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DOI: 10.2478/ata-2023-0019

Acta Technologica Agriculturae 3
Nitra, Slovaca Universitas Agriculturae Nitriae, 2023, pp. 142–151

PHYSICO-MECHANICAL PROPERTIES OF SUGARCANE STALKS

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Manual harvesting of sugarcane requires skilled labourers, as improper harvesting leads to a significant loss of yield. Therefore, it is necessary to move towards designing a system capable of harvesting sugarcane on smallholdings, with high harvesting efficiency. This study aims to determine some physico-mechanical properties of sugarcane stalks related to harvester by making a comprehensive analysis of the compressing, bending, and shearing properties of sugarcane stalks. These properties were measured at three moisture content levels at three positions (base, middle, and top) of the stalk with three sugarcane varieties (G.T.54-9, IK 76-66, and HAO3-55-24). The different moisture contents were fresh stalk, after 7 days, and after 15 days. The values of different content with different varieties were (70.3, 42.1, and 23.2%), (68.7, 61.3, and 42.7%) and (66.4, 48.6, and 30.5%), respectively. The physico-mechanical properties of stalks were measured in terms of diameter, length, fresh mass, moisture content, sugarcane stalk bulk density, compression stress, shear stress and bending stress at three different positions (top, middle, and base).The most important results showed that the decreasing stalk moisture content of three sugarcane varieties led to an increase in compression, shear, and bending stresses.

Keywords: mass; compression; bending stress; moisture; dimensions; sugarcane

In Egypt, the total sugarcane cultivated area reached nearly 139,587.84 ha. The total sugarcane production for harvest was 15.307×10^6 t (with an average of producing 109 t·ha^{-1}); 85% of which is delivered to sugar mills for sugar production; 4% is used for treacle manufacturing; 2% is kept as seeds, and nearly 9% is consumed fresh as juice. Moreover, the sugarcane production of more than 20 byproducts, among them, alcohols, vinegar, yeasts, potassium sulphate, acetone, paper pulp, fiberboard, wax, and other substances, as well as a filter cake, are added to the soil to increase its fertility (Alonso-Monge et al., 2007), while green and dry leaves are used as forage. Sugar cane factories are 8 mills located in Abou Korkas (El Menia), Gerga (Sohag), Naga Hammadi, Deshna and Qus (Qena), Armant (Luxor), and Edfu and Komombo (Aswan) (Nakhla, 2015).

Sugarcane is often cultivated in small sizes of land holdings, which impedes the use of big mechanical harvesters. Therefore, sugarcane harvesting is done manually using small hand axes between December and April. Manual harvesting requires skilled labourers as an improper harvest of cane leads to the loss of cane and sugar yield. In addition, harvesting labour is becoming scarce and costly in view of the diversion of labour to other remunerative work in industry, construction, business, etc. Day by day, labour wages are increasing and, at the same time, the demands for sugar and byproducts are also increasing (Nikesh et al., 2020). Therefore, it is essential moving towards overcoming hand labour shortage and higher harvesting efficiencies, but to concurrently utilize a system capable of harvesting sugarcane in small areas. One method used to increase harvesting efficiencies is the use of appropriate mechanical cutting machines for Egyptian farms and sugar mill conditions.

Growing sugarcane suffers from a casual labour shortage. Moreover, day by day, labour wages are increasing rapidly (Jain et al., 2013; Nagarjun et al., 2021), especially for planting and harvesting operations. The advent of mechanical harvesting stalks frees harvest labours from the drudgery of field operation. The operation of harvesting one unit area of sugarcane with an average production of 45 t requires 16 labourers (Abd-El Mawla and Hemeida, 2015), but according to Yadav et al. (2002), the harvesting of one hectare of sugarcane requires 3.3–4.2 machine hours by mechanical harvesting, whereas 850–1000 man hours by manual harvesting. The operating costs for mechanical harvesting were $ 53.97 to cut 0.676 ha (Ma et al., 2014). According to Nagarjun et al. (2021), the cost and time of harvesting can be significantly reduced by employing a developed harvester, leading to increased productivity. The rotary leaf cutter mechanism was evaluated using software and a digital solution for harvesting sugar beet. It has been reported that optimizing dynamic system design such as the vibrations of the cutting mechanism in the longitudinal vertical position results in increased harvest quality (Bulgakov et al., 2017). Nikesh et al. (2020) designed and fabricated a small-scale sugarcane harvesting machine for sugarcane harvesting and also for cutting different types of crops to reduce farmers' efforts and to increase the production of agricultural products. Also, Ali et al. (2022) mentioned that machinery design for small-scale

applications depends on the physical, mechanical, and aerodynamic properties of the crop before manufacturing and assessment. Amer et al. (2008) concluded that results obtained from measuring the mechanical properties (average tensile and compressive strength) of sugarcane stalks were (4.38, 9.5, and 11 MPa) with different moisture content (8.1, 15.31, and 24%), respectively.

