Investigating Biomechanical Properties of *A. tortilis* as Related to their Habitat: A novel approach to characterize bending

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Field grown *Acacia* have higher values of Young's and Flexural Moduli than nursery grown ones thus conferring them more elasticity and flexibility.

1   **ABSTRACT**

2   The biomechanical properties of *Acacia tortilis* were investigated considering

3   its habitat (wild vs. nursery). The plant materials were collected from partially

4   urbanized area in Doha city and from Qatar Foundation Nursery. The results show

5   that *Acacia* grown in field are more flexible than those grown in nursery. Young's

6   Modulus of Elasticity was found to be 191 MPa and 617 MPa and the Flexural

7   Modulus was found to be 49 MPa and 575 MPa and the breaking force was found to

8   be 210 and 550 N for nursery and field Acacia, respectively. The deflection angle

9   was measured using sensitive flex sensors connected to Arduino boards and was

10   found to be higher for field Acacia (50∘). Image processing techniques were used to

11   mathematically describe the branch motion versus time diagrams.

12   The plant part being investigated was covered with red tape and videotaped while

13   subjected to a force causing it to bend. The stem was divided into 745 successive

14   points and the change in their position with time taken frame by frame was converted

15   into a change in position expressed through mathematical parameters. The bending

16   movement of the branch was found to follow a power function $H = (4001 - e^{0.06m})$.

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18   Keywords:

19   Acacia tortilis, Arduino, Biomechanics, Deflection angle, Elasticity, Flex sensors,

20   Flexural modulus, Image Processing, Mathematical Modelling, Young's modulus.

1- INTRODUCTION

Acacia spp. are native shrubs in the Middle East and African Savanna. They occupy a wide range of habitats including the tropical and subtropical areas. *Acacia tortilis* (fig. 1), is a kind of spiny shrubs that belongs to the Fabaceae family (peas). It can grow very well in extremely arid conditions, in sunny, high temperature and dry environments as well as in drained alkaline sandy soil. *Acacia* has a high economic importance due to its wide range of uses. It is used in gardening as ornamental plant and as wind breaks. *Acacia* wood is used in furniture industries. Moreover, different chemical compounds isolated from *acacia* have medical and pharmaceutical applications.

The distribution of *acacia* spp. and their success in occupying certain areas depend on many factors, some of them are closely related to the physical and climate conditions particularly the wind speed and axial loads acting on the plant in compression and tension.

According to the Qatar Meteorology Department (QMD) and Qatari Civil Aviation Authority (https://qweather.gov.qa/ClimateInfo.aspx), in the end of October 2018, Qatar has suffered from heavy thunderstorms with strong wind speed that has reached 85 km/hr with maximum rainfall exceeding 84mm. Worth noting that the average rainfall in October in Doha is about 1.1mm with wind speed less than 7 km/hr. The wind and moving debris had led to the destruction of *Acacia* shrubs planted in Doha city that were originally grown under optimum conditions in Qatar Foundation Nursery. The thunderstorms accompanied by the strong winds and heavy rains have caused plants failure due to uprooting and snapping that led to breaking and felling of trees. Most nursery-grown *Acacia* plants used in gardening were damaged or broken in their weakest. On the other hand, the *Acacia* plants naturally grown in wild could persist and withstand the extreme physical conditions they were exposed to. This has stimulated us to investigate the biomechanical, morphological, and anatomical adaptations that enable wild Acacia to cope with the harsh physical conditions.

The success of a shrub in arid and semi-arid conditions depends on its adaptive capacity to the harsh physical conditions that protrude from its biomechanical properties. Young's modulus of Elasticity, flexural stiffness, and area moment of

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inertia are three important parameters that are used to describe the mechanical behavior of a plant. Young's modulus of elasticity is used to characterize the overall bending behavior of a stem regardless of its size and shape while flexural stiffness characterizes the flexibility of the stem section. The area moment of inertia rather than the diameter or the length is used to describe the geometry and the size of the plant part to which the force is applied (Hossein and Jacob, 2015). The angle of deflection is used to describe the whole stem flexibility.

The aims of the current study were to compare the biomechanical properties of *Acacia tortilis* naturally grown in wild to those grown in nursery. The current study was divided into 3 parts: 1- finding the Young's Modulus and the Flexural Modulus of *Acacia* stem parts using materials testing machines in compression, tension, and bending, 2- Finding the deflection (bending) angle of *Acacia* stem in field using flex sensors and Arduino boards, and 3- using image processing techniques to mathematically describe the bending movement of the tree.

The biomechanical properties were studied by applying bending, compression, and tension tests using mechanical machines, flex sensors for bending, and image processing technique to simulate the stem movement and describe it mathematically. To understand the behavior and adaptations of *Acacia* to different wind speeds, its biomechanical behavior was analyzed considering its habitat characteristics.

The techniques used in this study utilize advanced technology that is being used for the first time in investigating the biomechanical properties of plants. The results of the current research are important to agricultural and mechanical engineers, botanists, gardening specialist, municipality policy makers, as well as to taxonomists and evolutionists.

Knowing the biomechanical properties of *Acacia* would enable the prediction of their growth success and failure under particular weather conditions. This is extremely important when setting plans for the conservation of rare plant species.

Analyzing the biomechanical properties of *Acacia* and generally of plant fibers would facilitate their utilization in the synthesis of synthetic polymers made of natural fibers. Using plant fibers in composite materials would reduce the pollution, the cost, and make the performance better.

1   Knowledge about plants biomechanics is necessary in agricultural researches aiming
2   to stop crop loss due to stem breakage or uprooting (Robertson *et al.*, 2015) as well
3   as in forest management for the protection of large tree trunks from damage by
4   winds (Hale *et al.*, 2012).   Moreover, knowledge about stem deformation when
5   processed by machines is extremely important for materials sciences and
6   engineering processes (Leblicq *et al.*, 2015). Knowledge about plants biomechanics
7   is also important for pure theoretical evolutionary studies as biomechanics provide
8   with additional criteria for phenotype characterization and doing comparisons among
9   different plant phyla and species (Shah *et al.*, 2017). It also may explain the failure of
10   certain plant species and their extinction. Biomechanics can be used to draw
11   conclusions and suggest new hypotheses or confirm old ones discussing the
12   evolution of land plants.
13   Searching the open literature has revealed that the interest in plants biomechanics is
14   substantially increasing that is evident by the increase in the number of publications
15   addressing the impacts of mechanical forces on plants behavior, stability, and failure
16   (Raines *et.al.*, 2013) as this issue is critical for abstract and applied sciences as well
17   as for commercial purposes.
18   Many studies had investigated the biomechanical behavior of terrestrial and aquatic
19   plants since 1970. However, relatively few researches studied the biomechanical
20   features of shrubs in arid and semi-arid environments (Shah *et al.*, 2017).

21   For instance, Niklas (1997) studied the biomechanics of hollow septate internodes
22   and concluded that increasing the internodal length decreases the bending stiffness
23   and the ability to resist torsion. Boller and Carrington (2007) have studied the
24   biomechanics of different seaweeds living in tidal zones that are exposed to and
25   suffer from high wave stresses; thus, creating a high selective pressure. They
26   concluded that only seaweeds with high flexural modulus and high ultimate tensile
27   strength could survive, reproduce, and evolve.

28   Miler *et al.* (2010) have investigated the biomechanical properties of four aquatic
29   species living in river and under danger of being washed by the stream. They
30   concluded that the forces created by the flow of water are faced by the bending and
31   tension abilities of the plant causing the whole system of the plant the forces
32   affecting it to be in equilibrium. This balance holds the plants in place and is used to
33   predict their biomechanical behavior.

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1 Asner and Goldstein (1997) have studied the correlation between wood
2 biomechanical properties and stem failure of trees subjected to strong winds. Their
3 results indicated that for canopy trees under windstorms the stem condition whether
4 it would withstand the hurricane, get uprooted or snapped is determined by its
5 mechanical properties particularly with the elastic modulus. The snapped trees had
6 higher elastic moduli than the other groups and that stem's morphological
7 characteristics such as diameter and density are not related to stem's failure.

8 In their study about the physical resilience of selected shrubs in semi-arid regions,
9 Hossein and Jacob (2015) have found that *Acacia nilotica* was the best mechanically
10 adapted among the 5 studied species with the highest value of Young's Modulus
11 (332.61KPa) and flexural stiffness (7.46Nm^2). the other 4 species were arranged in
12 order of decreasing their mechanical properties as follows: *Ziziphus mucronate*,
13 *Grewia bicolor*, *Acacia tortilis*, and *Bosica grandiflora* with the lowest Young's
14 modulus (20.94 KPa) and flexural stiffness of 2.90 Nm^2.

