2019-08-01

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

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The strength of leaf fibers and the nutritional value of the edible fruit of several yucca species native to the U.S. southwest were studied to aid in the determination of species best suited for commercial cultivation by the Navajo Nation. The leaves were softened in an autoclave to facilitate the removal of the leaf matrix, conditioned in environmentally controlled chambers, and the fibers were broken using a texture analyzer. The fibers were frozen and cross sectioned and photographed to determine cross sectional area. Official methods were used to determine the nutritional content of the fruit. The mean tensile strength of *Y. angustissima, Y. baccata, and Y. glauca* was 484 ±79, 710±174, and 388±104 MPa, respectively. Fibers from the leaves of *Y. baccata* had a significantly higher tensile strength than the leaves of the other two species. Nutritional profiling of the fruit of *Y. angustissima and Y. baccata* indicated that the fruit of both species are good sources of vitamin C (73-119 mg/100g) and thiamin (0.20 to 0.22 mg/100g). Because of its edible fruit and superior leaf fiber tensile strength, *Y. baccata* is recommended as the best species for cultivation and commercialization.

Keywords: yucca fiber, tensile strength, micronutrients, *Y. angustissima, Y. baccata, Y. glauca*

ACKNOWLEDGMENTS

A special thanks to Oscar A. Pike, Michael L. Dunn, and J. Ryan Stewart for the hours of work they contributed to giving feedback and reviewing this work. I thank Dennis L. Eggett for providing the statistical analysis. Thank you to Diné College for providing the yucca plants and fruit and to Richard's Garden Center for providing the *Agave sisalana* leaves.

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INTRODUCTION

Three *Yucca* species (*Yucca angustissima, Yucca baccata,* and *Yucca glauca*) native to the Navajo Nation, which have been harvested in the wild by the Navajo people for food, fiber, and religious ceremonies (Castetter 1935, Steggerda and Eckardt 1941, Wyman and Harris 1941, Elmore 1944, Wyman 1983, Mayes and Lacy 1989), show potential to be cultivated as crops. The survival and productivity of these *Yucca* species has been studied at two sites in the Navajo Nation (Tsaile, AZ and Shiprock, NM). Decisions regarding the economic viability of cultivating *Yucca* native to the Navajo Nation requires additional information about the physical properties of the leaf and nutritional content of the fruit of these species. A better understanding of the strength of the *Yucca* fibers and the nutritional value of the plant's edible fruit will determine which of the species is best suited for cultivation and commercialization.

The tensile strength of a fiber must be known to determine if it is suitable for any given application. Plant fibers are used extensively to produce textiles and rope, as a reinforcement in polymer composites, and in many other applications (Thamae et al. 2009). Some of the world's major plant fibers are abaca, coir, cotton, flax, hemp, jute, ramie, and sisal (FAO 2009). Tensile strengths for such natural fibers typically range from 45 to 1500 MPa (Sathishkumar et al. 2013). Dewey (1943) reported that *Y. glauca* fibers were used extensively during World War I as a substitute for jute because the U.S. was unable to obtain enough jute from India for their needs. However, historically, yucca fibers have not been used because jute and other fibers were less expensive. Dewey (1943) also reported that shortly after World War I, facilities in Ledge, California and Kingman, Arizona extracted fibers from Mojave yucca (*Y. schidigera*) and banana yucca (*Y. baccata*) primarily due to the high cost of imported fibers. He also reported that the quality of the yucca fiber was inferior to henequen (*Agave fourcroydes*) imported from Yucatán, Mexico. Because of the shortage of jute and Manila hemp from East Asia caused by the war, a study was conducted of fiber sources in the U.S. Results indicated that *Y. glauca* and *Y. elata* fibers were equal in strength to hemp fibers and stronger than *Nolina* fibers (Botkin et al. 1943). A subsequent study (Botkin and Shires 1944) determined the tensile strength of six *Yucca* species. The study reported the fiber strength in kilometers, making results difficult to compare with more recent findings, which are reported in units of mega-Pascal (MPa). However, the results provide a comparison of the relative fiber strength of certain yucca species and other plant fibers. The data indicated *Y. glauca* fiber strength was 35% stronger than jute and similar in strength to sisal.

Wakil and Khan (1975) conducted a study on the tensile strength of *Y. glauca*. Their results agreed with those of Botkin and Shires (1944), regarding the superior strength of *Y. glauca* compared to jute. However, they reported sisal to be 33% stronger than *Y. glauca*. Nevertheless, it is clear that various *Yucca* species studied have a tensile strength equal to or greater than many commercially significant fibers.

In addition to the yucca leaf providing strong natural fiber, some species, including *Y. baccata* and *Y. angustissima*, produce edible fruit, which has been eaten by the people indigenous to the Navajo Nation (Wolfe et al. 1985). For example, the Diné ate the sweet fresh fruits of several *Yucca* species, particularly *Y. baccata.* Freshly harvested, the fruit have a taste similar to that of dates, but they were also roasted and cooked for consumption (Castetter 1935, Elmore 1944, Hodgson 2001). They would also grind the pulp into a paste or cakes to store for later use during the winter to mix with cornmeal, meat, and other foods (Bailey 1940, Bell and Castetter 1941, Steggerda and Eckardt 1941, Elmore 1944). The pulp of *Y. baccata* was also boiled, ground, partly dried, molded into a roll on a stick and dried (Wolfe et al. 1985). In addition, dried fruit pulp was often boiled to make a sweet beverage (Bell and Castetter 1941).

This work had two objectives. The first was to determine the leaf fiber tensile strength of *Y. angustissima, Y. baccata, and Y. glauca*. The second was to evaluate the proximate composition, the vitamin, and the mineral content of the two species we studied that bear edible fruit, *Y. angustissima and Y. baccata*.

MATERIALS AND METHODS

Four cultivated plants (1 to 2 years old) of each of the following three yucca species were provided by colleagues at Diné College, Tsaile, AZ, USA: *Y. angustissima, Y. baccata,* and *Y. glauca*. For comparison, leaves from *Agave sisalana* were also evaluated. Six leaves, which averaged 86 cm in length, from *A. sisalana* were provided by a garden center in Phoenix, AZ USA. Fruit was collected from *Yucca* plants growing in the wild in the Navajo Nation (USA). Eleven fruits were harvested from four *Y. angustissima* plants, and seven fruits were harvested from two *Y. baccata* plants. Because the wild fruit was sparse and difficult to find, it had to be harvested early to prevent it from becoming infested with insects or eaten by birds and rodents.