Taghijarah et al. (2011) showed that loading rate had a significant effect on the shear strength and specific shearing energy of the stalk. With increasing loading rate, shear strength and specific shearing energy increased. In addition, the internode position had a significant effect on specific shearing energy, while it did not have a significant effect on shear strength. The average shear strength was 3.64 MPa, varying from 3.03 to 4.43 MPa. Average specific shearing energy was 51.41 mJ·mm^{-2}, ranging from 37.42 to 64.25 mJ·mm^{-2}.

Manual sugarcane harvesting is a very labour-intensive and labourious activity. Stalk cutting energy requirements were studied by many investigators, such as Amer et al. (2008) and Khazaei et al. (2002). The mentioned studies showed that the design of a sugarcane harvesting machine is related to stalk´s physical properties (such as stalk diameter, dry matter density, and moisture content) and mechanical properties (such as shear, compression, and bending stress). Therefore, this investigation aims to study the physico-mechanical properties of sugarcane stalks that related to the design of cutting machines.

Fig. 2 Sampling internode
Source: Khaire et al., 2021

Material and methods

Experiments were carried out at Sugar Crops Research Institute, Agricultural Research Centre, Ministry of Agriculture, Egypt, to investigate physical properties and to estimate the characteristics of stalks of the sugarcane crop. Experiments were conducted using three sugarcane varieties (G.T.54-9, IK 76-66, and HAO3-55-24).

Determination of physical properties

The present study included the physical properties of stalks (diameter, length, fresh mass, moisture content, and stalk bulk density) in the sugarcane crop grown in Sugar Crops Research Institute – Agricultural Research Centre, Ministry of Agriculture, (longitude 30.02° N and latitude 31.21° E), Giza Governorate, Egypt, during the 2020/2021 season. Moisture content was estimated as a wet base in three positions (top, middle, and base) of the stalk (Figs 1 and 2).

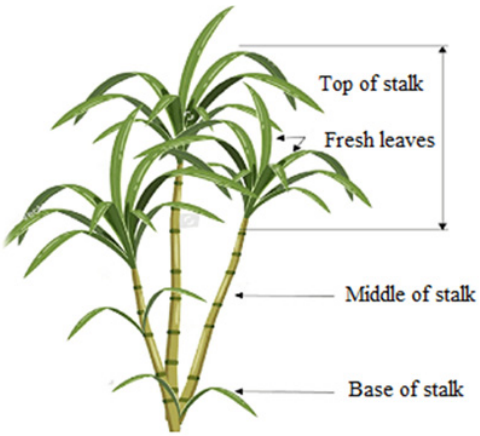

Fig. 1 Sampling positions
Source: Khaire et al., 2021

Measurements and calculations

Sugarcane harvesting was done after twelve-months age from planting. Samples of ten sugarcane stalks were randomly taken for each variety to determine the physical properties of sugarcane stalks:

- Stalk diameter: The diameter of each stalk was measured in its central part of the internode in three postions (top, middle, and base) of the stalk. It was measured using a digital caliper with an accuracy of 0.01 mm.
- Stalk length was measured from the ground level up to the Top Visible Dewlap (TVD), as described by Van Dillewijn (1952).
- Stalk mass/plant was measured by a digital balance (50 kg) with an accuracy of 0.5 g (VOSAREA, China).
- Stalk moisture content: The moisture content of the sugarcane was determined according to ASAE (2008). Samples were placed in an oven (BINDER, Germany) at 70 °C for 72 h; samples were weighed before and after drying. Moisture content wet basis was calculated using Eq. (1):

$$stalk\ moisture\ content\ (\%) = \frac{FM - DM}{FM} \times 100 \quad (1)$$

where: *FM* – fresh mass (g); *DM* – dry mass (g)

Fig. 3 A benchtop materials testing machine

– Internode bulk density: Internode mass (kg) was measured by a digital balance (3 kg) with an accuracy of 0.01 g (VIBRA, Japan) and its volume (m^3) was measured with the water displaced by using a glass measuring cylinder to find the internode bulk density according to Huang et al. (2015), using Eq. (2):

$$IBD = \frac{Im}{Iv} \quad (2)$$

where: *IBD* – internode bulk density ($kg \cdot m^{-3}$); *Im* – internode mass (kg); *Iv* – internode volume (m^3)

Mechanical properties of sugarcane stalk

Determination of forces

Some of the mechanical properties (shearing, bending, and compression forces) of the sugar cane samples were measured at the Agricultural Engineering Department, Faculty of Agriculture, Ain Shams University, Egypt by using "the Benchtop Materials Testing Machine" (Tinius Olsen, model H5Ks, USA, capacity 5 kN with an accuracy of 0.01 N, max. sample diameter 200 mm, load cells with digital encoding for automatic recognition and scaling available, and testing speed 50 $mm \cdot min^{-1}$) (Fig. 3).

