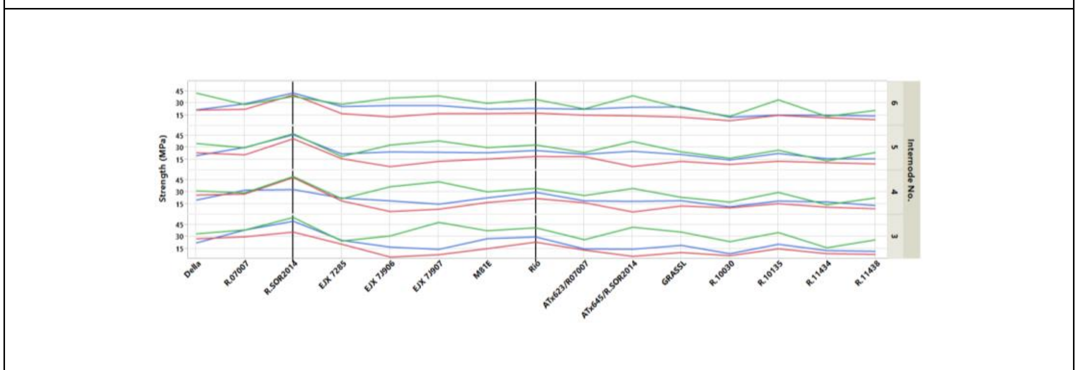
/1 CS Early = College Station Early; CS Late = College Station Late

Figure 26. Internode(genotype) x environment interaction: a) internode length, b) internode diameter c) internode volume, and d) slenderness ratio

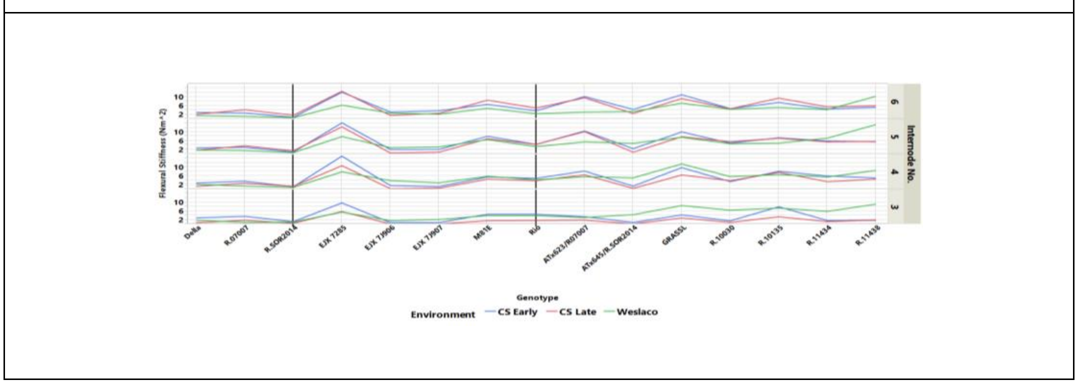
e/1



f



g



/1 CS Early = College Station Early; CS Late = College Station Late

Figure 27. Internode(genotype) x environment interaction: e) E-Young's modulus, f) strength, and g) flexural stiffness

Moderate Photoperiod Sensitive Maturity Group

Analysis of variance of the MPS group detected significant effects for all main effects and their interactions except for the rep(env) effect on flexural stiffness (Table 39). A significant [env*int(gen)] interaction was detected, as a reflection of the specific growing and developing conditions each genotype at each environment.

The MPS genotypes were the tallest in CSE and had the thickest diameter in CSL (Table 40 and Figure 28 a, b). Genotypes from the MPS group also had a greater internode slenderness ratio, longer internodes, highest *E*-young's modulus, and highest internode strength at WE (Table 40 and Figure 28 g, d, h, i).

Of the MPS genotypes, EJX7285 was the tallest, thickest plant diameter, longest internode length, thickest internode diameter, a moderate internode slenderness ratio, and the highest internode flexural stiffness (Table 41 and Figure 22-23. a, b, d, e, g, j). Rio had the largest plant and internode slenderness ratio as well as the highest internode *E*-young's modulus and strength (Table 41 and Figure 22-23. c, j, h, i)

Several genotypes experienced a significant Genotype x Environment interaction (Figure 29-30). For example, the genotypes EJX7J906 and EJX7J907 where the shortest in WE and CSE but among the tallest in CSL (Figure 28 a). EJX7J906 and EJX7J907 also had among the lowest internode slenderness ratio, *E*-young's modulus in CSE and CSL, however at WE they were among the highest for internode slenderness ratio and *E*-young's modulus (Figure 30 g, h). In addition, both genotypes were consistently the lowest for flexural stiffness in all environments (Figure 30 j). Rio had a higher internode strength in CSE and CSL except at WE.

Table 39. Model 3-ANOVA for all traits collected for a group of moderate photoperiod sensitive sorghum genotypes evaluated at three environments in Texas during the 2014 season.

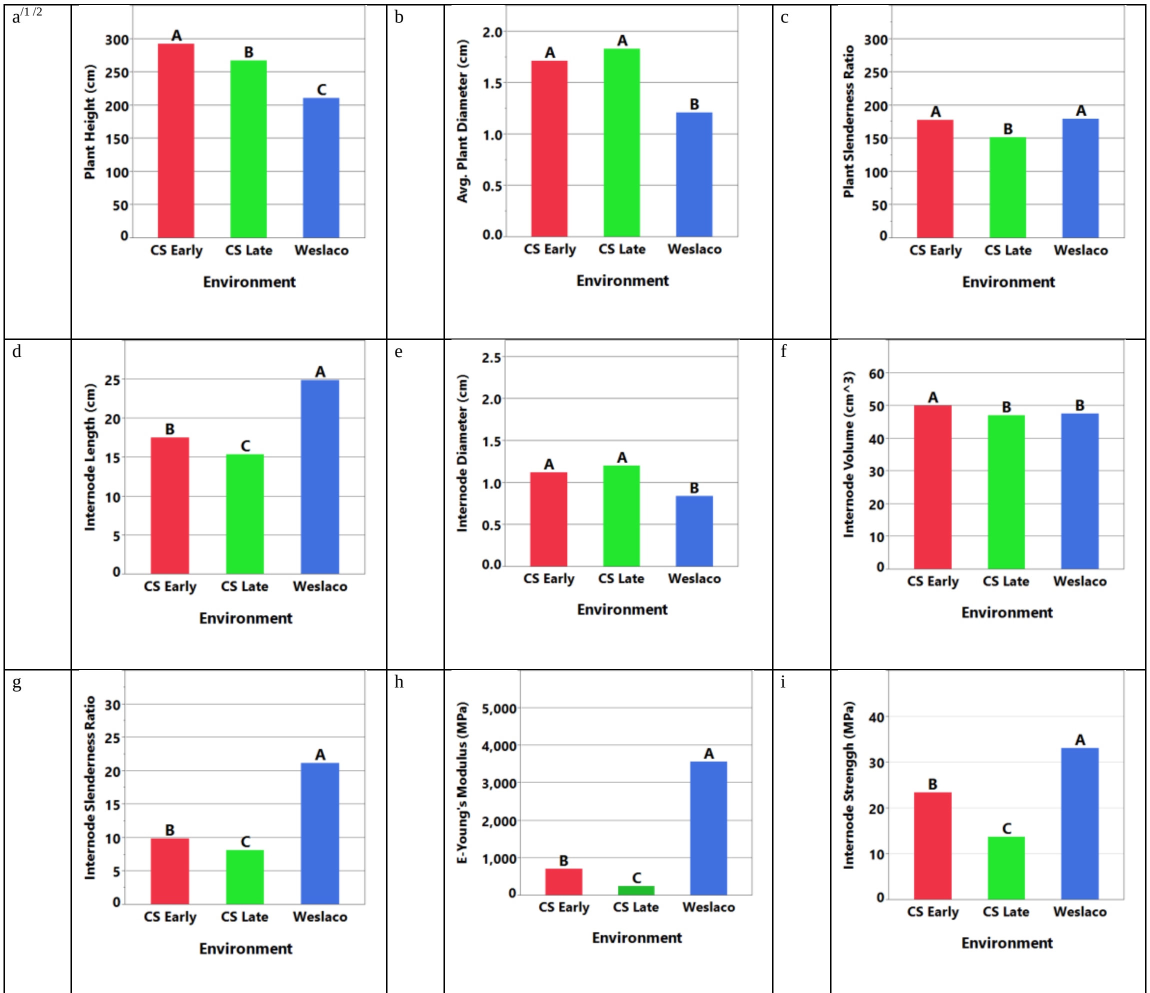
	Whole Plant Geometry & Shape						Internode Geometry and Shape					Biomechanics			
	Plant Height		Avg, Plant Diameter		Plant Slenderness Ratio			Length	Diameter	Volume	Slenderness Ratio		*E*-Young's Modulus	Strength	Flexural Stiffness
Source	DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F	Prob > F	Prob > F	Prob > F	DF	Prob > F	Prob > F	Prob > F
Model	23	<.0001[1]		<.0001		<.0001	68	<.0001	<.0001	<.0001	<.0001	68	<.0001	<.0001	<.0001
env	2	<.0001		<.0001		<.0001	2	<.0001	<.0001	<.0001	<.0001	2	<.0001	<.0001	<.0001
rep(env)	9	<.0001		<.0001		<.0001	9	0.0007	<.0001	0.0147	<.0001	9	<.0001	0.019	0.366
gen	4	<.0001		<.0001		<.0001	4	<.0001	<.0001	<.0001	<.0001	4	<.0001	<.0001	<.0001
env*gen	8	<.0001		<.0001		<.0001	8	<.0001	<.0001	<.0001	<.0001	8	<.0001	<.0001	<.0001
int no.(gen)							15	<.0001	<.0001	<.0001	<.0001	15	<.0001	<.0001	<.0001
env*int no. (gen)							30	<.0001	<.0539	<.0001	<.0001	30	<.0001	<.0001	<.0001
Error	2,073		1,997		1,997		1,723	.	.	.	.	1,700	.	.	.
C. Total	2,096		2,020		2,020		1,791	.	.	.	.	1,768	.	.	.
RSquare		0.95		0.82		0.76		0.88	0.87	0.83	0.9		0.87	0.61	0.76
CV%		4.58		9.46		9.61		11.6	9.7	14.4	15.8		7.6	10.3	19.4

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

Table 40. LSMeans for all traits for a group of moderate photoperiod sensitive sorghum evaluated at three environments in Texas during the 2014 season.

	Whole Plant Geometry & Shape			Internode Geometry & Shape				Biomechanical Properties		
	Plant Height	Avg. Plant Diameter	Plant Slenderness Ratio	Length	Diameter	Volume	Slenderness Ratio	E-Young's Modulus	Strength	Flexural Stiffness
Environment	(cm)	(cm)		(cm)	(cm)	(cm^3)		MPa	MPa	Nm^2
CSE[2]	293 A[1]	1.67 B	179 A	17.6 B	1.8 B	50.1 A	9.9 B	666.51 B	666.51 B	5.17 B
CSL	268 B	1.82 A	151 B	15.4 C	2 A	47 B	8.2 C	327.74 C	327.74 C	4.2 C
WE	211 C	1.23 C	175 A	24.9 A	1.2 C	47.6 B	21.2 A	2,239.55 A	2,239.55 A	6.21 A
Average	257	1.57	168	19.3	1.7	48.2	13.1	1,077.93	1,077.93	5.19

/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.
/2 CSE =College Station Early; CSL = College Station Late; WE = Weslaco



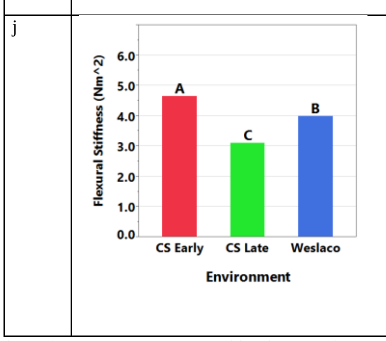


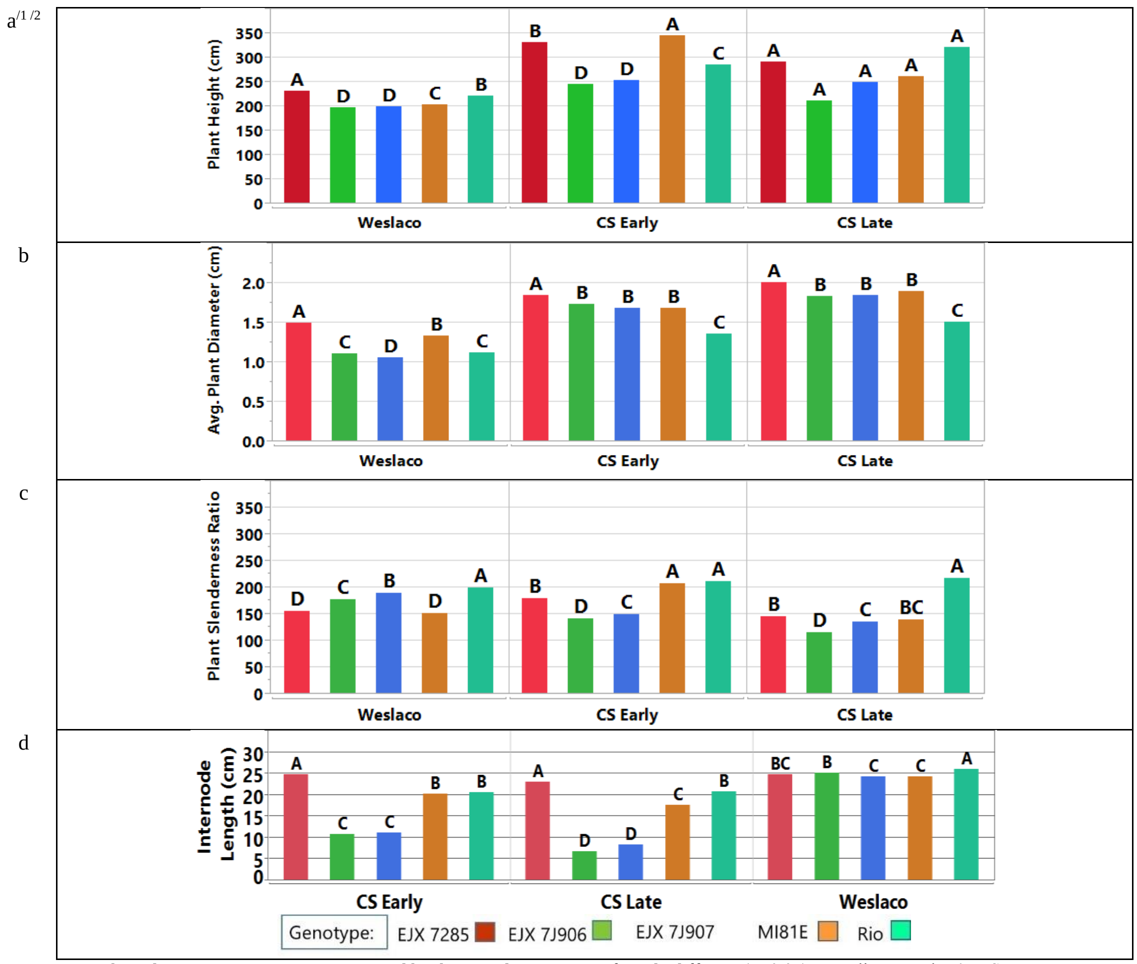
Figure 28. LSMeans for all traits for a group of moderate photoperiod sensitive sorghum evaluated at individual environments (CSE), (CSL), and (WE), Texas in the 2014 season: a) plant height b) avg. plant diameter, c) plant slenderness ratio, d) internode length, e) internode diameter, f) internode volume, g) internode slenderness ratio, h) E-Young's modulus i) internode strength, j) flexural stiffness

/1 environments not connected by the same letter are significantly different at (α=0.05) according to tukey's hsd.
/2 CS Early = College Station Early; CS Late = College Station Late

Table 41. LSMeans for all traits collected for a group of moderate photoperiod sensitive genotypes evaluated in three environments in Texas during the 2014 season.

		Whole Plant Geometry & Shape			Internode Geometry				Internode Biomechanics		
	Lodging Rating	Plant Height	Avg, Plant Diameter	Plant Slenderness Ratio	Length	Diameter	Volume	Slenderness Ratio	E-Young's Module	Internode Strength	Flexural Stiffness
Genotypes	1-9	(cm)	(cm)		(cm)	(cm)	(cm^3)		(MPa)	(MPa)	(Nm^2)
EJX 7285	7	286 A[/1]	1.79 A	161 C	24.3 A	1.7 A	72.1 A	13.2 B	1,478 B	21.76 C	9.63 A
EJX 7J906	1	219 E	1.56 C	145 D	14.3 D	1.6 C	31.8 D	11.1 C	309 E	17.44 D	1.41 D
EJX 7J907	1	234 D	1.53 C	159 C	14.7 D	1.8 D	32.4 D	11.6 C	428 D	20.48 C	1.6 D
M81E	5	270 C	1.64 B	167 B	20.8 C	1.4 B	56.4 B	12.6 B	1,122 C	23.46 B	5.46 B
Rio	5	277 B	1.33 D	209 A	22.5 B	1.7 E	48.5 C	17.0 A	2,015 A	27.33 A	3.77 C
Average		257	1.57	168	19.3	1.64	48.2	13.1	1,070	22.09	4.37

/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.

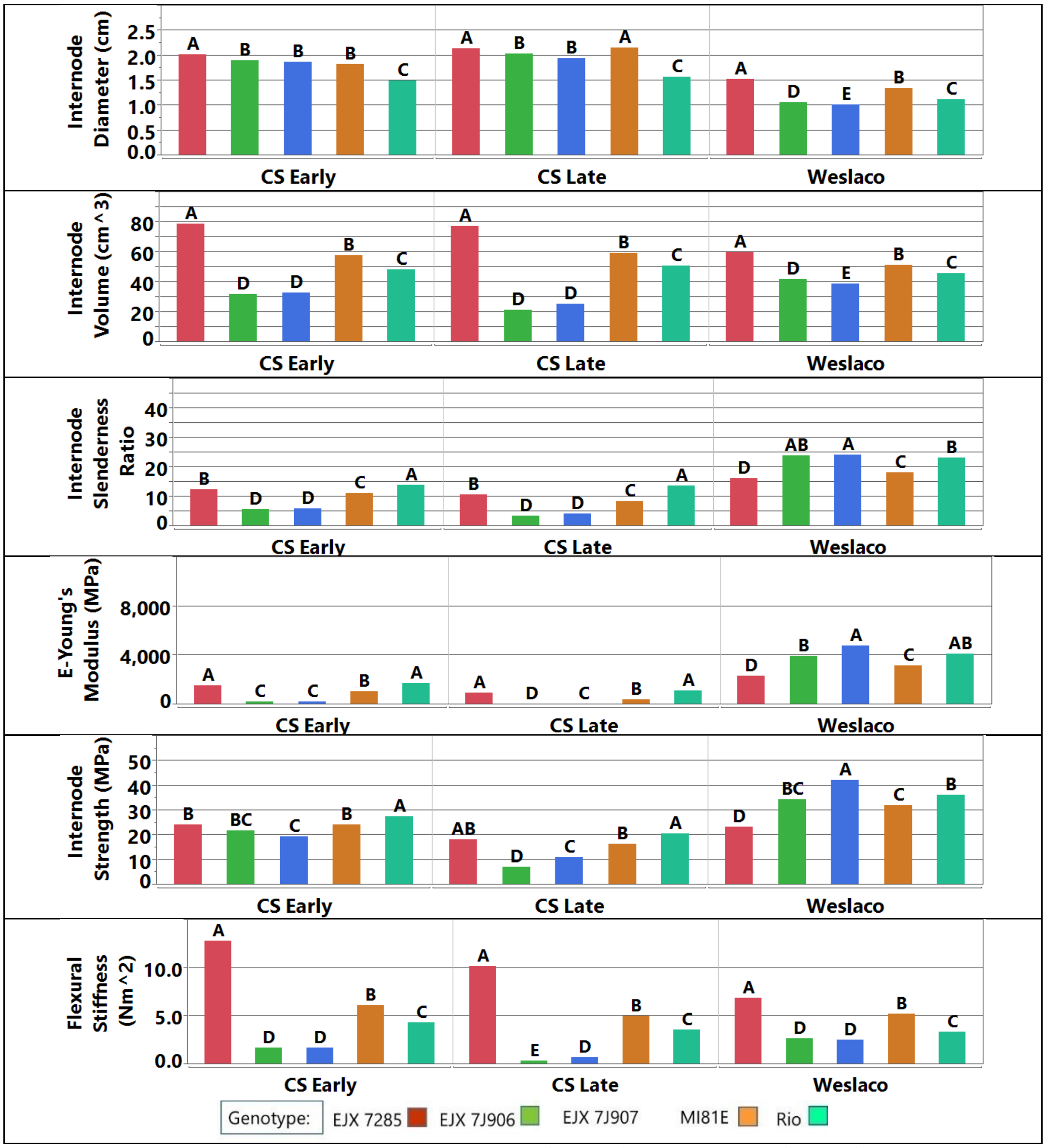


/1 Within a location, genotypes not connected by the same letter are significantly different (α=0.05) according to Tukey's HSD

/2 CSE =College Station Early; CSL = College Station Late; WE = Weslaco

Figure 29. LSMeans for whole plant and geometry, shape, and biomechanical properties for a group of moderate photoperiod insensitive sorghum genotypes evaluated three environments in Texas during the 2014 season: a) plant height, b) avg. plant diameter, c) plant slenderness ratio, d) internode length

e[1/2]



/1 Within a location, genotypes not connected by the same letter are significantly different (α=0.05) according to Tukey's HSD
/2 CSE =College Station Early; CSL = College Station Late; WE = Weslaco

Figure 30. LSMeans for whole plant and geometry, shape, and biomechanical proeprties for a group of moderate photoperiod insensitive sorghum genotypes evaluated at three environments in Texas during the 2014 season: e) internode diameter, f) internode volume, g) internode slenderness ratio, h) E-Young's modulus, i) internode strength, j) internode flexural stiffness.