Fiber processing and analysis.

Fibers were extracted from the leaves using a modification of the method of Chaabouni and Drean (2006). The yucca and sisal leaves were autoclaved to soften the leaf matrix. The autoclave procedure was accomplished by placing the leaves in a plastic tub and submerging them in tap water and then autoclaving for 90 minutes at 121 °C. After autoclaving, the leaves were left submerged in the water so that the leaves remained soft and supple until they could be processed. The softened outer material of the leaves was removed from the fibers by gently scraping by hand using a stainless steel laboratory scoop. To assist with removing the plant debris from the fibers, the fibers were scraped then dipped into the autoclave water repeatedly. If the water became too murky, it was replaced with fresh tap water. The scraping and rinsing was repeated until the fibers were free of the leaf matrix. A final rinse of the fibers was done under running tap water to produce clean fibers.

The clean fibers were pre-conditioned by holding them for four hours at 45 ± 5°C and 15 ± 5% relative humidity in an environmental controlled chamber (Model I-36NL; Percival Scientific, Perry, IA). They were then conditioned for at least eight hours at 21 ± 1°C and 65 ± 2 relative humidity in a walk-in controlled atmosphere room according to the ASTM International fiber testing method (2016). The fibers were stored in the controlled atmosphere room until ready for analysis.

The conditioned fibers were mounted on tabs cut from construction paper, measuring 6.4 cm x 6.4 cm. A 2.5 cm round hole was punched in the center of the tab using a hole punch. The fiber was attached to the tab using double-stick tape and lab labeling tape, until it could be more securely clamped into the texture analyzer's tensile grip attachment. Tensile testing was performed on a TA-XT2 Texture Analyzer (XT-Plus Upgrade, serial no. 10211; Stable Micro Systems, Godalming, UK) using a TA-96B miniature tensile grip attachment under the following test conditions: 25 mm gauge length, 1 mm/sec stretching speed, ~ 21°C ambient temperature, ~20% relative humidity. The tab holding the fiber was mounted onto the tensile grip at both ends, the tab was cut, and the texture analyzer pulled the fiber until it broke. A representative peak strength curve is shown in Fig. 1. Some fibers were discarded because of questionable results due to faulty breaks. Fibers that broke at the edge of the hole of the tab were discarded, as were those that were not held firmly in place on the tab by the tape and those that were excessively split.

The cross sectional area of each fiber was then determined. Following the modified method of Peng et al. (2018), the broken fibers were embedded vertically in Tissue-Tek O.C.T. Compound 4583 (Sakura Finetek, USA) using a small plastic mold. Plasticine® modelling clay was placed on both edges of the mold and the tab holding the fiber was pushed into the clay, which held the fiber in a vertical position, allowing for a cross-sectional cut of the fiber. The embedded fiber was placed in a -60°C freezer for about five minutes. The frozen sample was removed from the mold and sectioned using a Microm HM 550 cryostat microtome (Thermo Scientific, USA) set at -20°C with a sectioning thickness of 20 µm. The cross sections were mounted on pre-cleaned microscope slides and photographed using a digital camera (Model K100D; Pentax Corp., Tokyo, JP) attached to an Axiovert 135 microscope (Zeiss, Oberkochen, Germany). A representative micrograph is shown in Fig 2a. As shown in Fig 2b, the area of the cross sections was calculated in mm using *ImageJ 1.50i* software (National Institutes of Health, USA). The results were tabulated in an Excel spreadsheet.

The peak strength (in kg) obtained from the texture analyzer was divided by the cross sectional area (in mm^2) to determine the tensile strength in kg/mm^2. The kg/mm^2 was converted to MPa by multiplying by the conversion factor 9.80665 (Shen et al. 2019). Young's modulus and strain-at-break was calculated in the elastic portion of the stress-strain curve, between 35% maximum force and 85% maximum force. Young's modulus is a numerical constant that describes the elastic properties of a solid undergoing tension or compression and how it withstands changes in length. It is sometimes referred to as the modulus of elasticity (Augustyn 2019). A representative curve of Young's modulus is shown in Fig. 3.

Fruit processing and analysis.

The fresh whole fruit was shipped from Diné College to Brigham Young University packaged in sealed plastic bags in an insulated shipping container kept cold with frozen ice packs. The fruit was peeled, the seeds were removed, and the edible portion was placed in plastic bags and frozen at -60°C for several days. The frozen samples were packed in dry ice in an insulated shipping container and were shipped to Medallion Labs (Minneapolis, MN) for proximate analysis, vitamin, and mineral determination.

AOAC Method 925.10 (AOAC 2019) was used to determine moisture gravimetrically by forced air oven. Calories were determined using the general factors of 4, 4, and 9 calories/g of protein, carbohydrate, and fat, respectively (Whitney and Rolfes 1999). Protein was measured by AOAC Method 992.15 where samples were combusted and the % N converted to % protein using the conversion factor of 6.25 (AOAC 2019). Fat was determined gravimetrically after extraction in mixed ethers using a combination of AOAC 922.06, 925.32, 948.15, and 950.54. Carbohydrates were determined by difference [Carbohydrates = 100 – (% moisture) – (% ash) – (% fat) – (% protein)]. Ash was measured gravimetrically by muffle furnace using AOAC Method 923.03. Minerals were quantified by inductively coupled plasma optical emission spectrometry (ICP-OES) using AOAC Method 2011.14, where samples were prepared by microwave closed-vessel digestion with nitric acid. Vitamin C results were obtained using fluorescence spectroscopy, AOAC Methods 984.26. Thiamin and riboflavin were measured by AOAC Method 981.15. Niacin was obtained using the microbiological approach, AOAC Method 960.46. Folic acid was determined after solid phase tri-enzyme extraction and UPLC-MS/MS, using AOAC Method 2011.06. Vitamin E was determined using AACC Method 86-06 (AACC

2019), where samples were saponified, the extract was refluxed in ethanolic KOH, and analyzed using reverse-phase HPLC.

Statistical analysis.