Determination of area

The area was determined using two VL53L0X sensors. The sensors can measure distances up to 2 m with a resolution of ±0.1 mm. They can be operated by 5 V connected to Arduino UNO R3 (UNSPSC Code 43201500) with an input voltage of 7–12 V (recommended). Arduino UNO Rev3 (ELEGOO Brand, China) is a microcontroller board based on ATmega328P. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16-MHz ceramic resonator (CSTCE16M0V53-R0), a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller – simply to connect it to a computer with a USB cable, or power it with an AC-to-DC adapter. The Arduino UNO board has 14 digital I/O pins, with a 32 KB flash memory, of which 0.5 KB is used by the bootloader, SRAM 2 KB, 1 KB EEPROM, 16 MHz main processor ATmega328P, length is 68.6 mm, width 53.4 mm, and weight 25 g. The sensor uses a 940-nm infrared emitter, which is invisible to the human eye and eye-safe, meaning that it will not cause any damage to vision (as shown in Fig. 4 a, b, c, d, and e). Distances were measured in two directions of the cane internode, using Eq. (3):

$$A_i = a \times b \quad (3)$$

where: A_i – internode material area (mm); *a* – cane internode length at direction *X* (mm); *b* – cane internode width at direction *Y* (mm)

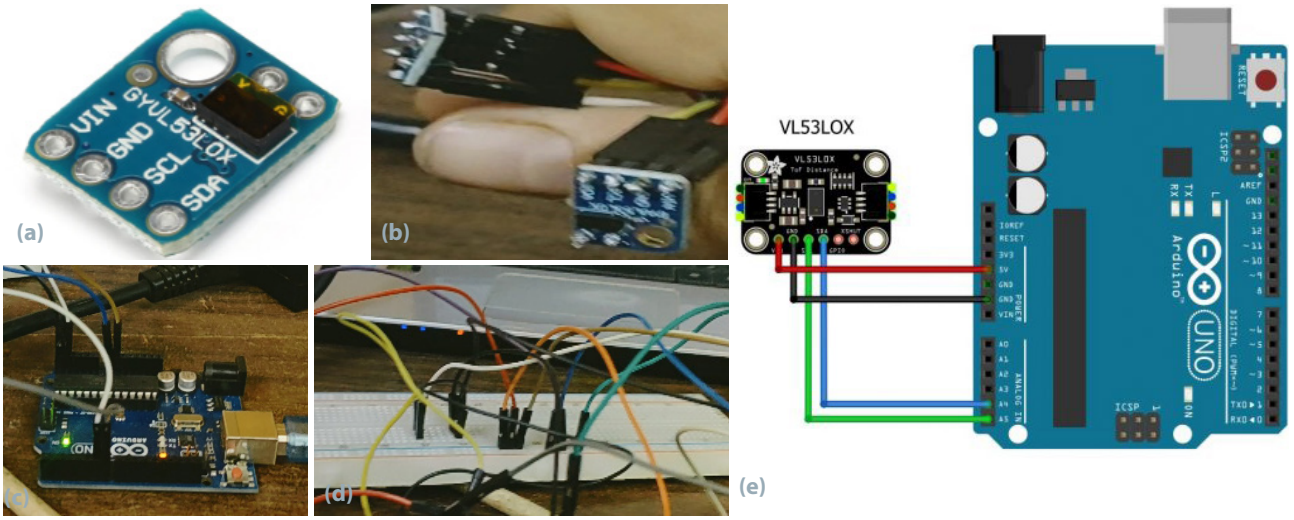

Fig. 4 The VL53L0X sensor and connection with Arduino (a, b, c, d and e)
Source: Latha et al., 2016

Fig. 5 Determination of compression stress by a benchtop materials testing machine

Compression stress

The cane internode was fixed to the driving unit of the testing machine, as shown in Fig. 5.

$$CS = \frac{F}{A} \tag{4}$$

where: CS – compression stress (MPa); F – concentrated load (N); and the cane internode area A – an area of the half rectangle with sides equal to radius r (mm) and pressing length a (mm^2)

Shear stress

The cane internode was fixed to the driving unit of the testing machine (Fig. 6). The shear stress τ of the internode sugarcane stalk can be calculated according to Eq. (5) (Zareiforoush et al., 2010).

$$\tau = \frac{F}{A} \tag{5}$$

where: τ – shear stress (N·mm^{-2}); F – shear force (N); A – the effective shear area (mm^2)