15 Onada et al. (2009) investigated the impact of environmental conditions such as
16 rainfall on the relationship between the biomechanical properties of the stem and the
17 wood density in 32 plant species in Australia and concluded that the mechanical
18 properties of plants are not merely due to genetics but also dictated by the
19 environment.

20 Alvarez-Clare and Kitajima (2007) investigated the physical traits that enhance the
21 defensive capability and survival of neotropical woody plants, and they concluded
22 that stems with higher strength resist buckling better and suffer less from breakage
23 due to winds and herbivores.

24 Gibson (2012) investigated the biomechanical properties of three plant materials
25 (parenchyma, dense arborescent palm stems, and wood) considering their cell wall
26 microstructure and composition. He concluded that parenchyma has the least
27 Young's modulus value of (0.3 MPa) and also 0.3 MPa compressive strength while
28 the palm stem has the highest Young's modulus value of 30 GPa and tensile
29 strength over than 300 MPa.

2- MATETRIALS AND METHODS

2-1 Study area, samples collection and preparation

Doha Municipal is in the central-east part of Qatar with an elevation of 10m and bordered by the Arabian Gulf on its coast. Doha is covered by desert plants and shrubs with almost no trees.

The plant materials were collected in the first week of December 2018 from a partially urbanized area in Doha city called Ar-Rayyan located at latitude: 25.333883 and Longitude: 51.411684 eastern to Qatar Foundation and from Qatar Foundation Nursery (Fig. 2). A quick survey of the area and consulting the local experts revealed that *Acacia* species are abundant and are among the most dominant species in that area covering more than 25% of the total vegetation.

After carrying out the field study, fresh cutting specimens of *Acacia tortilis* were collected from the named location and transported to the Science, Technology, Engineering and Math (STEM) laboratories at Qatar Science and Technology Secondary School (QSTSS) for further investigations. Prior to applying the mechanical tests, the plant materials were first prepared, the thorns were removed, and initial measurements for lengths and diameters were taken using an electronic caliper. The collected samples were and stored in sealed plastic bags under cool conditions and were analyzed within one week after collection.

The length of each plant stem ranges between (50 – 85) cm. The stems were cut into three parts (top section, middle section, and bottom section), each of the sections was further cut into ~ 10cm length, a length suitable and standardized for the bench top testing machine. The average of the length /diameter ratio was about 1:13, this ratio is enough to reduce the effect of the shear stress (Shah *et al.*, 2017). For each 10 cm sample, the diameter was measured at three positions near the two ends and in the middle, or in some cases at the thickest or thinnest points, then the average value was taken.

2-2 Experimental setup

The collected *Acacia* samples were divided into two groups: field samples and nursery samples. For each group, the bending, tension, and compression properties were investigated using PASCO materials testing system Model ME-8230 (Fig. 3).

1 The material testing apparatus consists of two major parts: the upper load anvil and
2 the lower base with the two support anvils. The load anvil sticks up through the
3 cross-head and is held in place by knurled cap nut. The base (for the support anvils)
4 fastens directly to the load cell using the two cap screws as shown in figure 3.

5 The materials testing machine is provided with a built-in load cell that can create and
6 measure a force up to 7100N. The machine is also provided with a built-in optical
7 encoder for measuring the change in the linear position (displacement) of the cross-
8 head load bar. The load cell also contains a transducer that converts the mechanical
9 measurements (force and displacement) into electronic signals. PASCO Interface
10 operated by PASCO Capstone Software was used to record, save, retrieve, display,
11 and analyze the force and displacement data from the load cell and the encoder,
12 respectively. The materials testing machine was calibrated and used as per the
13 instructions of the manufacturer.

14 Because of their anisotropic nature, taking biomechanical measurements for plant
15 materials and interpreting them is more difficult than it is for metals. Plant tissues are
16 heterogeneous therefore they may show different values for Young's and Flexural
17 Moduli when measured at different parts along the stem. Therefore, the experiment
18 was repeated many times to determine the range of values that the moduli can take.

19 When carrying out the tension experiment (fig. 4), the plant material slipped from the
20 clamps when the applied force reached a certain value so only the first portion that is
21 the linear portion of the force vs. deflection graphs was considered valid. However,
22 this linear portion was enough to calculate Young's Modulus but not the tensile
23 strength or the breaking force.

24 Force vs. deflection and stress vs. strain graphs for the plant materials within the
25 elastic region were constructed. For each stem cut, three 10 cm samples were taken
26 and examined. The mean value of Young's Modulus and Flexural Modulus for the
27 tested plant samples of the same plant cut were determined. The high accuracy of
28 the load cells and the materials testing system used allowed us to measure the small
29 forces during bending and compression.

30

1 **2-3 Three Point Bending Test**

2 Three-point bending tests were performed using a bench-top testing machine

3 provided with two electronic sensors for measuring and recording the load force and

4 the deflection in the form of change in position (fig. 5).

5 To apply the force on the sample through the plunger, the crank was turned slowly at

6 a rate between 10 and 20 mm/minute. The materials testing machine was then

7 connected to the PASCO interface for data collection and recording. The force vs.

8 position graph was constructed.

9 As the plunger applied a downward load (force, F) in the middle of the plant section,

10 the flexure (vertical deflection) was recorded. Materials tested included 20

11 specimens for field plant and 20 for nursery plant. For each field and nursery plant

12 sample, the force (F, N) vs. deflection represented as a change in the linear position

13 (ΔX, mm) was constructed and the slope was measured directly. The slope (F/ ΔX

14 ratio) reflects the effective stiffness of the measured plant part. According to the

15 elastic theory, the material's stiffness depends on its length, shape and the cross-

16 sectional area in addition to the nature of the material.   The Flexural Elastic Modulus

17 (E_b) for the tested plant part was calculated as follows:

18 $$F/_{\Delta X} = 48 I_b E/L^3$$, where "**I**" is the area moment of inertia for the sample.

19 Solving for E_b, yields $$E_b = (F/\Delta X)\frac{L^3}{48I}$$.

20 The area moment of inertia depends on the shape of the cross section of the

21 sample. For the round solid stem of diameter d and radius r, I_{stem}= ¼ π r^4 = 1/64 π

22 d^4 .

23 The value (EI) is an indicator for the plant stiffness and important for stem length and

24 corresponding plant height (Gere and Timoshenko, 1999).

25 **2-4 Axial Loading Tests**

26 **2-4-1 Tensile Tests**

27 The plant sample (fig. 6) was firmly fixed in the materials testing machine from its

28 two ends using two adapters that are connected to the load cell from one side and to

29 the cross-head component from the other side. The crank of the materials testing

30 machine was turned slowly to raise the cross-head to which the sample is attached

31 at a rate between 10 and 20 mm/minute and pulling the stem section apart while

32 both the load and the extension are being recorded until the stem breaks or slips.

7

1   The PASCO Sparkvue software was used to record the force vs displacement graph

2   from which the breaking force was determined and the stress vs. strain graph

3   constructed.   Several different materials mechanical properties including Young's

4   modulus, tensile strength, resilience modulus, ductility and yield strength could be

5   calculated from the data collected.   However, in this study only Young's modulus

6   was calculated due to the slippage of the specimen.

7   The stress σ (N/m^2) was used to express the strength of the stem section tested

8   under tension or compression and was calculated using the formula σ = F/A, where

9   F is the applied tensile force (N) and A is the sample's cross-sectional area (m^2). As

10   the plant section is loaded under tension, it stretches and is supposed to become

11   thinner; however, the change in diameter was neglected and the initial value of A

12   was only considered.

13   The strain ☐ (m/m) was calculated using the formula: ☐ = ΔL / L, where L (m) is the

14   plant sample's initial length and ΔL (m) is the change in the length (amount of

15   elongation) of the plant sample. When a plant sample is subjected to tension, it will

16   first exhibit some temporary elongation within the elastic region then it will exhibit

17   plastic deformation after which if the sample is pulled far enough it will break into two

18   pieces. The maximum load that the sample can sustain is referred to as tensile

19   strength. The stiffness of the material under tension or compression is described

20   using Young's modulus (E$_t$ or E$_c$) (N/m^2) which is calculated from the slope of the

21   linear portion of the stress vs. strain graph (E= σ/☐). Young's Modulus.

