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Biomechanics of Wheat/Barley Straw and Corn Stover

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Abstract

The lack of understanding the mechanical characteristics of cellulosic feedstocks is a limiting factor in economically collecting and processing crop residues, primarily wheat and barley stems and corn stover. Several testing methods—compression, tension, and bend—were investigated to increase the understanding of the biomechanical behavior of cellulosic feedstocks. Biomechanical data from these tests can provide required input to numerical models and help advance harvesting, handling, and processing techniques. In addition, integrating the models with the complete data set from this study can identify potential tools for manipulating the biomechanical properties of plant varieties in such a manner as to optimize their physical characteristics to produce higher-value biomass and more energy-efficient harvesting practices.

Index Entries: Modulus of elasticity; biomechanics; wheat straw; corn stover; feedstock development.

Introduction

The vision for a viable bioenergy and bioproducts industry in the United States by 2030 estimates that 1 billion dry tons of sustainable lignocellulosic feedstock will be needed annually *(1)*. Meeting this goal will require a wide variety of feedstock streams as inputs to biorefineries and power plants. Improved harvesting, processing, and bulk handling systems that are capable of separating the more valuable components and densifying the material for transportation and processing will need to be developed. Successfully designing and developing these systems requires a fundamental knowledge of the biomechanical properties and characteristics of feedstock.

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The importance of biomechanical data has long been recognized *(2,3)*. However, the ability to characterize the physical properties of biomass in a manner that allows estimation of the energy consumption and power requirements of engineered feedstock systems has not been effectively addressed. In fact, the current biomechanical property data are generally limited to one or two varieties and do not attempt to apply the results to broad-scale harvesting, processing, and bulk handling systems. In addition, intervariety comparisons have not been widely investigated to determine the potential sources of mechanical variations. These relationships are necessary to develop predictive models that can potentially improve the effectiveness and efficiencies of these systems. Furthermore, intervariety comparisons can help connect the mechanical behavior of specific plant components to particular loading configurations, providing a path forward for genetically manipulating the varieties in order to optimize their macroscopic and microscopic characteristics.

Addressing the goal of processing 1 billion dry tons of biomass annually requires focusing the research, at least initially, on the most available, sustainable, and cost-effective feedstocks. Agricultural crop residues have been identified as the most likely high-volume lignocellulosic feedstocks available, with stover and straw being the feedstocks of choice *(1)*. The aim of the present study was to determine the biomechanical properties of wheat and barley straw and corn stover for the purpose of characterizing differences between varieties and their constitutive components. The long-term goal is to provide significant insight into the macroscale harvesting, handling, and processing operations and the microscale plant genetics and fracture behavior *(4)*.

Determining the biomechanical properties of wheat, barley, and corn is challenging for several reasons. First, biologic materials, by their very nature, are complex composite structures whose components are intimately connected. Unlike engineered composite materials, their interconnected behavior makes it difficult to attribute particular mechanical characteristics to any one component. As a result, only bulk material properties can be easily measured, with additional microscale analysis and numerical models needed to discern the attributes of the segregated components. Second, the small size of biologic materials makes the specimens difficult to handle with standard mechanical test equipment. Likewise, their relatively soft tissue structure and unique anatomic arrangement compared to traditionally engineered materials increases the need for highly sensitive and delicate instruments. Finally, the variability of biologic materials requires the testing of several specimens in order to statistically characterize untested parameters such as harvest location, soil composition, stages of maturity, and other variables dictated by nature and not controlled in engineering environments. Thus, results from the mechanic testing of biologic materials have an element of error that is not readily quantifiable.

The testing and measuring of mechanical properties may be considered to be a macroscale operation. Standard testing procedures used on engineered composite structures can be applied to biologic structures to test their performance and determine their material properties under laboratory-applied loads. These loads are within the ranges typically seen in industrial machinery that harvest or process biologic materials and include chopping, grinding, chipping, and billeting *(3,5)*. However, because of the complexity of biologic structures, unique methods must be developed and used to provide sensitive and reliable data within the range of applied loads *(6)*. Mechanical properties determined through laboratory compression, tension, and bend tests can be used as required input to numerical models capable of predicting parameters that affect energy consumption, power requirements, and efficiencies of engineered feedstock-processing systems *(7–9)*. These models will ultimately help optimize machinery design and increase the potential for lowering harvesting, handling, and processing costs.