A mixed model analysis of variance (ANOVA) was used for the statistical analysis of fiber strength using SAS® 9.4 software (SAS, Cary, NC). The dependent variable was the tensile strength. The independent variable was the species. We blocked (grouped) the plants of each species so that we could compare the averages of the groups. We used the plants as a blocking factor. A post-hoc Tukey's pairwise comparison was done to determine significant differences among means at $P < 0.05$.

RESULTS AND DISCUSSION

Fiber tensile strength.

As shown in Table 1, the mean fiber tensile strengths of *Y. angustissima, Y. baccata*, and *Y. glauca* were 484 ± 79, 710 ± 174, and 388 ± 104 MPa, respectively. Tensile strength of *Y. baccata* fibers was 32% stronger than that of *Y. angustissima*, and 45% stronger than *Y. glauca*. These data can be compared in a relative way to those reported by Botkin and Shires (1944), who reported that fibers of *Y. baccata* were 26% stronger than those of *Y. glauca*.

Because of limited and dated information in the literature regarding the leaf fiber tensile strength of *Yucca* fibers from the Navajo Nation, species were compared to those from sisal (*Agave sisalana*), which have commonly been used for making rope and cordage. As shown in Table 2, sisal fibers collected and prepared as part of this study had a mean tensile strength of 478 ± 24.5 MPa. This is comparable to the 484 ± 135 MPa tensile strength for *A. sisalana* reported by Fidelis et al. (2013) and to the 392 ± 105 MPa value reported by Silva et al. (2008). In contrast, a review by Sathishkumar et al. (2013) reported the tensile strength of sisal to be higher at 530-640 MPa. Such differences in tensile strengths may be due to differences in test conditions, such as using a different gauge length, strain rate, type of grip, or perhaps using a different method of retting. In addition, results may differ because of plant characteristics, such as plant age or source. Finally, and most importantly, using different methods of measuring the cross-sectional area can produce different results. Because natural fibers are not circular, measuring the diameter of the fiber and calculating the area from that measurement will produce a less accurate result than if one measured the cross-sectional area directly.

Considering the range of sisal fiber data reported in the literature, the tensile strengths of the fibers from the three Navajo Nation *Yucca* species were comparable to, or – in the case of *Y. baccata* – much greater than those reported here or elsewhere for sisal. The fact that the sisal tensile strength data collected in the present study were comparable to results reported in previous studies, supports the validity of the methodology used here to collect *Yucca* and sisal fiber values.

Despite *Y. baccata* having a comparatively stronger fiber, the usefulness of *Y. angustissima* and *Y. glauca* fibers is not diminished. The fiber strengths of *Y. angustissima* and *Y. glauca* fiber were similar to sisal, which is, as stated previously, a widely used natural fiber. Futhermore, Fidelis et al. (2013) reported the strength of jute fiber, another commonly used natural fiber, to be 249 ± 89 MPa, which is weaker than *Y. angustissima*, *Y. glauca*, and sisal. Sathishkumar et al. (2013) reported the tensile strength of multiple natural plant fibers. Assuming the values for tensile strength of the yucca species reported in the current study are comparable, *Y. baccata* would rank sixth in strength, *Y. angustissima*, 18th, and *Y. glauca*, 23rd, among the 42 natural fibers reviewed in that study. Each yucca species, depending upon its strength, might be useful in different applications.

Fruit nutritional value.

The results of the nutritional analyses for fruits from *Y. angustissima* and *Y. baccata* are shown in Table 3. As would be expected, many of the values for the two *Yucca* species were similar. Because of limited sample availability and large variation in the data, significant differences between the two varieties were not able to be determined for most nutrients. Based on 100 g of fresh fruit (edible portion), vitamins that exceeded 10% of the U.S. Recommended Daily Intake (RDI) were vitamin C, vitamin E, thiamin, vitamin B6 and folate for *Y. angustissima*, and vitamin C and thiamin for *Y. baccata*. Minerals that exceeded 5% of the RDI were calcium, potassium and magnesium for *Y. angustissima*. None of the minerals in *Y. baccata* exceeded 5% of the RDI. High variation in the values for many of these nutrients suggests additional work must be done before making meaningful comparisons.

Wolfe et al. (1985) reported the proximate analysis, various minerals, and vitamins A and C content of *Y. angustissima* (desert yucca) and *Y. baccata* (mountain yucca). Unfortunately, they did not report any measure of statistical error nor did they report the maturity stage of the fruit. Nevertheless, a comparison of means on a dry weight basis is informative. For *baccata* species, proximate composition values for energy, carbohydrates, and fat on a dry weight basis were higher in the current study than those reported by Wolfe et al. (1985). There was a 34% difference in energy, a 46% difference in carbohydrates, and a 115% difference in fat. Mineral content was similar in the two studies except the values for potassium and phosphorus were much higher in the current study. There was a 199% difference in potassium and a 197%

difference in phosphorus for *angustissima*. There was a 181% difference in potassium and a 197% difference in phosphorus for *baccata*. Additionally, Wolfe et al. (1985) reported small amounts of iron, sodium, copper, and zinc, whereas the levels of these minerals were below the limit of detection in the current study. Regarding vitamin content, Wolfe et al. reported vitamin A content for dried *Y. baccata* to be 71 RE/100g (35.5 RAE). The current study reports 110 RAE/100g of vitamin A in this species. In contrast to Wolfe et al. (1985) where no other vitamins were reported, the current study measured additional vitamins. The level of vitamin C in both species is of practical significance. Vitamin C in *Y. angustissima* is 73 mg/100g and *Y. baccata* is 119 mg/100g, which represent 80% and 130% of the RDI, respectively. Differences in nutrient values between the current and other studies may be attributable to such variables as stage of fruit maturity, plant growing conditions, and improvements in analytical methodology.

Further work to determine nutritional quality as consumed should evaluate *Yucca* fruit at its optimum stage of ripeness, include more samples (to decrease the amount of error), and determine the amount of fruit that would constitute an appropriate serving size.

CONCLUSION

Yucca angustissima, Y. baccata, and *Y. glauca* are all good sources of relatively strong fibers that could be used in applications were natural plant fibers are typically used. Both *Y. angustissima* and *baccata* have the added advantage of bearing edible fruit that contain appreciable levels of several important vitamins and minerals. Because of its edible fruit and superior leaf fiber tensile strength, *Y. baccata* is recommended as the best species for cultivation and commercialization.