22   **2-4-2 Compression Buckling Test**

23   Buckling tests help in explaining the failure of stems and determining the largest

24   length a stem can attain and support (Frese and Blass, 2014). When an object is

25   subjected to compression forces, it compresses until a point where the object

26   suddenly buckles. At that point, the applied force is called the critical force (F$_{crit}$).

27   Euler equation ($Fcrit = 4(\pi^2\,EI)/L^2$), where **E** is the Young's Modulus and the **I** is

28   the area moment of inertia, and L is the object length describes the relationship

29   between the F$_{crit}$ and the geometry of the object. The area moment of inertia (I) was

30   calculated using the formula ($I_{rod} = 1/4\pi r^2$), where (r) is the radius. The buckling

31   test (Fig. 7) was carried out as follows: the sample was first mounted in the machine.

32   The crank was turned out slowly counter clockwise until the beam buckles. The data

1   were recorded and the force (F, N) vs. deflection (ΔX, mm) graph was constructed.

2   The slope (F/ΔX) was calculated from the linear portion of the graph. Young's

3   modulus was calculated from the formula $(E = L * (Slope)/A)$.

2-5 Deflection Angle

5   When a tree stem is subjected to a wind force, it bends with an angle called the

6   deflection angle (α). The deflection angle represents the flexibility of the whole stem.

7   It shows the bending capability of the stem section. Traditionally, the deflection angle

8   is measured using the cantilever or two-point bending test using G-clamp to fix stem

9   cuttings from one side and applying a known force from the free end (Shah et al.,

10 2017, Hossein and Jacob, 2015, Caliaro et al., 2013, Moulia et al., 1994). However;

11 in this study, the deflection angle was measured in field using flex sensors

12 (Sparkfun.com) applied on intact living whole stem (Fig. 8).

13 The Flex sensor is basically a tape shaped flexible resistor that varies with

14 deflection. On one side, it is coated with little conductive particles. When the sensor

15 is flat the conductive particles are close together with a total resistance of 30

16 kiloohms (fig. 9). The conductive particles are stretched apart when the sensor is

17 deflected causing it to be less conductive, thus higher on resistance. The resistance

18 was measured to be around 70 kiloohms at 90 degrees angle.

19 Three sensors connected to an Arduino Uno board were placed along the stem

20 (L=~1.2m, $D_{nursery}$=9.34mm D_{field}=8.14mm) at three different positions: the base, the

21 middle, and the end (fig. 10). Known masses ranging from 100 to 4000 grams were

22 hanged sequentially from the smallest to the largest from the tip of the stems causing

23 them to bend.

24 The flex sensors detected the deflections in the tested plant part when subjected to a

25 bending force and the Arduino board interpreted the change in resistance of the flex

26 sensors into a change in voltage signals. The signals were sent to the laptop though

27 serial communication and shown as angles in degrees.

2-6 Mathematical Modeling of the stem behavior

29 The Acacia branches were observed to bend as the weights hanged sequentially at

30 their tips increase in magnitude. To find out the mathematical equation and the graph

31 representing the branch movement when it bends due to winds or other loads, the

32 branches were first subjected to sequential weights and the height in meters of the

33 branch tip above the ground was measured. Estimating the mass that would cause

1   the branch tip to reach or to touch the ground was not always a possible task as the

2   branch length in many cases were not enough to reach the ground and in other

3   cases it was broken before it could touch the ground. Moreover, generating the

4   equation and the graph representing this kind of movements require enormous

5   amount of data to ensure the accuracy and guarantee that the equation would give

6   real solutions. However, considering the nature of the problem, we assumed that the

7   equation would follow a polynomial function of n degree:

$$f(x) = a_n x^n + a_{n-1} x^{n-1} + \cdots + a_2 x^2 + a_1 x + a_0$$

8   Where X represents the weights hanged from the tip and F(x) represents the height

9   of the branch's tip from the ground.

10 The equation might also be represented by a power function following the general

11 formula:

$$H = a - bc^{nm}$$

12

13 where H is the plant height at a given weight and a is the maximum plant height; the

14 coefficient (b) and the base of the power (c) might take any real positive number; m

15 represents the mass hanged at the tip; the coefficient (n) is a positive fraction

16 (between 0 and 1).

17 In this study, image processing technique (IPT) was used to mathematically describe

18 the actual bending movement of the tree. The continuous bending movement of

19 *Acacia* resulting from wind forces was simulated by tying a rope to the tip of *Acacia*

20 branch under study and then stretching the rope using known forces.

21 The movement of *Acacia* was tracked and videotaped. Python + Opencv were used

22 to plot the branch motion versus time diagrams and therefore to describe the

23 maximum forces the branch can tolerate. To do so, the plant part being investigated

24 (branch) was covered with red tape and videotaped while subjected to a force

25 causing it to bend (fig. 11).

26 The video was then filtered and processed using special image processing software

27 to highlight the bending branch. The color was converted to HSV color, and a red

28 color   filter   was   applied   using   the   site

29 (https://solarianprogrammer.com/2015/05/08/detect-red-circles-image-using-

1   opencv/). After that binary image was produced, the red pix was changed to white

2   pix and the rest of pixs changed to black. Then binary erosion and dilation functions

3   were used to remove the small noise. The bending movement of the branch was

4   then linearized and described mathematically using the site (https://scikit-

5   learn.org/stable/auto_examples/linear_modal/plot_ols.html).

6   **2-7 Statistical Analysis**

7   T-test was performed with Excel to test if there are any statistically significant

8   differences between the mean values of Young's and flexural moduli between the

9   field *Acacia* and the nursery *Acacia*.

10 **3- Results**

11 **3-1 Bending Test**

12 For each stem section, the length and the diameter at the midpoint and at both ends

13 were measured then the area moment of inertia (I, m^4) was calculated (table 1). The

14 data show that the specimens had approximately equal length with varied diameters.

15 Figures 12, 13 show the force (F, N) vs. deflection (ΔX, mm) for some of the

16 naturally grown and nursery grown *Acacia* samples subjected to bending. The slope

17 of the linear portion ($F/\Delta X$) represents the stiffness. The curves also show the critical

18 force (F_{crit}) after which the sample breaks.

19 Table 2 shows the calculations for the flexural modulus for some of the samples in

20 the two Acacia groups.

21 The average value of E_b for nursery *Acacia* was (49.88 ± 3.03, n=20) while the

22 average E_b value for field *Acacia* was (575.46 ± 3.54, n=20). Since the value of the

23 calculated t_{stat} (t=2.78) is higher than the tabulated value (t=2.13) at (P=0.05), we

24 accept the hypothesis that states that there are statistically significant differences in

25 the E_b values for field and nursery *Acacia*. The results revealed that field *Acacia* had

26 a significantly higher value for flexural modulus than the nursery *Acacia* (table 2)

27 indicating that the field *Acacia* is the most flexible among the two groups even

28 though it has the smallest area moment of inertia due to the small stem diameter

29 (table 1).

30 **3-2 Axial tests: tension and compression tests**

1   The force (F, N) vs. deflection (ΔX, m) was constructed (fig. 14). The slope (F/ ΔX)

2   was calculated from the linear portion of the graph and was found to be 543000 N/m.

3   The stress vs. strain graphs for the tested plant materials followed the general shape

4   of a typical stress / strain graph starting with a linear portion then the slope gradually

5   decreases until it flattens followed by breakage at the maximum tensile strength.

6   Young's modulus was calculated from the linear part of the stress vs. strain graph. At

7   high tensile forces by the end of the test, the stem segments slipped from the clamps

8   and no breakage occurred. Therefore, only Young's modulus could be calculated

9   from the slope of the linear portion of the graph before breakage and even slipping.

10 The average Young's modulus for field *Acacia* was found to be (617.75 ± 67.71)

11 MPa while for nursery *Acacia* (191.25 ± 16.37) MPa. The results show a statistically

12 significant difference between the two values (n=16, t_{tab}=2.14, It_{calc}I=15.37, d.f=14,

13 P=0.05). The breaking force, breaking stress, breaking strain, and the work of

14 fracture couldn't be obtained for both groups (field and nursery) because at high

15 forces the plant samples slipped from the clamps.