The physical and mechanical properties of the feedstock are related to the environmental conditions and genetic makeup of the biomass, leading to an additional microscale investigation of the biologic material *(10)*. Data associated with the anatomic structure of the plant material are helpful in interpreting the mechanical property results and determining modes of failure. Thus, it is useful to record and synchronize the visual aspects of the experimental events with load data to determine microscale failure patterns associated with the type of material tested *(11)*. Pre- and posttest observations are also necessary to identify failure mechanisms related to differences in the structure of individual plant components (i.e., vascular bundles, sclerenchyma, parenchyma, and so on) *(12–15)*.

This article presents an approach in which mature (harvested) biomass was collected and tested to determine the modulus of elasticity and ultimate strength for internodal stems of two varieties each of wheat and barley, and four cultivars of corn. A miniature load frame used for an environmental scanning electron microscope was adapted to work with barley and wheat straw, and an Instron load frame was adapted for work with corn *(11)*. The main objective was to develop a database for each variety and determine whether individual varieties could be identified and separated from one another based on differences in biomechanical properties. This database will be used to develop a conceptual use model for testing biomass materials to estimate biomass performance in harvesting, handling, and processing systems. It is recognized that environmental conditions (i.e., temperature, humidity), stages of maturation, matrix composition, and cell matrix configuration are important test parameters to consider *(16–22)*. For purposes of simplicity, this study primarily focuses on matrix composition and cell configuration in mature plant biomass for the determination of biomechanical properties.

Table 1
Plant Variety, Growth Site, and Collection and Testing Dates for Biomechanical Tests

Variety	Growth site	Collection date	Testing date
Amidon (wheat)	Aberdeen, ID	08/2002	03/2003–03/2004
Westbred 936 (wheat)	Aberdeen, ID	08/2002	03/2003–03/2004
Bowman (barley)	Aberdeen, ID	08/2002	03/2003–03/2004
Fragile Stem 1 (barley)	Aberdeen, ID	08/2002	03/2003–03/2004
Bearclaw 7998 (corn)	Ames, IA	10/2002	04/2004
Dekalb 611 (corn)	Ames, IA	10/2002	04/2004
Garst 8550 (corn)	Ames, IA	10/2002	04/2004
Iowa 550473 (corn)	Ames, IA	10/2002	04/2004

Materials and Methods

Feedstock

Two varieties each of wheat and barley straw and four cultivars of corn stover were selected for use. Table 1 presents the growth site and collection and testing dates for each variety. Selection of the varieties was based on the physical characteristics of straw and stover, primarily those that distinguished one from another.

Westbred 936 is a semidwarf variety of hard red spring wheat with a strong, stiff straw giving it lodging resistance (a plant's tendency not to tipover from external forces). In 2002, it was the top wheat variety grown in southeastern Idaho, and its chemical composition (lignin, hemicellulose, and cellulose content) has also been extensively analyzed at Idaho National Engineering and Environmental Laboratory (INEEL) *(23)*.

Amidon, a standard height hard red spring wheat variety, was chosen because of its moderate resistance to lodging, intermediate level of stem solidness, and medium straw strength. Its semisolid stem distinguishes its cross-sectional composition from that of the more typical hollow-stemmed Westbred 936.

The varieties of wild-type (WT) Bowman and its fragile stem mutant, *fst 1.d (24)*, were chosen because of their closely tied genetic makeup. The leaves and stems of the fragile stem mutant plants easily break when physically bent. They are extraordinarily fragile even after maturity. In homozygous lines, straw collapse and/or lodging occurs more frequently compared to the WT Bowman. By contrast, Bowman has good tolerance to late-season lodging and postmaturity straw breakage. It is the parental line used in the introgression of *fst 1.d*.