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TABLES AND FIGURES

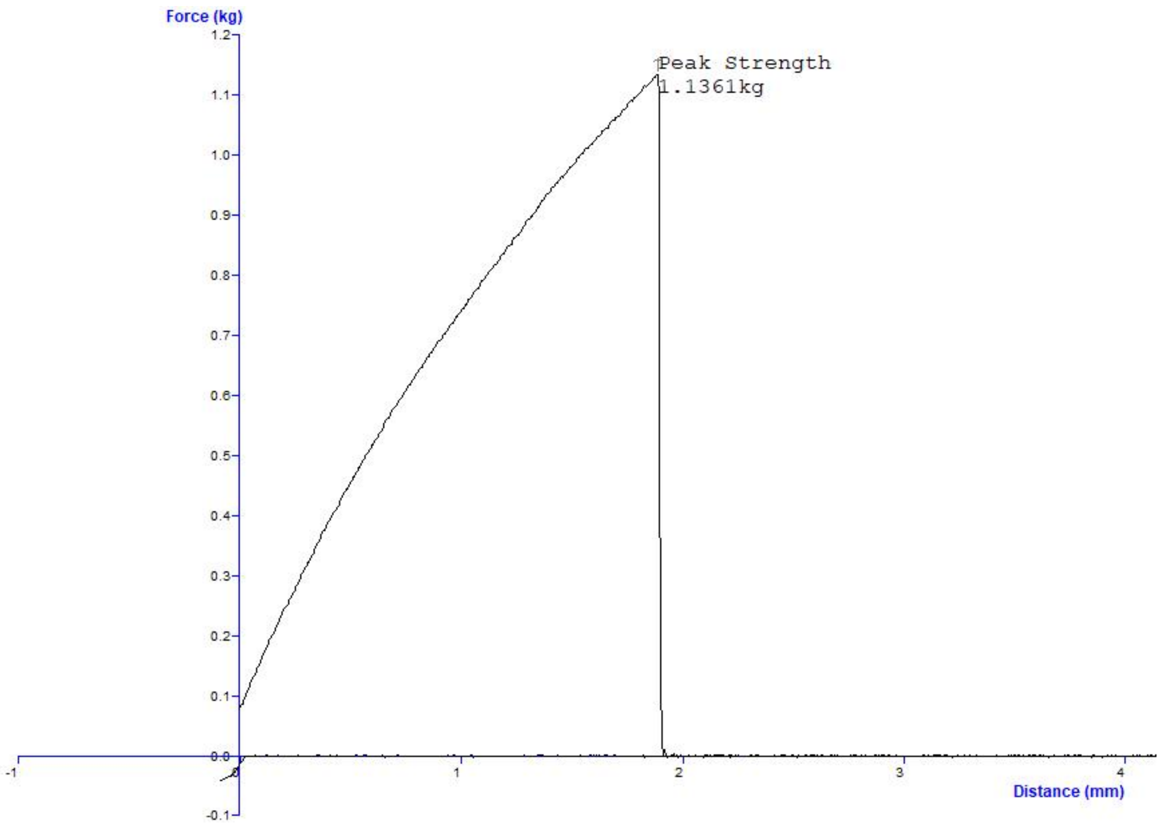


Figure 1. Typical peak strength curve of *Y. baccata* fiber.

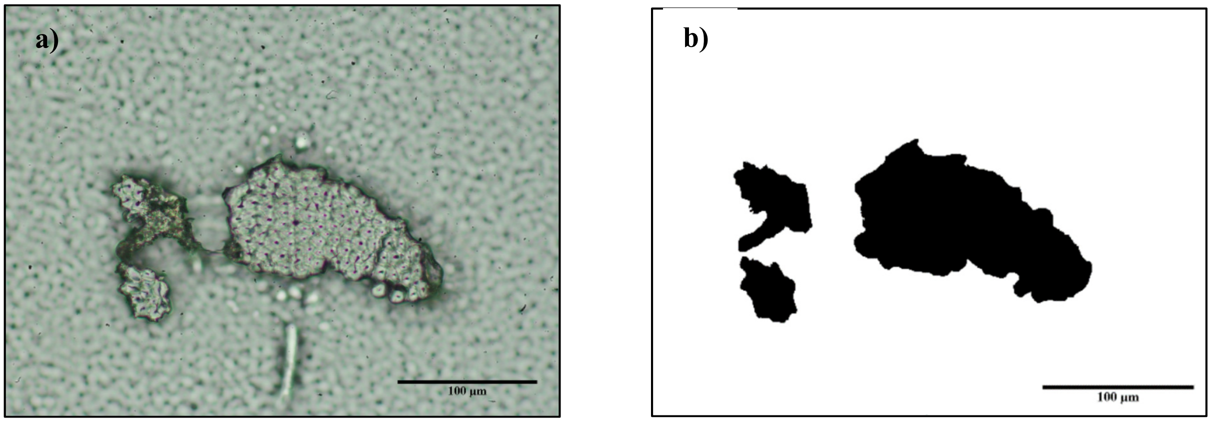


Figure 2. *Y. baccata* fiber (a) cross-section micrograph and (b) cross-sectional visual using *ImageJ* to determine total, combined area of split fiber ends.