16 All Acacia stem samples buckle when compressed. The force (F, N) vs. deflection

17 (m) were constructed, the slope of the linear portion (F/ΔX) was calculated and the

18 critical force (F_{crit}) was determined (Fig. 15). Young's modulus of elasticity in

19 compression (E_c) was calculated.

20 The results show that field Acacia had a significantly higher value for Young's

21 modulus under compression (E_c=84.13 ± 7.77) Kpa than the nursery acacia

22 (E_c=17.75 ± 2.12) Kpa, (n=16, t_{tab}=2.14, t_{calc}=32.3, d.f=14, P=0.05) (table 3).

23 **3-3 Deflection Angle**

24 The results (table, 4) show that the maximum deflection (bending) angle of *Acacia*

25 grown in field is approximately 50◦ (fig. 16) and is greater than that of *Acacia* grown

26 in nursery. Therefore, it was concluded that the field Acacia is more elastic than the

27 nursery Acacia as the higher the angle, the higher the elasticity.

28 **3-4 Mathematical modeling of the stem's movement during bending**

29 (0.1-4) masses kg were hanged from the tip of the branch and its height from the

30 ground was measured (table 5).

31 Applying the regression analysis using the software (http://www.xuru.org/rt/), it was

32 revealed that the data follow the binomial equation:

$$y = (2.84)(10^{-2})(x^2) - (3.23)(10^{-1})(x) + 1.03$$

1   Residual Sum of Squares: rss = $(6.11)(10^{-2})$,

2   Coefficient of Determination: R^2 = $(9.21)(10^{-1})$,

3   Where y is the branch tip height above the ground. However, there are no real
4   solutions for this equation at (y = 0) making the above equation not useful in finding
5   the force that can cause the branch tip to touch the ground. Moreover, the limited
6   number of data makes the probability of errors high. Therefore, we decided to use
7   image processing techniques to get a more accurate equation based on the
8   observation that when the *Acacia* branch is subjected to a bending force, it moves in
9   a parabolic fashion. To mathematically represent this movement in space with time,
10   the stem was divided into 745 successive points each has its own spatial
11   coordinates based on a given reference system (fig. 17). As time passes with the
12   movement of the stem, the coordinates of the successive points change yielding an
13   overall parabolic diagram. Image processing technique (IPT) was used to determine
14   the initial and the final position for each of the points. Then the change in position
15   with time taken frame by frame was converted into a change in position expressed
16   through mathematical parameters (table 6) using the site (https://scikit-
17   learn.org/stable/auto_examples/linear_modal/plot_ols.html) (Pedregosa *et al.*, 2011).

18   In table 6, the slope, the Y-intercept, the r value, the P value, and the standard
19   deviation describe the linear equations of the lines connecting the initial and the final
20   positions of the 745 points. Knowing the equations of the lines joining the initial and
21   the final positions due to a certain force can help determining the polynomial or the
22   parabolic equation for the stem branch in its initial rest state and its final state as a
23   function of force; thus, enable making predictions about the movement due to a
24   variable force causing bending.

25   Using the abovementioned software, it was shown that the data follow the equation:

$$H = (4001 - e^{0.06m})$$

26   Where H is the height of the plant tip above the ground and m is the mass of the load
27   in Kg (fig. 18).

13

4- Discussion:

Knowing the biomechanical properties of *Acacia* enables the prediction of their growth success and failure under particular weather conditions. Searching the open literature revealed that there no studies related to plants biomechanics in Qatar. This topic, plants biomechanics has never been addressed before in this region. In the current research, the mechano-morphological properties of two acacia groups naturally grown in field and nursery grown were investigated and analyzed for the first time. The plant – habitat interaction was investigated in this study to determine the way in which *Acacia tortilis* responds mechanically in controlled (nursery) and dry (field) environments. All measurements and calculations based on Young's modulus of elasticity and flexural modulus were taken on stems at a nearly equal diameters in order to reduce any effects of size on the values of the measured biomechanical properties.

The study was divided into 3 parts:

1- Using mechanical instruments to find out Young's and Flexural moduli:

Using three-point bending test and axial tests, it was found that naturally grown *Acacia* in fields have better mechanical properties than nursery grown ones. This explains the local wide spread of *Acacia* and their ability to resist harsh environmental conditions such as rain beating and strong winds where nursery grown *Acacia* failed to do.   It seems that growing *Acacia* under special conditions in nursery in abundance of nutrients and water, would increase the plant's biomass, resulting in increase in the number or size of the parenchyma storing cells. Those cells have primary thin cell walls and therefore less amount of the mechanically outstanding polymer "cellulose". On the other hand, naturally grown *Acacia* in poor soil with limited amount of water results in the reduction in the size and / or the number of the mechanically weak parenchyma cells. This gives more space for sclerenchyma and collenchyma cells to grow. These cells have thicker cell walls with more amount of cellulose, hemicellulose, lignin, and pectin. Moreover, field *Acacia* has developed stronger hard wood due to well-developed xylem vessels. However, to verify this result, cross sections in field and nursery *Acacia* must be prepared and compared.

14

Acacia grown in nursery with high soil nutrients and good irrigation tend to have less dense stem compared to *Acacia* grown in field in dry and low nutrient soil. The density is correlated with the biomechanical properties of the stem. We recommend measuring the density as the shrub's density gives an indication for the cellulose and hemicellulose fibers content in the cell. The bark in *Acacia* stems has low strength and removing it would not affect the overall biomechanical behavior of *Acacia* (Fig. 19).

Among the biomechanical features that make a shrub competent in its environment are Young's Modulus of Elasticity that describes the overall bending properties of a stem despite of the size and shape. Our values for flexural modulus generally match the results of other studies investigating the biomechanical properties of *Acacia* or a similar shrub including the study of Nakai T. (1985), Rokeya *et al.* (2010), Hossein and Jacob (2015), and the wood database (https://www.wood-database.com/koa/). However, our value for Young's Modulus of Elasticity is less than the reported values in the above studies. This can be partially explained by the conditions of the test e.g. how moist or fresh was the stem at the time of testing or to the differences in the accuracy of the different machines and instruments used. Shah *et al.* (2017) in their review about the theory and experiments used in studying plants strength thoroughly discussed the pros and cons of each of the mechanical tests and the proper conditions for each test. It was also noted that the flexural modulus and the Young's modulus have different values for all the studied samples. While axial forces result in either compressive or tensile stresses, bend testing produces both tensile and compressive stresses.

2- Using electronic sensors to find out the angle of deflection:

Stem angle of deflection is an indicator for the bending capability of the whole stem and for stem's sections. Traditionally, deflection angles are measured in the lab using cantilever bending test by fixing the stem cutting to the bench using G-clamp and tying loads to the free end; however, in this study the deflection angles were measured in field using flex sensors.

The results showed that naturally grown field *Acacia* have larger deflection angles than the nursery grown ones. Having large deflection angles implies that the field *Acacia tortilis* can withstand strong winds and loads by bending without being

broken. However, the nursery *Acacia* with their low deflection angles are more susceptible to breakage under strong winds.

The whole stem flexibility was calculated as a ratio between the deflection angle and the weight applied. The results show that field *Acacia* has higher value than nursery *Acacia* and this must to a certain extent reflect the survival value of both shrubs.

3- Using image processing techniques to mathematically describe the motion of the Acacia stem when bending.

It was shown how image processing technique along with python and opencv can be used to describe the movement of the bending stem as a displacement time function. The stem was divided into successive points, and when it bends the position in space of these points change. The equations of the lines connecting the initial and final positions of these points were described using the slope, the Y-intercept, the r- and the P values.

This work can be extended to make predictions about the behavior of the *Acacia* stem under any variable forces causing bending. Predicting the bending behavior of *Acacia*, can help in planting it in a manner that makes it less suffer from beating rains and strong winds.

Acacia tortilis grown in arid wild conditions develop many thin stems, each bear thinner branches with reduced size but densely arranged leaves. The height of *Acacia* reaches 160cm with about 7cm diameter. The thin *Acacia* branches intermingle with each other forming a web like structure. This plant configuration enables it to withstand strong wind speeds as it reduces the pressure created by axial and orthogonal forces (stresses) acting on it by increasing the overall surface area. The plant network configuration makes the thin branches connected to each other via hinge (pivot) or node like connections, so if any of the branches is dragged or pulled, other branches will be pulled too. This way of pressure transmission and distribution over a wide plant surface area reduces the stress yielded by wind, sand, beating rain, snow and confers the plant structure more elasticity under bending, tension and compression conditions. However, for this to be achieved *Acacia* must possess high level of flexibility and elasticity.