Photoperiod Sensitive Maturity Group

For the PS maturity group, ANOVA detected highly significant effects (P<0.0001) from all sources of variation and all traits measured (Table 12). The [env*int(gen)] interaction was highly significant (Table 41 and Figure 26 and 27). This was due to the growth and development conditions during plant cycle. General trends where that internodes six were longer in most all environment for most genotypes and internode 3 was consistently thicker in all environments (Figure 26 a, b). In addition internode 6 had a greater E-young's modulus in most genotypes for all environments (Figure 27. e).

Like the other two maturity groups, PS genotypes were tallest in CSE, had the thickest plant diameter in CSL, and a greater plant slenderness ratio in (WE) (Table 42, Figure 31 a, b, c). Interestingly, the internodes of all genotypes were longer, more slender, stiffer, stronger, and exhibited a greater resistance to bending in WE (Table 42 and Figure 31. a, g, h, i, j).

The genotype R.10135 was the tallest, exhibited the highest plant slenderness ratio, the longest internodes, and the greatest internode volume among all genotypes (Table 44 and Fig. 22-23 a, c, d, f). The genotype ATx645/RSOR2014 exhibited the shortest internodes, a thin internode diameter, low volume, low slenderness ratio, low E-young's modulus, low internode flexural stiffness, and among the strongest internodes (Table 44 and Fig. 22-23 d, e, f, g, h, j, i).

There were highly significant differences for the photoperiod sensitive genotypes within each environment (Table 42). Results demonstrate that the genotype ATx645/RSOR2014 was consistently the tallest and the most slender in all environments evaluated (Figure 32 a, c). In addition it had the shortest internode in CSE and CSL but the longest internodes in WE (Figure 32 d). Similarly, the genotype ATx645/RSOR2014 had the lowest E-Young's modulus in CSE and CSL, but the highest in WE (Figure 33 h).

Table 42. Model 3-ANOVA for all traits collected from a group of photoperiod sensitive sorghum genotypes evaluated at three environment in Texas during the 2014 season.

	Whole Plant Geometry & Shape						Internode Geometry & Shape					Biomechanics			
		Plant Height		Avg, Plant Diameter		Plant Slenderness Ratio		Length	Diameter	Volume	Slenderness ratio		*E*-Young's Modulus	Strength	Flexural Stiffness
Source	DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F	Prob > F	Prob > F	Prob > F	DF	Prob > F	Prob > F	Prob > F
Model	29	<.0001	29	<.0001	29	<.0001	92	<.0001	<.0001	<.0001	<.0001	92	<.0001	<.0001	<.0001
env	2	<.0001	2	0.0036	2	<.0001	2	<.0001	<.0001	<.0001	<.0001	2	<.0001	<.0001	0.0001
rep(env)	9	<.0001	9	<.0001	9	<.0001	9	<.0001	<.0001	<.0001	0.0011	9	<.0001	0.0002	<.0001
genotype	6	<.0001	6	<.0001	6	<.0001	6	<.0001	<.0001	<.0001	<.0001	6	<.0001	<.0001	<.0001
env*gen	12	<.0001	12	<.0001	12	<.0001	12	<.0001	<.0001	<.0001	<.0001	12	<.0001	<.0001	<.0001
int No.(gen)							21	<.0001	<.0001	<.0001	<.0001	21	<.0001	<.0001	<.0001
env*int No.(gen)							42	<.0001	0.0297	<.0001	<.0001	42	<.0001	<.0001	<.0001
Error	1,790		1,736		1,736		1,379	.	.	.	.	1,379			
C. Total	1,819		1,765		1,765		1,471	.	.	.	.	1,471			
RSquare		0.88		0.75		0.85		0.80	0.80	0.79	0.84		0.81	0.67	0.70
CV%		5.35		10.34		11.4		11.6	10.5	14.4	15.8		9.4	11.8	20.0

P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

Table 43. LSMeans for all traits collected from a group of photoperiod sensitive sorghum genotypes evaluated at three environment in Texas during the 2014 season.

	Whole Plant Geometry & Shape			Internode Geometry & Shape				Biomechanical Properties		
	Plant Height	Avg. Plant Diameter	Plant Slenderness Ratio	Length(cm)	Diameter (cm)	Volume (cm^3)	Slenderness Ratio	Young's Module	Strength	Flexural Stiffness)
Environment	(cm)									
CSE	255 A[1]	1.79 B	145 B	20.2 B	1.9 B	60.5 A	10.9 B	666.51 B	666.51 B	5.17 B
CSL	224 B	2 A	114 C	18.7 C	2.1 A	60.6 A	9.2 C	327.74 C	327.74 C	4.2 C
WE	229 B	1.53 C	160 A	23.5 A	1.6 C	56.5 B	16.2 A	2,239.55 A	2,239.55 A	6.21 A
Average	240	1.45	180	20.8	1.9	59.2	12.1	1,077.93	1,077.93	5.19

/1 Environments not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD

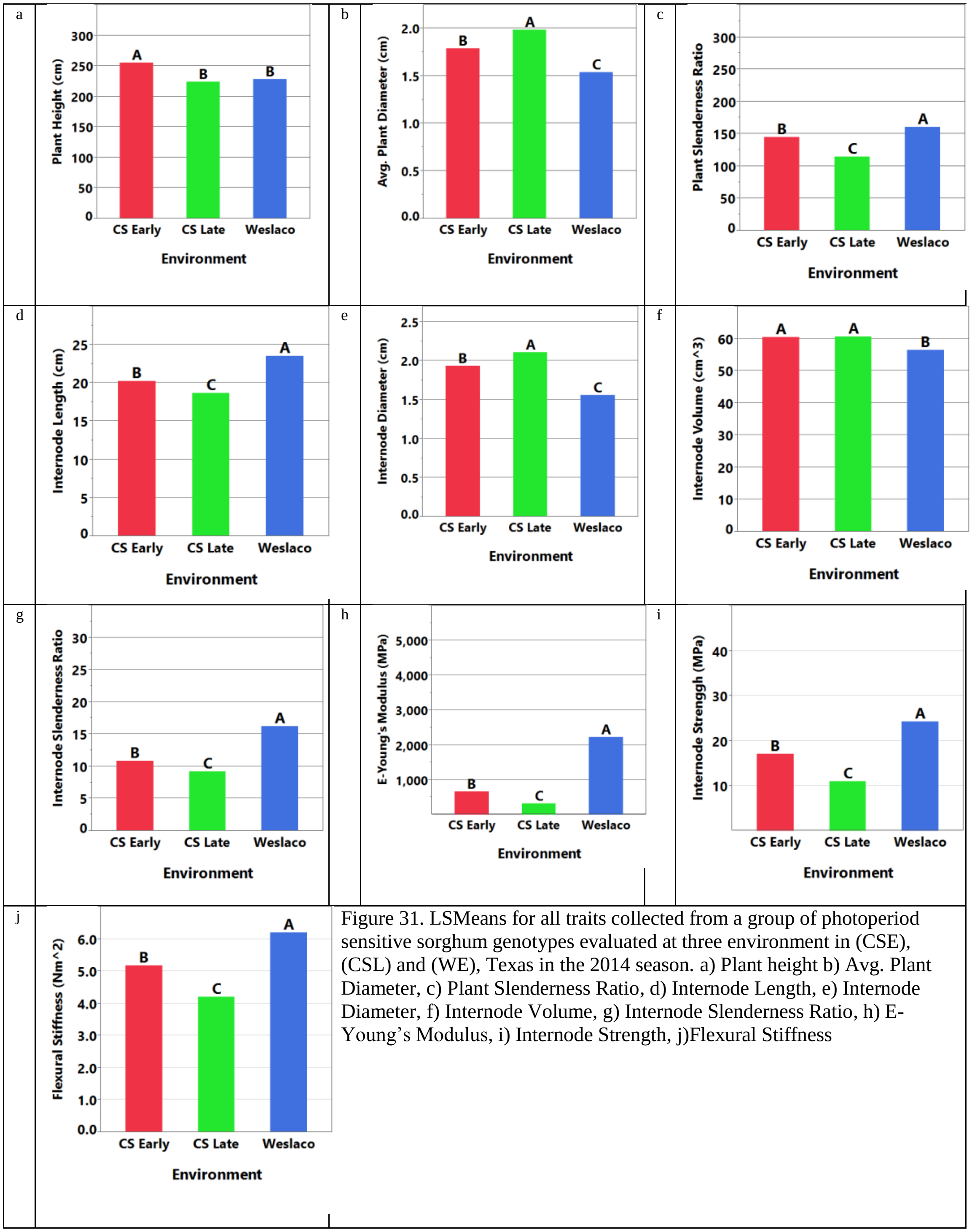


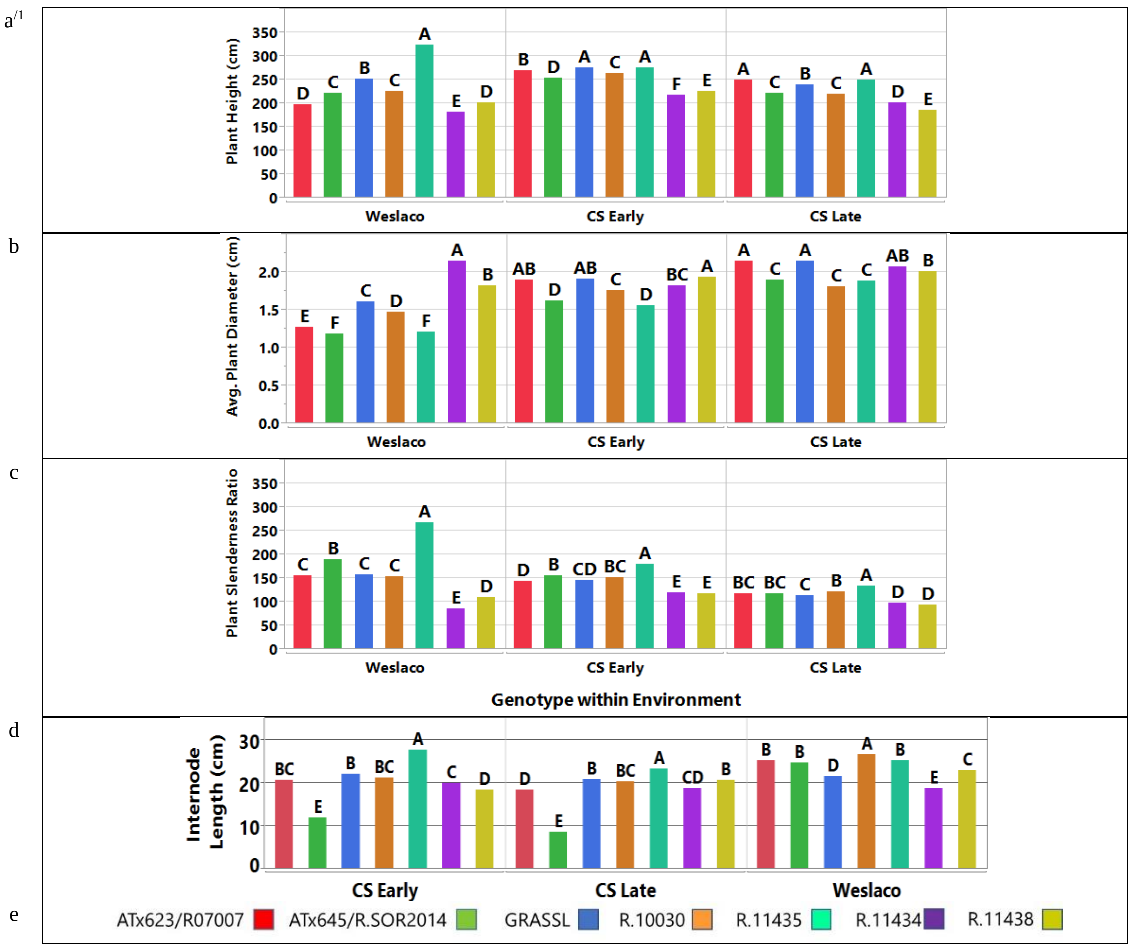
Figure 31. LSMeans for all traits collected from a group of photoperiod sensitive sorghum genotypes evaluated at three environment in (CSE), (CSL) and (WE), Texas in the 2014 season. a) Plant height b) Avg. Plant Diameter, c) Plant Slenderness Ratio, d) Internode Length, e) Internode Diameter, f) Internode Volume, g) Internode Slenderness Ratio, h) E-Young's Modulus, i) Internode Strength, j)Flexural Stiffness

1/ Location not connected by the same letter are significantly different (α=0.05) according to Tukey's HSD.
/2 CSE =College Station Early; CSL = College Station Late; WE = Weslaco

Table 44. LSMeans for all traits collected for a group of photoperiod sensitive sorghum genotypes evaluated at three environments in Texas during the 2014 season.

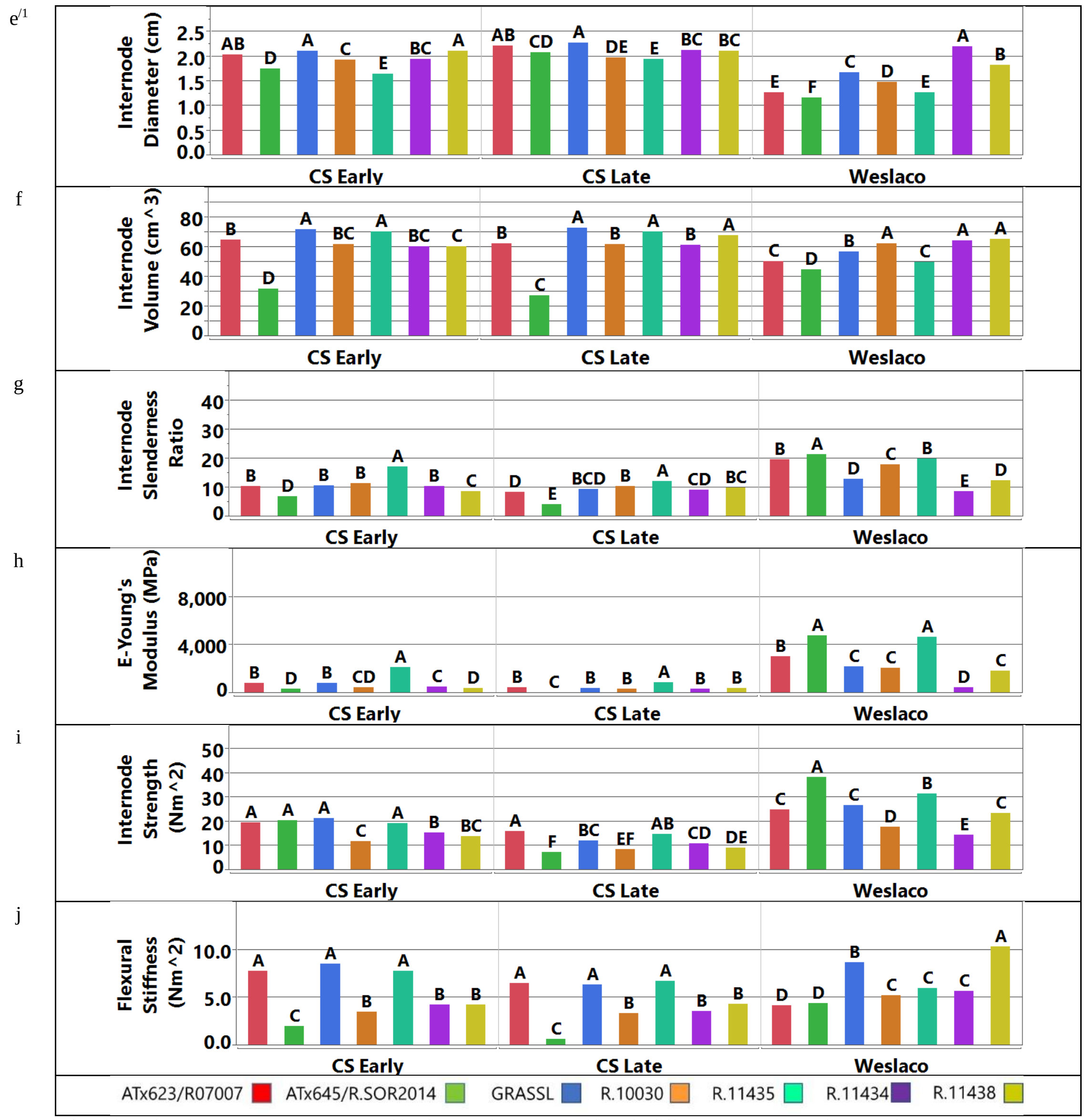
Genotypes	Lodging Rating 1-9	Whole Plant Geometry & Shape: Plant Height	Avg, Plant Diameter	Plant Slenderness Ratio	Internode Geometry: Length (cm)	Diameter (cm)	Volume (cm^3)	Slenderness Ratio	Internode Biomechanics: E-Young's Module (MPa)	Internode Strength (MPa)	Flexural Stiffness (Nm^2)
ATx623/R07007	3	239 C[1]	1.77 C	139 C	21.4 C	1.7 C	59.4 C	13.0 B	1,080 B	19.92 A	6.10 C
ATx645/R.SOR2014	1	233 D	1.57 E	155 B	15.0 E	2.0 D	34.8 D	10.9 C	437 D	18.09 B	2.10 E
GRASSL	7	256 B	1.90 B	139 C	21.5 C	1.8 B	67.4 A	11.1 C	930 B	19.25 AB	7.82 A
R.10030	5	236 C	1.68 D	143 C	22.7 B	1.6 C	62.2 BC	13.4 B	696 C	12.28 D	4.02 D
R.10135	5	283 A	1.55 E	194 A	25.4 A	2.1 D	63.8 B	16.5 A	2,082 A	20.90 A	6.81 B
R.11434	5	200 F	2.02 A	101 E	19.2 D	2.0 A	62.2 BC	9.5 D	448 D	13.59 CD	4.49 D
R.11438	5	204 E	1.92 B	107 D	20.6 C	1.9 B	64.7 AB	10.4 C	662 C	14.57 C	6.02 C
Average		236	1.77	140	20.8	1.9	59.2	12.1	905	16.94	5.34

/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.



/1 Within a location, genotypes not connected by the same letter are significantly different (α=0.05) according to Tukey's HSD

Figure 32. LSMeans for whole plant geometry and shape for a group of photoperiod sensitive sorghum genotypes evaluated at three environments in Texas during the 2014 season. a) plant height, b) avg. plant diameter c) plant slenderness ratio, d) internode length.



/1 Within a location, genotypes not connected by the same letter are significantly different (α=0.05) according to Tukey's HSD

Figure 33. LSMeans for whole plant geometry and shape for a group of photoperiod sensitive sorghum genotypes evaluated at three environments in Texas in the 2014 season. e) internode diameter, f) internode volume, g) slenderness ratio, h) E-Young's modulus, i) internode strength, j) flexural stiffness.

Variance Component for Internode Geometry, Shape, and Biomechanical Properties

To estimate variance associated with each effect, an all random model was also fitted (Model 4). Significant genetic variability was detected among the 15 bioenergy sorghum genotypes for all traits (Table 45-46), but a greater proportion of total variation was associated with environment and genotype x environment effects. The genetic component for internode diameter and volume accounted for more than 42% and 50% of the total variability (Table 45). Similarly, the genotypic contribution to the total variability for internode slenderness ratio was almost 22% (Table 45). The influence of the genotypic component to the total variability was significant and ranged from 14%, 18%, and 48% for E-Young's modulus, strength, and flexural stiffness respectively

The environmental contribution to the total variability was highly significant for all geometric, shape, and biomechanical traits except for internode volume and flexural stiffness. The environment component ranged from 0.69% to 42% for geometric, shape, and biomechanical traits. The environmental influence on the total variability of internode volume and flexural stiffness was <1.6% (Table 45-46). The (gen x env) interaction was highly significant for all traits (P<0.0001) (Table 45-46). The traits that exhibited the most (gen x env) interaction were internode length and E-Young's modulus which accounted for almost 22% of the total variability.