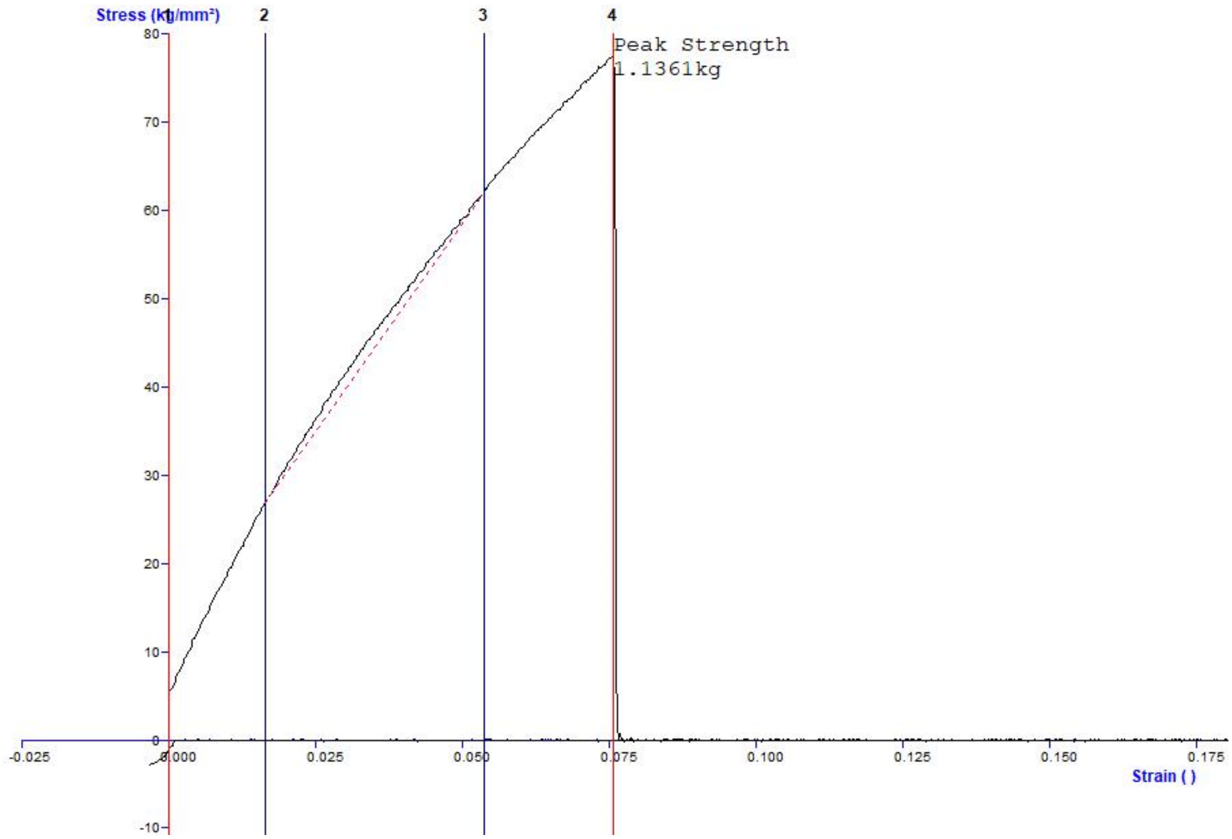


Figure 3. Typical stress-strain curve for *Y. baccata* fiber showing straight dotted line corresponding to Young's modulus. Vertical line 2 is anchored at 35% maximum force and line 3 is anchored at 80% maximum force.

Table 1. Leaf fiber tensile strength of yucca spp. Mean ± S.D. (n = 6).[a]

Plant	Leaf	Tensile Strength (MPa)	Young's Modulus (GPa)	Strain at Break (%)
Y. angustissima				
1	1	499 ± 162	12.3 ± 3.69	3.85 ± 0.75
	2	429 ± 129	9.21 ± 3.33	4.40 ± 0.72
2	1	470 ± 202	12.2 ± 6.81	3.36 ± 1.20
	2	658 ± 257	13.4 ± 2.45	3.87 ± 1.17
3	1	422 ± 192	7.32 ± 3.07	5.43 ± 0.97
	2	490 ± 200	10.6 ± 3.18	4.20 ± 0.93
4	1	495 ± 165	10.7 ± 4.12	4.45 ± 1.78
	2	406 ± 59.9	8.71 ± 1.26	4.43 ± 0.58
Overall Mean		484 ± 79.1	10.6 ± 2.05	4.25 ± 0.61
Y. baccata				
1	1	862 ± 159	10.2 ± 2.50	8.01 ± 1.09
	2	636 ± 92.1	10.2 ± 3.07	6.15 ± 2.00
2	1	859 ± 387	9.84 ± 4.61	8.02 ± 1.29
	2	489 ± 195	7.08 ± 2.61	6.39 ± 2.16
3	1	890 ± 382	8.99 ± 1.72	7.94 ± 2.25
	2	443 ± 134	11.9 ± 4.59	4.11 ± 2.80
4	1	696 ± 299	9.29 ± 2.59	7.07 ± 1.97
	2	807 ± 79.0	10.5 ± 2.13	7.33 ± 1.72
Overall Mean		710 ± 174	9.75 ± 1.39	6.88 ± 1.33
Y. glauca				
1	1	214 ± 56.3	4.57 ± 1.36	4.33 ± 0.93
	2	362 ± 153	6.97 ± 3.60	4.54 ± 0.78
2	1	565 ± 209	10.5 ± 3.30	3.44 ± 0.18
	2	492 ± 136	11.4 ± 1.56	3.75 ± 1.20
3	1	368 ± 90.8	8.11 ± 1.81	4.46 ± 1.31
	2	378 ± 104	10.1 ± 2.31	3.39 ± 0.82
4	1	383 ± 122	8.23 ± 3.92	4.41 ± 1.35
	2	339 ± 143	6.74 ± 2.45	4.53 ± 0.44
Overall Mean		388 ± 104	8.33 ± 2.26	4.11 ± 0.50

[a]*Baccata* was significantly stronger than *angustissima* and *glauca*.

Table 2. Leaf fiber tensile strength of sisal (*Agave sisalana*). Mean ± S.D. (n = 8).

Leaf	Tensile Strength (MPa)	Young's Modulus (GPa)	Strain at Break (%)
1	498 ± 118	7.44 ± 1.90	6.57 ± 1.54
2	466 ± 52.7	7.18 ± 0.60	6.27 ± 0.91
3	488 ± 103	7.13 ± 1.28	6.55 ± 1.29
4	508 ± 127	7.85 ± 1.92	6.18 ± 1.12
5	468 ± 136	6.97 ± 1.63	6.37 ± 2.09
6	441 ± 54.5	6.07 ± 1.46	6.97 ± 1.88
Overall Mean	478 ± 24.5	7.11 ± 0.59	6.49 ± 0.28

Table 3. Nutrients in *Y. angustissima* and *Y. baccata* fruit. Mean ± S.D. (n = 2).