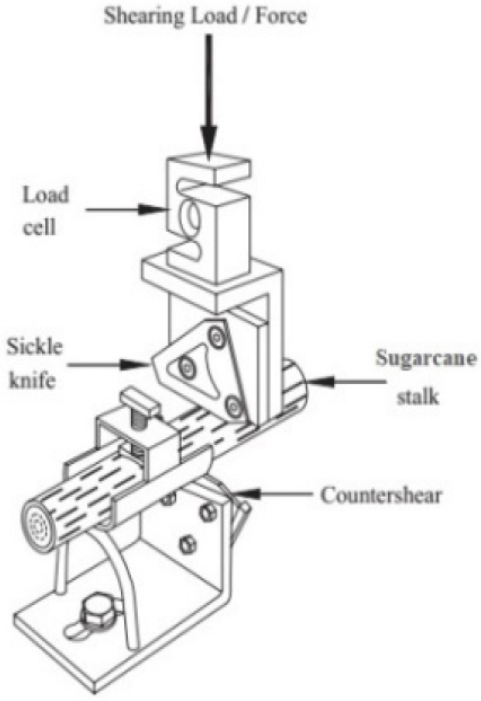

Fig. 6 Determination of shear stress by a benchtop materials testing machine

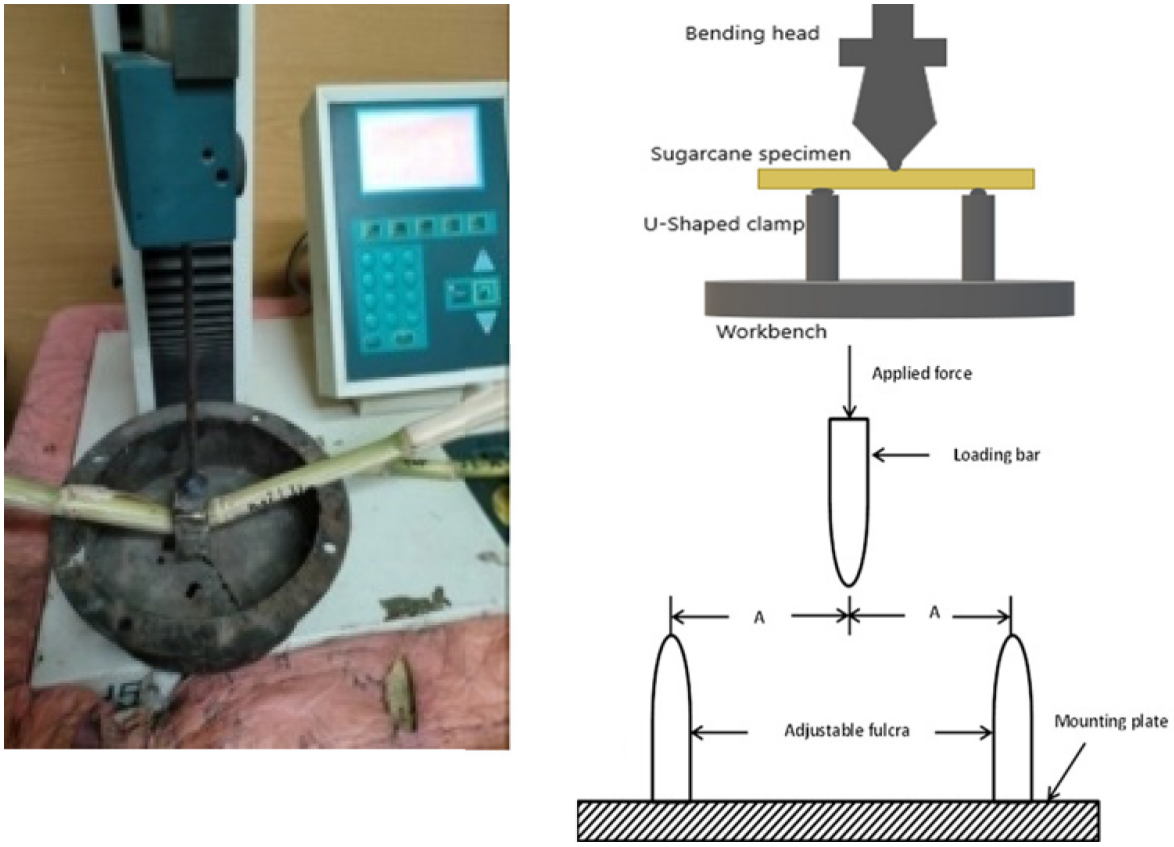

Fig. 7 Determination of bending stress by a benchtop materials testing machine

Bending stress

The cane internode was fixed to the driving unit of the testing machine (Fig. 7). Bending stress σ_b was calculated using the equations as following (Stubbs et al., 2018):

$$D = \frac{F_b L^3}{3EI} \quad (6)$$

$$M_b = F_b L \quad (7)$$

$$\sigma_b = \frac{M_b y}{I} \quad (8)$$

where: D – deflection under load (mm); E – the modulus of elasticity in bending (MPa); I – the moment of inertia of the cross-sectional area (mm^2); F_b – bending force (N); L – the length of the beam between the load and support (mm); σ_b – bending stress (MPa); M_b – bending moment (N·mm); y – the distance of the outermost fiber from the neutral axis (mm)

Statistical analysis

Measurements were carried out in a split-split plot design (design with 3 replicates). Data were subjected to the proper statistical analysis of variance according to Snedecor and Cochran (1980). The significance of difference among means was compared using Least Significant Difference (LSD) test at the 0.05 level of significance.