Analyzed by maturity group, the genetic component for the PI group was only significant for internode diameter and internode strength (Table 47-48 and Figure 34). The (gen x env) interaction variance component was significant for internode geometry, shape, and all biomechanical properties (Table 47-48). For the MPS group, genotypic variability was significant for internode diameter and flexural stiffness (Table 49-50, Figure 35). For the PS group, the genotypic component was significant for internode volume and flexural stiffness (Table 51-52). In addition, the (gen x env) interaction was significant for all geometry, shape, and biomechanical properties (Table 51-52, Figure. 36). The variance component due to the internode within genotype [int(gen)] was very important. For example, in the PI group the variance component due to [int(gen)] for internode strength accounted for 37% of the total variation (Table 48).

Table 45. Model 4- variance components estimates for geometry and shape traits of 15 bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

		Internode Length					Internode Diameter					Internode Volume					Internode Slenderness Ratio				
Source	DF	MS Num	F Ratio	Prob > F	Var Comp Est	Percent of Total	MS Num	F Ratio	Prob > F	Var Comp Est	Percent of Total	MS Num	F Ratio	Prob > F	Var Comp Est	Percent of Total	MS Num	F Ratio	Prob > F	Var Comp Est	Percent of Total
Model	53	1742.59	81.84	<.0001	.	.	16.57	579.67	<.0001	.	.	8.64	142.34	<.0001	.	.	4546.56	209.04	<.0001	.	.
Env	2	15168.16	16.82	<.0001	11.81	23.57	121.86	42.40	<.0001	0.10	35.90	4.07	1.61	0.22	0.00	0.69	39700.80	35.86	<.0001	31.94	37.66
rep(env)	9	17.99	0.85	0.57	-0.01	-0.02	0.43	15.07	<.0001	0.00	0.41	0.13	2.08	0.03	0.00	0.10	85.98	3.95	<.0001	0.18	0.21
gen	14	2549.05	2.61	0.01	6.03	12.04	32.76	11.98	<.0001	0.12	41.94	27.31	10.26	<.0001	0.09	50.64	5870.42	5.17	<.0001	18.14	21.39
env*gen	28	1003.96	47.15	<.0001	10.96	21.89	2.82	98.52	<.0001	0.03	11.34	2.74	45.15	<.0001	0.03	16.03	1169.21	53.76	<.0001	12.80	15.09
Error	4234	21.29		.	.	.	0.03	.	.	.	.	0.06	.	.	.	.	21.75	.	.	.	.
C. Total	4287	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
RSquare	0.51	.	.	.	.	.	0.88	.	.	.	.	0.64	.	.	.	.	0.72	.	.	.	.
CV	21.7						11.2					6.5					28.5				
Res Var	.	.	.	.	21.29	42.51	.	.	.	0.03	10.42	.	.	.	0.06	32.54	.	.	.	21.75	25.64
Total Var	.	.	.	.	50.08	100.00	.	.	.	0.27	100.00	.	.	.	0.19	100.00	.	.	.	84.81	100.00
Repeatability					0.53					0.90					0.86					0.75	
90% UCL					0.81					0.96					0.95					0.91	
90% LCL					0.11					0.81					0.77					0.55	

P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.
Repeat=Repeatability; UCL= Upper Confidence Limit; LCL= Lower Confidence Limit

Table 46. Overall variance components estimates for biomechanical traits of 15 bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

		E-Young's Modulus					Strength					Flexural Stiffness				
Source	DF	MS Num	F Ratio	Prob > F	Var Comp Est	Percent of Total	MS Num	F Ratio	Prob > F	Var Comp Est	Percent of Total	MS Num	F Ratio	Prob > F	Var Comp Est	Percent of Total
Model	53	113.30	191.04	<.0001	.	.	16.54	122.94	<.0001	.	.	33.30	132.54	<.0001	.	.
Env	2	1333.03	29.97	<.0001	1.07	41.67	159.97	28.82	<.0001	0.13	32.09	24.05	2.46	0.10	0.01	1.61
rep(env)	9	2.41	4.07	<.0001	0.01	0.20	0.52	3.83	<.0001	0.00	0.27	0.38	1.50	0.14	0.00	0.05
gen	14	142.62	3.08	0.01	0.37	14.42	24.34	4.32	0.00	0.07	18.00	102.96	9.88	<.0001	0.35	48.25
env*gen	28	47.72	80.46	<.0001	0.53	20.54	5.80	43.14	<.0001	0.06	15.88	10.73	42.71	<.0001	0.12	15.91
Error	4234	0.59	.	.	.	.	0.13	.	.	.	.	0.25	.	.	.	.
C. Total	4287	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
RSquare	0.51	0.71	.	.	.	.	0.61	.	.	.	.	0.62	.	.	.	.
CV	21.7	10.59					11.59					26.07				
Residual Var	.	.	.	.	0.59	23.17	.	.	.	0.13	33.77	.	.	.	0.25	34.19
Total Var	.	.	.	.	2.56	100.00	.	.	.	0.40	100.00	.	.	.	0.73	100.00
Repeatbility					0.62					0.69					0.86	
90% UCL					0.84					0.89					0.95	
90% LCL					0.24					0.46					0.76	

P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.
UCL= Upper Confidence Limit; LCL= Lower Confidence Limit

Table 47. Variance components estimates for geometry of photoperiod insensitive group of bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

Source	DF	Internode Length Prob > F	Var Comp Est	Percent of Total	CV	Internode Diameter Prob > F	Var Comp Est	Percent of Total	CV	Internode Volume Prob > F	Var Comp Est	Percent of Total	CV	Internode Slenderness Ratio Prob > F	Var Comp Est	Percent of Total	CV
Model	44	<.0001[1]	.	.	.	<.0001	.	.	.	<.0001	.	.	.	<.0001	.	.	.
env	2	0.0353	10.2204	30.9	14.82	0.0372	0.036616	34.42	18.51	0.2288	9.1537	8.12	8.87	0.0043	55.0831	40.86	32.25
rep[env]	9	0.0501	0.0637	0.2	1.17	<.0001	0.003349	3.15	5.60	<.0001	3.2808	2.91	5.31	<.0001	1.6700	1.24	5.62
gen	2	0.8258	-3.5788	-10.8	0.00	0.0429	0.03452	32.45	17.97	0.1300	20.9716	18.61	13.43	0.0566	22.7898	16.91	20.75
env*gen	4	0.0457	2.7211	8.2	7.65	<.0001	0.016829	15.82	12.55	0.0142	18.3761	16.31	12.57	0.0025	6.9449	5.15	11.45
int no.(gen)	9	0.0001	12.3433	37.3	16.29	0.0001	0.002165	2.04	4.50	0.0225	15.3367	13.61	11.49	<.0001	22.6226	16.78	20.67
env * int no. (gen)	18	<.0001	5.1692	15.6	10.54	0.0070	0.000476	0.45	2.11	<.0001	22.1011	19.62	13.79	<.0001	4.5222	3.35	9.24
Error	979	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
C. Total	1023	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
RSquare		0.8099	.	.	.	0.8355	.	.	.	0.7675	.	.	.	0.8088	.	.	.
CV%		11.4655				10.7827				14.2033				19.9952			
Residual Var		.	6.1159	18.5	11.47	.	0.012428	11.68	10.78	.	23.4459	20.81	14.20	.	21.1690	15.70	20.00
Total Var		.	33.0546	100.0	26.66	.	0.106382	100.00	31.55	.	112.6659	100.00	31.14	.	134.8016	100.00	50.46

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

Table 48. Variance components estimates for biomechanical properties of photoperiod insensitive group of bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

Source	DF	E-Young's Modulus Prob > F	Var Comp Est	Percent of Total	CV	Internode Strength Prob > F	Var Comp Est	Percent of Total	CV	Internode Flexural Stiffness Prob > F	Var Comp Est	Percent of Total	CV
Model	44	<.0001[1]			.	<.0001	.	.	.	<.0001	.	.	.
env	9	0.0083	0.300	32.2	6.9	0.2843	0.000	2.9	2.3	0.2344	0.000	10.1	11.9
rep[env]	2	<.0001	0.000	3.1	2.1	<.0001	0.000	6.0	3.4	<.0001	0.000	1.3	4.2
gen	2	0.0974	0.100	9.0	3.7	0.0473	0.100	25.3	6.9	0.1243	0.100	26.2	19.1
env*gen	4	0.0389	0.000	5.1	2.8	0.001	0.000	10.7	4.5	0.0021	0.100	23.1	17.9
int no.(gen)	9	0.0217	0.100	6.3	3.1	0.3802	0.000	0.3	0.8	0.8687	0.000	-2.9	0.0
env * int no. (gen)	18	<.0001	0.100	7.9	3.4	<.0001	0.000	4.7	3.0	<.0001	0.000	16	14.9
Error	979				.								
C. Total	1023				.								
RSquare		0.57				0.45				0.67			
CV%		7.38				9.67				19.12			
Residual Var			0.300	36.4	7.4		0.100	50	9.7		0.100	26.2	19.1
Total Var			1.000	100	12.2		0.200	100	13.7		0.200	100	37.3

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

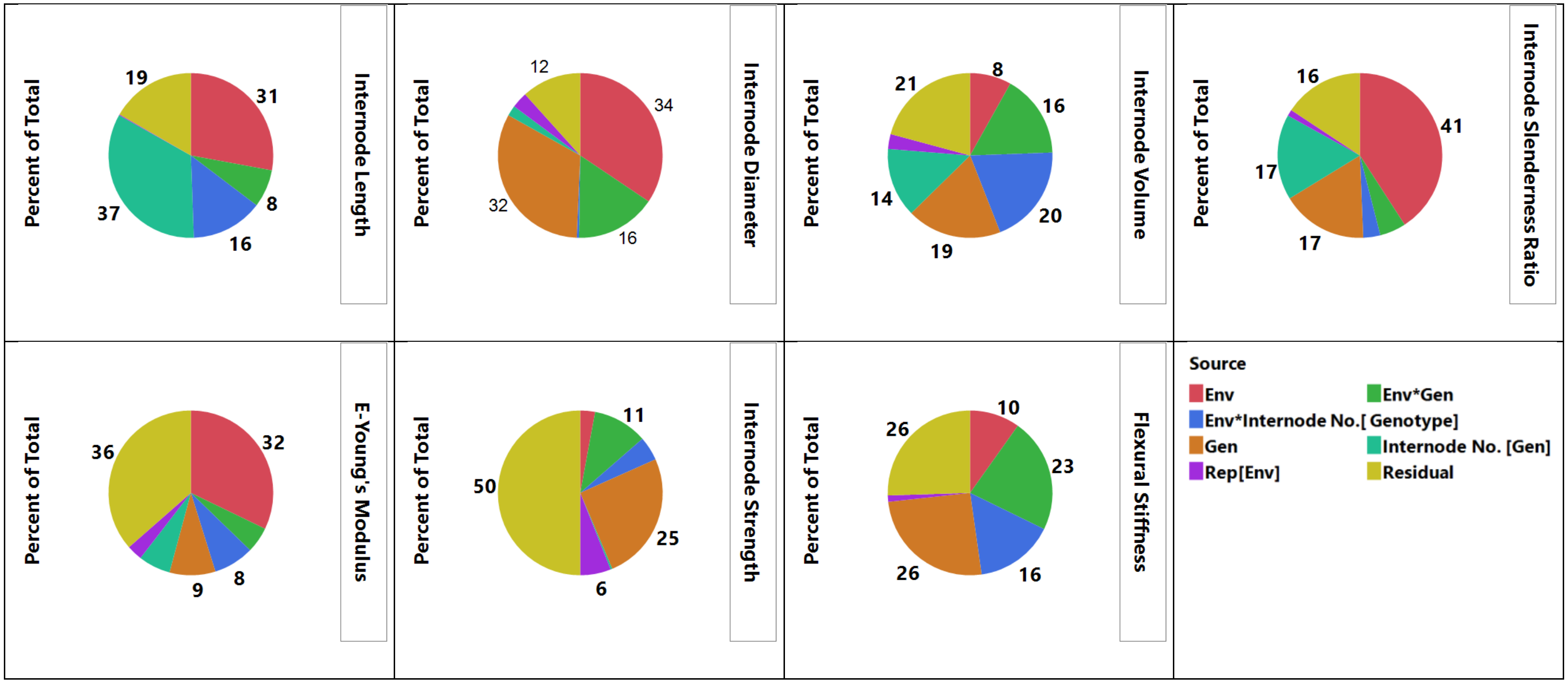


Figure 34. Variance components estimates (%) for geometry, shape and biomechanical traits of a group of photoperiod insensitive bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

Table 49. Variance components estimates for geometry of moderate photoperiod sensitive group of bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

		Internode Length				Internode Diameter				Internode Volume				Internode Slenderness Ratio			
Source	DF	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV
Model	68	<.0001	.	.	.	<.0001	.	.	.	<.0001	.	.	.	<.0001	.	.	.
env	2	0.0065	26.4778	36.6	24.23	<.0001	0.1854	69.49	27.88	0.8407	-10.2998	-2.70	0.00	0.0007	56.6279	64.88	48.67
rep[env]	9	0.0007	0.0901	0.1	1.41	<.0001	0.0017	0.64	2.67	0.0147	0.4313	0.11	1.34	<.0001	0.1586	0.18	2.58
gen	4	0.1240	9.0112	12.4	14.14	0.0158	0.0332	12.43	11.79	0.0034	185.2520	48.48	27.74	0.4425	-0.0189	-0.02	0.00
env*gen	8	<.0001	13.5027	18.6	17.31	<.0001	0.0207	7.75	9.31	<.0001	53.1479	13.91	14.86	<.0001	13.7029	15.70	23.94
int no.(gen)	15	<.0001	12.9903	17.9	16.97	<.0001	0.0029	1.09	3.49	<.0001	70.1276	18.35	17.07	<.0001	7.0861	8.12	17.22
env * int no. (gen)	30	<.0001	4.2935	5.9	9.76	0.0539	0.0004	0.14	1.24	<.0001	33.6495	8.81	11.82	<.0001	3.7473	4.29	12.52
Error	1723	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
C. Total	1791	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
RSquare		0.8815	.	.	.	0.8721	.	.	.	0.8317	.	.	.	0.9018	.	.	.
CV%		11.5822				9.7284				14.3808				15.8197			
Residual Var	.	.	6.0481	8.4	11.58	.	0.02258	8.46	9.73	.	49.7946	13.03	14.38	.	5.9837	6.86	15.82
Total Var	.	.	72.4137	100.0	40.08	.	0.266859	100.00	33.44	.	382.1031	100.00	39.84	.	87.2875	100.00	60.42

P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

Table 50. Variance components estimates for biomechanical properties of moderate photoperiod sensitive group of bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

		Internode Length				Internode Diameter				Internode Volume				Internode Slenderness Ratio			
Source	DF	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV
Model	68	<.0001	.	.	.	<.0001	.	.	.	<.0001	.	.	.	<.0001	.	.	.
env	2	0.0065	26.4778	36.6	24.23	<.0001	0.1854	69.49	27.88	0.8407	-10.2998	-2.70	0.00	0.0007	56.6279	64.88	48.67
rep[env]	9	0.0007	0.0901	0.1	1.41	<.0001	0.0017	0.64	2.67	0.0147	0.4313	0.11	1.34	<.0001	0.1586	0.18	2.58
gen	4	0.1240	9.0112	12.4	14.14	0.0158	0.0332	12.43	11.79	0.0034	185.2520	48.48	27.74	0.4425	-0.0189	-0.02	0.00
env*gen	8	<.0001	13.5027	18.6	17.31	<.0001	0.0207	7.75	9.31	<.0001	53.1479	13.91	14.86	<.0001	13.7029	15.70	23.94
int no.(gen)	15	<.0001	12.9903	17.9	16.97	<.0001	0.0029	1.09	3.49	<.0001	70.1276	18.35	17.07	<.0001	7.0861	8.12	17.22
env * int no. (gen)	30	<.0001	4.2935	5.9	9.76	0.0539	0.0004	0.14	1.24	<.0001	33.6495	8.81	11.82	<.0001	3.7473	4.29	12.52
Error	1723	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
C. Total	1791	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
RSquare		0.8815	.	.	.	0.8721	.	.	.	0.8317	.	.	.	0.9018	.	.	.
CV%		11.5822				9.7284				14.3808				15.8197			
Residual Var	.	.	6.0481	8.4	11.58	.	0.02258	8.46	9.73	.	49.7946	13.03	14.38	.	5.9837	6.86	15.82
Total Var	.	.	72.4137	100.0	40.08	.	0.266859	100.00	33.44	.	382.1031	100.00	39.84	.	87.2875	100.00	60.42

P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

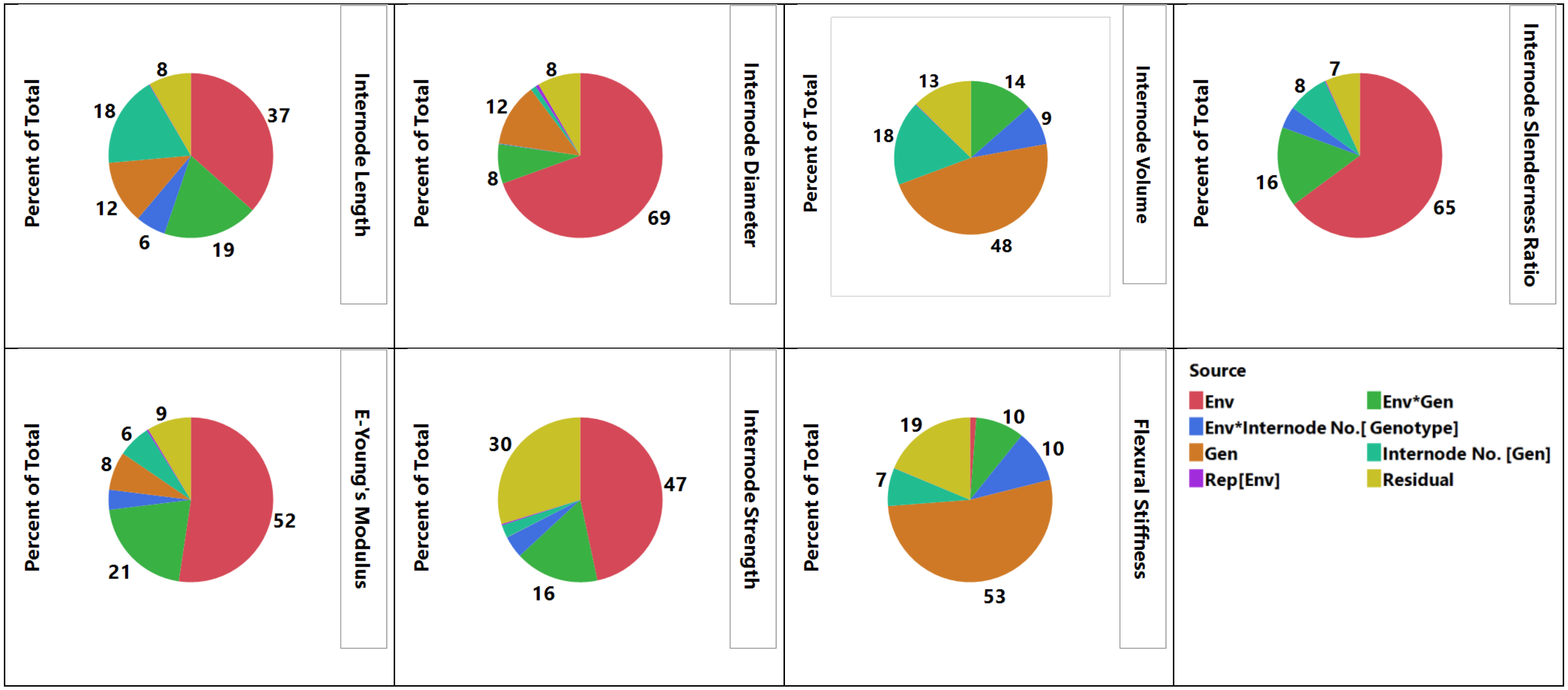


Figure 35. Variance components estimates (%) for geometry, shape and biomechanical traits of a group of moderate photoperiod sensitive bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

Table 51. Variance components estimates for geometry of photoperiod sensitive group of bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

		Internode Length				Internode Diameter				Internode Volume				Internode Slenderness Ratio			
Source	DF	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV
Model	92	<.0001	.	.	.	<.0001	.	.	.	<.0001	.	.	.	<.0001	.	.	.
env	9	<.0001	0.2631	0.5	2.42	<.0001	0.00157	0.87	2.19	<.0001	3.4609	0.97	3.20	0.0011	0.1109	0.29	2.59
rep[env]	2	0.0638	4.5368	9.4	10.06	0.0009	0.075503	41.84	15.16	0.5676	-4.1438	-1.16	0.00	0.0079	12.2172	31.44	27.22
gen	6	0.2319	3.4177	7.1	8.73	0.1162	0.017719	9.82	7.34	0.0201	90.7274	25.50	16.36	0.4840	-0.2925	-0.75	0.00
env*gen	12	<.0001	10.6892	22.2	15.44	<.0001	0.043194	23.94	11.47	0.0004	48.5000	13.63	11.96	<.0001	12.5916	32.41	27.63
int no.(gen)	21	<.0001	12.9338	26.9	16.98	<.0001	0.004531	2.51	3.71	<.0001	85.0162	23.89	15.84	<.0001	5.4028	13.90	18.10
env * int no. (gen)	42	<.0001	7.0477	14.7	12.53	0.0297	0.000993	0.55	1.74	<.0001	60.2047	16.92	13.33	<.0001	2.3619	6.08	11.97
Error	1379	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
C. Total	1471	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
RSquare		0.7993	.	.	.	0.7979	.	.	.	0.7872	.	.	.	0.8370	.	.	.
CV%		14.2906				10.6023				14.5817				19.7973			
Residual Var		.	9.1624	19.1	14.29	.	0.036934	20.47	10.60	.	72.0434	20.25	14.58	.	6.4648	16.64	19.80
Total Var		.	48.0507	100.0	32.73	.	0.180444	100.00	23.43	.	355.8088	100.00	32.41	.	38.8568	100.00	48.54