Each cultivar of corn was chosen based on field standability; apparent strength when handled; and, for logistical purposes, internodal stalk length. The first variety, Bearclaw 7998, is a popcorn cultivar originating in Ohio. It is smaller in stature compared with the other cultivars and has an apparent weaker stock than most. The next two varieties, Dekalb 611 and Garst 8550, are both commercial cultivars managed in fields at Iowa State University. Dekalb 611 was chosen for its poor standability and long, straight internodal regions. Garst 8550, on the other hand, was chosen for its high standability and long internodal regions. Finally, Iowa 550473 is a parental stiff stalk cultivar originating from Ontario, Canada. It was chosen because of its stiff stalk genetic background and noticeably larger stalk geometry.

The various samples tested were collected during the 2002 cropping season and put into dry, boxed storage until the time of use. The moisture content, though an important physical parameter of biobased materials *(5)*, was not a variable in this study in order to limit the parameters tested and focus on the cellulosic and lignin components of the material.

Testing Methods

Several testing methods—compression, tension, and bend—were used to determine the mechanical characteristics of agricultural residues. These methods were performed with load frames sized to accommodate both wheat and barley stems and corn stover. Video-imaging techniques were used to follow and confirm load test measurements. Pre- and postmortem microscopic analyses helped to identify changes in structural components based on the type of test conducted. Each test provided a range of mechanical data from different parts of the plant and from different varieties of wheat, barley, and corn.

The test results provided two useful quantities: the modulus of elasticity and the ultimate strength of the material. Seven samples from each variety were tested in order to represent their material properties statistically. The mean and standard deviation of these quantities were used to establish similarities and differences among varieties according to their mechanical behavior. Only test data that were complete at the time that this article was written are reported. Therefore, this article contains results from compression, tension, and bend tests of wheat and barley specimens and compression tests of corn specimens.

Selection of Specimens

Test specimens from specific internodal regions were obtained from different plants and different varieties. The testing region chosen for the wheat and barley varieties was the second internode down from the top of the plant, or grain head, as seen in Fig. 1A. Other investigators have used this region, which provides opportunities to compare test results *(5,25)*. Similarly, the corn samples were cut from internodal regions consistent across the four varieties chosen for this study. These regions, however, were referenced from the cob location and not the top of the plant, because the internodes at the cob locations are significantly deformed during growth. Thus, all corn samples were cut from the internodal regions just above and just below the cob locations according to Fig. 1B.