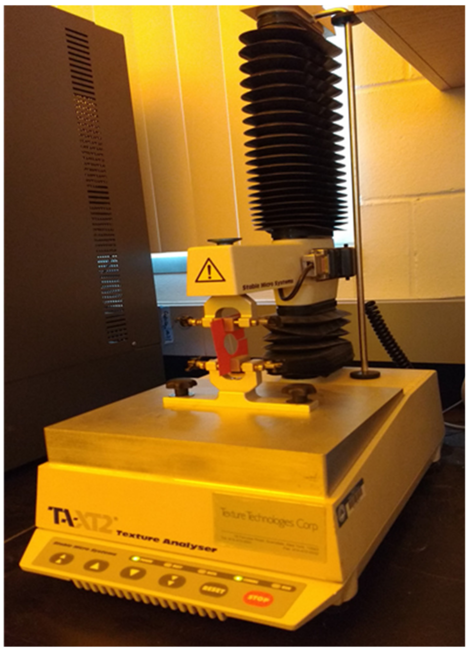
	Y. angustissima				*Y. baccata*			
Nutrient	fresh		dry weight basis		fresh		dry weight basis	
Moisture (%)	86.4	± 1.5			80.3	± 3.5		
Energy (cal)	54	± 6	399	± 3	80	± 14	588	± 39
Protein (%)	< 0.78[1]				<0.78			
Fat (%)	0.7	± 0.0	5.2	± 0.6	0.6	± 0.1	4.1	± 1.0
Carbohydrates %)	11.5	± 0.8	84.7	± 3.7	18.8	± 3.6	137.7	± 11.3
Ash (%)	0.9	± 0.0	6.8	± 0.7	0.4	± 0.0	3.1	± 0.4
Calcium (mg)	110	± 46	796	± 248	37	± 6	276.0	± 74.0
Copper (mg)	<1.00				<1.00			
Iron (mg)	<1.00				<1.00			
Magnesium (mg)	22.6	±17.5	160.5	± 111.5	13.8	± 0.8	101.8	± 5.6
Manganese (mg)	<1.00				<1.00			
Phosphorus (mg)	33.9	± 6.7	248.5	± 21.9	33.5	± 0.0	248.7	± 27.7
Potassium (mg)	394	± 30	2937	± 546	224	± 20	1671	± 332
Sodium (mg)	<3.00				<3.00			
Zinc (mg)	<1.00				<1.00			
Vitamin C (mg)	73	± 53	566	± 456	119	± 41	900	± 404
Thiamin (mg)	0.20	± 0.02	1.5	± 0.3	0.22	± 0.06	1.7	± 0.6
Riboflavin (mg)	<0.03				<0.03			
Niacin (mg)	0.566	± 0.03	4.2	± 0.2	0.500	± 0.15	3.6	± 0.7
Vitamin B6 (mg)	0.170	± 0.003	1.3	± 0.16	0.075	± .013	0.56	± 0.16
Folic Acid (µg)	14.5[2]		99.2		27.10	± 13.29	206.68	± 121.09
Vitamin A (µg)	11.7	± 3.03	87.8	± 32.1	15.0	± 1.48	110	± 1.3
Vitamin E (mg)	1.56	± 0.53	11.8	± 5.2	0.57	± 0.52	4.0	± 3.4

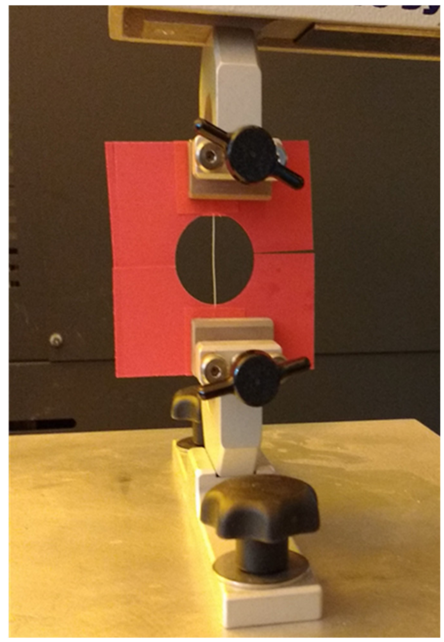
[1]The < symbol signifies that the results are below the level of detection.
[2]Outlier precluded a standard deviation.

APPENDIX

A. TA-XT2 Plus Texture Analyzer and Attachment.

Photos of (a) instrument and (b) detail of grip and fiber mounted on tab prior to testing.





B. Expanded statistical output.

The SAS System

The Mixed Procedure

Model Information	
Data Set	WORK.GOOD
Dependent Variable	strength__MPa_
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Containment

Class Level Information		
Class	**Levels**	**Values**
planta	13	11 12 13 14 21 22 23 24 31 32 33 34 41
leafa	30	111 112 121 122 131 132 141 142 211 212 221 222 231 232 241 242 311 312 321 322 331 332 341 342 411 412 413 414 415 416
species	4	Angustissima Baccata Glauca Sisal

Dimensions	
Covariance Parameters	2
Columns in X	5
Columns in Z	30
Subjects	1
Max Obs per Subject	192

Number of Observations	
Number of Observations Read	192
Number of Observations Used	192
Number of Observations Not Used	0

Iteration History			
Iteration	**Evaluations**	**-2 Res Log Like**	**Criterion**
0	1	2524.75722693	
1	2	2512.97919394	0.00000281
2	1	2512.97608411	0.00000000

Convergence criteria met.