P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

Table 52. Variance components estimates for biomechanical properties of photoperiod sensitive group of bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

		E-Young's Modulus				Internode Strength				Internode Flexural Stiffness			
Source	DF	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV	Prob > F	Var Comp Est	Percent of Total	CV
Model	44	<.0001	.	.	.	<.0001	.	.	.	<.0001	.	.	.
env	9	<.0001	0.0105	0.44	1.50	0.0002	0.0024	0.66	1.72	<.0001	0.0055	0.75	3.29
rep[env]	2	0.0010	0.8996	38.21	13.93	0.0002	0.1521	41.27	13.61	0.1726	0.0251	3.44	7.03
gen	2	0.3344	0.0554	2.35	3.46	0.1234	0.0228	6.18	5.27	0.0391	0.1402	19.16	16.61
env*gen	4	<.0001	0.4643	19.72	10.01	<.0001	0.0511	13.87	7.89	0.0003	0.1248	17.05	15.67
int no.(gen)	9	0.0003	0.2449	10.40	7.27	0.4057	0.0009	0.23	1.02	0.0037	0.0872	11.92	13.10
env * int no. (gen)	18	<.0001	0.2668	11.33	7.59	<.0001	0.0266	7.20	5.69	<.0001	0.1478	20.19	17.05
Error	979	.	.	.	.	.	.	.	.	.	.	.	.
C. Total	1023	.	.	.	.	.	.	.	.	.	.	.	.
RSquare		0.8070	.	.	.	0.6742	.	.	.	0.6997	.	.	.
CV%		9.4433				11.7151				19.8943			
Residual Var		.	0.4133	17.55	9.44	.	0.1127	30.58	11.72	.	0.2012	27.49	19.89
Total Var		.	2.3547	100.00	22.54	.	0.3686	100.00	21.19	.	0.7318	100.00	37.94

P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

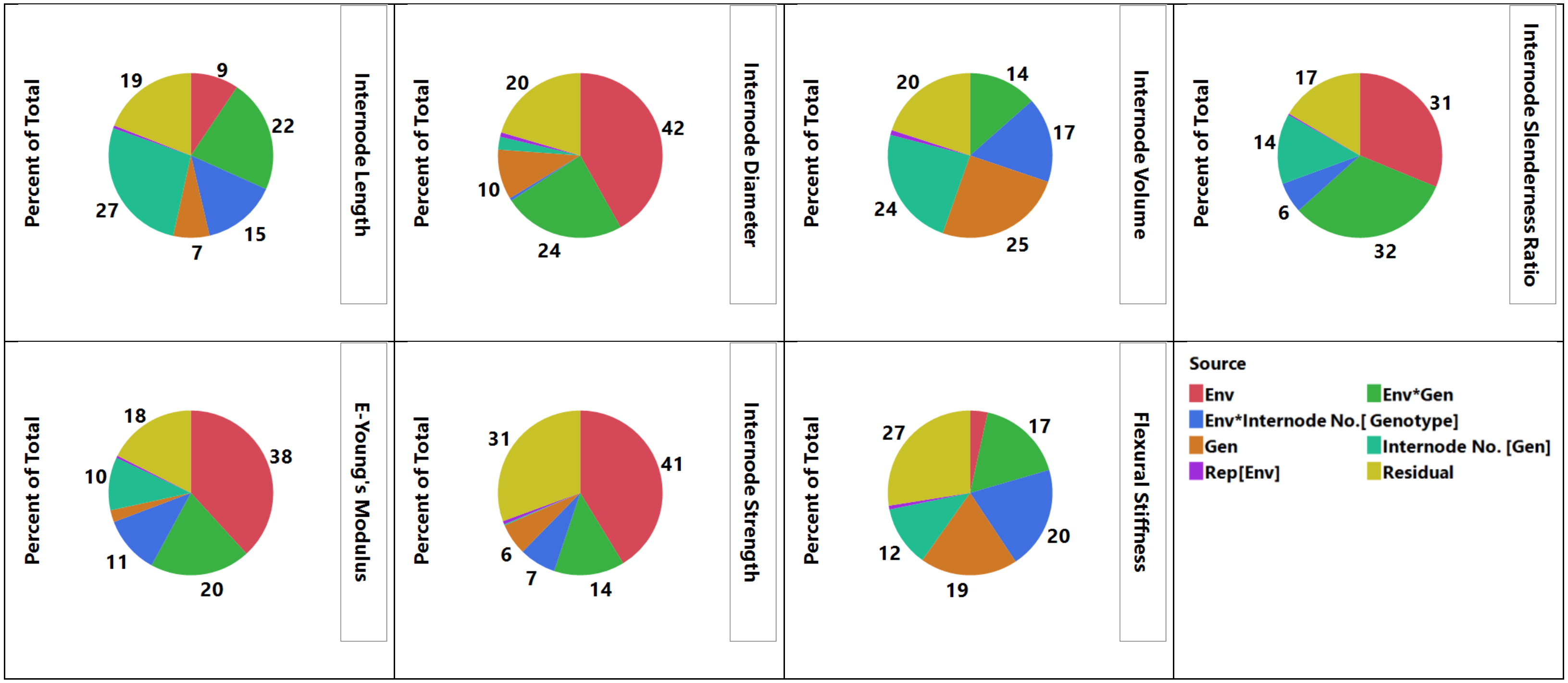


Figure 36. Variance components estimates (%) for geometry, shape and biomechanical traits of a group of photoperiod sensitive bioenergy sorghum genotypes, planted in Texas during 2014. Analyses performed using the EMS method.

Correlation among Traits

Across all genotypes and overall maturity, several correlations of importance were detected. A negative correlation between internode diameter and both internode *E*-young's modulus and strength as well as a strong positive correlation between *E*-young's modulus and internode length was detected (Table 53). Within maturity group, additional important correlations were noted. For example, flexural stiffness and internode diameter were strongly correlated in the PI group, less so in the MPS group and not at all in the PS group (Table 53). Correlations between internode diameter and plant height were also inconsistent where the PI and MPS groups showed moderate correlations but the PS had no correlations. These differences demonstrates the need to analyze by maturity groups (Table 53).

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Table 53. Correlations for all traits combined and grouped by photoperiod insensitive, moderate photoperiod sensitive, photoperiod sensitive bioenergy sorghum genotypes evaluated at three environments in Texas during the 2014 season.

		Overall		Photoperiod Insensitive		Moderate Photoperiod Sensitive		Photoperiod Sensitive	
Variable	by Variable	Correlation	Signif Prob	Correlation	Signif Prob	Correlation	Signif Prob	Correlation	Signif Prob
Avg. Plant Diameter	Plant Height	0.32	<.0001	0.6	<.0001	0.42	<.0001	-0.13	<.0001
Plant Slenderness Ratio	Plant Height	0.24	<.0001	0.32	<.0001	0.31	<.0001	0.65	<.0001
Plant Slenderness Ratio	Avg. Plant Diameter	-0.76	<.0001	-0.54	<.0001	-0.63	<.0001	-0.8	<.0001
Internode Length	Plant Height	-0.14	<.0001	-0.44	<.0001	-0.14	<.0001	0.09	0.0003
Internode Length	Avg. Plant Diameter	-0.34	<.0001	-0.27	<.0001	-0.47	<.0001	-0.38	<.0001
Internode Length	Plant Slenderness Ratio	0.21	<.0001	-0.13	<.0001	0.35	<.0001	0.34	<.0001
Internode Diameter	Plant Height	0.39	<.0001	0.67	<.0001	0.55	<.0001	-0.07	0.0074
Internode Diameter	Avg. Plant Diameter	0.93	<.0001	0.94	<.0001	0.85	<.0001	0.92	<.0001
Internode Diameter	Plant Slenderness Ratio	-0.69	<.0001	-0.4	<.0001	-0.49	<.0001	-0.73	<.0001
Internode Diameter	Internode Length	-0.41	<.0001	-0.4	<.0001	-0.54	<.0001	-0.49	<.0001
Internode Volume	Plant Height	0.27	<.0001	0.18	<.0001	0.36	<.0001	0.05	0.0651
Internode Volume	Avg. Plant Diameter	0.48	<.0001	0.58	<.0001	0.16	<.0001	0.29	<.0001
Internode Volume	Plant Slenderness Ratio	-0.38	<.0001	-0.49	<.0001	0.03	0.2183	-0.21	<.0001
Internode Volume	Internode Length	0.56	<.0001	0.55	<.0001	0.67	<.0001	0.7	<.0001
Internode Volume	Internode Diameter	0.49	<.0001	0.52	<.0001	0.23	<.0001	0.25	<.0001
Internode Slenderness Ratio	Plant Height	-0.41	<.0001	-0.6	<.0001	-0.43	<.0001	0.08	0.002
Internode Slenderness Ratio	Avg. Plant Diameter	-0.74	<.0001	-0.7	<.0001	-0.72	<.0001	-0.73	<.0001
Internode Slenderness Ratio	Plant Slenderness Ratio	0.55	<.0001	0.25	<.0001	0.45	<.0001	0.62	<.0001
Internode Slenderness Ratio	Internode Length	0.73	<.0001	0.78	<.0001	0.86	<.0001	0.85	<.0001
Internode Slenderness Ratio	Internode Diameter	-0.82	<.0001	-0.8	<.0001	-0.84	<.0001	-0.83	<.0001
Internode Slenderness Ratio	Internode Volume	-0.1	<.0001	-0.05	0.0908	0.21	<.0001	0.22	<.0001
E-Young’s Modulus	Plant Height	-0.2	<.0001	-0.51	<.0001	-0.24	<.0001	0.15	<.0001
E-Young’s Modulus	Avg. Plant Diameter	-0.68	<.0001	-0.65	<.0001	-0.65	<.0001	-0.63	<.0001
E-Young’s Modulus	Plant Slenderness Ratio	0.53	<.0001	0.26	<.0001	0.47	<.0001	0.56	<.0001
E-Young’s Modulus	Internode Length	0.76	<.0001	0.65	<.0001	0.83	<.0001	0.82	<.0001
E-Young’s Modulus	Internode Diameter	-0.76	<.0001	-0.74	<.0001	-0.76	<.0001	-0.77	<.0001
E-Young’s Modulus	Internode Volume	0.09	<.0001	-0.06	0.0662	0.36	<.0001	0.32	<.0001
E-Young’s Modulus	Internode Slenderness Ratio	0.81	<.0001	0.82	<.0001	0.84	<.0001	0.87	<.0001
Internode Strength	Plant Height	-0.14	<.0001	-0.3	<.0001	-0.23	<.0001	0.21	<.0001
Internode Strength	Avg. Plant Diameter	-0.67	<.0001	-0.67	<.0001	-0.56	<.0001	-0.59	<.0001
Internode Strength	Plant Slenderness Ratio	0.59	<.0001	0.49	<.0001	0.42	<.0001	0.56	<.0001
Internode Strength	Internode Length	0.4	<.0001	0.19	<.0001	0.48	<.0001	0.47	<.0001
Internode Strength	Internode Diameter	-0.74	<.0001	-0.71	<.0001	-0.69	<.0001	-0.71	<.0001
Internode Strength	Internode Volume	-0.24	<.0001	-0.48	<.0001	0.02	0.4571	-0.02	0.534
Internode Strength	Internode Slenderness Ratio	0.65	<.0001	0.59	<.0001	0.61	<.0001	0.65	<.0001
Internode Strength	E-Young’s Modulus	0.83	<.0001	0.76	<.0001	0.83	<.0001	0.83	<.0001
Flexural Stiffness	Plant Height	0.34	<.0001	0.39	<.0001	0.33	<.0001	0.2	<.0001
Flexural Stiffness	Avg. Plant Diameter	0.37	<.0001	0.63	<.0001	0.1	<.0001	0.05	0.064

P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

Table 53. Continued.

Variable	by Variable	Overall		Photoperiod Insensitive		Moderate Photoperiod Sensitive		Photoperiod Sensitive	
		Correlation	Signif Prob	Correlation	Signif Prob	Correlation	Signif Prob	Correlation	Signif Prob
Flexural Stiffness	Plant Slenderness Ratio	-0.25	<.0001	-0.32	<.0001	0.05	0.0451	0.05	0.0436
Flexural Stiffness	Internode Length	0.5	<.0001	0.19	<.0001	0.58	<.0001	0.69	<.0001
Flexural Stiffness	Internode Diameter	0.36	<.0001	0.6	<.0001	0.14	<.0001	-0.04	0.1007
Flexural Stiffness	Internode Volume	0.86	<.0001	0.75	<.0001	0.87	<.0001	0.78	<.0001
Flexural Stiffness	Internode Slenderness Ratio	-0.1	<.0001	-0.27	<.0001	0.17	<.0001	0.36	<.0001
Flexural Stiffness	E-Young's Modulus	0.28	<.0001	0.05	0.0991	0.5	<.0001	0.63	<.0001
Flexural Stiffness	Internode Strength	0.06	<.0001	-0.21	<.0001	0.29	<.0001	0.43	<.0001

P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.

Discussion

In the previous study (Chapter 3), the 3PBT was effective in detecting significant differences for biomechanical properties of bioenergy sorghum genotypes. Furthermore, the previous study highlighted the profound effect geometry has on the mechanical behavior of stem and its material properties. In previous results of this study, there was little to no correlation between lodging tendencies and individual measurements which confirms the complexity of stem lodging. Thus, sampling a broader genotype base under different environmental conditions, additional genotypes are needed to fully understand stem lodging.

Herein, fifteen bioenergy sorghum genotypes with a history of contrasting lodging performance were characterized for whole plant and internode geometry, shape, and biomechanical properties in three distinct Texas environments in the 2014 season.

First, the effect of the maturity response and its interaction with the environment had a significant effect on all traits under study (Table 34). Because all plant traits including biomechanical properties are affected by conditions during the growth and development stages (Bashford et al., 1976), analysis were conducted completed by maturity group (Table 27).

The contribution of the genotype was very important. Genotype contributed to 42% of the total variability for internode diameter and volume (Table 45). Similarly, the contribution of the genotype to the total variability in internode slenderness ratio was almost 22% (Table 45). Likewise, the influence of the genotypic component to the total variability was significant and ranged from 14%, 18%, and 48% for E-young's modulus, strength, and flexural stiffness respectively (Table 46). This indicates that this set of bioenergy sorghum genotypes from the Texas A&M Sorghum Breeding Program does contain important genetic variation that may allow to identify quantitative trait loci (QTL) related to these geometric, shape, and biomechanical properties toward applying marker assisted recurrent selection (MAS). Currently, these results are being followed in the analysis of biomechanical traits of RSOR2014 derived populations.

A genotype x environment interaction occurs when genotypes differ in their relative performance across environments (Bernardo 2010). The significant genotype x environment interaction detected for all traits indicate that the genetic contribution for each trait will be dependent in the environment where it is grown (Table 45-46). The traits that exhibited the most genotype x environment interaction were internode length and E-Young's modulus with both close to 22% of the total variability. Thus, selecting for internode diameter, volume, and flexural stiffness should be effective in any environment.

The genotypic repeatability based on the variance components indicated that the expression of most traits were consistent across environments for these sorghum genotypes. For example, repeatability ranged from 0.53 to 0.90. Internode length had a significant (P<0.0001) and large (gen x env) significant effect g x e effect (P<0.0001) and a large g x e component, thus affected the repeatability estimate and was low. This indicates gain of selection may be challenging for this trait. Estimates of repeatability established the relative effect of genotype on phenotype but they do not estimate heritability (Falconer & Mackay 1996, Hallauer & Miranda 2010). Thus, if selection to improve the trait is the goal of a program, then a high repeatability means it could be possible to improve, assuming most of this genotypic variation is heritable. If repeatability is low, then selection may not be effective for improvement. Either way, heritability must be assessed on these traits to verify if selection gain is possible.

Among all the genotypes involved in this study most of the significant and important genetic component were among the PI group, which contained distinct inbred lines. For instance the genetic components for internode diameter and strength internode were high (Tables 47-48). For the PS group the genetic components for internode volume and flexural stiffness were 26% and 19%, respectively (Tables 51-52). Based on this, internode diameter and strength characteristics associated with the lodging resistant PI genotype RSOR2014 are likely to be inherited as it may be indicated in the hybrid ATx645/RSOR2014 that had a similar low lodging rating. The strong heritable lodging resistance of RSOR2014 was evident in the hybrids EJX7J906 and EJX7J907 (L. W. Rooney 2015).

The genotype-environment interactions were significant for whole plant internode geometry, shape, and biomechanical properties in all maturity groups (Table 36, 39, 42). Compared to the other groups, the PI maturity group's genotypes were in reproductive growth and had already attained maximum whole plant and internode geometry, shape, and biomechanical properties. Thus, they were possibly more resistant to lodging because they were more mechanically stable. In contrast, the MPS and PS groups were still growing vegetative, which, as (Bashford 1976) described is not as strong. In support of that observation, the E-young's modulus of dry cellulose is higher than that of wet cellulose (K. J. Niklas 1992).

The genotype effect within all maturity groups for whole plant and internode geometry, shape, and biomechanical properties was highly significant (P<0.0001) (Table 36, 39, 41). The genotype RSOR2014 in the (PI) group, known to be lodging resistant was the shortest (217 cm), had the thinnest average plant diameter (0.77 cm), and the highest slenderness ratio (286). In addition it had the longest internode length (21.07 cm), thinnest internode diameter (1.1 cm), lowest internode volume (26.9 cm^3), and highest internode slenderness ratio (28.7). It also had the highest E-young's modulus (4,062 MPa), the strongest internode strength (44.26 MPa), and lowest internode flexural stiffness (0.88 Nm^2). These characteristics make RSOR2014 the most lodging resistance genotype out of the PI group and further parental source of stem lodging resistant germplasm (Table 27).

The most lodging resistant genotypes from the MPS group were EJX 7J906 and EJX 7J907 (Table 27). These two genotypes were the shortest in that maturity group. Both had moderate plant diameter (1.56 and 1.53 cm), and the lowest plant slenderness ratio. Internode geometry and shape of these two genotypes were consistent; both had short internode length (14.3 and 14.7 cm), moderate internode diameter and the lowest internode volume (31.8 and 32.4 cm^3), and the lowest Internode Slenderness Ratio (11.1 and 11.6). The biomechanical properties of these two genotypes were the lowest for internode *E*-young's modulus (309 & 428 MPa), were the lowest and slightly differed for internode strength (17.44 & 20.48 MPa), and lowest internode flexural stiffness (1.41 & 1.60 Nm^2). The lodging resistance of the hybrids EJX7J906 and EJX7J907 could be accounted for one of its parents RSOR2014, which demonstrated to be highly resistant to stem lodging.

The most lodging resistant genotype in the PS group was ATx645/RSOR2014 (Table 27). This genotype had an average plant height (233 cm), low plant diameter (1.57 cm), and was among the highest for plant slenderness ratio. This genotype had the shortest internode length (15 cm), had relatively thin internode diameter (2.0 cm), low internode volume (34.8 cm^3), and a moderate internode slenderness ratio (10.9). ATx645/RSOR2014 had relatively low internode *E*-young's modulus (437 MPa), had strong internodes (18.09 MPa), and the lowest internode flexural stiffness (2.10 MPa). Again the lodging resistance of the hybrid ATx645/RSOR2014 could be accounted for one of its parents RSOR2014, which demonstrated to be highly resistant to stem lodging.

Among the maturity groups, these lodging resistant genotypes had similar and different characteristics for plant geometry and biomechanical properties. For example, they all were relatively shorter, had thin to average plant diameter, and moderate to high plant slenderness ratios. Of the internode geometry traits, all of these genotypes were consistently low in internode volume, and inconsistent for the other traits measured. For the biomechanical properties, flexural stiffness was consistently low in these genotypes. These trends suggest that lodging resistance can be associated with specific plant architecture, internode geometry and biomechanical properties or combinations thereof.

However, the trait associations have a maturity component. The PI genotype had the highest internode slenderness ratio, whereas the MPS and PS genotypes had a low internode slenderness ratio. PI genotype displayed the highest internode *E*-young's modulus, however the MPS and PS genotypes showed the lowest internode *E*-young's modulus. These trends demonstrate the relative effect of maturity on lodging ratings. These examples demonstrate the complexity of mechanical design in plants, and the interaction between geometry, shape, and biomechanical properties in relation to stem lodging. Ultimately, there is not one specific trait that confers lodging resistance. However, it is important to take into consideration the growth and development patterns when assessing field lodging, as plants biomechanical properties change as they age or their physiological state.