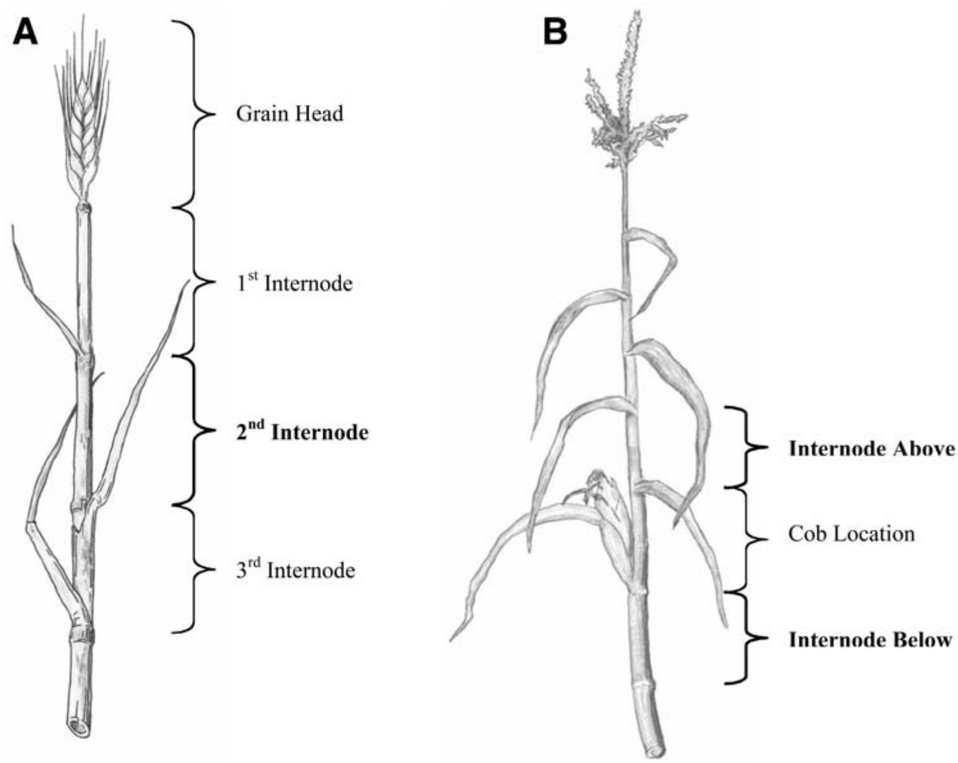

Fig. 1. Illustration of **(A)** a wheat or barley stem and **(B)** corn stock. The internodal test regions used are identified in bold.

Bend and Tension Tests

Wheat and barley specimens for the bend and axial tension tests were cut to 76-mm lengths from the center of the second internodal region, providing one specimen per internode per plant. Each specimen was set in the cradle of the bend apparatus with its major axis aligned perpendicularly to the applied load. Data were logged at a rate of two points per second with a load travel rate of 2.4 mm/min. The data included the applied transverse load, the absolute displacement of the load point, and the magnified stem images corresponding to each data point. The image data were used to record surface features and structural failures, and to capture the deflection of the stem needed to calculate the bending modulus for each tested specimen.

Tension test specimens were prepared with special end grips owing to the delicate nature of cereal stems and the waxy coating on the surface. The grips consisted of inner pins that fill the ends of the hollow stems, providing structural support as the jaws were tightened. On the outside of the stem, a self-adhesive heat shrink-wrap was applied to protect the surface of the stem from damage owing to direct contact with the metal jaws.

Fig. 2. Tension test setup for wheat/barley specimens. Shown are the load frame jaws, the end grips, the heat shrink collars, and the extensometer.

Separate collars made from the same heat shrink-wrap were fixed to the stem 1 in. apart and provided attachment points for the knife edges of the extensometer, which was used to measure accurately the strain resulting from the tension loading. Each specimen was clamped within the jaws of the load frame and pulled at a uniform rate of 5 mm/min. Data were logged at a rate of two points per second and included the tension load and the jaw and extensometer displacements. These data were used to create stress-strain curves, from which the slope of the linear portion of the curve was recorded as Young's modulus. Figure 2 is a picture showing the tension test setup.

After testing, both the bend and tension specimens were sectioned through the gage region and a stereo-zoom microscope was used to measure total cross-sectional area, individual component areas, major and minor stem diameters, and wall thickness. These geometric measurements were directly used in the calculation of the area moment of inertia needed for the bending modulus and in the calculations of stress and strain needed for Young's modulus.

Compression Tests

Wheat and barley specimens for the compression tests were taken from the same internodal regions described for the bend and tension tests. Each specimen was cut to an equal height-to-length ratio (1:1) to increase its resistance to buckling. Two samples each were cut from the top and bottom of the internodal region, allowing the potential for differences across internodal stem lengths to be examined. Once cut, the specimens were placed vertically