The biomechanical properties of *Acacia* shoots enable it to reconfigure and adapt to the harsh sandy winds and rainy storms. Therefore, when *Acacia* plants are planted

16

1   or trimmed much attention must be paid to their biomechanical properties otherwise

2   failure would be unavoidable. The overall surface area and the number of main

3   stems bearing the overall plant's weight determine the plant's success or failure.

4   Hence, the proper growth and distribution of *Acacia* would make them potent wind

5   breaks and confer them economic importance.

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8   ***math part in this study.***

References

Alvarez-Clare S, Kitajima K. 2007. Physical defence traits enhance seedling survival of neotropical tree species. Functional Ecology 21: 1044– 1054.

Asner, G., & Goldstein, G. (1997). Correlating Stem Biomechanical Properties of Hawaiian Canopy Trees with Hurricane Wind Damage. Biotropica, 29(2), 145-150. Retrieved on Dec 20, 2018 from http://www.jstor.org/stable/2389029

Caliaro, M., Schmich, F., Speck, T., and Speck, O. (2013). Effect of drought stress on bending stiffness in petioles of Caladium bicolor (Araceae). American Journal of Botany, 100(11):2141–2148.

Frese, M. and Blass, H. (2014). Naturally Grown Round Wood – Ideas for an Engineering Design. In Materials and Joints in Timber Structures, pages 77–88. Springer Netherlands, Dordrecht.

Gibson L. (2012) The hierarchical structure and mechanics of plant materials. Journal of The Royal Society Interfacehttp://doi.org/10.1098/rsif.2012.0341

Hale, S., Gardiner, B., Wellpott, A., Nicoll, B., and Achim, A. (2012). Wind loading of trees: influence of tree size and competition. European Journal of Forest Research, 131:203–217.

Hossein, M. and Jacob, E. (2015) Bio-Mechanical Investigation on the Physical Resilience of Selected Dominating Shrubs in Semi-Arid Region of Dodoma. Journal of Biosciences and Medicines, 3, 136-142. http://dx.doi.org/10.4236/jbm.2015.311018 [accessed Dec 24 2018].

Leblicq, T., Vanmaercke, S., Ramon, H., and Saeys, W. (2015). Mechanical analysis of the bending behaviour of plant stems. Biosystems Engineering, 129:87–99.

Miler O, Albayrak I, Nikora V, O'Hare M (2011) Biomechanical properties of aquatic plants and their effects on plant-flow interactions in streams and rivers. Aquat Sci. doi: 10.1007/s00027-011-0188-5

Moulia, B., Fournier, M., and Guitard, D. (1994). Mechanics and form of the maize leaf: in vivo qualification of flexural behaviour. Journal of Materials Science, 29(9):2359–2366.

Nakai T. (1985). Mechanical properties of Tropical Woods . JARQ Vol. 18, No. 4.

Niklas, K.J. (1992) Plant Biomechanics. An Engineering Approach to Plant Form and Function. University of Chicago Press, Chicago.

Pedregosa et al. (2011). Scikit-learn: Machine Learning in Python. JMLR 12, pp. 2825-2830.

Raines, C. et.al. (2013). Special Issue: Plant Biomechanics and Mechanobiology. Journal of
Experimental Botany, 64:4617–4827.

Robertson, D., Smith, S., and Cook, D. (2015). On measuring the bending strength of septate
grass stems. American Journal of Botany, 102(1):5–11.

Rokeya U., Hossein M., Aki M., and Paul P. (2010). PHYSICAL AND MECHANICAL PROPERTIES OF (ACACIA AURICULIFORMIS × A. MANGIUM) HYBRID ACACIA. Journal of Bangladesh Academy of Sciences, Vol. 34, No. 2, 181-187.

Shah, Darshil & Reynolds, Thomas & Ramage, Michael. (2017). The strength of plants: theory and experimental methods to measure the mechanical properties of stems. Journal of Experimental Botany. 68. 10.1093/jxb/erx245.

2

TABLES

Nursery Samples						
Material Sample	D1, mm	D2, mm	D3, mm	Average D, mm	R, mm	L, m	I, m^4 ($X10^{-12}$)
1	15.08	14.82	14.91	14.94	7.47	0.095	2444.28
2	11.61	10.36	10.72	10.89	5.45	0.093	692.56
3	14.65	13.92	14.43	14.33	7.17	0.097	2074.66
4	9.77	9.01	9.23	9.34	4.67	0.094	373.37
5	13.79	13.50	13.70	13.66	6.83	0.095	1708
Field Samples						
1	8.00	8.32	8.11	8.14	4.07	0.095	215.4
2	6.74	6.72	6.56	6.67	3.33	0.095	96.52
3	6.08	5.14	6.25	5.82	2.91	0.120	56.29
4	7.85	9.02	9.40	8.75	4.38	0.096	288.00
5	6.62	6.42	6.71	6.58	3.29	0.097	91.97

Table 1. Length and diameter measurements of the studied stem samples.

Three – Point Bending Test: Nursery Samples					
Material sample	L, m	L^3, m^3 (X 10^{-4})	I, m^4 (X10^{-12})	F / ΔX, (N/m)	E_b, MN/m^2
1	0.095	8.57	2444.28	2000	14.60
2	0.093	8.04	692.56	1820	44.02
3	0.097	9.13	2074.66	8700	79.76
4	0.094	8.30	373.37	2000	92.62
5	0.095	8.84	1708	1710	18.44
Three – Point Bending Test: Field Samples					
1	0.095	8.57	215.4	4500	372.99
2	0.095	8.57	96.52	2000	369.96
3	0.120	1.72	56.29	1820	1158.50
4	0.096	8.84	288.00	2000	127.89
5	0.097	9.13	91.97	4100	847.94

Table 2. Flexural modulus values for some of the field and nursery grown Acacia specimens.

Biomechanical Parameter	Unit	Mean	
		Nursery Acacia	Field Acacia
Mean Radius	mm	6.32	3.59
Mean C.S. Area	mm^2	125.41	40.46
Young's Modulus (E_t)	MN / m^2	191.25 ± 16.37	617.75 ± 67.71
Young's Modulus (E_c)	KPa	17.75 ± 2.12	84.13 ± 7.77
Breaking force (F_{crit})	N	210	550
Flexural Modulus (E_b)	MN / m^2	49.88 ± 3.03	575.46 ± 3.54
Area Moment of Inertia	m^4	1458.58	149.64
Flexural rigidity (E_bI)	MNm^2	72753.97	86111.24

Table 3. Mean ± S.D. values of the biomechanical properties of the studied field and nursery Acacia groups (n=20).

Mass, g	F, N	Deflection Angle (Field)	Ratio (Force/Angle)	Deflection Angle (nursery)	Ratio (Force/Angle)
100	0.98	7	0.14	8	0.12
500	4.9	15	0.37	18	0.27
1500	14.7	22	0.67	28	0.53
2000	19.6	28	0.70	32	0.61
2500	24.5	37	0.66	38	0.64
3000	29.4	43	0.68	breakage	
4000	39.2	50	0.78		

Table 4. Whole stem flexibility values (force / deflection angle) for field and nursery Acacia.

Mass, Kg	Force, N	Branch tip height above the ground, m
0	0	1.2
0.1	0.98	0.91
0.5	4.9	0.73
1.5	14.7	0.66
2	19.6	0.52
2.5	24.5	0.4
3	29.4	0.32
4	39.2	0.18

Table 5. Change in the branch tip height from the ground in response to the hanged masses.

Point No.	slope	intercept	r-value	p-value	stderr
1	4.453618	-1635.6	0.495481	0	0.045093
2	4.589312	-1712.43	0.523913	0	0.043236
3	4.76606	-1798.82	0.554214	0	0.040997
4	4.645092	-1744.36	0.551811	0	0.04082
5	4.750322	-1790.95	0.562888	0	0.040882
6	5.131369	-1985.66	0.618514	0	0.038065
7	4.420355	-1619.58	0.521333	0	0.042286
8	4.396112	-1604.37	0.530569	0	0.040691
9	4.031862	-1416.58	0.488447	0	0.041636
10	4.39763	-1614.49	0.560166	0	0.037358

Table 6. The slope, Y-intercept, r-value, p value and st. dev. for the first 10 points.