If stem lodging resistance cannot be specifically designed, it is logical to ask if specific factors cause stem lodging. Of the PI genotypes, R.07007 and Della were taller, and had thicker stem diameter and lower slenderness ratios than RSOR2014. R.07007 and Della also had shorter, thicker, and larger volume internodes and thus exhibited a lower internode slenderness ratio. R.07007 and Della exhibited a lower internode *E*-young's modulus and strength, but had higher internode flexural stiffness than RSOR2014.

In the most lodging susceptible genotype from the MPS, EJX7285 was taller and thicker in diameter than the lodging tolerant genotypes EJX7J906 and EJX7J907 (Table 41). EJX 7285 also differed from EJX7J906 and EJX7J907 by having longer and thicker internodes, a higher internode volume, and slightly higher internode slenderness Ratio. EJX 7285 also had a higher internode *E*-young's modulus, strength, and flexural stiffness then the two low lodged rated genotypes.

Among PS genotypes, GRASSL was the most lodging susceptible, was taller, thicker stems, and had a lower plant slenderness ration than the lodging tolerant genotype ATx645/RSOR2014 (Table 44). GRASSL also exhibited longer and thicker internodes, as well as higher internode volume than ATx645/RSOR2014. GRASSL showed higher internode E-young's modulus and flexural stiffness than ATx645/RSOR2014. The lodging susceptible genotypes are typically taller, have thicker internodes, and have high levels of flexural stiffness.

These traits are in exact contrast of lines with lodging tolerance. Other traits were not as consistent in their relationship with lodging. Furthermore, none of these three traits are exclusively associated with lodging tolerance (i.e., it is possible to identify short genotypes that lodge).

Associations between plant height and lodging have been known for many years. Height reducing genes have been the major sources of lodging tolerance in many cereal crops such as rice, wheat, and sorghum. However, reduced plant height in a bioenergy sorghum breeding program may limit yield potential. In some cases, plant height is associated with lodging, for example in barley where one QTL was found to be associated with plant height. But in other instances in rice, wheat, and sorghum it is independent, and this may suggest that genetic gain in lodging tolerance can be obtained, to some extent, independent of plant height (Rajkumara 2008) (Godoy and Tesso 2013). In any case, there is a physical limit to plant height before it lodges in bioenergy sorghum. Engineering theory may provide useful calculations for this relationship such as the extent to which a sorghum stem can grow vertically before it will deflect under an applied axial compressive load (K. J. Niklas 1992). Greenhill's and Euler column formulas have been applied to plants and given valuable insight into the relationship, between plant height, density, and stem diameter (K. J. Niklas 1993). However certain assumptions have to be met and oversimplified, nevertheless these estimates may provide useful knowledge to understand stem lodging events in bioenergy sorghum. Still, the relationship between shorter plants and stem lodging resistance observed in this study is consistent with the notion that reduced height will limit the bending moment of the stem and lower the risk of a range of excessive mechanical strains, plastic deformations, uprooting, stem buckling, and failure (Paul-Victor and Rowe 2010).

Internode flexural stiffness was consistently low in the lodging resistant genotypes and high in the susceptible types. Flexural stiffness or rigidity is the product of *E*-Young's Modulus and Second Moment of an Area *I* which gives the plant-internode resistance to bending, can be attributed to the materials property *E* or geometry *I* or both. For example, in the PI genotype RSOR2014, *E* was high and *I* was low (thin diameter) thus it had a low flexural stiffness. In the MPS and PS stem lodging resistant cultivars EJX 7J906, EJX 7J907, and ATx645/RSOR2014 all genotypes have a low *E* and a moderate *I* within their maturity group and thus a low flexural stiffness. Thus, the path to low flexural stiffness can vary and still infer lodging resistance. A low flexural stiffness indicates that plants do not resist to bending very well allowing them to oscillate easily; it was hypothesized as an important factor inferring stem lodging resistance.

Niklas (1989) reported as such in two oat (*Avena sativa* L.) cultivars where 'Astro' (a lodging resistance cultivar) had significantly lower flexural stiffness for internodes 4 to 6 than Garry a lodging susceptible cultivar. Flexural stiffness for mechanically perturbed plants of *Arabidopsis thaliana* were shorter and flexible stems composed of less stiff material (Paul-Victor and Rowe 2010). This may indicate that plants may change and adapt their geometry and materials in order to obtain a lower flexural stiffness to become more lodging resistant. Thus, future studies should focus on identifying QTL for this important trait.

This study provided evidence that increasing strength does not necessarily increase stem strength, as previously thought and validates the previous study. Similarly, a strong significant negative correlation was found between internode length and *E*-young's modulus. Correlation between flexural stiffness and internode diameter were variable and depended on the maturity group. *E*-young's modulus and internode slenderness ratio exhibited a strong significant positive correlation in all maturity groups PI (0.82), MPS (0.84), PS (0.87). The correlations between some traits collected varied among maturity groups. Indicating that maturity response is a factor to consider when assessing biomechanical properties. For instance, overall correlation between flexural stiffness and internode length was moderate and positive (0.5), but varied depending on maturity group, where for the PI it was a low positive correlation of (0.19), for the MPS it was a positive moderate correlation of (0.58), and for the PS group it was a positive moderate to high correlation of (0.69) (Table 53). This is strong evidence that when analyzing such traits on bioenergy sorghum maturity and development should be taken into account.

This study has found that stem lodging is a highly complex trait and several factors contribute to the expression of lodging resistance. There were indications that genetic effects contribute to lodging resistance and there is indication that biomechanical properties are heritable as was found with the genotype RSOR2014 and its hybrid ATx645/RSOR2014 which was the most lodging resistance. It was also found that the growth stage (maturity) highly affects the geometric and biomechanical properties. These differences need to be taken into consideration when breeding parental stocks with high lodging resistance. This study also validates that applying a 3PBT is an accurate methodology to discriminate against genotypes, and a low flexural stiffness as well as having short internodes are good properties to infer lodging resistance in these particular genotypes. Among these genotypes an ideal low lodging bioenergy sorghum would be similar to ATx645/RSOR2014 because it combines lodging resistance, high biomass production, and desirability. However, more research is required to fundamentally understand the true factors of stem lodging resistance in the field such as rind thickness and composition analysis on stem are traits that would be likely associated with stem lodging resistance. This study provided an accurate methodology for any bioenergy sorghum breeding program to adopt and assess their biomechanical variation in order to identify stem lodging resistant cultivars.

Conclusion

A 3PBT is powerful tool to determine biomechanical properties and detect significant variation among sorghum genotypes. Significant genetic effect and variability was identified for a group of 15 bioenergy sorghum genotypes that may allow to identify quantitative trait loci (QTL) related to these geometric, shape, and biomechanical properties toward applying marker assisted recurrent selection (MAS). Geometry, shape, and biomechanical properties are influenced by maturity and developmental stages of a growing sorghum plant. Plant height, internode length, volume and flexural stiffness are particular important trait that that may serve an important trait to dissect to select for lodging resistance in plants. Future studies should focus on stem composition, rind thickness and computerized tomography (CT) scan in the sorghum plant to develop a better model of the sorghum stem. This will allow sorghum breeders to select important traits that infer to lodging resistance in a bioenergy sorghum breeding program to improve germplasm with lodging resistance characteristics.

CHAPTER V

SIGNIFICANCE OF BIOMECHANICS IN SORGHUM BREEDING FOR LODGE RESISTANCE CULTIVARS

Summary and Conclusion

Nature and it's physical laws have shaped all living organisms on this plant and it is the fundamental premise that plants like all other organisms, cannot violate physical principles. Thus, understanding the physical sciences is a requisite for understanding biology. Nikolai Vavilov defined Plant Breeding as applied evolution. Therefore evolutionary change is a vector having magnitude and direction, which requires genetic diversity and the ability of an organisms to adapt to its environment and increase its fitness. Plant biomechanics provides an excellent tool for sorghum breeders to study the biological expressions of traits related to stem lodging in sorghum and provide insight into sorghums evolutionary history to mechanical stability in its environment.

This study provides the first insight into the usefulness of a 3PBT to detect significant variation for biomechanical properties among and within the stems of a diverse set of sorghum germplasm. As expected biomechanical properties in a sorghum stem were highly influenced by its geometry and shape. Which provided a better understanding to the inherent assumption that increasing stem diameter does not necessary increase stem strength. Moreover, a 3PBT was able to identify the weakest section of the stem that is most likely to fail (internodes 3-6); and nodes enhance the biomechanical properties of the stem to withstand failure. The 3PBT also allowed to associate biomechanical properties with stem geometry and elucidate traditional beliefs to increase stem strength in sorghum, in order to reduce the likelihood of stem lodging.

Importantly, significant genetic variation was identified in a group of 15 bioenergy sorghum genotypes that may allow to identify quantitative trait loci (QTL) related to these geometric, shape, and biomechanical properties toward applying marker assisted recurrent selection (MAS). Geometry, shape, and biomechanical properties are influenced by maturity and developmental stages of a growing sorghum plant. As found in other studies but the first one in sorghum, plant height together with flexural stiffness stalk strength, E-Young modulus, internode volume, and slenderness ratio are particular important traits that that may serve an important trait to study and select for lodging resistance in plants. Future studies to study composition and rind thickness in plants to develop a better model of stem lodging resistance in sorghum where plant breeders will be able to use and integrate into their bioenergy sorghum breeding program to improve germplasm with lodging resistance characteristics.

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APPENDIX I

CHAPTER III

Table A-III.1. Pairwise Correlations, using Pearson product-moment estimated with for all traits evaluated at Weslaco, Texas during the 2013 season.

TYPE VAR	Variable	TYPE BY VAR	by Variable	Correlation	Count	Lower 95%	Upper 95%	Signif Prob
Plant Geometry	No. of Internodes/ Plant	Plant Geometry	Plant Height	0.63	863	0.5891	0.6696	<.0001
Plant Geometry	Plant Slenderness Ratio	Plant Geometry	Plant Height	0.57	96	0.4124	0.6885	<.0001
Plant Geometry	No. of Internodes/ Plant	Plant Geometry	Plant Diameter	0.27	96	0.074	0.4467	0.0077
Plant Geometry	No. of Internodes/ Plant	Plant Geometry	Plant Slenderness Ratio	0.27	96	0.071	0.4444	0.0084
Plant Geometry	Plant Diameter	Plant Geometry	Plant Height	0.13	96	-0.0742	0.3204	0.2134
Plant Geometry	Plant Slenderness Ratio	Internode Geometry	Internode Density	0.08	95	-0.1205	0.2799	0.4235
Plant Geometry	Plant Height	Internode Geometry	Internode Density	0.02	857	-0.0509	0.083	0.6374
Plant Geometry	No. of Internodes/ Plant	Internode Geometry	Internode Density	-0.01	856	-0.0794	0.0546	0.7169
Plant Geometry	Plant Diameter	Internode Geometry	Internode Density	-0.04	95	-0.2355	0.1671	0.7319
Plant Geometry	Plant Slenderness Ratio	Plant Geometry	Plant Diameter	-0.73	96	-0.8111	-0.6192	<.0001
Internode Geometry	Internode Diameter	Plant Geometry	Plant Diameter	0.85	96	0.7786	0.8954	<.0001
Internode Geometry	Internode Slenderness Ratio	Internode Geometry	Internode Length	0.77	864	0.7464	0.7999	<.0001
Internode Geometry	Internode Volume	Internode Geometry	Internode Length	0.75	864	0.7178	0.7766	<.0001
Internode Geometry	Internode Volume	Plant Geometry	Plant Diameter	0.57	96	0.4171	0.6914	<.0001
Internode Geometry	Internode Volume	Internode Geometry	Internode Diameter	0.45	864	0.3951	0.5016	<.0001
Internode Geometry	Internode Diameter	Plant Geometry	No. of Internodes/ Plant	0.27	863	0.203	0.327	<.0001
Internode Geometry	Internode Volume	Plant Geometry	Plant Height	0.22	864	0.1577	0.2845	<.0001
Internode Geometry	Internode Slenderness Ratio	Plant Geometry	Plant Slenderness Ratio	0.21	96	0.0105	0.3944	0.0395
Internode Geometry	Internode Slenderness Ratio	Internode Geometry	Internode Volume	0.17	864	0.1078	0.2372	<.0001
Internode Geometry	Internode Length	Plant Geometry	Plant Height	0.16	864	0.0904	0.2205	<.0001
Internode Geometry	Internode Volume	Plant Geometry	No. of Internodes/ Plant	0.08	863	0.0139	0.1465	0.0179
Internode Geometry	Internode Length	Plant Geometry	Plant Diameter	0.07	96	-0.1358	0.2635	0.5197
Internode Geometry	Internode Diameter	Plant Geometry	Plant Height	0.06	864	-0.0074	0.1256	0.0812
Internode Geometry	Internode Slenderness Ratio	Internode Geometry	Internode Density	0.06	857	-0.0067	0.1267	0.0779
Internode Geometry	Internode Slenderness Ratio	Plant Geometry	Plant Height	0.02	864	-0.0457	0.0876	0.5365
Internode Geometry	Internode Length	Plant Geometry	Plant Slenderness Ratio	-0.08	96	-0.2763	0.1222	0.437
Internode Geometry	Internode Length	Internode Geometry	Internode Density	-0.09	857	-0.1514	-0.0185	0.0125
Internode Geometry	Internode Length	Plant Geometry	No. of Internodes/ Plant	-0.11	863	-0.1719	-0.0399	0.0018
Internode Geometry	Internode Diameter	Internode Geometry	Internode Density	-0.17	857	-0.2352	-0.1051	<.0001
Internode Geometry	Internode Volume	Internode Geometry	Internode Density	-0.19	857	-0.2557	-0.1266	<.0001
Internode Geometry	Internode Slenderness Ratio	Plant Geometry	No. of Internodes/ Plant	-0.22	863	-0.2788	-0.1516	<.0001
Internode Geometry	Internode Diameter	Internode Geometry	Internode Length	-0.23	864	-0.2889	-0.1623	<.0001
Internode Geometry	Internode Volume	Plant Geometry	Plant Slenderness Ratio	-0.32	96	-0.4919	-0.1313	0.0013
Internode Geometry	Internode Diameter	Plant Geometry	Plant Slenderness Ratio	-0.41	96	-0.5604	-0.2231	<.0001

Table A-III.1. Continued

TYPE VAR	Variable	TYPE BY VAR	by Variable	Correlation	Count	Lower 95%	Upper 95%	Signif Prob
Internode Geometry	Internode Slenderness Ratio	Plant Geometry	Plant Diameter	-0.46	96	-0.6072	-0.2894	<.0001
Internode Geometry	Internode Slenderness Ratio	Internode Geometry	Internode Diameter	-0.75	864	-0.7743	-0.715	<.0001
Biomechanics	Internode Strength	Biomechanics	Internode Strength	0.92	845	0.9057	0.9272	<.0001
Biomechanics	E-Young's Modulus	Internode Geometry	Internode Slenderness Ratio	0.79	843	0.7643	0.815	<.0001
Biomechanics	Flexural Stiffness	Internode Geometry	Internode Volume	0.76	843	0.7295	0.7867	<.0001
Biomechanics	Internode Strength	Biomechanics	E-Young's Module	0.64	843	0.6033	0.6824	<.0001
Biomechanics	E-Young's Modulus	Internode Geometry	Internode Length	0.61	843	0.5697	0.654	<.0001
Biomechanics	E-Young's Modulus	Biomechanics	Internode Strength	0.58	843	0.5338	0.6235	<.0001
Biomechanics	Flexural Stiffness	Internode Geometry	Internode Length	0.58	843	0.5353	0.6247	<.0001
Biomechanics	Flexural Stiffness	Biomechanics	E-Young's Module	0.47	843	0.414	0.5195	<.0001
Biomechanics	Internode Strength	Internode Geometry	Internode Slenderness Ratio	0.38	845	0.3169	0.4328	<.0001
Biomechanics	Flexural Stiffness	Internode Geometry	Internode Diameter	0.38	843	0.3247	0.4399	<.0001
Biomechanics	Internode Strength	Plant Geometry	Plant Slenderness Ratio	0.28	96	0.0864	0.4566	0.0054
Biomechanics	E-Young's Modulus	Plant Geometry	Plant Slenderness Ratio	0.23	96	0.0274	0.4086	0.0264
Biomechanics	Flexural Stiffness	Plant Geometry	Plant Height	0.18	843	0.1115	0.2423	<.0001
Biomechanics	E-Young's Modulus	Internode Geometry	Internode Volume	0.11	843	0.0395	0.173	0.0019
Biomechanics	Flexural Stiffness	Internode Geometry	Internode Volume	0.1	843	0.0307	0.1644	0.0044
Biomechanics	Internode Strength	Internode Geometry	Internode Density	0.09	838	0.0173	0.1518	0.0139
Biomechanics	Flexural Stiffness	Plant Geometry	No. of Internodes/ Plant	0.09	842	0.0257	0.1596	0.0069
Biomechanics	Flexural Stiffness	Plant Geometry	Plant Diameter	0.07	96	-0.1326	0.2665	0.4993
Biomechanics	Flexural Stiffness	Biomechanics	Internode Strength	0.04	843	-0.0229	0.1118	0.1954
Biomechanics	E-Young's Modulus	Internode Geometry	Internode Density	0.03	836	-0.0354	0.1001	0.3485
Biomechanics	E-Young's Modulus	Plant Geometry	Plant Height	0.02	843	-0.0438	0.0912	0.4905
Biomechanics	Flexural Stiffness	Biomechanics	Internode Strength	0.01	843	-0.0585	0.0765	0.7932
Biomechanics	Internode Strength	Internode Geometry	Internode Length	-0.01	845	-0.0786	0.0563	0.7449
Biomechanics	Flexural Stiffness	Plant Geometry	Plant Slenderness Ratio	-0.06	96	-0.2565	0.1432	0.5679
Biomechanics	Internode Strength	Plant Geometry	Plant Height	-0.08	845	-0.1489	-0.015	0.0167
Biomechanics	E-Young's Modulus	Plant Geometry	No. of Internodes/ Plant	-0.11	842	-0.1759	-0.0424	0.0014
Biomechanics	Flexural Stiffness	Internode Geometry	Internode Density	-0.18	836	-0.2404	-0.109	<.0001
Biomechanics	Internode Strength	Plant Geometry	No. of Internodes/ Plant	-0.21	844	-0.2778	-0.149	<.0001
Biomechanics	Internode Strength	Internode Geometry	Internode Volume	-0.42	845	-0.4713	-0.3598	<.0001
Biomechanics	E-Young's Modulus	Plant Geometry	Plant Diameter	-0.5	96	-0.6359	-0.3317	<.0001
Biomechanics	E-Young's Modulus	Internode Geometry	Internode Diameter	-0.63	843	-0.6682	-0.5865	<.0001
Biomechanics	Internode Strength	Internode Geometry	Internode Diameter	-0.63	845	-0.673	-0.5922	<.0001
Biomechanics	Internode Strength	Plant Geometry	Plant Diameter	-0.65	96	-0.7502	-0.5131	<.0001

P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant

APPENDIX II

CHAPTER IV

Table A-IV.1. ANOVA summaries for geometry and shape of internodes (3-6) for 15 sorghum bioenergy genotypes at different maturity groups evaluated in three locations in Texas 2014 season.

Maturity Response	Environment	Genotype	Source	Internode Geometry							
				Diameter		Length		Slenderness Ratio		Volume	
				DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F
Photoperiod Insensitive	CS Early	Della	Model	6	<.0001	6	<.0001	6	0.0002	6	<.0001
			Replicate	3	0.0404	3	0.0006	3	0.0243	3	0.0015
			Internode #	3	<.0001	3	<.0001	3	0.0004	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.67		0.31		0.19		0.52	
			CV%	6.37		9.85		8.75		14.57	
		R.07007	Model	6	<.0001	6	0.0363	6	0.0293	6	<.0001
			Replicate	3	0.0080	3	0.0496	3	0.2009	3	0.0033
			Internode #	3	<.0001	3	0.1102	3	0.0208	3	0.0002
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.44		0.20		0.21		0.40	
			CV%	6.46		7.23		9.31		10.24	
		R.SOR2014	Model	6	<.0001	6	<.0001	6	0.0087	6	<.0001
			Replicate	3	0.0147	3	0.1983	3	0.3130	3	0.0044
			Internode #	3	<.0001	3	<.0001	3	0.0030	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.61		0.62		0.25		0.72	
			CV%	10.28		6.38		11.57		12.65	
	CS Late	Della	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0024	3	<.0001	3	0.0018	3	<.0001
			Internode #	3	<.0001	3	0.3741	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.83		0.54		0.79		0.77	
			CV%	14.18		10.00		15.43		19.56	
		R.07007	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	<.0001	3	<.0001	3	0.4998	3	<.0001
			Internode #	3	<.0001	3	0.0908	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.80		0.38		0.72		0.75	
			CV%	11.75		7.80		13.40		15.06	
		R.SOR2014	Model	6	<.0001	6	0.0022	6	<.0001	6	<.0001
			Replicate	3	0.1474	3	0.0920	3	0.1084	3	0.1302
			Internode #	3	<.0001	3	0.0018	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.66		0.29		0.62		0.65	
			CV%	25.81		7.04		26.16		28.05	
	Weslaco	Della	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0467	3	<.0001	3	<.0001	3	<.0001
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	249	.	249	.	249	.	249	.
			C. Total	255	.	255	.	255	.	255	.
s			RSquare	0.72		0.56		0.50		0.75	
			CV%	10.30		7.60		13.17		12.84	

Table A-IV.1. Continued.