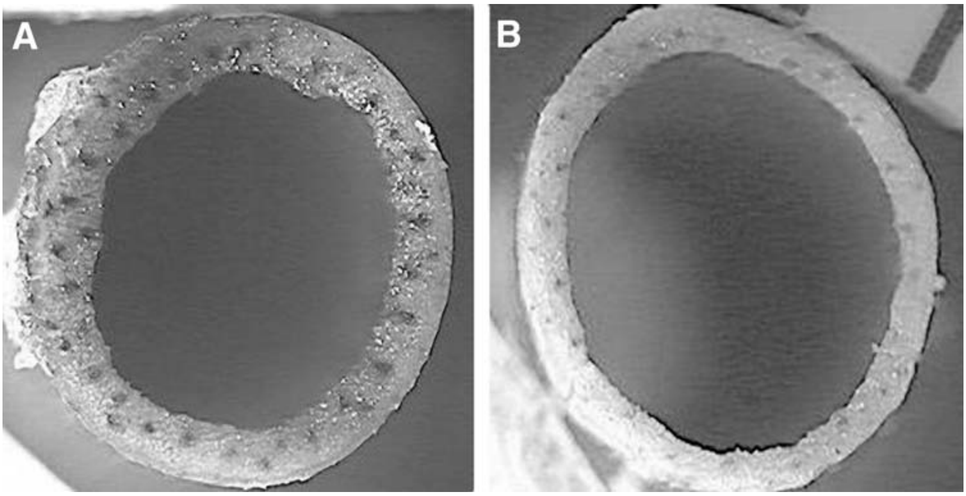

Fig. 3. Cross-sectional images of (A) Westbred wheat and (B) Fragile Stem 1 barley varieties, stained with alcian blue dye *(26)*.

in the load frame and compressed at a rate of 2.4 mm/min. Image data were logged at a rate of two frames per second to record surface features as the specimens failed owing to buckling. Prior to each test, end cross-section images were collected with a stereo-zoom microscope to obtain geometric data required for the calculation of stress-strain curves. The slope of the linear portion of these curves was used to determine the compressive modulus of the specimens.

The compression specimens for corn were prepared in a manner similar to those for wheat and barley, keeping the same length-to-diameter ratio of 1:1. Unlike the wheat and barley specimens, however, the set of seven corn specimens for each variety was cut from the same internodal region, one internode above and below the cob location. This sampling technique provided the means to test variations in the same plant across different stover locations. The test specimens were compressed at a rate of 5 mm/min with load, displacement, and image data collected over the course of the test. These data, along with each specimen's geometric measurements made prior to testing, were used to construct stress-strain curves and determine the compression modulus from the linear portion of these curves.

Results

Figures 3 and 4 show representative stained cross-sectional images of the wheat and barley stems, and corn stover, respectively. These images show details of the sclerenchyma (outer rind or epidermis), parenchyma (inner cells or matrix of the structure), and vascular bundles. These images provide the cross-sectional area data necessary to calculate

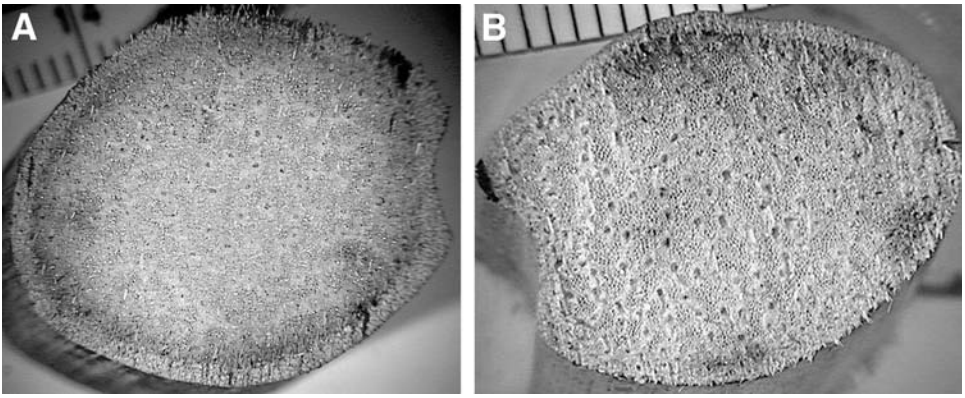

Fig. 4. Cross-sectional images of (A) Iowa 550473 and (B) Dekalb 611 corn varieties.