Results and discussion

Physical properties

The physical properties of stalks in the sugarcane crop included diameter, length, fresh mass, moisture content, and stalk bulk density. Moisture content was estimated by three positions (top, middle, and base) of the stalk (Figs 1 and 2), which were used with three averages of moisture content in the fresh stalk, after 7 days and after 15 days, i.e. (70.3, 42.1, and 23.2%), (68.7, 61.3, and 42.7%) and (66.4, 48.6, and 30.5%), respectively.

Mechanical properties

Compression stress

The testing machine produces a compression force-depth diagram, as shown in Fig. 8.

The sugarcane IK-76-66 variety recorded the highest values of compression for stalk, followed by HAO3-55-24 and then G.T.54-9. This result may be due to a decrease in fiber content (%). The values of compression stress of stalk for varieties G.T.54-9, HAO3-55-24, and IK-76-66 increased by 1.922, 2.136 and 2.311 MPa at the base of stalk and stalk moisture content 60 and 73%, respectively.

On the other hand, the compression stress of the stalk for varieties G.T.54-9, HAO3-55-24, and IK-76-66 increased

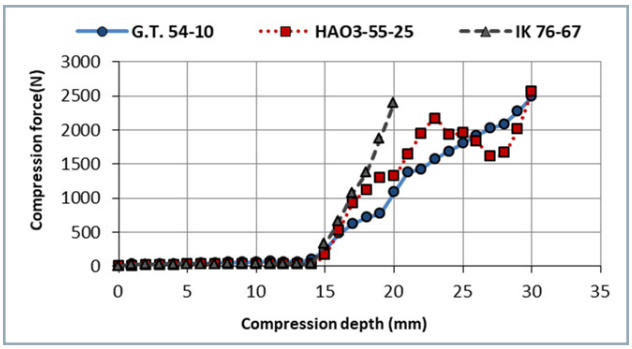

Fig. 8 The force-compression depth diagram of the fresh cane internode at the top, middle, and base of the stalk during the compression process

from the top to the base of the stalk by 10.6, 11.1, and 11.6%, respectively. The observed data indicate that although there was an effect of compressive strength from a 1 mm depth of compression, the onset of the impact of large compressive force on all sugarcane cultivars began to occur at a depth of compression starting from 15 mm. This is due to the higher thickness of the shell and the increased fibre content of sugarcane, which makes it more resistant to compression. Taghijarah et al. (2011) concluded that when using three load rates (5, 10, and 15 mm·min^{-1}) with 10 positions of the sugar cane stalk, the loading rate had a significant effect on the shear strength and specific shear energy of the stalk. As loading rate increased, so did shear strength and specific shear energy.

Table 1 indicates that, according to LSD 0.05, significant differences were observed for the three replicates and all mean values of moisture content and compression stress for all the sugarcane cultivars under study. The highest values of moisture content were in the IK 76-66 variety, and the lowest values were in the G.T.54-9 variety for the top, middle, and base position. There is the same trend between compression stress and moisture content for all the varieties in the top, middle, and base position. On the other hand, there is an inverse relationship between moisture content and compression stress in the top, middle, and base of sugarcane stalks for all the cultivars.

Stalk moisture content decreased from 72.82% to 27.29% at the top of the stalk, from 66.88% to 24.32% in the middle of the stalk, and from 60.73% to 18.1% in the base of the stalk due to an increase in the compression stress of stalk for the varieties G.T.54-9, HAO3-55-24, and IK-76-66, respectively, and this result agrees with Liu et al. (2021) (Figs 9–11).

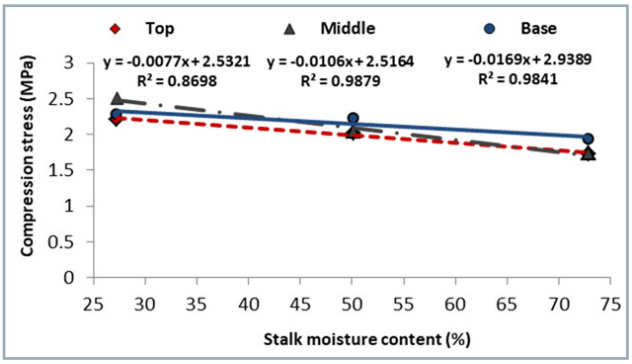

Fig. 9 The effect of stalk moisture content on compression stress in the G.T.54-9 variety

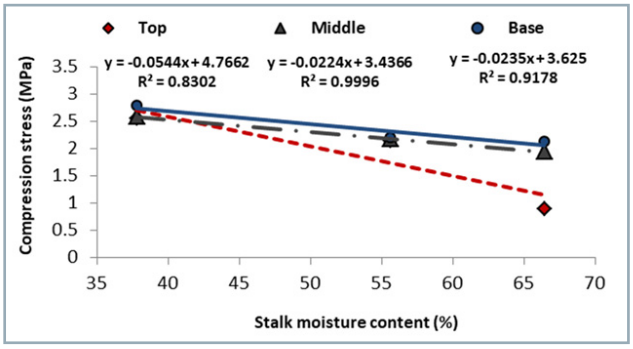

Fig. 10 The effect of stalk moisture content on compression stress in the HAO3-55-24 variety