Maturity Response	Environment	Genotype	Source	Internode Geometry: Diameter		Length		Slenderness Ratio		Volume	
				DF				DF			
		R.07007	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.8450	3	<.0001	3	0.0001	3	<.0001
			Internode #	3	<.0001	3	0.3880	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.83		0.40		0.71		0.77	
			CV%	8.75		8.11		13.39		10.81	
		R.SOR2014	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.1122	3	<.0001	3	<.0001	3	0.0125
			Internode #	3	<.0001	3	0.1481	3	0.0328	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.52		0.26		0.27		0.33	
			CV%	10.88		22.29		23.29		26.17	
Moderate Photoperiod Sensitive	CS Early	EJX 7285	Model	6	<.0001	6	0.0040	6	<.0001	6	<.0001
			Replicate	3	0.1108	3	0.0037	3	0.1216	3	0.0058
			Internode #	3	<.0001	3	0.0928	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.58		0.28		0.45		0.52	
			CV%	11.71		10.35		15.71		14.99	
		EJX 7J906	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0640	3	0.0045	3	0.2294	3	0.0154
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.78		0.42		0.73		0.76	
			CV%	10.64		5.89		9.83		13.51	
		EJX 7J907	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.2203	3	0.0189	3	0.3669	3	0.0842
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.72		0.60		0.61		0.75	
			CV%	14.00		4.69		13.43		16.04	
		M81E	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0397	3	0.0250	3	0.7574	3	0.0045
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.69		0.21		0.44		0.63	
			CV%	10.68		10.43		14.68		15.07	
		Rio	Model	6	<.0001	6	0.0035	6	0.0003	6	<.0001
			Replicate	3	0.0008	3	0.4032	3	0.0009	3	0.4103
			Internode #	3	<.0001	3	0.0009	3	0.0250	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.33		0.15		0.18		0.24	
			CV%	7.24		9.26		9.68		14.08	
	CS Late	EJX 7285	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0015	3	<.0001	3	0.0016	3	<.0001
			Internode #	3	<.0001	3	0.0119	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.80		0.50		0.76		0.79	
			CV%	10.08		6.23		11.41		11.40	

Table A-IV.1. Continued.

Maturity Response	Environment	Genotype	Source	Internode Geometry: Diameter		Length		Slenderness Ratio		Volume	
				DF				DF			
		EJX 7J906	Model	6	<.0001	6	0.0001	6	<.0001	6	<.0001
			Replicate	3	0.0099	3	<.0001	3	0.0784	3	0.0009
			Internode #	3	<.0001	3	0.6913	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.78		0.37		0.82		0.71	
			CV%	21.60		9.64		17.82		28.56	
		EJX 7J907	Model	6	<.0001	6	0.0016	6	<.0001	6	<.0001
			Replicate	3	0.1570	3	0.1289	3	0.1684	3	0.1614
			Internode #	3	<.0001	3	0.0009	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.67		0.30		0.67		0.66	
			CV%	26.80		4.04		24.65		29.38	
		M81E	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	<.0001	3	<.0001	3	0.0260	3	<.0001
			Internode #	3	<.0001	3	0.0721	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.73		0.24		0.73		0.63	
			CV%	17.32		9.13		15.93		24.04	
		Rio	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0009	3	<.0001	3	0.0499	3	<.0001
			Internode #	3	<.0001	3	0.9167	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.67		0.23		0.64		0.52	
			CV%	18.87		15.93		19.81		29.27	
	Weslaco	EJX 7285	Model	6	<.0001	6	0.0018	6	<.0001	6	<.0001
			Replicate	3	0.3612	3	0.0036	3	0.1892	3	0.0150
			Internode #	3	<.0001	3	0.0428	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.71		0.16		0.65		0.48	
			CV%	8.35		7.95		10.93		12.51	
		EJX 7J906	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.6964	3	0.0020	3	0.0512	3	0.3268
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.75		0.48		0.60		0.78	
			CV%	9.67		6.83		11.22		11.37	
		EJX 7J907	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.2612	3	0.0048	3	0.0058	3	0.0274
			Internode #	3	<.0001	3	0.0001	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.92		0.23		0.67		0.79	
			CV%	6.74		11.34		13.84		13.73	
		M81E	Model	6	<.0001	6	0.0003	6	<.0001	6	<.0001
			Replicate	3	0.0001	3	0.2747	3	0.0101	3	0.0004
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	249	.	249	.	249	.	249	.
			C. Total	255	.	255	.	255	.	255	.
			RSquare	0.80		0.10		0.72		0.71	
			CV%	8.18		6.17		10.60		10.41	
		Rio	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0874	3	0.2448	3	0.4027	3	0.0272
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	249	.	249	.	249	.	249	.
			C. Total	255	.	255	.	255	.	255	.
			RSquare	0.57		0.36		0.40		0.60	
			CV%	10.30		7.41		13.27		12.27	

Table A-IV.1. Continued.

Maturity Response	Environment	Genotype	Source	Internode Geometry							
				Diameter		Length		Slenderness Ratio		Volume	
				DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F
Photoperiod Sensitive	CS Early	ATx623/R07007	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0564	3	<.0001	3	0.1957	3	0.0016
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.64		0.60		0.65		0.62	
			CV%	16.83		7.66		13.28		22.26	
		ATx645/R.SOR2014	Model	6	<.0001	6	0.0008	6	<.0001	6	<.0001
			Replicate	3	0.2423	3	0.0673	3	0.2331	3	0.1905
			Internode #	3	<.0001	3	0.0007	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.66		0.32		0.64		0.63	
			CV%	17.16		7.56		14.68		21.61	
		GRASSL	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0406	3	<.0001	3	0.0009	3	<.0001
			Internode #	3	<.0001	3	0.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.78		0.62		0.64		0.72	
			CV%	9.47		9.29		12.09		16.04	
		R.10030	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0003	3	0.0203	3	0.0385	3	0.0006
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.71		0.47		0.57		0.67	
			CV%	17.00		9.94		16.89		24.38	
		R.10135	Model	6	<.0001	6	0.0003	6	0.1914	6	<.0001
			Replicate	3	<.0001	3	0.0003	3	0.2475	3	<.0001
			Internode #	3	0.0019	3	0.0408	3	0.1986	3	0.0084
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.43		0.35		0.14		0.40	
			CV%	11.19		11.03		10.53		19.84	
		R.11434	Model	6	<.0001	6	0.0015	6	<.0001	6	<.0001
			Replicate	3	0.0002	3	0.0014	3	0.4374	3	<.0001
			Internode #	3	<.0001	3	0.0721	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.80		0.31		0.72		0.70	
			CV%	11.55		9.18		12.46		18.51	
		R.11438	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0001	3	<.0001	3	0.0011	3	<.0001
			Internode #	3	<.0001	3	0.0220	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.74		0.42		0.66		0.74	
			CV%	13.42		6.28		14.74		15.19	
	CS Late	ATx623/R07007	Model	6	<.0001	6	0.0400	6	<.0001	6	<.0001
			Replicate	3	0.3365	3	0.0646	3	0.0901	3	0.2515
			Internode #	3	<.0001	3	0.0960	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.72		0.20		0.82		0.59	
			CV%	18.55		12.11		12.39		28.19	

Table A-IV.1. Continued

Maturity Response	Environment	Genotype	Source	Internode Geometry							
				Diameter		Length		Slenderness Ratio		Volume	
				DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F
		ATx645/R.SOR2014	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0039	3	<.0001	3	0.0566	3	0.0007
			Internode #	3	<.0001	3	0.0232	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.74		0.43		0.74		0.71	
			CV%	25.18		6.50		22.87		29.64	
		GRASSL	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	<.0001	3	<.0001	3	0.0005	3	<.0001
			Internode #	3	<.0001	3	0.1165	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.82		0.56		0.76		0.76	
			CV%	13.01		8.60		12.49		19.82	
		R.10030	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.9245	3	0.3369	3	0.9284	3	0.8682
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.65		0.54		0.59		0.67	
			CV%	24.48		5.28		24.04		25.93	
		R.10135	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.1973	3	0.1007	3	0.3751	3	0.0988
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.78		0.40		0.71		0.76	
			CV%	12.18		6.62		12.06		15.16	
		R.11434	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0001	3	<.0001	3	<.0001	3	<.0001
			Internode #	3	<.0001	3	0.1171	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.83		0.76		0.88		0.79	
			CV%	14.05		8.54		10.23		19.92	
		R.11438	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.5847	3	<.0001	3	0.0212	3	0.1372
			Internode #	3	<.0001	3	0.0135	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.73		0.43		0.68		0.71	
			CV%	16.56		8.50		17.58		19.85	
	Weslaco	ATx623/R07007	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.4811	3	<.0001	3	0.0005	3	0.0053
			Internode #	3	<.0001	3	0.0373	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.71		0.30		0.72		0.55	
			CV%	11.39		7.98		12.33		15.71	
		ATx645/R.SOR2014	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0488	3	0.0027	3	0.0050	3	0.0926
			Internode #	3	<.0001	3	<.0001	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.	127	.
			RSquare	0.63		0.32		0.47		0.61	
			CV%	11.30		8.66		14.17		14.25	
		GRASSL	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.4318	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.61		0.49		0.58		0.54	
			CV%	7.54		9.44		12.02		11.92	

Table A-IV.1. Continued

Maturity Response	Environment	Genotype	Source	Internode Geometry							
				Diameter		Length		Slenderness Ratio		Volume	
				DF	Prob > F	DF	Prob > F	DF	Prob > F	DF	Prob > F
		R.10030	Model	6	0.1198	6	0.0004	6	0.0033	6	0.0894
			Replicate	3	0.7275	3	<.0001	3	0.0027	3	0.2826
			Internode #	3	0.0329	3	0.3391	3	0.1021	3	0.0622
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.16		0.34		0.28		0.17	
			CV%	12.87		7.90		13.57		16.83	
		R.10135	Model	6	<.0001	6	<.0001	6	0.0126	6	<.0001
			Replicate	3	0.4122	3	<.0001	3	0.0151	3	0.0019
			Internode #	3	<.0001	3	<.0001	3	0.0944	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.40		0.61		0.24		0.63	
			CV%	7.30		5.43		8.72		9.51	
		R.11434	Model	6	<.0001	6	0.0318	6	<.0001	6	<.0001
			Replicate	3	<.0001	3	0.0130	3	0.0178	3	<.0001
			Internode #	3	<.0001	3	0.3564	3	<.0001	3	0.0084
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.63		0.21		0.43		0.48	
			CV%	9.74		10.40		12.59		15.56	
		R.11438	Model	6	<.0001	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0009	3	<.0001	3	<.0001	3	0.0003
			Internode #	3	<.0001	3	0.2583	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.	63	.
			RSquare	0.74		0.44		0.71		0.70	
			CV%	7.99		4.53		8.83		9.49	

Table A-IV.2. LSMeans for geometry and shape of internodes (3-6) for 15 sorghum bioenergy genotypes at different maturity groups evaluated in three locations in Texas 2014 season.

Maturity Response	Environment	Genotype	Internode No.	Length (cm)	Diameter (cm)	Volume (cm^3)	Slenderness
Photoperiod Insensitive	CS Early	Della	3	18.76	1.48	43.52	12.84
			4	20.85	1.41	45.89	15.06
			5	21.72	1.36	46.12	16.25
			6	23.86	1.28	47.92	18.82
		R.07007	3	19.78	1.24	38.37	16.04
			4	22.38	1.21	42.50	18.58
			5	21.75	1.18	40.39	18.51
			6	21.56	1.17	39.47	18.67
		R.SOR2014	3	20.00	0.86	26.95	23.34
			4	23.41	0.85	31.22	27.80
			5	26.83	0.73	30.66	37.05
			6	26.32	0.74	30.72	35.44
	CS Late	Della	3	10.24	1.23	19.82	8.50
			4	13.48	1.22	25.64	11.37
			5	17.24	1.20	32.14	14.82
			6	23.22	1.18	43.05	19.95
		R.07007	3	12.54	1.48	28.76	8.71
			4	14.77	1.44	33.44	10.32
			5	19.30	1.51	45.61	12.87
			6	21.41	1.41	47.17	15.41
		R.SOR2014	3	9.21	1.01	14.59	9.16
			4	15.01	0.94	22.01	16.20
			5	20.98	0.94	31.17	22.28
			6	23.89	0.92	34.45	26.19
	Weslaco	Della	3	18.74	1.03	30.34	18.34
			4	26.34	0.99	40.86	26.85
			5	29.42	0.91	41.89	32.67
			6	27.79	0.85	37.10	32.95
		R.07007	3	14.26	0.88	19.75	16.36
			4	20.81	0.91	29.85	22.95
			5	24.44	0.91	34.83	27.29
			6	22.73	0.90	31.99	25.61
		R.SOR2014	3	20.08	0.73	23.15	28.43
			4	22.38	0.70	24.52	33.82
			5	25.65	0.67	26.92	40.64
			6	26.36	0.65	26.70	43.71
Moderate Photoperiod Sensitive	CS Early	EJX 7285	3	19.98	2.08	64.65	9.81
			4	25.71	2.06	82.98	12.63
			5	28.52	2.04	91.58	14.12
			6	25.45	1.91	76.62	13.45
		EJX 7J906	3	8.23	1.99	25.50	4.20
			4	10.04	1.96	30.78	5.15
			5	11.24	1.86	32.88	6.06
			6	13.69	1.81	38.80	7.60
		EJX 7J907	3	8.66	2.00	27.15	4.34
			4	9.77	1.91	29.33	5.13
			5	11.90	1.84	34.28	6.51
			6	14.77	1.74	40.40	8.50
		M81E	3	16.10	1.89	47.98	8.58
			4	18.66	1.92	55.87	9.89
			5	23.73	1.83	67.91	13.17
			6	22.67	1.71	60.94	13.40
		Rio	3	19.28	1.55	46.87	12.53
			4	20.98	1.53	50.35	13.92
			5	20.96	1.49	48.93	14.22
			6	21.62	1.42	47.87	15.45

Table A-IV.2. Continued

Maturity Response	Environment	Genotype	Internode No.	Length (cm)	Diameter (cm)	Volume (cm^3)	Slenderness
	CS Late	EJX 7285	3	16.29	2.15	54.50	7.73
			4	22.58	2.20	78.02	10.31
			5	26.29	2.19	90.30	12.10
			6	27.11	2.05	87.48	13.22
		EJX 7J906	3	4.25	2.05	13.55	2.12
			4	5.16	2.07	16.63	2.54
			5	7.21	2.03	22.75	3.64
			6	10.93	1.99	33.40	5.68
		EJX 7J907	3	5.19	1.98	16.16	2.62
			4	6.73	2.00	21.09	3.38
			5	8.70	1.95	26.43	4.51
			6	13.06	1.89	38.55	6.95
		M81E	3	10.87	2.18	37.03	5.06
			4	16.38	2.21	56.10	7.58
			5	20.44	2.18	69.05	9.60
			6	23.28	2.09	75.75	11.39
		Rio	3	12.82	1.58	31.51	8.42
			4	19.58	1.59	47.81	12.92
			5	24.16	1.60	59.36	15.85
			6	26.83	1.56	65.16	18.01
	Weslaco	EJX 7285	3	20.53	1.52	48.99	13.59
			4	27.47	1.56	67.27	17.72
			5	28.10	1.56	69.01	18.08
			6	23.01	1.49	53.75	15.64
		EJX 7J906	3	18.52	1.12	32.47	16.69
			4	25.26	1.12	44.55	22.63
			5	27.96	1.06	46.42	26.57
			6	28.90	0.97	43.98	29.87
		EJX 7J907	3	16.27	1.09	27.84	15.17
			4	22.76	1.03	36.83	22.69
			5	28.03	1.03	45.43	27.71
			6	30.33	0.95	45.43	31.91
		M81E	3	17.92	1.34	37.67	13.44
			4	24.75	1.37	53.24	18.14
			5	28.25	1.37	60.74	20.72
			6	26.52	1.31	54.58	20.33
		Rio	3	20.85	1.19	38.88	17.64
			4	27.73	1.17	51.12	23.72
			5	28.20	1.12	49.89	25.19
			6	27.23	1.03	44.12	26.58
Photoperiod Sensitive	CS Early	ATx623/R07007	3	13.86	2.20	47.00	6.48
			4	20.58	2.10	66.16	10.16
			5	24.13	1.98	74.36	12.43
			6	24.31	1.91	73.02	12.81
		ATx645/R.SOR2014	3	8.82	1.86	25.36	4.85
			4	10.34	1.80	29.11	5.80
			5	12.43	1.73	33.57	7.26
			6	15.76	1.66	40.87	9.58
		GRASSL	3	15.78	2.26	55.67	7.09
			4	23.99	2.20	82.22	11.14
			5	24.39	2.01	77.12	12.38
			6	24.13	1.97	73.98	12.69
		R.10030	3	13.21	2.14	43.92	6.26
			4	21.04	2.01	65.47	10.69
			5	24.71	1.79	68.71	14.24
			6	25.51	1.77	70.76	14.68
		R.10135	3	25.33	1.75	68.45	14.95
			4	28.19	1.65	72.52	17.51
			5	27.59	1.60	68.97	17.62
			6	29.76	1.58	73.00	19.26

Table A-IV.2. Continued

Maturity Response	Environment	Genotype	Internode No.	Length (cm)	Diameter (cm)	Volume (cm^3)	Slenderness
		R.11434	3	12.93	2.05	41.66	6.35
			4	22.20	1.97	67.69	11.56
			5	23.62	1.90	70.24	12.64
			6	21.06	1.90	62.90	11.23
		R.11438	3	12.32	2.21	42.67	5.61
			4	18.92	2.12	62.81	9.03
			5	20.06	2.09	65.87	9.65
			6	21.86	2.07	70.73	10.63
	CS Late	ATx623/R07007	3	10.38	2.35	38.00	4.54
			4	17.24	2.26	59.90	7.90
			5	22.46	2.14	74.73	10.70
			6	23.31	2.15	77.15	11.22
		ATx645/R.SOR2014	3	5.01	2.15	16.81	2.35
			4	6.55	2.12	21.58	3.14
			5	8.99	2.09	28.81	4.44
			6	13.64	2.00	42.49	6.92
		GRASSL	3	14.09	2.32	50.37	6.26
			4	19.79	2.33	71.01	8.80
			5	23.33	2.29	82.21	10.57
			6	26.01	2.18	88.20	12.26
		R.10030	3	10.69	2.13	35.40	5.09
			4	19.23	2.01	60.48	9.63
			5	24.02	1.94	73.32	12.38
			6	27.61	1.84	79.58	15.08
		R.10135	3	15.86	2.05	50.47	7.88
			4	22.49	1.99	70.22	11.36
			5	25.35	1.94	76.95	13.16
			6	29.44	1.81	83.58	16.34
		R.11434	3	11.11	2.19	37.39	5.46
			4	17.13	2.17	57.59	8.23
			5	22.61	2.12	73.66	11.12
			6	24.31	2.04	76.93	12.30
		R.11438	3	12.61	2.19	43.16	5.85
			4	19.26	2.16	64.83	9.05
			5	24.53	2.09	80.61	11.83
			6	26.37	1.99	82.58	13.39
	Weslaco	ATx623/R07007	3	18.88	1.28	37.88	14.92
			4	28.90	1.30	58.62	22.56
			5	29.55	1.31	60.55	22.82
			6	23.17	1.24	45.06	18.86
		ATx645/R.SOR2014	3	19.03	1.22	36.83	15.58
			4	25.57	1.21	48.39	21.30
			5	28.51	1.14	50.99	25.13
			6	25.47	1.08	43.09	23.98
		GRASSL	3	19.59	1.69	51.85	11.74
			4	24.50	1.72	66.22	14.54
			5	21.77	1.67	57.34	13.18
			6	20.22	1.65	52.15	12.51
		R.10030	3	25.75	1.49	60.35	17.44
			4	25.73	1.54	61.97	16.92
			5	26.18	1.47	60.11	18.08
			6	28.88	1.47	66.80	19.73
		R.10135	3	23.82	1.33	49.63	18.02
			4	25.54	1.31	52.59	19.59
			5	24.34	1.28	48.82	19.10
			6	27.36	1.16	49.86	23.72
		R.11434	3	17.33	2.17	58.74	8.10
			4	18.29	2.27	64.87	8.22
			5	21.21	2.24	74.09	9.63
			6	18.31	2.14	61.22	8.71
		R.11438	3	20.22	1.81	57.50	11.20
			4	20.84	1.86	61.10	11.21
			5	27.20	1.81	77.41	15.06
			6	23.26	1.83	66.92	12.74

Table A-IV.3. ANOVA summaries for biomechanical properties of internodes (3-6) for 15 sorghum bioenergy genotypes at different maturity groups evaluated in three locations in Texas 2014 season.