Table 2
Polymer and Ash Compositions of Wheat, Barley, and Corn Varieties Tested[a]

Variety	Cellulose (%)	Hemicellulose (%)	Lignin and extractives (%)	Ash (%)	Unidentified (%)
Amidon (wheat)	38.2	18.7	20.0	5.1	17.9
Westbred 936 (wheat)	39.9	18.6	21.4	6.0	14.1
Bowman (barley)	35.3	16.2	18.2	7.1	23.2
Fragile Stem 1 (barley)	11.1	22.1	16.7	18.3	31.8
Bearclaw 7998 (corn)	32.2	18.1	17.7	5.8	26.1
Dekalb 611 (corn)	35.2	17.6	17.7	3.6	26.0
Garst 8550 (corn)	33.9	13.0	19.1	3.2	30.7
Iowa 550473 (corn)	33.3	17.5	19.5	4.3	25.4

[a]Compositions were calculated using a standard quantitative saccharification wet chemistry method *(27)*.

the stress in the stem during testing and to detail the major components of the specimens, which are responsible for the mechanical behavior of each variety.

Table 2 contains details of the chemical composition of each variety tested. The percentages of the four major components of the plant structures (i.e., cellulose, hemicelluloses, lignin, and ash) are reported.

Table 3 provides the modulus of elasticity results from the 3- and 4-point bend, axial compression, and axial tension tests. In all cases, applied load, displacement, and total cross-sectional area measurements were used to calculate the respective modulus. Modulus values for compression and tension were calculated from the slope of the linear portion of the stress-strain curves. For the 3- and 4-point bend tests, moduli were calculated using equations derived from standard beam theory for specimens with

Table 3
Mean Modulus of Elasticity Values for Wheat and Barley Stems, and Corn Stover

	Modulus (GPa)[a]			
Variety	3-Point bend	4-Point bend	Compression	Tension
Amidon (wheat)	2.2 ± 0.23*	2.2 ± 0.18*	0.60 ± 0.11*	7.3 ± 0.92*
Westbred 936 (wheat)	1.1 ± 0.076†	1.3 ± 0.020†	0.90 ± 0.47*	4.9 ± 0.74†
Bowman (barley)	1.3 ± 0.087†	1.4 ± 0.058†	0.42 ± 0.08†	3.4 ± 0.57‡
Fragile Stem 1 (barley)	1.1 ± 0.063†	1.3 ± 0.035†	0.97 ± 0.38*	3.5 ± 0.37‡
Bearclaw 7998 (corn)	—	—	0.26 ± 0.06*	—
Dekalb 611 (corn)	—	—	0.38 ± 0.04†	—
Garst 8550 (corn)	—	—	0.47 ± 0.12‡	—
Iowa 550473 (corn)	—	—	0.40 ± 0.10†	—

[a]Means followed by the same symbol in a column do not differ significantly ($p > 0.05$) according to the Student-Newman-Keuls pairwise multiple comparison method. Scatter in the data is reported with a standard error.

circular cross-sections *(28)*. The equations for 3-point and 4-point bends, respectively, are

$$E = \frac{PL^3}{48\delta I_b} \tag{1}$$

$$E = \frac{Pa}{48\delta I_b}(3L^2 - 4a^2) \tag{2}$$

in which P is the applied load, L is the distance between the support points, δ is the deflection of the stem, and a is the distance between the support and load points. The area moment of inertia in bending about the major axis, I_b, is given by *(18)*

$$I_b = \frac{\pi}{4}[ab^3 - (a-t)(b-t)^3] \tag{3}$$

in which a is the semimajor axis, b is the semiminor axis, and t is the mean wall thickness of the stem cross-section.

Table 4 presents the structural variations of the varieties tested. These values were optically measured using images from a stereo-zoom microscope and analysis tools from Image Pro Plus software. The reported values represent statistical means calculated from the specimens used in each test. Each measured component represents only the major part of the plant's structure that could be readily segregated with the microscope. To illustrate the correlation among the columns of data in Table 4, the product of columns 2 and 3 is statistically equal to the product of columns 2, 5, and 6, which is the total fiber cross-sectional area.