Table 1 The effect of stalk moisture content and internode position sampling on compression stress of the stalks of sugarcane varieties

Variety	Sample position	Measurements	
		moisture content (%)	compression stress (MPa)
		mean	mean
G.T.54-9	top	50.10	1.98
	middle	45.56	2.10
	base	37.15	2.14
HAO3-55-24	top	53.28	1.87
	middle	49.68	2.24
	base	42.58	2.37
IK 76-66	top	57.38	2.29
	middle	58.52	2.51
	base	56.91	2.54
LSD 0.05		–	0.19

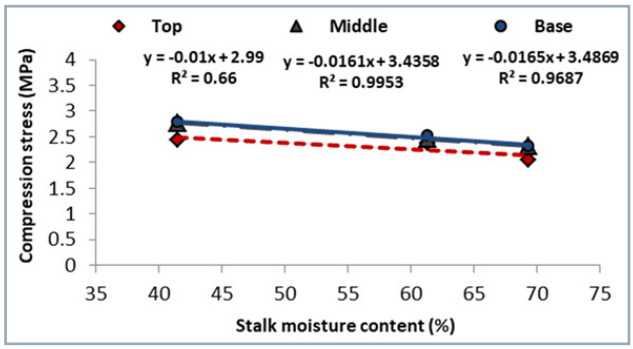

Fig. 11 The effect of stalk moisture content on compression stress in the IK 76-66 variety

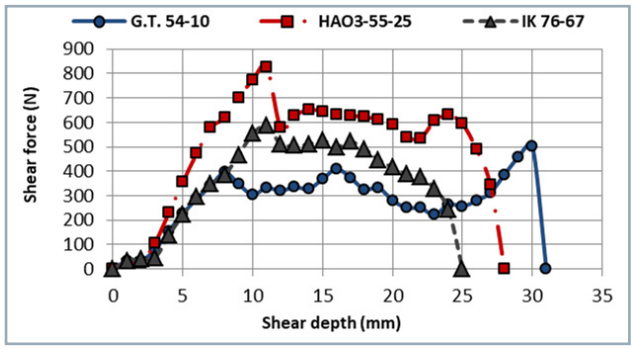

Fig. 12 The force-shear depth diagram of the freash cane internode during the shear process

Shear stress

The testing machine produces a shear force-depth diagram, as shown in Fig. 12. The results showed that the sugarcane variety HAO3-55-24 recorded the highest values of shear stress (N·mm^{-2}), followed by G.T.54-9 and then IK-76-66. The data indicate that the maximum value of shear force was 826, 586.25, and 504 N with a shear depth of 11, 11, and 30 mm for HAO3-55-24, IK-76-66, and G.T.54-9, respectively. This result may be due to an increase in the stalk diameter of varieties, which led to increasing shear stress that may be due to an increase in the cross-sectional area of the stalk during the operation.

The values of shear of the stalk for the varieties G.T.54-9, HAO3-55-24, and IK-76-66 increased by 10.45, 10.602, and 7.049 N·mm^{-2} and 17.90, 26.245, and 14.729 N·mm^{-2} at the base of the stalk and stalk moisture content (60.73 and 18.1%), respectively.

On the other hand, the shear stress of the stalk for the varieties G.T.54-9, HAO3-55-24, and IK-76-66 increased from the top to the base of the stalk by 36.3, 56.4, and 81.8%, respectively.

Table 2 indicates that, according to LSD 0.05, significant differences were observed for all the replicates and all the mean values of moisture content and shear stress for all the sugarcane cultivars under study.

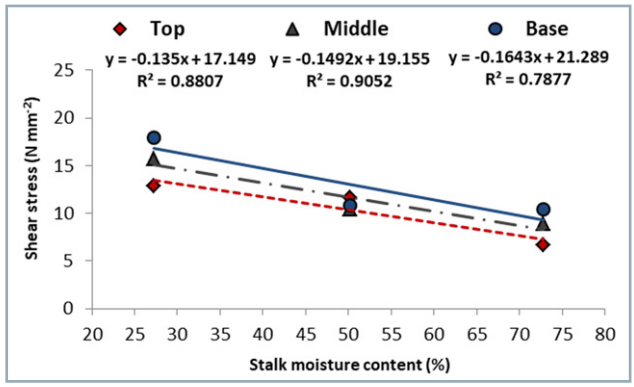

Fig. 13 The effect of stalk moisture content on shear stress in the G.T.54-9 variety

Stalk moisture content decreased from 72.82% to 27.29% at the top of the stalk, from 66.88% to 24.32% in the middle of the stalk, and from 60.73% to 18.1% in the base of stalk due to an increase in the shear stress of stalk for the varieties G.T.54-9, HAO3-55-24, and IK-76-66, respectively

Table 2 The effect of stalk moisture content and internode position sampling on the shear stress of the stalks of sugarcane varieties