Covariance Parameter Estimates	
Cov Parm	**Estimate**
planta(leafa*specie)	7671.65
Residual	30138

Fit Statistics	
-2 Res Log Likelihood	2513.0
AIC (Smaller is Better)	2517.0
AICC (Smaller is Better)	2517.0
BIC (Smaller is Better)	2519.8

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
species	3	26	11.87	<.0001

Least Squares Means						
Effect	**species**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
species	Angustissima	483.73	39.8351	26	12.14	<.0001
species	Baccata	710.44	39.8351	26	17.83	<.0001
species	Glauca	387.65	39.8351	26	9.73	<.0001
species	Sisal	478.23	43.6633	26	10.95	<.0001

Differences of Least Squares Means									
Effect	**species**	**species**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Adjustment**	**Adj P**
species	Angustissima	Baccata	-226.71	56.3353	26	-4.02	0.0004	Tukey-Kramer	0.0023
species	Angustissima	Glauca	96.0871	56.3353	26	1.71	0.1000	Tukey-Kramer	0.3412
species	Angustissima	Sisal	5.5061	59.1043	26	0.09	0.9265	Tukey-Kramer	0.9997
species	Baccata	Glauca	322.80	56.3353	26	5.73	<.0001	Tukey-Kramer	<.0001
species	Baccata	Sisal	232.22	59.1043	26	3.93	0.0006	Tukey-Kramer	0.0030
species	Glauca	Sisal	-90.5810	59.1043	26	-1.53	0.1375	Tukey-Kramer	0.4334

C. Nutritional raw data.

Medallion Labs Sample ID: 2017-MED-9384-02		Yucca Angustissima Fruit	
Customer Sample ID: A2			
Assay Group	**Test**	**Results**	**Test Date**
Sample Handling Processing Level 1	Sample Process Fee	Sample Processed	07/27/17
[2] Carbohydrates	Carbohydrates	12.0 %	08/09/17
[2] Calories	Calories	58 Calories/100 g	08/09/17
	Calories from Fat	6 Calories/100 g	
Metals Screen 2	Metals Screen	Discount	07/27/17
Vitamin C	Vitamin C	35.6 mg/100g	08/03/17
[2] Carotenoids	alpha carotene (IU/100g)	<0.500 IU/100 g	08/02/17
	trans beta carotene (IU/100g)	177 IU/100 g	
	cis beta carotene (IU/100g)	13.1 IU/100 g	
	Total beta Carotene (IU/100g)	190 IU/100 g	
	Total Carotene (IU/100g)	190 IU/100 g	
	alpha carotene (µg RAE)	<0.0250 µg/100 g	
	trans beta carotene (µg RAE)	8.86 µg/100 g	
	cis beta carotene (µg RAE)	0.655 µg/100 g	
	Total beta Carotene (µg RAE)	9.52 µg/100 g	
	Total Carotene (µg RAE)	9.52 µg/100 g	
Vitamin E	Vitamin E	1.32 Synthetic IU/100g	08/07/17
Moisture by Vacuum Oven (70° C/16 hrs)	Moisture	85.379 %	08/09/17
Ash, Overnight	Ash	0.925 %	08/01/17
Protein, by Dumas	Protein (6.25)	1.03 %	08/07/17
Fat, Gravimetric	Total Fat	0.7 %	08/03/17
Niacin	Niacin	0.588 mg/100g	08/03/17
Vitamin B1 (Thiamine)	Vitamin B1 (Thiamine-HCl (US))	0.180 mg/100g	08/03/17
	Vitamin B1 (Thiamine (EU))	0.142 mg/100g	
Vitamin B2 (Riboflavin)	Vitamin B2 (Riboflavin)	<0.0300 mg/100g	08/04/17
Vitamin B6	Vitamin B6	0.168 mg/100g	08/02/17
Calcium	Calcium	142 mg/100g	08/08/17
Iron	Iron	<1.00 mg/100g	08/08/17
Sodium	Sodium	<3.00 mg/100g	08/08/17
Phosphorus	Phosphorus	29.1 mg/100g	08/08/17
Copper	Copper	<1.00 mg/100g	08/08/17
Potassium	Potassium	415 mg/100g	08/08/17
Magnesium	Magnesium	10.2 mg/100g	08/08/17
Manganese	Manganese	<1.00 mg/100g	08/08/17
Zinc	Zinc	<1.00 mg/100g	08/08/17
[1] [2] Folic Acid	Folic Acid	237.0 µg/100 g	08/16/17

Medallion Labs Sample ID: 2017-MED-9384-02 Yucca Angustissima Fruit

Customer Sample ID: A2

Assay Group	Test	Results	Test Date
Sample Handling Processing Level 1	Sample Process Fee	Sample Processed	07/27/17
[2] Carbohydrates	Carbohydrates	12.0 %	08/09/17
[2] Calories	Calories	58 Calories/100 g	08/09/17
	Calories from Fat	6 Calories/100 g	
Metals Screen 2	Metals Screen	Discount	07/27/17
Vitamin C	Vitamin C	35.6 mg/100g	08/03/17
[2] Carotenoids	alpha carotene (IU/100g)	<0.500 IU/100 g	08/02/17
	trans beta carotene (IU/100g)	177 IU/100 g	
	cis beta carotene (IU/100g)	13.1 IU/100 g	
	Total beta Carotene (IU/100g)	190 IU/100 g	
	Total Carotene (IU/100g)	190 IU/100 g	
	alpha carotene (µg RAE)	<0.0250 µg/100 g	
	trans beta carotene (µg RAE)	8.86 µg/100 g	
	cis beta carotene (µg RAE)	0.655 µg/100 g	
	Total beta Carotene (µg RAE)	9.52 µg/100 g	
	Total Carotene (µg RAE)	9.52 µg/100 g	
Vitamin E	Vitamin E	1.32 Synthetic IU/100g	08/07/17
Moisture by Vacuum Oven (70° C/16 hrs)	Moisture	85.379 %	08/09/17
Ash, Overnight	Ash	0.925 %	08/01/17
Protein, by Dumas	Protein (6.25)	1.03 %	08/07/17
Fat, Gravimetric	Total Fat	0.7 %	08/03/17
Niacin	Niacin	0.588 mg/100g	08/03/17
Vitamin B1 (Thiamine)	Vitamin B1 (Thiamine-HCl (US))	0.180 mg/100g	08/03/17
	Vitamin B1 (Thiamine (EU))	0.142 mg/100g	
Vitamin B2 (Riboflavin)	Vitamin B2 (Riboflavin)	<0.0300 mg/100g	08/04/17
Vitamin B6	Vitamin B6	0.168 mg/100g	08/02/17
Calcium	Calcium	142 mg/100g	08/08/17
Iron	Iron	<1.00 mg/100g	08/08/17
Sodium	Sodium	<3.00 mg/100g	08/08/17
Phosphorus	Phosphorus	38.6 mg/100g	08/08/17
Copper	Copper	<1.00 mg/100g	08/08/17
Potassium	Potassium	373 mg/100g	08/08/17
Magnesium	Magnesium	35.0 mg/100g	08/08/17
Manganese	Manganese	<1.00 mg/100g	08/08/17
Zinc	Zinc	<1.00 mg/100g	08/08/17
[1] [2] Folic Acid	Folic Acid	14.50 µg/100 g	08/16/17