Maturity Response	Environment	Genotype	Source	E-Young's Modulus		Strength		Flexural Stiffness	
				DF	Prob > F	DF	Prob > F	DF	Prob > F
Photoperiod Insensitive	CS Early	Della	Model	6	<.0001	6	0.0558	6	0.2575
			Replicate	3	0.0129	3	0.1889	3	0.0767
			Internode No.	3	<.0001	3	0.0538	3	0.8393
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.34	.	0.10	.	0.06	.
			CV%	4.45		5.92		12.84	
		R.07007	Model	6	0.4658	6	0.0022	6	0.008
			Replicate	3	0.2484	3	0.3675	3	0.5761
			Internode No.	3	0.6899	3	0.0005	3	0.0015
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.09	.	0.29	.	0.26	.
			CV%	3.74		5.26		11.55	
		R.SOR2014	Model	6	0.0003	6	0.0002	6	<.0001
			Replicate	3	0.0371	3	0.9337	3	0.6695
			Internode No.	3	0.0003	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.35	.	0.36	.	0.49	.
			CV%	3.28		5.56		12.24	
	CS Late	Della	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	<.0001	3	<.0001	3	0.0523
			Internode No.	3	<.0001	3	0.0043	3	<.0001
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.61	.	0.39	.	0.54	.
			CV%	6.92		9.04		19.40	
		R.07007	Model	6	<.0001	6	0.0002	6	<.0001
			Replicate	3	<.0001	3	0.6309	3	0.5189
			Internode No.	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.58	.	0.36	.	0.56	.
			CV%	5.98		6.48		15.23	
		R.SOR2014	Model	6	<.0001	6	0.507	6	0.0002
			Replicate	3	0.5835	3	0.779	3	0.3068
			Internode No.	3	<.0001	3	0.2464	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.47	.	0.09	.	0.36	.
			CV%	10.80		11.02		34.18	
	Weslaco	Della	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0009	3	<.0001	3	0.0005
			Internode No.	3	<.0001	3	<.0001	3	<.0001
			Error	249	.	249	.	249	.
			C. Total	255	.	255	.	255	.
			RSquare	0.32	.	0.28	.	0.16	.
			CV%	4.12		6.00		20.25	
		R.07007	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	<.0001	3	<.0001	3	0.0047
			Internode No.	3	<.0001	3	<.0001	3	<.0001
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.36	.	0.41	.	0.38	.
			CV%	4.58		6.87		16.12	
		R.SOR2014	Model	6	0.0158	6	0.0011	6	<.0001
			Replicate	3	0.0018	3	0.0004	3	<.0001
			Internode No.	3	0.9295	3	0.2182	3	0.0002
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.12	.	0.17	.	0.31	.
			CV%	13.33		17.40		29.77	

Table A-IV.3. Continued.

Maturity Response	Environment	Genotype	Source	E-Young's Modulus		Strength		Flexural Stiffness	
				DF	Prob > F	DF	Prob > F	DF	Prob > F
Moderate Photoperiod Sensitive	CS Early	EJX 7285	Model	6	0.0001	6	0.0204	6	0.011
			Replicate	3	0.0028	3	0.0099	3	0.2953
			Internode No.	3	0.0013	3	0.2689	3	0.0042
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.37	.	0.22	.	0.25	.
			CV%	5.71		8.03		17.23	
		EJX 7J906	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.1705	3	0.0177	3	0.611
			Internode No.	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.68	.	0.45	.	0.68	.
			CV%	9.49		8.05		18.43	
		EJX 7J907	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.3857	3	0.9394	3	0.396
			Internode No.	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.73	.	0.57	.	0.72	.
			CV%	9.90		8.70		20.11	
		M81E	Model	6	<.0001	6	0.0658	6	<.0001
			Replicate	3	0.002	3	0.1785	3	0.4465
			Internode No.	3	<.0001	3	0.0703	3	<.0001
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.43	.	0.09	.	0.31	.
			CV%	6.39		10.13		16.74	
		Rio	Model	6	0.2629	6	0.0011	6	<.0001
			Replicate	3	0.1712	3	0.1453	3	0.0009
			Internode No.	3	0.4435	3	0.0006	3	0.0013
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.06	.	0.17	.	0.22	.
			CV%	5.50		7.68		14.91	
	CS Late	EJX 7285	Model	6	<.0001	6	0.02	6	<.0001
			Replicate	3	0.0086	3	0.0721	3	0.0189
			Internode No.	3	<.0001	3	0.0352	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.49	.	0.23	.	0.52	.
			CV%	6.39		8.44		16.29	
		EJX 7J906	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0001	3	0.0003	3	0.0376
			Internode No.	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.73	.	0.54	.	0.77	.
			CV%	25.06		22.31		36.01	
		EJX 7J907	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0352	3	0.0321	3	0.2356
			Internode No.	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.73	.	0.59	.	0.63	.
			CV%	16.69		12.19		43.63	
		M81E	Model	6	<.0001	6	0.3004	6	<.0001
			Replicate	3	0.0002	3	0.197	3	0.3414
			Internode No.	3	<.0001	3	0.465	3	<.0001
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.59	.	0.06	.	0.64	.
			CV%	10.93		13.20		22.20	

Table A-IV.3. Continued.

Maturity Response	Environment	Genotype	Source	E-Young's Modulus		Strength		Flexural Stiffness	
				DF	Prob > F	DF	Prob > F	DF	Prob > F
Moderate Photoperiod Sensitive		Rio	Model	6	<.0001	6	0.0004	6	<.0001
			Replicate	3	<.0001	3	0.0007	3	0.0003
			Internode No.	3	<.0001	3	0.0337	3	<.0001
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.38	.	0.18	.	0.50	.
			CV%	10.83		13.78		21.18	
	Weslaco	EJX 7285	Model	6	0.0136	6	0.0004	6	<.0001
			Replicate	3	0.0036	3	0.0004	3	0.0005
			Internode No.	3	0.4665	3	0.0769	3	0.0069
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.12	.	0.18	.	0.21	.
			CV%	10.17		20.12		24.35	
		EJX 7J906	Model	6	<.0001	6	0.2512	6	<.0001
			Replicate	3	0.4333	3	0.609	3	0.1504
			Internode No.	3	<.0001	3	0.1121	3	<.0001
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.49	.	0.06	.	0.39	.
			CV%	5.41		8.91		20.28	
		EJX 7J907	Model	6	<.0001	6	0.0021	6	<.0001
			Replicate	3	0.0006	3	0.0029	3	0.0225
			Internode No.	3	<.0001	3	0.0665	3	<.0001
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.33	.	0.15	.	0.43	.
			CV%	5.29		9.76		11.62	
		M81E	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0066	3	0.2888	3	0.0236
			Internode No.	3	<.0001	3	<.0001	3	<.0001
			Error	249	.	249	.	249	.
			C. Total	255	.	255	.	255	.
			RSquare	0.25	.	0.20	.	0.35	.
			CV%	3.95		5.73		13.99	
		Rio	Model	6	0.0727	6	<.0001	6	<.0001
			Replicate	3	0.1121	3	0.0293	3	0.0464
			Internode No.	3	0.1313	3	<.0001	3	<.0001
			Error	249	.	249	.	249	.
			C. Total	255	.	255	.	255	.
			RSquare	0.04	.	0.14	.	0.33	.
			CV%	4.81		6.56		16.60	
Photoperiod Sensitive	CS Early	ATx623/R07007	Model	6	<.0001	6	0.0001	6	<.0001
			Replicate	3	0.0028	3	0.0082	3	0.2509
			Internode No.	3	<.0001	3	0.0005	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.61	.	0.37	.	0.57	.
			CV%	9.43		9.73		18.97	
		ATx645/R.SOR2014	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	0.0835	3	0.0567	3	0.2663
			Internode No.	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.60	.	0.40	.	0.67	.
			CV%	12.57		11.28		24.07	
		GRASSL	Model	6	<.0001	6	0.0412	6	<.0001
			Replicate	3	0.0008	3	0.0653	3	<.0001
			Internode No.	3	<.0001	3	0.0985	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.66	.	0.20	.	0.60	.
			CV%	7.65		11.19		18.72	

Table A-IV.3. Continued.

Maturity Response	Environment	Genotype	Source	E-Young's Modulus		Strength		Flexural Stiffness	
				DF	Prob > F	DF	Prob > F	DF	Prob > F
Photoperiod Sensitive		R.10030	Model	6	<.0001	6	0.0194	6	<.0001
			Replicate	3	0.0061	3	0.242	3	0.0341
			Internode No.	3	<.0001	3	0.0103	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.61	.	0.23	.	0.45	.
			CV%	12.30		16.57		27.46	
		R.10135	Model	6	0.0027	6	0.0002	6	0.0658
			Replicate	3	0.0024	3	0.0005	3	0.0149
			Internode No.	3	0.0886	3	0.0128	3	0.7359
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.29	.	0.36	.	0.18	.
			CV%	5.32		11.68		130.51	
		R.11434	Model	6	<.0001	6	0.0003	6	<.0001
			Replicate	3	0.0003	3	0.022	3	0.1898
			Internode No.	3	<.0001	3	0.0006	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.74	.	0.35	.	0.70	.
			CV%	6.65		7.97		16.00	
		R.11438	Model	6	<.0001	6	0.1133	6	<.0001
			Replicate	3	0.075	3	0.4678	3	0.0249
			Internode No.	3	<.0001	3	0.0503	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.70	.	0.16	.	0.64	.
			CV%	6.94		11.47		17.02	
	CS Late	ATx623/R07007	Model	6	<.0001	6	0.0225	6	<.0001
			Replicate	3	0.1741	3	0.0496	3	0.5319
			Internode No.	3	<.0001	3	0.0596	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.59	.	0.22	.	0.69	.
			CV%	12.62		13.13		20.45	
		ATx645/R.SOR2014	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	<.0001	3	0.0006	3	0.0095
			Internode No.	3	<.0001	3	<.0001	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.69	.	0.55	.	0.71	.
			CV%	24.46		21.91		38.70	
		GRASSL	Model	6	<.0001	6	0.0051	6	<.0001
			Replicate	3	<.0001	3	0.0012	3	<.0001
			Internode No.	3	<.0001	3	0.4118	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.64	.	0.27	.	0.61	.
			CV%	11.32		16.99		20.59	
		R.10030	Model	6	<.0001	6	0.017	6	<.0001
			Replicate	3	0.7646	3	0.3887	3	0.7712
			Internode No.	3	<.0001	3	0.0055	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.59	.	0.23	.	0.47	.
			CV%	15.79		18.07		34.25	
		R.10135	Model	6	<.0001	6	0.1562	6	<.0001
			Replicate	3	0.3099	3	0.1261	3	0.593
			Internode No.	3	<.0001	3	0.294	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.55	.	0.15	.	0.53	.
			CV%	8.60		9.95		18.03	

Table A-IV.3. Continued.

Maturity Response	Environment	Genotype	Source	E-Young's Modulus		Strength		Flexural Stiffness	
				DF	Prob > F	DF	Prob > F	DF	Prob > F
Photoperiod Sensitive		R.11434	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	<.0001	3	<.0001	3	0.0035
			Internode No.	3	<.0001	3	0.1293	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.77	.	0.47	.	0.80	.
			CV%	9.78		15.29		14.97	
		R.11438	Model	6	<.0001	6	0.6116	6	<.0001
			Replicate	3	0.8356	3	0.6859	3	0.0264
			Internode No.	3	<.0001	3	0.3977	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.49	.	0.07	.	0.56	.
			CV%	12.65		16.15		20.65	
	Weslaco	ATx623/R07007	Model	6	0.0001	6	0.0181	6	<.0001
			Replicate	3	0.2434	3	0.0213	3	0.0866
			Internode No.	3	<.0001	3	0.1192	3	<.0001
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.20	.	0.12	.	0.44	.
			CV%	6.48		8.00		18.05	
		ATx645/R.SOR2014	Model	6	<.0001	6	0.0019	6	<.0001
			Replicate	3	0.9792	3	0.0878	3	0.0029
			Internode No.	3	<.0001	3	0.002	3	<.0001
			Error	121	.	121	.	121	.
			C. Total	127	.	127	.	127	.
			RSquare	0.24	.	0.16	.	0.27	.
			CV%	3.22		5.33		17.04	
		GRASSL	Model	6	0.0002	6	<.0001	6	<.0001
			Replicate	3	0.0001	3	0.0006	3	0.017
			Internode No.	3	0.0904	3	0.0002	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.36	.	0.44	.	0.41	.
			CV%	4.95		8.48		14.07	
		R.10030	Model	6	0.0082	6	<.0001	6	0.025
			Replicate	3	0.0045	3	0.0072	3	0.1401
			Internode No.	3	0.1927	3	<.0001	3	0.0243
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.25	.	0.41	.	0.22	.
			CV%	6.02		10.82		19.16	
		R.10135	Model	6	0.0014	6	0.0004	6	<.0001
			Replicate	3	0.117	3	0.0699	3	0.0202
			Internode No.	3	0.0009	3	0.0003	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.31	.	0.34	.	0.42	.
			CV%	3.34		5.31		12.24	
		R.11434	Model	6	<.0001	6	<.0001	6	<.0001
			Replicate	3	<.0001	3	<.0001	3	<.0001
			Internode No.	3	0.1856	3	0.2306	3	0.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.46	.	0.42	.	0.56	.
			CV%	8.53		10.42		15.61	
		R.11438	Model	6	<.0001	6	0.0266	6	<.0001
			Replicate	3	0.1104	3	0.5542	3	0.0137
			Internode No.	3	<.0001	3	0.0066	3	<.0001
			Error	57	.	57	.	57	.
			C. Total	63	.	63	.	63	.
			RSquare	0.38	.	0.22	.	0.41	.
			CV%	4.35		5.35		13.38	

Table A-IV.4. LSMeans for biomechanical properties of internodes (3-6) for 15 sorghum bioenergy genotypes at different maturity groups evaluated in three locations in Texas during the 2014 season.

Maturity Response	Environment	Genotype	Internode No.	E-Young's Modulus (MPa)	Internode Strength (MPa)	Flexural Stiffness (Nm^2)
Photoperiod Insensitive	CS Early	Della	3	1,224	22.5	2.9
			4	1,460	20.4	2.8
			5	1,674	20.3	2.8
			6	2,159	21.9	2.9
			Avg.	1,629	21.3	2.8
		R.07007	3	3,111	38.7	3.6
			4	3,370	32.8	3.6
			5	3,173	30.7	3.1
			6	2,967	29.4	2.7
			Avg.	3,155	32.9	3.2
		R.SOR2014	3	4,408	49.7	1.2
			4	4,042	33.6	1.0
			5	6,110	46.5	0.9
			6	4,245	43.1	0.6
			Avg.	4,701	43.2	0.9
		Avg.		3,162	32.5	2.3
	CS Late	Della	3	581	27.7	0.7
			4	1,077	26.6	1.2
			5	1,651	23.9	1.7
			6	2,141	21.7	2.1
			Avg.	1,362	25.0	1.4
		R.07007	3	748	30.2	1.8
			4	1,236	28.0	2.6
			5	1,443	21.4	3.7
			6	2,157	22.6	4.2
			Avg.	1,396	25.5	3.1
		R.SOR2014	3	680	36.1	0.4
			4	2,733	48.6	1.2
			5	3,291	41.5	1.4
			6	4,462	40.7	1.6
			Avg.	2,791	41.7	1.2
		Avg.		1,850	30.7	1.9
	Weslaco	Della	3	3,178	33.9	1.8
			4	4,432	31.9	2.2
			5	5,220	35.5	1.7
			6	5,519	42.9	1.5
			Avg.	4,587	36.1	1.8
		R.07007	3	2,790	38.8	0.8
			4	3,848	29.5	1.3
			5	4,642	30.2	1.5
			6	3,515	28.6	1.1
			Avg.	3,699	31.8	1.2
		R.SOR2014	3	6,567	54.4	1.0
			4	6,876	50.0	0.8
			5	6,405	47.8	0.6
			6	5,699	38.7	0.5
			Avg.	6,387	47.7	0.7
		Avg.		4,891	38.5	1.2
	Avg.			3,301	33.9	1.8
Moderate Photoperiod Sensitive	CS Early	EJX 7285	3	1,062	25.7	9.8
			4	1,691	23.0	15.2
			5	1,702	22.6	14.3
			6	1,885	26.1	12.3
			Avg.	1,585	24.3	12.9
		EJX 7J906	3	85	17.3	0.7
			4	215	19.5	1.6
			5	337	25.0	2.0
			6	574	27.3	3.1
			Avg.	303	22.3	1.9
		EJX 7J907	3	86	14.4	0.7
			4	167	15.4	1.1
			5	357	24.6	2.1
			6	796	27.3	3.7
			Avg.	351	20.4	1.9

Biomechanical Properties: E-Young's Modulus, Internode Strength, Flexural Stiffness.

Table A-IV.4. Continued

Maturity Response	Environment	Genotype	Internode No.	E-Young's Modulus	Biomechanical properties Internode Strength	Flexural Stiffness
				(MPa)	(MPa)	(Nm^2)
		M81E	3	716	27.8	4.6
			4	837	23.2	5.6
			5	1,489	24.0	8.1
			6	1,581	23.0	6.6
			Avg.	1,156	24.5	6.2
		Rio	3	1,589	30.0	4.6
			4	1,836	30.2	4.9
			5	1,805	26.8	4.4
			6	1,827	23.8	3.7
			Avg.	1,764	27.7	4.4
		Avg.		1,032	23.8	5.5
	CS Late	EJX 7285	3	545	20.9	5.8
			4	898	19.3	10.8
			5	1,102	16.5	12.5
			6	1,427	17.2	12.7
			Avg.	993	18.5	10.4
		EJX 7J906	3	7	4.9	0.1
			4	16	6.1	0.2
			5	46	6.6	0.4
			6	183	13.1	1.6
			Avg.	63	7.7	0.5
		EJX 7J907	3	17	7.8	0.1
			4	49	9.0	0.4
			5	93	13.2	0.8
			6	339	17.3	2.5
			Avg.	125	11.8	1.0
		M81E	3	135	15.4	1.6
			4	363	17.4	4.5
			5	625	16.1	7.0
			6	908	17.3	8.6
			Avg.	508	16.6	5.4
		Rio	3	548	23.5	1.7
			4	1,229	22.5	3.8
			5	1,370	19.3	4.4
			6	1,788	17.9	5.0
			Avg.	1,234	20.8	3.7
		Avg.		584	15.1	4.2
	Weslaco	EJX 7285	3	1,929	24.9	5.6
			4	2,435	22.1	7.9
			5	2,349	19.3	8.0
			6	2,603	29.0	6.3
			Avg.	2,329	23.8	6.9
		EJX 7J906	3	1,949	31.3	1.6
			4	4,789	37.2	3.9
			5	4,599	33.7	2.9
			6	5,875	36.6	2.6
			Avg.	4,303	34.7	2.7
		EJX 7J907	3	3,099	48.3	2.1
			4	5,426	43.3	2.9
			5	5,984	38.8	3.2
			6	5,183	39.4	2.1
			Avg.	4,923	42.4	2.6
		M81E	3	2,435	37.8	3.9
			4	3,339	30.8	5.9
			5	3,815	30.4	6.6
			6	3,327	30.1	4.8
			Avg.	3,229	32.3	5.3
		Rio	3	3,811	41.5	3.9
			4	4,507	35.1	4.3
			5	4,214	33.7	3.3
			6	4,140	34.9	2.3
			Avg.	4,168	36.3	3.5
		Avg.		3,790	33.9	4.2
	Avg.			1,802	24.3	4.6

Table A-IV.4. Continued

Maturity Response	Environment	Genotype	Internode No.	E-Young's Modulus (MPa)	Internode Strength (MPa)	Flexural Stiffness (Nm^2)
				Biomechanical properties		
Photoperiod Sensitive	CS Early	ATx623/R07007	3	278	15.0	3.4
			4	845	19.5	8.3
			5	1,405	22.2	10.5
			6	1,557	22.7	10.3
			Avg.	1,021	19.9	8.1
		ATx645/R.SOR2014	3	120	14.6	0.8
			4	255	18.8	1.3
			5	518	25.8	2.4
			6	1,115	25.2	4.3
			Avg.	502	21.1	2.2
		GRASSL	3	310	19.5	4.2
			4	844	19.7	9.9
			5	1,257	21.7	10.1
			6	1,523	25.6	11.1
			Avg.	983	21.6	8.8
		R.10030	3	132	9.1	1.5
			4	381	12.0	3.4
			5	967	15.0	5.0
			6	941	12.7	4.7
			Avg.	605	12.2	3.7
		R.10135	3	1,740	20.8	8.0
			4	2,298	19.3	8.1
			5	2,320	23.1	7.4
			6	2,454	15.4	7.5
			Avg.	2,203	19.7	7.8
		R.11434	3	190	12.9	1.7
			4	806	18.1	6.0
			5	917	16.5	5.9
			6	700	15.2	4.5
			Avg.	653	15.7	4.5
		R.11438	3	147	12.0	1.8
			4	509	13.6	5.1
			5	596	16.3	5.6
			6	563	14.3	5.3
			Avg.	454	14.0	4.4
		Avg.		917	17.7	5.6
	CS Late	ATx623/R07007	3	120	13.5	1.8
			4	486	17.2	6.5
			5	994	19.1	10.3
			6	936	15.3	9.7
			Avg.	634	16.3	7.1
		ATx645/R.SOR2014	3	12	5.7	0.1
			4	25	5.6	0.3
			5	62	6.7	0.8
			6	282	14.5	2.4
			Avg.	95	8.1	0.9
		GRASSL	3	168	10.6	2.8
			4	421	13.1	6.5
			5	577	13.2	7.9
			6	851	12.8	9.3
			Avg.	504	12.4	6.6
		R.10030	3	61	6.5	0.8
			4	420	10.8	3.8
			5	743	9.4	5.6
			6	756	8.4	4.6
			Avg.	495	8.8	3.7
		R.10135	3	344	15.2	3.4
			4	993	16.0	7.6
			5	995	13.4	7.2
			6	1,811	15.1	9.5
			Avg.	1,036	14.9	6.9

Table A-IV.4. Continued

Maturity Response	Environment	Genotype	Internode No.	Biomechanical properties E-Young's Modulus (MPa)	Internode Strength (MPa)	Flexural Stiffness (Nm^2)
		R.11434	3	106	9.1	1.2
			4	321	11.6	3.4
			5	570	11.6	5.5
			6	657	12.1	5.5
			Avg.	413	11.1	3.9
		R.11438	3	127	8.2	1.9
			4	411	9.6	4.5
			5	611	10.0	5.7
			6	785	9.8	6.0
			Avg.	483	9.4	4.5
		Avg.		523	11.6	4.8
	Weslaco	ATx623/R07007	3	2,282	26.6	3.1
			4	3,913	26.1	5.7
			5	3,854	24.3	5.5
			6	2,632	23.2	3.1
			Avg.	3,170	25.1	4.3
		ATx645/R.SOR2014	3	3,844	42.2	4.4
			4	4,875	35.0	5.2
			5	5,855	38.0	4.9
			6	4,870	39.6	3.3
			Avg.	4,861	38.7	4.4
		GRASSL	3	2,136	36.1	8.6
			4	2,736	23.9	11.6
			5	2,030	25.1	7.7
			6	2,022	24.2	7.2
			Avg.	2,231	27.3	8.7
		R.10030	3	2,583	24.1	6.4
			4	2,099	18.0	5.7
			5	2,004	17.1	4.7
			6	1,823	13.9	4.4
			Avg.	2,127	18.3	5.3
		R.10135	3	4,814	35.5	7.4
			4	4,552	30.0	6.6
			5	3,749	27.2	5.0
			6	5,773	34.5	5.2
			Avg.	4,722	31.8	6.0
		R.11434	3	528	16.5	5.9
			4	422	14.7	5.5
			5	574	13.8	7.3
			6	405	13.7	4.2
			Avg.	482	14.7	5.7
		R.11438	3	1,721	26.4	9.2
			4	1,387	23.1	8.6
			5	2,545	24.3	13.5
			6	1,856	21.3	10.4
			Avg.	1,877	23.8	10.4
		Avg.		2,782	25.7	6.4
	Avg.			1,407	18.3	5.6
Avg.				1,918	23.4	4.5

Table A-IV.5. GxE ANOVA for whole plant geometry and shape traits for a group of photoperiod insensitive sorghum genotypes evaluated at three environments in Texas during the 2014 season.