Variety	Sample position	Measurements	
		moisture content (%)	shear stress (N·m^{-2})
		mean	mean
G.T.54-9	top	50.10	9.96
	middle	45.56	11.82
	base	37.15	13.35
HAO3-55-24	top	53.28	8.02
	middle	49.68	11.87
	base	42.58	16.96
IK 76-66	top	57.38	4.38
	middle	58.52	6.97
	base	56.91	10.22
LSD 0.05		–	0.70

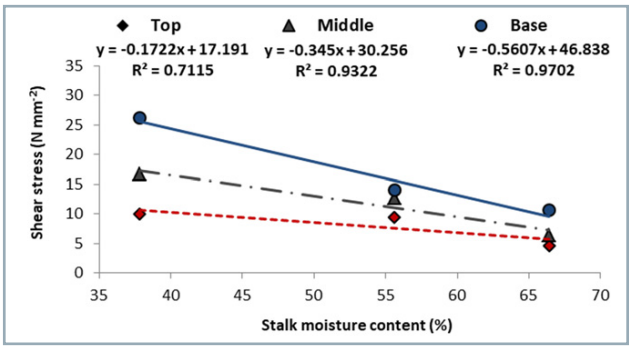

Fig. 14 The effect of stalk moisture content on shear stress in the HAO3-55-24 variety

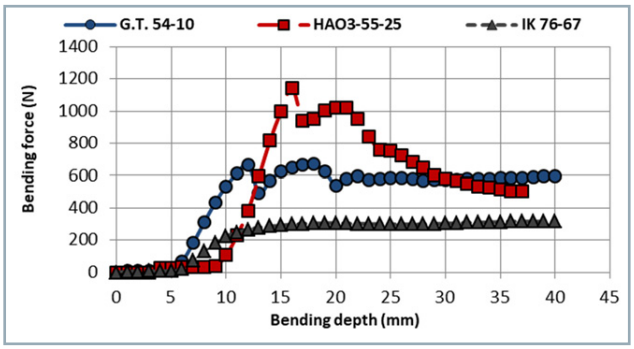

Fig. 16 The force-bending depth diagram of the fresh cane internode during the bending process

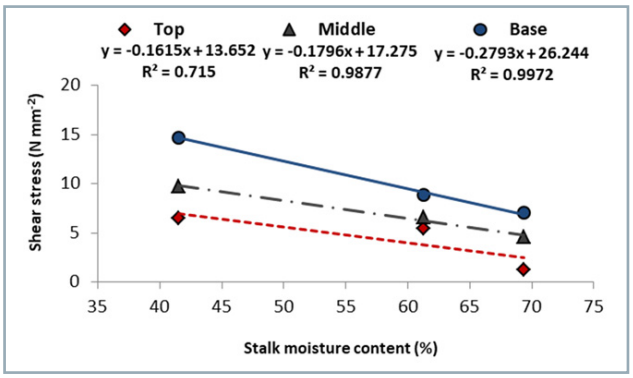

Fig. 15 The effect of stalk moisture content on shear stress in the IK 76-66 variety

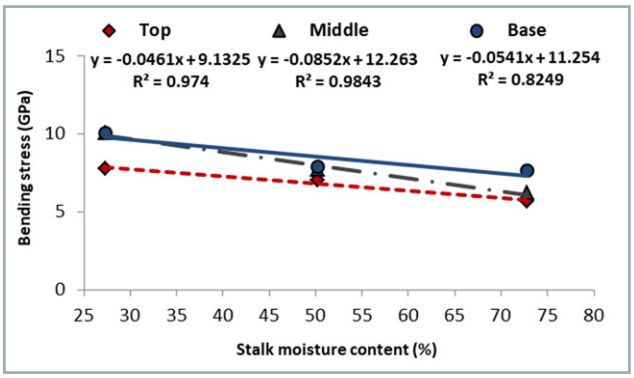

Fig. 17 The effect of stalk moisture content on bending stress in the G.T.54-9 variety

and this result agrees with Taghijarah et al. (2011), Zong et al. (2012), Meizhou et al. (2021) (Figs 13–15).

Bending stress

The testing machine produces a bending force-depth diagram, as shown in Fig. 16. The data indicate that the maximum value of bending force was 1143.74, 668.25, and 319.2 N with a bending depth of 16, 11, and 39 mm for HAO3-55-24, IK-76-66, and G.T.54-9, respectively.

Table 3 indicates that, according to LSD 0.05, significant differences were observed for all the replicates and all the mean values of moisture content and bending stress for all the sugarcane cultivars under study. On the other hand, the bending stress of the stalk for the varieties G.T.54-9, HAO3-55-24, and IK-76-66 increased from the top to the base of the stalk by 25.8, 17.9, and 37.2%, respectively. The data indicate that an increase in moisture content from the top to the base of the stalk leads to a decrease in bending stress (Galedar et al., 2008)

The bending stress of stalks of the G.T.54-9, HAO3-55-24, and IK-76-66 varieties with regard to the moisture content of stalk from 72.82% to 27.29% in the top of stalk, from 66.88% to 24.32% in the middle of stalk, and from 60.73% to 18.1% in the base of stalk amounted to (5.67 and 7.64 GPa), (6.46 and 7.8 7GPa), and (3.06 and 4.88 GPa), respectively, and this result agrees with Zong et al. (2012) (Figs 17–19).