Medallion Labs Sample ID: 2017-MED-9384-03 Yucca Baccata Fruit

Customer Sample ID: B1

Assay Group	Test	Results	Test Date
Sample Handling Processing Level 1	Sample Process Fee	Sample Processed	07/27/17
[2] Carbohydrates	Carbohydrates	16.2 %	08/09/17
[2] Calories	Calories	70 Calories/100 g	08/09/17
	Calories from Fat	5 Calories/100 g	
Metals Screen 2	Metals Screen	Discount	07/27/17
Moisture by Vacuum Oven (70° C/16 hrs)	Moisture	82.761 %	08/09/17
Ash, Overnight	Ash	0.426 %	08/01/17
Protein, by Dumas	Protein (6.25)	<0.781 %	08/01/17
Fat, Gravimetric	Total Fat	0.6 %	08/03/17
Niacin	Niacin	0.393 mg/100g	08/03/17
Vitamin B1 (Thiamine)	Vitamin B1 (Thiamine-HCl (US))	0.260 mg/100g	08/03/17
	Vitamin B1 (Thiamine (EU))	0.205 mg/100g	
Vitamin B2 (Riboflavin)	Vitamin B2 (Riboflavin)	<0.0300 mg/100g	08/04/17
Vitamin B6	Vitamin B6	0.084 mg/100g	08/02/17
Calcium	Calcium	41.0 mg/100g	08/08/17
Iron	Iron	<1.00 mg/100g	08/08/17
Sodium	Sodium	<3.00 mg/100g	08/08/17
Phosphorus	Phosphorus	33.5 mg/100g	08/08/17
Copper	Copper	<1.00 mg/100g	08/08/17
Potassium	Potassium	238 mg/100g	08/08/17
Magnesium	Magnesium	13.2 mg/100g	08/08/17
Manganese	Manganese	<1.00 mg/100g	08/08/17
Zinc	Zinc	<1.00 mg/100g	08/08/17
[2] Carotenoids	alpha carotene (IU/100g)	<0.500 IU/100 g	08/02/17
	trans beta carotene (IU/100g)	260 IU/100 g	
	cis beta carotene (IU/100g)	17.4 IU/100 g	
	Total beta Carotene (IU/100g)	277 IU/100 g	
	Total Carotene (IU/100g)	277 IU/100 g	
	alpha carotene (µg RAE)	<0.0250 µg/100 g	
	trans beta carotene (µg RAE)	13.0 µg/100 g	
	cis beta carotene (µg RAE)	0.871 µg/100 g	
	Total beta Carotene (µg RAE)	13.9 µg/100 g	
	Total Carotene (µg RAE)	13.9 µg/100 g	
Vitamin E	Vitamin E	0.219 Synthetic IU/100g	08/07/17
[1] [2] Folic Acid	Folic Acid	36.50 µg/100 g	08/16/17
Vitamin C	Vitamin C	148 mg/100g	08/03/17

Medallion Labs Sample ID: 2017-MED-9384-04 Yucca Baccata Fruit

Customer Sample ID: B2

Assay Group	Test	Results	Test Date
Sample Handling Processing Level 1	Sample Process Fee	Sample Processed	07/27/17
[2] Carbohydrates	Carbohydrates	21.3 %	08/09/17
[2] Calories	Calories	90 Calories/100 g	08/09/17
	Calories from Fat	5 Calories/100 g	
Metals Screen 2	Metals Screen	Discount	07/27/17
Moisture by Vacuum Oven (70° C/16 hrs)	Moisture	77.749 %	08/09/17
Ash, Overnight	Ash	0.409 %	08/01/17
Protein, by Dumas	Protein (6.25)	<0.781 %	08/01/17
Fat, Gravimetric	Total Fat	0.5 %	08/03/17
Niacin	Niacin	0.607 mg/100g	08/03/17
Vitamin B1 (Thiamine)	Vitamin B1 (Thiamine-HCl (US))	0.180 mg/100g	08/03/17
	Vitamin B1 (Thiamine (EU))	0.142 mg/100g	
Vitamin B2 (Riboflavin)	Vitamin B2 (Riboflavin)	<0.0300 mg/100g	08/04/17
Vitamin B6	Vitamin B6	0.066 mg/100g	08/02/17
Calcium	Calcium	32.7 mg/100g	08/08/17
Iron	Iron	<1.00 mg/100g	08/08/17
Sodium	Sodium	<3.00 mg/100g	08/08/17
Phosphorus	Phosphorus	33.5 mg/100g	08/08/17
Copper	Copper	<1.00 mg/100g	08/08/17
Potassium	Potassium	210 mg/100g	08/08/17
Magnesium	Magnesium	14.3 mg/100g	08/08/17
Manganese	Manganese	<1.00 mg/100g	08/08/17
Zinc	Zinc	<1.00 mg/100g	08/08/17
[2] Carotenoids	alpha carotene (IU/100g)	<0.500 IU/100 g	08/02/17
	trans beta carotene (IU/100g)	302 IU/100 g	
	cis beta carotene (IU/100g)	19.8 IU/100 g	
	Total beta Carotene (IU/100g)	322 IU/100 g	
	Total Carotene (IU/100g)	322 IU/100 g	
	alpha carotene (µg RAE)	<0.0250 µg/100 g	
	trans beta carotene (µg RAE)	15.0 µg/100 g	
	cis beta carotene (µg RAE)	0.987 µg/100 g	
	Total beta Carotene (µg RAE)	16.0 µg/100 g	
	Total Carotene (µg RAE)	16.0 µg/100 g	
Vitamin E	Vitamin E	1.04 Synthetic IU/100g	08/07/17
[1] [2] Folic Acid	Folic Acid	17.70 µg/100 g	08/16/17
Vitamin C	Vitamin C	89.8 mg/100g	08/03/17

D. Summary graph.

Tensile strength of plant fibers for yucca species and *Agave sisalana*. Bars represent standard error of the mean. Different letters indicate significant differences ($P < 0.05$). ($n = 48$ for yucca and $n = 8$ for sisal).