Table 4
Structural Analysis of Wheat, Barley, and Corn Materials Identifying Various Components[a]

Variety	Stem/stalk cross-sectional area (mm^2)	Total fiber area (%)	Total rind area (%)	Fiber density (no. of fibers/total cross-sectional area)	Fiber area (mm^2)
Amidon (wheat)	4.5 ± 0.30*	10.5 ± 0.80*	19.8 ± 1.2*	8.9 ± 0.95*	0.012 ± 0.0010*
Westbred 936 (wheat)	4.9 ± 0.25*	7.2 ± 0.77†	15.1 ± 0.98†	7.0 ± 0.57†	0.011 ± 0.0011‡
Bowman (barley)	2.5 ± 0.086†	8.6 ± 0.49†	15.8 ± 1.5†	15.9 ± 1.4‡	0.006 ± 0.0005†
Fragile Stem 1 (barley)	2.9 ± 0.073‡	8.1 ± 0.43†	15.5 ± 0.93†	9.5 ± 0.39*	0.009 ± 0.0006‡
Bearclaw 7998 (corn)	180.6 ± 3.4*	—	22.6 ± 0.45*	—	—
Dekalb 611 (corn)	205.2 ± 1.3†	—	20.1 ± 0.98*	—	—
Garst 8550 (corn)	184.6 ± 2.1*	—	17.5 ± 0.88†	—	—
Iowa 550473 (corn)	368.2 ± 13.1‡	—	21.4 ± 0.85*	—	—

[a]Means followed by the same symbol in a column do not differ significantly ($p > 0.05$) according to the Student-Newman-Keuls pairwise multiple comparison method. Scatter in the data is reported with a standard error.

Discussion

The modulus of elasticity data for the two varieties of wheat and barley and four cultivars of corn indicated significant differences in their mechanical behavior (Table 3). These differences can be attributed to the individual structure and composition of the stems as shown in Figs. 3 and 4 and the measured results of the testing. The structural differences (Table 4) can partially be attributed to the size of the cell structures and vascular bundles, and in the case of corn, the thickness of the rind region, which are common across the respective varieties. These structural differences and how they relate to the modulus values illustrated the anisotropic behavior of the material, which was consistent with composite structures.

The compositional differences, shown in Table 2, provide another degree of comparison between varieties. One example of these differences is shown in Fig. 3, in which the images were obtained using the alcian blue staining technique, which highlights the polysaccharides or cellulose content *(26)*, applied to a Westbred and a Fragile Stem 1 specimen, capturing the compositional differences reported in Table 2. These compositional differences directly apply to the biomechanical characteristics of a plant through the expression of the individual components. For example, lignin provides structural strength and rigidity to the plant while cellulose and hemicellulose hold the plant together and give it the necessary substance to perform biologic operations.

With both structural and compositional data available, specific mechanical characteristics among different plant varieties can be attributed to specific plant structures. An ideal example is a comparison between the WT Bowman and Fragile Stem 1 barleys. These two varieties are genetically identical with the exception of one gene *(24)*. This genetic difference affects many parameters, one of which is the cellulose composition in the plant (Table 2). Because of the close relationship and known genetic differences of these two barleys, a comparison of their mechanical properties can trace differences back to changes in their respective ultrastructures, helping to identify specific stem components that contribute to a particular mechanical behavior.

The basic structure of WT Bowman and Fragile Stem 1 barleys, quantified by the individual and combined percentages of stem cross-sectional areas occupied by the rind and the vascular bundles, is the same. However, the vascular bundle density per unit area (the number of fibers normalized by the cross-sectional area) between the two varieties was different (Table 4). Taking an engineered composite structure approach, we theorized that the rind and vascular bundles make up the primary structural support of the stem, while the remaining cell structures, commonly known as the parenchymatic tissue, make up the matrix fill holding the structural components together. Because the fiber and matrix components of engineered composites are made from different materials, they each have different material properties, causing the structure as a whole to behave differently depending on the applied load. Similarly, the Bowman and Fragile Stem 1 varieties of barley are seen to behave the same under bending and tension loads but differently under compression based on the measured bulk modulus values.