Overall, an increase in the moisture content of the stem causes a drop in bending stress, as well as an increase in shear strength and shearing energy (Galedar et al., 2008).

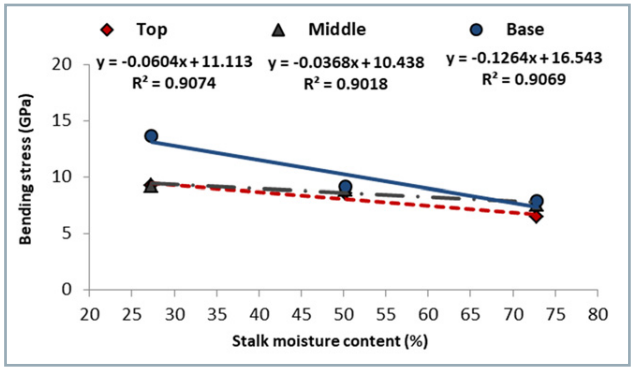

Fig. 18 The effect of stalk moisture content on bending stress in the HAO3-55-4 variety

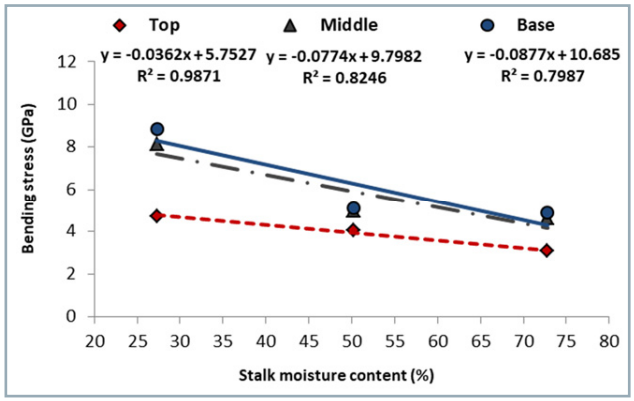

Fig. 19 The effect of stalk moisture content on bending stress in the IK-76-66 variety

Table 3 The effect of stalk moisture content and internode position sampling on the bending stress of the stalks of sugarcane varieties

Variety	Sample position	Measurements	
		moisture content (%)	bending stress (GPa)
		mean	mean
G.T.54-9	top	50.10	6.82
	middle	45.56	7.99
	base	37.15	8.54
HAO3-55-24	top	53.28	8.09
	middle	49.68	8.59
	base	42.58	10.21
IK 76-66	top	57.38	3.94
	middle	58.52	5.92
	base	56.91	6.28
LSD 0.05		–	0.37

Conclusions

The physical properties of stalks in the sugarcane crop included diameter, length, fresh mass, moisture content, and stalk bulk density. Moisture content was estimated by three positions (top, middle, and base) of the stalk which was used with three averages of moisture content in the fresh stalk, after 7 days and after 15 days, (70.3, 42.1, and 23.2%), (68.7, 61.3, and 42.7%) and (66.4, 48.6, and 30.5%), respectively. The mechanical properties include compression, shear, and bending stresses. The IK-76-66 variety recorded the highest values of compression for stalk, followed by HAO3-55-24 and then G.T.54-9. The values of compression stress of stalk for the varieties G.T.54-9, HAO3-55-24, and IK-76-66 increased by 1.922, 2.136, and 2.311 MPa at the base of the stalk, and stalk moisture content 60.73%. The results showed that the sugarcane variety HAO3-55-24 provided the highest values of shear stress, followed by G.T.54-9 and then IK-76-66, respectively. The shear values of the stalk for the varieties G.T.54-9, HAO3-55-24, and IK-76-66 increased by (10.45, 10.602, and 7.049 $N \cdot m^{-2}$) and (17.90, 26.245, and 14.729 $N \cdot m^{-2}$) at the base of the stalk and stalk moisture content (60.73 and 18.1%), respectively. The bending stress of stalks for the varieties G.T.54-9, HAO3-55-24, and IK-76-66 with regard to the moisture content of stalk from 72.82% to 27.29% in the top of stalk, from 66.88% to 24.32% in the middle of stalk, and from 60.73% to 18.1% in the base of stalk amounted to (5.67 and 7.64 GPa), (6.46 and 7.87 GPa), and (3.06 and 4.88 GPa). The decreasing stalk moisture content of three sugarcane varieties (G.T.54-9, IK 76-66, and HAO3-55-24) led to an increase in compression, shear, and bending stresses. Compression stress, shear stress, and bending stress increased in the base of stalk. Overall, an increase in the moisture content of the stalk causes a drop in bending stress, as well as an increase in shear strength and shearing energy. In general, the results of the current study can help in the design of sugarcane cutting machines.

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