Figure legends:

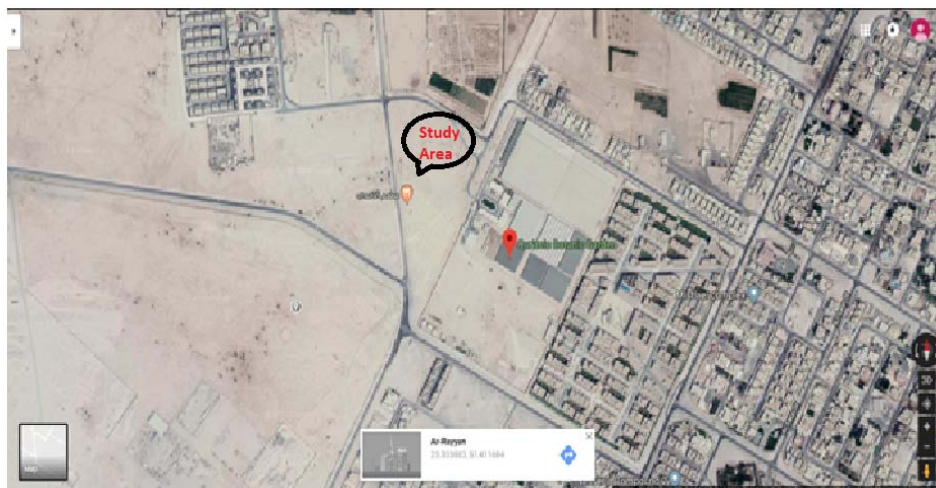| No.	Figure
1.	Figure 1. *Acacia tortilis* shrub in the study area.
2.	Fig. 2. The study area showing the location of samples collection pointed at in red.
3.	Fig. 3. PASCO materials bench top testing machine used in the present study.
4.	Fig. 4. The setup for tension tests.
5.	Fig. 5. The setup for the bending test.
6.	Fig. 6. Setup for tensile tests
7.	Fig. 7 The setup for compression buckling test
8.	Fig. 8 Flexi sensors used in determining the deflection angle.
9.	Fig. 9 The operation of flex sensors.
10.	Fig. 10. Deflection angle measurement setup.
11.	Fig. 11 Acacia branch being studied using IPT (covered in red tape).
12.	Fig. 12 Force (N) vs. deflection (ΔX, mm) for a nursery grown *Acacia totilis*. (S=1.82 N/mm, F_{crit} = 160N).
13.	Fig. 13 Force (N) vs. deflection (ΔX, mm) for a field grown *Acacia totilis* (brown) and a nursery grown one (violet). (Field Acacia: S=2.00 N/mm and F_{crit} = 260N. Nuresry Acacia: S= 1.71 and F_{crit}=210N).
14.	Fig. 14 Force (F, N) vs. deflection (ΔX, m) graph for field Acacia.
15.	Fig. 15 Force (N) vs. deflection (ΔX, mm) for a field grown *Acacia totilis*. (S=2 N/mm, F_{crit} = 550N)
16.	Fig 16. Snapshot of the computer screen showing the output of the Arduino IDE (www.arduino.cc) expressed in deflection angles.
17.	Fig. 17 A snapshot of the video illustrating the results of IPT.
18.	Fig. 18 The graph representing the movement of the stem when subjected to different bending forces.
19.	Fig. 19 Longitudinal se k and the hard wood.

Figure 1. *Acacia tortilis* **shrub in the study area.** (colour online only)

Fig. 2. The study area showing the location of samples collection pointed at in red. (colour online only)
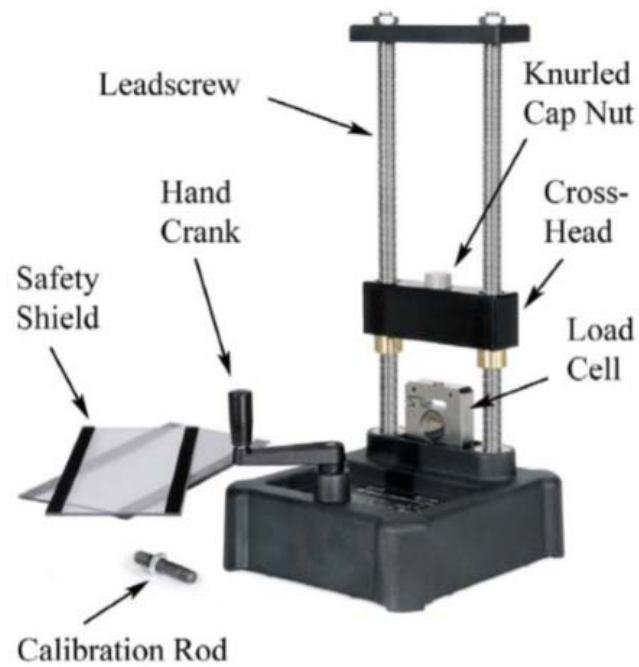
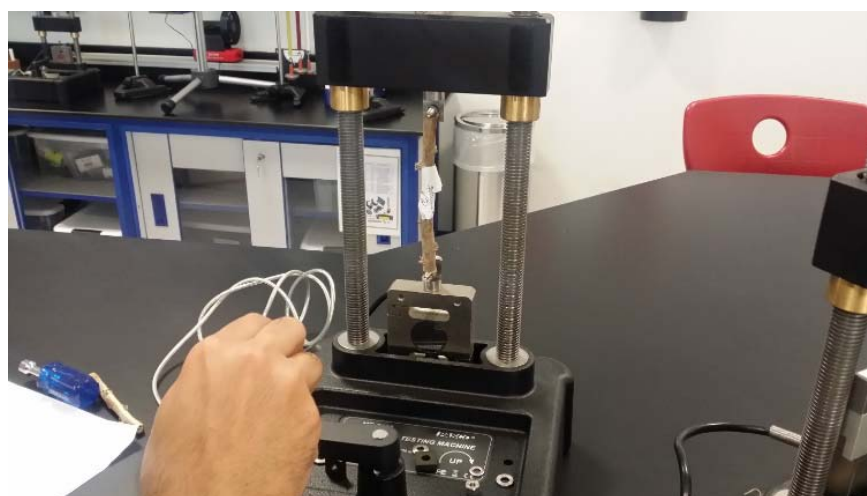**Fig. 3. PASCO materials bench top testing machine used in the present study.**
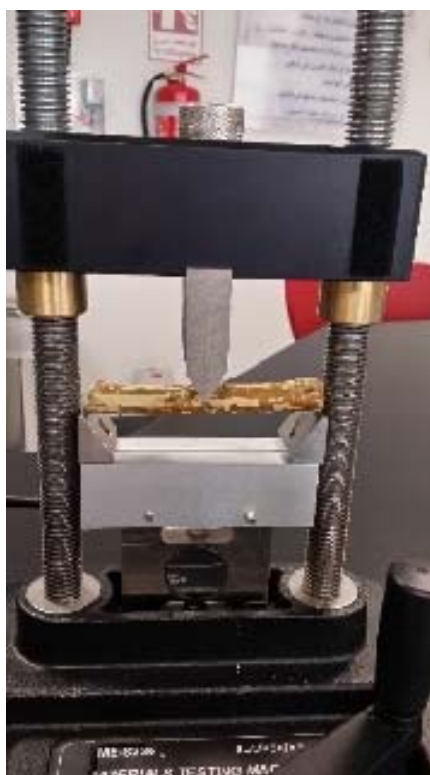
Fig. 4. The setup for tension tests. (colour online only)