Differences in the modulus values for WT Bowman and Fragile Stem 1 are in part owing to the difference in fiber density between the varieties (see Table 4). Under a compressive load, this difference can cause the apparent modulus of the Bowman variety to be lower than the Fragile Stem 1 because of a tendency for many small vascular bundles to bend more readily than a few large bundles. In other words, consider the apparent modulus of many thin columns, separated from each other by a distance more than their diameter, vs one thick column with the same total cross-sectional area under the same compressive load. It is accepted that the group of thin columns would buckle or deflect more easily than would the thicker column *(28)*. Thus, the modulus, being highly sensitive to deflection, would appear smaller for the bundle of thin columns compared with the single thick column. This effect was illustrated by the different modulus values of the Bowman and Fragile Stem 1 varieties.

The coupled relationship between compression and tension found in either the 3- or 4-point bend tests adds a new level of difficulty when making comparisons between varieties. The data, however, seem to support the notion that tension is more dominant than compression when determining the composite moduli under bending loads. This is evident by similar trends in tension and opposite trends in compression for the Bowman and Fragile Stem 1 varieties.

Similarly, a comparison of the modulus values between the two wheat varieties showed a comparable relationship between the percentage of cross-sectional area occupied by the vascular bundles and rind and the total number of vascular bundles present in a stem. This trend showed that the higher modulus values in bending and tension followed the stem with the largest percentage of vascular bundle, and rind cross-sectional area (Amidon), while the stem with fewer vascular bundles (Westbred) had the higher modulus value in compression.

Comparison of modulus values across wheat and barley varieties, however, does not reveal the same trends seen with interwheat or inter-barley comparisons. Instead, identifying the differences in the modulus values across wheat and barley varieties required additional information provided by the component compositions (Table 2). For example, using an engineered composite parallel, the fiber and composite material for the wheat and barley varieties was made from different substances making their bulk behavior dependent on both the type of material in each component and the physical structure of each component.

The data on corn presented in Fig. 4 and Tables 2–4 show significant differences among the cultivars tested. Similar to the trends seen in wheat and barley, the data on corn identify structural and compositional components that contribute to the bulk mechanical behavior of each cultivar. Future tension and bend tests will be conducted to verify that the approach used to distinguish varieties of wheat and barley can also be used to distinguish different cultivars of corn. Ultimately, the work done with wheat, barley, and corn will help support the application of the developed approach to other types and varieties of feedstocks.

Conclusion

The main objective of this work was to investigate the possibility of distinguishing wheat, barley, and corn (and their varieties) from one another based on their biomechanical properties. This was accomplished with a high degree of certainty by using a suite of tests: compression, tension, and bend. The results have increased the understanding of the biomechanical behavior of cellulosic feedstocks as they relate to harvest and postharvest handling practices and the molecular biology of the plants.

The calculations for the modulus of elasticity and ultimate strength required measuring the physical parameters of the stems (i.e., cross-sectional area, minimum/maximum diameters). Analysis based only on the physical parameters indicated that it was beneficial to measure other features such as the percentage of occupancy of the rind and vascular bundles. Furthermore, the chemical analyses of the plant material helped provide a more complete characterization of the stems. These data aid in the interpretation of the meaning of the biomechanical measurements, as in the case of the barley varieties during the compression and tension tests.

The ability to track significant differences between the varieties and their individual structural and compositional components provides a path forward for tailoring harvesting, handling, and processing operations. Computer models can be developed for parametric studies on specific structural and compositional components in order to optimize their effect on these operations. These models can help determine which biomechanical properties affect the energy efficiency relationships associated with harvest and postharvest handling practices.

Integration of the models with the complete data set from this study also identified the potential tools for manipulating biomechanical properties of the plant varieties. Because these characteristics are inherent to the biomass, genetic manipulation techniques may be applied to design or control the biomechanical properties in such a manner as to optimize their physical characteristics to produce higher-value biomass and provide more energy-efficient harvesting practices.

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