Environment	Source	Plant Geometry and Shape					
		Plant Height		Avg. Plant Diameter		Plant Slenderness Ratio	
		DF	Prob > F	DF	Prob > F	DF	Prob > F
CS Early	Model	5	<.0001[1]	5	<.0001	5	<.0001
	Replicate	3	<.0001	3	<.0001	3	<.0001
	Genotype	2	<.0001	2	<.0001	2	<.0001
	Error	314	.	314	.	314	.
	C. Total	319	.	319	.	319	.
	RSquare	0.94		0.79		0.56	
	CV%	2.84		9.65		10.09	
CS Late	Model	5	<.0001	5	<.0001	5	<.0001
	Replicate	3	<.0001	3	<.0001	3	<.0001
	Genotype	2	<.0001	2	<.0001	2	<.0001
	Error	309	.	309	.	309	.
	C. Total	314	.	314	.	314	.
	RSquare	0.87		0.7		0.81	
	CV%	4.21	10.62	9.06			
Weslaco	Model	5	<.0001	5	<.0001	5	<.0001
	Replicate	3	<.0001	3	<.0001	3	<.0001
	Genotype	2	<.0001	2	<.0001	2	<.0001
	Error	614	.	590	.	590	.
	C. Total	619	.	595	.	595	.
	RSquare	0.47		0.79		0.82	
	CV%	2.52		7.95		10.24	

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.
/2 CS Early = College Station Early; CS Late = College Station Late

Table A-IV.6. GxE LSMeans of whole plant geometry and shape for a group photoperiod insensitive sorghum genotypes evaluated at three environments in Texas during the 2014 season.

Environment		Plant Geometry and Shape		
		Plant Height (cm)	Avg. Plant Diameter (cm)	Plant Slenderness Ratio
Weslaco	Della	176 B[1]	0.96 B	184 B
	R.07007	167 C	0.90 C	189 B
	R.SOR2014	177 A	0.63 A	290 A
	Avg.	173	0.83	221
CS Early	Della	241 B	1.29 B	189 C
	R.07007	263 A	1.18 A	225 B
	R.SOR2014	189 C	0.79 C	241 A
	Avg.	231	1.09	218
CS Late	Della	242 C	1.12 C	218 B
	R.07007	306 A	1.37 A	225 B
	R.SOR2014	286 B	0.88 B	327 A
	Avg.	278	1.12	257
Avg.l		227	1.01	232

/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.
/2 CS Early = College Station Early; CS Late = College Station Late

Table A-IV.7. GxE ANOVA for whole plant and geometry for a group of moderate photoperiod insensitive sorghum genotypes evaluated at three environments in Texas during the 2014 season.

		Plant Geometry and Shape					
		Plant Height		Avg. Plant Diameter		Plant Slenderness Ratio	
Environment	Source	DF	Prob > F	DF	Prob > F	DF	Prob > F
CS Early[2]	Model	7	<.0001[1]	7	<.0001	7	<.0001
	Replicate	3	<.0001	3	<.0001	3	<.0001
	Genotype	4	<.0001	4	<.0001	4	<.0001
	Error	518					
	C. Total	525					
	RSquare	0.84		0.56		0.68	
	CV%	5.81		9.82		10.17	
CS Late	Model	7	<.0001	7	<.0001	7	<.0001
	Replicate	3	0.0827	3	<.0001	3	<.0001
	Genotype	4	<.0001	4	<.0001	4	<.0001
	Error	492	.	492	.	492	.
	C. Total	499	.	499	.	499	.
	RSquare	0.91		0.49		0.81	
	CV%	4.33		10		11.21	
Weslaco	Model	9	<.0001	9	<.0001	9	<.0001
	Replicate	3	0.0186	3	0.0722	3	<.0001
	Genotype	6	<.0001	6	<.0001	6	<.0001
	Error	710	.	656	.	656	.
	C. Total	719	.	665	.	665	.
	RSquare	0.85		0.82		0.87	
	CV%	7.46		10.07		11.99	

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.
/2 CS Early = College Station Early; CS Late = College Station Late

Table A-IV.8. LSMeans for whole plant and geometry for a group of moderate photoperiod insensitive sorghum genotypes evaluated at three environment in Texas during the 2014 season.

		Whole Plant Geometry and Shape		
Environment	Genotype	Plant Height (cm)	Avg. Plant Diameter (cm)	Plant Slenderness Ratio
Weslaco[2]	EJX 7285	232 A[1]	1.50 A	156 D
	EJX 7J906	198 D	1.11 C	179 C
	EJX 7J907	199 D	1.06 D	189 B
	M81E	203 C	1.34 B	152 D
	Rio	222 B	1.12 C	199 A
	Avg.	211	1.23	175
CS Early	EJX 7285	333 B	1.86 A	181 B
	EJX 7J906	246 D	1.74 B	142 D
	EJX 7J907	253 D	1.69 B	151 C
	M81E	345 A	1.68 B	208 A
	Rio	286 C	1.36 C	212 A
	Avg.	293	1.67	179
CS Late	EJX 7285	292 A	2.01 A	146 B
	EJX 7J906	212 A	1.84 B	116 D
	EJX 7J907	250 A	1.85 B	136 C
	M81E	262 A	1.89 B	140 BC
	Rio	322 A	1.51 C	217 A
	Avg.	268	1.82	151
Avg.		257	1.57	168

/1 Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD
/2 CS Early = College Station Early; CS Late = College Station Late.

Table A-IV.9. ANOVA for whole plant geometry and shape for a group of photoperiod sensitive sorghum genotypes evaluated at three environment in Texas during the 2014 season.

		Plant Geometry and Shape					
		Plant Height		Avg. Plant Diameter		Plant Slenderness Ratio	
Environment	Source	DF	Prob > F	DF	Prob > F	DF	Prob > F
CS Early	Model	9	<.0001[1]	9	<.0001	9	<.0001
	Replicate	3	<.0001	3	0.0003	3	0.0003
	Genotype	6	<.0001	6	<.0001	6	<.0001
	Error	550	.	550	.	550	.
	C. Total	559	.	559	.	559	.
	RSquare	0.94		0.39		0.65	
	CV%	2.24		10.06		10.23	
CS Late	Model	9	<.0001	9	<.0001	9	<.0001
	Replicate	3	<.0001	3	<.0001	3	<.0001
	Genotype	6	<.0001	6	<.0001	6	<.0001
	Error	530	.	530	.	530	.
	C. Total	539	.	539	.	539	.
	RSquare	0.83		0.34		0.56	
	CV%	4.85		11.06		11.28	
Weslaco	Model	9	<.0001	9	<.0001	9	<.0001
	Replicate	3	0.0186	3	0.0722	3	<.0001
	Genotype	6	<.0001	6	<.0001	6	<.0001
	Error	710	.	656	.	656	.
	C. Total	719	.	665	.	665	.
	RSquare	0.85		0.82		0.87	
	CV%	7.46		10.07		11.99	

/1 P > 0.05 non-significant; P <0.05 significant; P <0.01 highly significant.
/2 CS Early = College Station Early; CS Late = College Station Late

Table A-IV.10. LSMeans for whole plant geometry and shape for a group of photoperiod sensitive sorghum genotypes evaluated at three environment in Texas during the 2014 season.

		Whole Plant Geometry & Shape		
		Plant Height (cm)	Avg. Plant Diameter	Plant Slenderness Ratio
Weslaco	ATx623/R07007	197.20 D	197 E	156 C
	ATx645/R.SOR2014	222.61 C	223 F	191 B
	GRASSL	251.22 B	251 C	157 C
	R.10030	225.29 C	225 D	155 C
	R.10135	323.22 A	323 F	268 A
	R.11434	181.05 E	181 A	86 E
	R.11438	201.30 D	201 B	110 D
	Avg.	228.84	229	160
CS Early	ATx623/R07007	270.74 B	271 AB	143 D
	ATx645/R.SOR2014	253.47 D	253 D	156 B
	GRASSL	276.18 A	276 AB	147 CD
	R.10030	264.45 C	264 C	152 BC
	R.10135	275.75 A	276 D	179 A
	R.11434	217.17 F	217 BC	120 E
	R.11438	226.79 E	227 A	118 E
	Avg.	254.93	255	145
CS Late	ATx623/R07007	250.53 A	251 A	118 BC
	ATx645/R.SOR2014	222.15 C	222 C	119 BC
	GRASSL	239.34 B	239 A	114 C
	R.10030	219.63 C	220 C	123 CB
	R.10135	249.92 A	250 C	134 A
	R.11434	202.23 D	202 AB	99 D
	R.11438	185.30 E	185 B	93 D
	Avg.	224.16	224	114
Avg.				

1/ Genotypes not connected by the same letter are significantly different at (α=0.05) according to Tukey's HSD.
/2 CS Early = College Station Early; CS Late = College Station Late

Table A-IV.11. LSMeans for whole plant geometry and shape for a group of photoperiod sensitive sorghum genotypes evaluated at three environment in Texas during the 2014 season.

Maturity Response	Environment	Source	DF	Internode Length Prob > F	Internode Diameter Prob > F	Internode Slenderness Ratio Prob > F	Internode Volume Prob > F	E-Young's Module Prob > F	Internode Strength Prob > F	Flexural Stiffness Prob > F
PI	CS Early	Model	14	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Replicate	3	0.0008	0.0014	0.0017	0.0057	0.0372	0.5053	0.0738
		Gen	2	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Internode No.[Gen]	9	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Error	241	.	.	.	.	.	.	.
		C. Total	255	.	.	.	.	.	.	.
		RSquare		0.65	0.84.	0.87	0.77	0.72	0.75	0.77
		CV%		8.0	9.4	14.1	9.4	4.0	5.6	12.7
	CS Late	Model	14	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Replicate	3	0.4253	<.0001	0.0113	0.0187	<.0001	<.0001	0.1561
		Gen	2	0.0158	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Internode No.[Gen]	9	<.0001	0.2036	<.0001	<.0001	<.0001	0.0005	<.0001
		Error	241	.	.	.	.	.	.	.
		C. Total	255	.	.	.	.	.	.	.
		RSquare		0.72	0.70.	0.69	0.77	0.53	0.44	0.64
		CV%		18.4	10.8	25.3	17.4	8.4	9.5	21.5
	Weslaco	Model	14	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Replicate	3	0.2583	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Gen	2	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Internode No.[Gen]	9	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Error	497	.	.	.	.	.	.	.
		C. Total	511	.	.	.	.	.	.	.
		RSquare		0.75	0.63.	0.65	0.68	0.19	0.25	0.49
		CV%		10.3	11.5	19.5	15.4	8.0	10.9	21.8
MPS	CS Early	Model	22	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Replicate	3	0.003	0.0027	0.0047	0.0509	0.0386	0.1481	0.2152
		Gen	4	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Internode No.[Gen]	15	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Error	425	.	.	.	.	.	.	.
		C. Total	447	.	.	.	.	.	.	.
		RSquare		0.89	0.62.	0.83	0.84	0.80	0.31	0.80
		CV%		10.7	9.2	15.6	14.4	7.0	8.8	17.8
	CS Late	Model	22	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Replicate	3	0.0197	<.0001	<.0001	0.1806	<.0001	0.0577	0.7007
		Gen	4	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Internode No.[Gen]	15	<.0001	0.4365	<.0001	<.0001	<.0001	<.0001	<.0001
		Error	425	.	.	.	.	.	.	.
		C. Total	447	.	.	.	.	.	.	.
		RSquare		0.85	0.60.	0.75	0.87	0.81	0.54	0.83
		CV%		19.3	11.0	30.3	18.0	13.0	14.4	24.0
	Weslaco	Model	22	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Replicate	3	0.2756	0.035	0.0538	0.0932	0.0454	0.0626	0.0913
		Gen	4	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Internode No.[Gen]	15	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Error	873	.	.	.	.	.	.	.
		C. Total	895	.	.	.	.	.	.	.
		RSquare		0.75	0.78.	0.79	0.74	0.30	0.24	0.55
		CV%		9.1	7.8	12.4	12.0	5.9	10.1	18.8

Table A-IV.11. Continued

Maturity Response	Environment	Source	DF	Internode Length Prob > F	Internode Diameter Prob > F	Internode Slenderness Ratio Prob > F	Internode Volume Prob > F	E-Young's Module Prob > F	Internode Strength Prob > F	Flexural Stiffness Prob > F
PS	CS Early	Model	30	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Replicate	3	0.0002	0.0006	0.0003	0.0104	<.0001	0.0002	0.0121
		Gen	6	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Internode No.[Gen]	21	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Error	417	.	.	.	.	.	.	.
		C. Total	447	.	.	.	.	.	.	.
		RSquare		0.79	0.50.	0.70	0.78	0.69	0.41	0.70
		CV%		15.1	10.5	23.6	14.3	9.4	11.8	20.5
	CS Late	Model	30	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Replicate	3	0.0233	<.0001	0.0466	<.0001	0.0439	0.088	0.0002
		Gen	6	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Internode No.[Gen]	21	<.0001	0.0005	<.0001	<.0001	<.0001	<.0001	<.0001
		Error	417	.	.	.	.	.	.	.
		C. Total	447	.	.	.	.	.	.	.
		RSquare		0.80	0.30.	0.71	0.82	0.68	0.40	0.74
		CV%		18.8	10.9	25.7	16.2	14.8	17.2	23.4
	Weslaco	Model	30	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Replicate	3	0.0155	0.1072	0.8083	<.0001	0.1072	0.3072	0.2018
		Gen	6	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
		Internode No.[Gen]	21	<.0001	0.0005	<.0001	<.0001	<.0001	<.0001	<.0001
		Error	545	.	.	.	.	.	.	.
		C. Total	575	.	.	.	.	.	.	.
		RSquare		0.69	0.85.	0.79	0.68	0.73	0.62	0.58
		CV%		10.8	9.8	15.4	13.1	5.7	8.1	17.1

Table A-IV.9.12. LSMeans for internode geometry, shape, and biomechanical properties for a group of photoperiod sensitive sorghum genotypes evaluated at three environments in Texas during the 2014 season.

			Internode Geometry				Biomechanics		
Maturity Response	Environment	Genotype	Internode Length	Internode Diameter	Internode Volume	Internode Slenderness Ratio	E-Young's Modulus	Internode Strength	Flexural Stiffness
PI	CS Early	Della	21.3	1.4	45.9	15.7	1,594	21.2	2.8
		R.07007	21.4	1.2	40.2	18.0	3,152	32.7	3.2
		R.SOR2014	24.1	0.8	29.9	30.9	4,637	42.8	0.9
	CS Late	Della	16.0	1.2	30.2	13.7	1,219	24.9	1.3
		R.07007	17.0	1.5	38.7	11.8	1,302	25.3	3.0
		R.SOR2014	17.3	1.0	25.6	18.5	2,286	41.5	1.1
	Weslaco	Della	25.6	0.9	37.5	27.7	4,488	35.8	1.8
		R.07007	20.6	0.9	29.1	23.1	3,638	31.5	1.2
		R.SOR2014	23.6	0.7	25.3	36.6	6,372	47.3	0.7
MPS	CS Early	EJX 7285	24.9	2.0	79.0	12.5	1,549	24.3	12.8
		EJX 7J906	10.8	1.9	32.0	5.8	244	21.9	1.7
		EJX 7J907	11.3	1.9	32.8	6.1	252	19.6	1.7
		M81E	20.3	1.8	58.2	11.3	1,090	24.4	6.2
		Rio	20.7	1.5	48.5	14	1,761	27.6	4.4
	CS Late	EJX 7285	23.1	2.1	77.6	10.8	937	18.4	10.2
		EJX 7J906	6.9	2.0	21.6	3.5	31.0	7.1	0.4
		EJX 7J907	8.4	2.0	25.6	4.4	72.0	11.2	0.7
		M81E	17.7	2.2	59.5	8.4	409	16.5	5.0
		Rio	20.8	1.6	51.0	13.8	1,133	20.7	3.6
	Weslaco	EJX 7285	24.8	1.5	59.8	16.3	2,315	23.5	6.9
		EJX 7J906	25.2	1.1	41.9	23.9	3,985	34.6	2.7
		EJX 7J907	24.3	1.0	38.9	24.4	4,779	42.3	2.6
		M81E	24.4	1.3	51.6	18.2	3,187	32.1	5.3
		Rio	26.0	1.1	46.0	23.3	4,161	36.2	3.4
PS	CS Early	ATx623/R07007	20.7	2.0	65.1	10.5	847	19.6	7.8
		ATx645/R.SOR2014	11.8	1.8	32.2	6.9	364	20.6	2.0
		GRASSL	22.1	2.1	72.2	10.8	841	21.5	8.6
		R.10030	21.1	1.9	62.2	11.5	462	12.0	3.5
		R.10135	27.7	1.6	70.7	17.3	2,184	19.4	7.8
		R.11434	20.0	2.0	60.6	10.4	560	15.6	4.3
		R.11438	18.3	2.1	60.5	8.7	398	14.0	4.2
	CS Late	ATx623/R07007	18.3	2.2	62.4	8.6	483	16.1	6.5
		ATx645/R.SOR2014	8.5	2.1	27.4	4.2	48	7.5	0.7
		GRASSL	20.8	2.3	72.9	9.5	431	12.4	6.4
		R.10030	20.4	2.0	62.2	10.5	346	8.6	3.4
		R.10135	23.3	1.9	70.3	12.2	886	14.9	6.7
		R.11434	18.8	2.1	61.4	9.3	336	11.0	3.6
		R.11438	20.7	2.1	67.8	10.0	397	9.4	4.3
	Weslaco	ATx623/R07007	25.1	1.3	50.5	19.8	3,085	25.0	4.2
		ATx645/R.SOR2014	24.6	1.2	44.8	21.5	4,808	38.6	4.4
		GRASSL	21.5	1.7	56.9	13.0	2,213	26.9	8.7
		R.10030	26.6	1.5	62.3	18.0	2,110	17.9	5.3
		R.10135	25.3	1.3	50.2	20.1	4,667	31.6	6.0
		R.11434	18.8	2.2	64.7	8.7	477	14.6	5.7
		R.11438	22.9	1.8	65.7	12.6	1,832	23.7	10.3