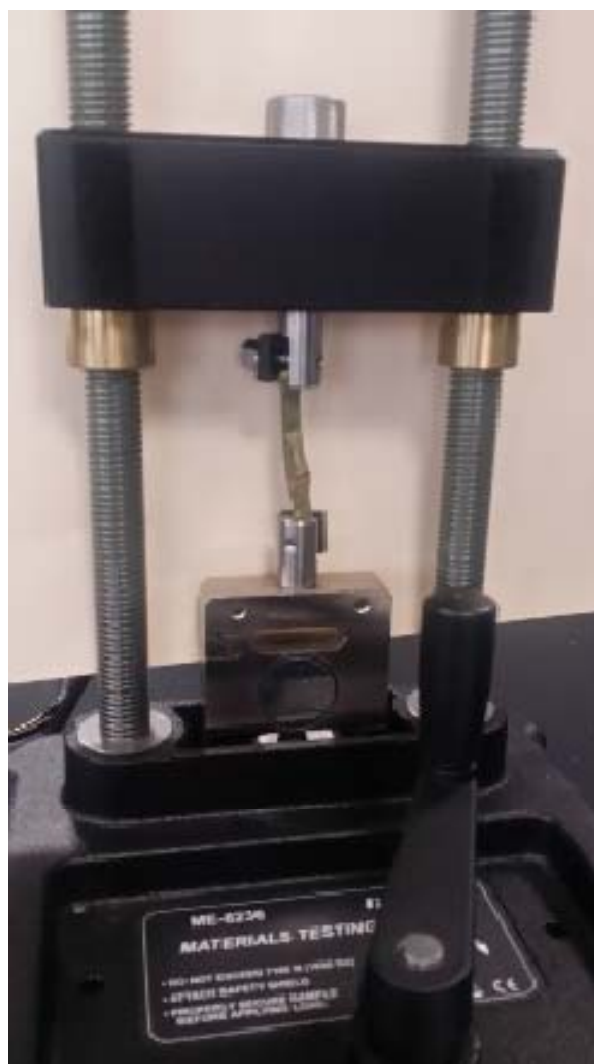**Fig. 5. The setup for the bending test.** (colour online only)

15
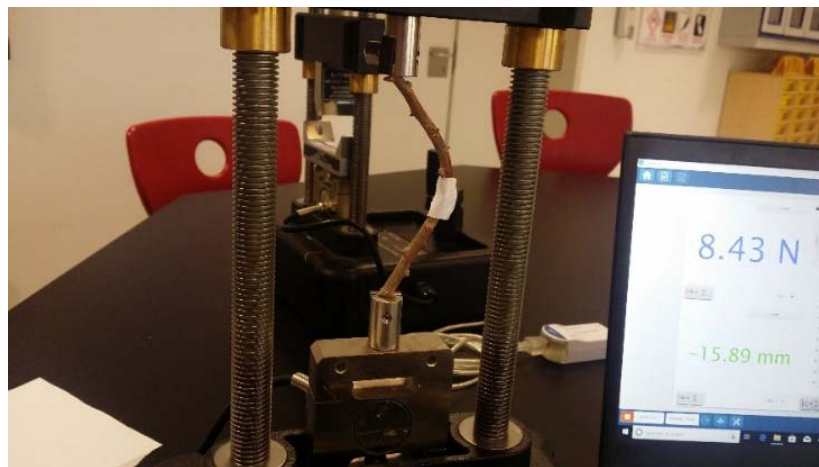
Fig. 6. Setup for tensile tests. (colour online only)

Fig. 7 The setup for compression buckling test. (colour online only)

Fig. 8 Flex sensors used in determining the deflection angle. (colour online only)

Conductive particles close together - 30kΩ.   Conductive particles further apart - 70kΩ.
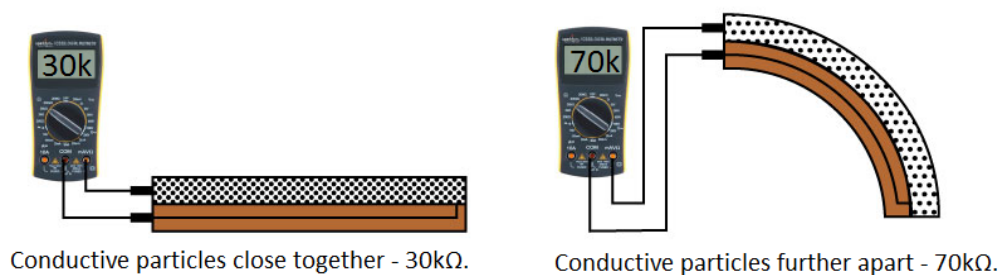
Fig. 9 The operation of flex sensors. (colour online only)

Fig. 10. Deflection angle measurement setup. (colour in print)

Fig. 11 Acacia branch being studied using IPT (covered in red tape). (colour in print)

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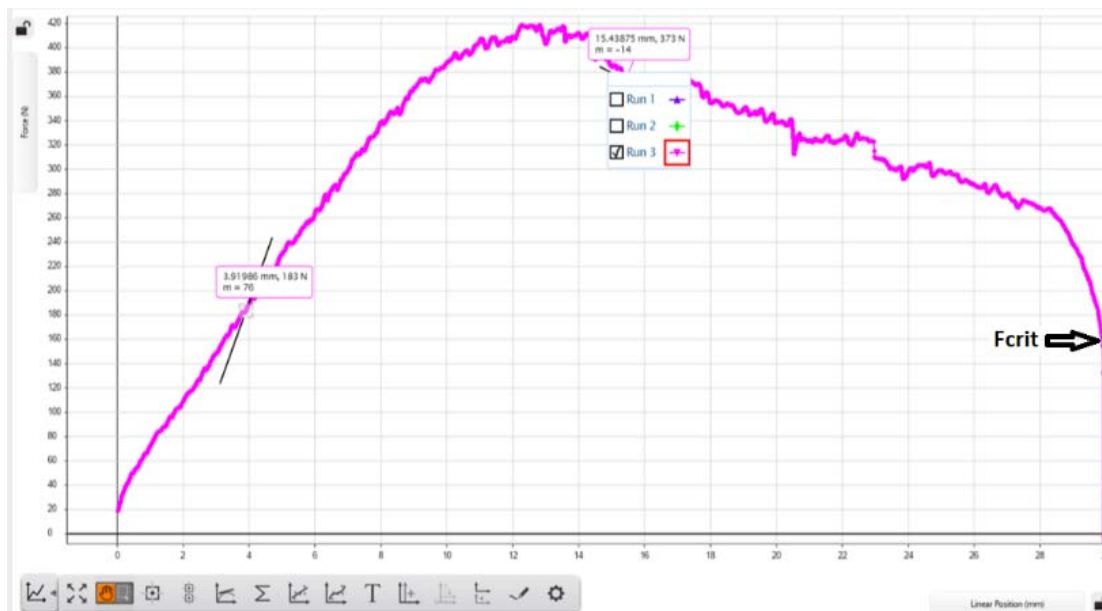
Fig. 12 Force (N) vs. deflection (ΔX, mm) for a nursery grown *Acacia totilis*. (Slope=1.82 N/mm, F_{crit} = 160N**).** (colour online only)

Fig. 13 Force (N) vs. deflection (ΔX, mm) for a field grown *Acacia totilis* (brown) and a nursery grown one (violet). (Field Acacia: S=2.00 N/mm and F_{crit} = 260N. Nuresry Acacia: Slope= 1.71 N/mm and F_{crit}=210N). (colour in print)
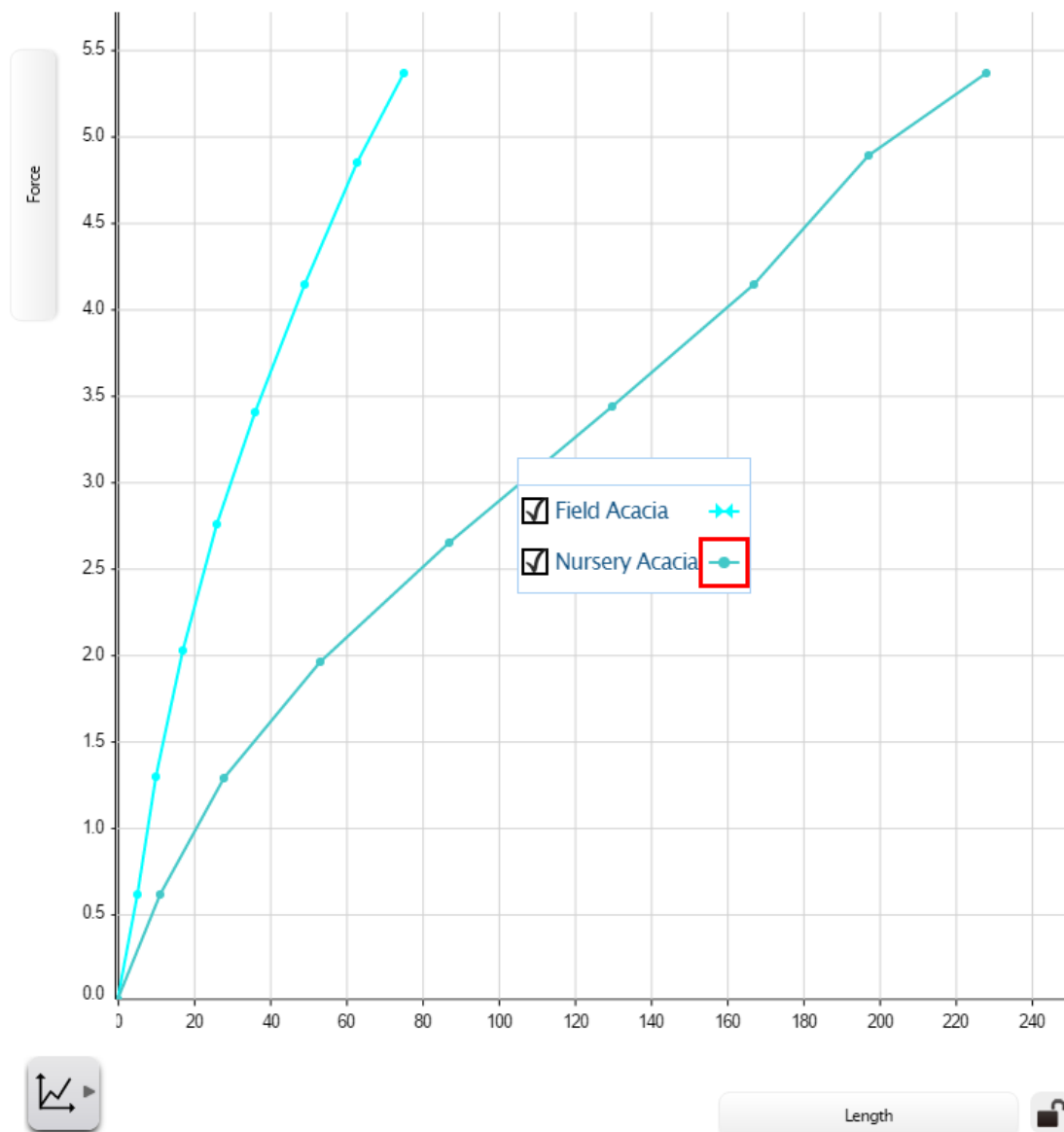
Fig. 14 Force (F, N) vs. deflection (ΔX, m) graph for field and nursery Acacia.
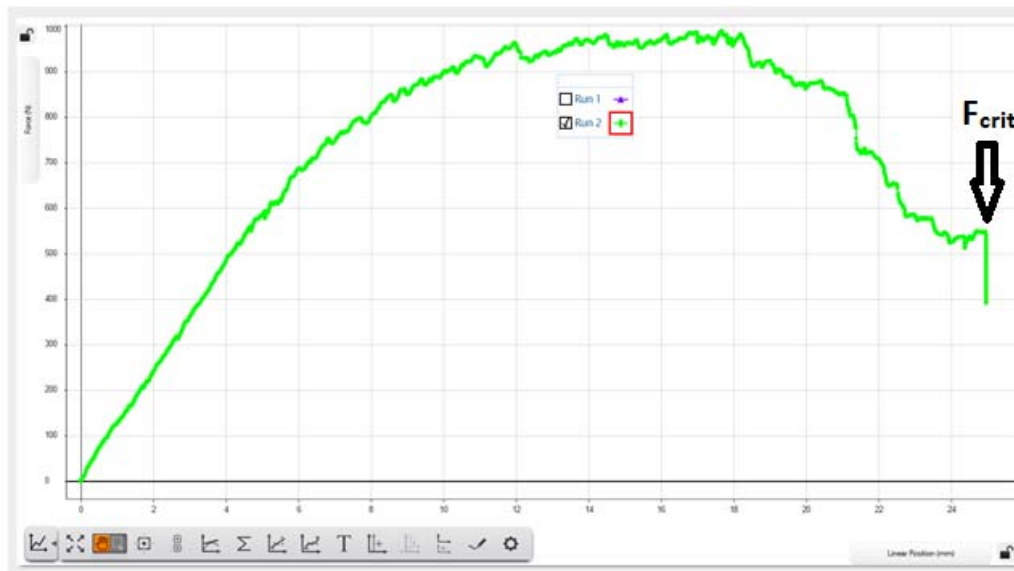
(colour in print)

Fig. 15 Force (N) vs. deflection (ΔX, mm) for a field grown *Acacia totilis*. (S=2 N/mm, F_{crit} = 550N). (colour online only)
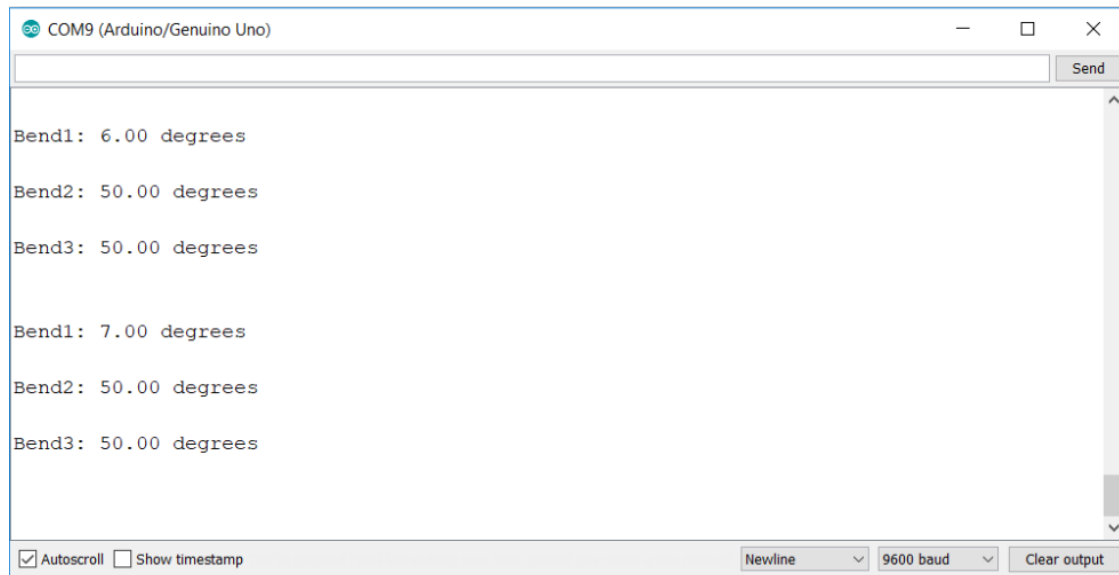
Fig 16. Snapshot of the computer screen showing the output of the Arduino IDE (www.arduino.cc) expressed in deflection angles. (colour online only)

Fig. 17 A snapshot of the video illustrating the results of IPT. The lower right panel shows the branch under study covered in red tip while subjected to a bending force. The right upper panel shows the branch highlighted. The left panels show the branch after the color was converted to HSV and a red filter was applied to produce a binary image. The red pix was changed to white and the rest of pixs were changed to black. To watch the video, follow the link (https://youtu.be/TSjYAzsahTk). (colour in print)
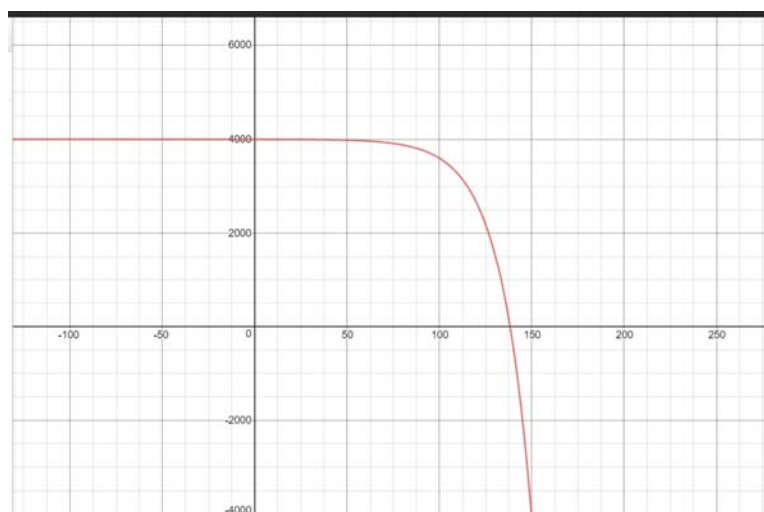
Fig. 18 The graph representing the movement of the stem when subjected to different bending forces. (colour online only)

Fig. 19. Longitudinal section of field Acacia showing the bark and the hard wood. (colour in print)