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Force and Energy Requirement for Cutting of Corn Stalk and Cob

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Abstract

In this study, the cutting force and energy requirement of corn (Zea mays L.) stalk at different internodes (diameter), from the bottom to the top internode positions for Pionner 2105, Pioner 1570, KWS and MAY 75 varieties, were determined. The mean diameter of internodes varied between 11.28-19.00 mm from top to bottom. Also, cob breakout force and energy requirements were determined for these varieties. According to test results, the cutting force requirement of the varieties were found statistically different. While the highest cutting force requirement was found in MAY75 variaty as 504.79 N and Pioneer 2105 as 537.80 N, the lowest values were obtained in the KWS variety as 409.50 N. Similar results were found for cutting energy values. While, there were no found difference between MAY 75 and Pioneer 2105 varieties, cutting energy requirements were found statistically different ($p<0.01$) among the other varieties. The highest cutting energy requirements has been found in Pioneer 2105 and MAY75 varieties, followed by Pioneer 1570 and KWS variaty, respectively. The lowest value was obtained in the KWS variety as 3.83 J. The difference between internodes was found statistically significant. The cutting force values varied between 806.00 N and 203.00 N, the cutting energy varied between 7.91 Joules and 1.56 Joules depend on internodes. The highest cutting force and cutting energy values were obtained at the first node as 806.00 N and 7.91 Joules, these values decreased as the diameter decreased from the bottom to the top. Tukey test results showed that there were no significant differences among the varieties in terms of both breakout force and breakout energy. However, the highest values were obtained as 382.7 N and 15.50 J in Pioneer1570 variety, while the lowest values were obtained as 319.0 N and 9.830 J in Pionner 2105 variety.

Keywords: Corn stalk, Cob breakout force, Cutting force, Cutting energy

Introduction

Corn (Zea mays L.) has a great importance in human and animal nutrition and it is the second most cultivated and produced in the world because of high consumption, quality, and food value after wheat and barley. Also, one of the most important agricultural residues is corn stalk. Corn stalk is produced huge quantities worldwide in relative the other crops. Because, it is the richest regenerative resource and offers huge potential as a renewable and domestic feedstock for bio-energy and fiber production and it is consists of rind, a high content of lignin, pith, leaf, etc., and the chemical components of the different parts vary greatly (Klingenfeld, 2008; Zhang et al.,2016). However, it is difficult to digest for the animals such as ruminants. So, rich corn stalk resources have not yet been effectively utilized. Plenty of them are burned off in farmland, and not only are the resources wasted, but the fires also leave the natural environment damaged. Therefore, for the most effective utilization of the different parts of corn stover resources, each part of corn stalk requires effective separation. The cutting characteristics of corn stalk are important parameters in the process of the separation of rind and pith (Zhang et al.,2016; Zhang et al.,2017). Information on plant properties and the power or energy requirement of equipment has been very valuable for selecting design and operational parameters of the equipment (Persson, 1987). Such information is needed for the design of corn harvesters and chopper, assuring appropriate machine functions and an efficient use of energy. So, knowing the stem cutting force energy required for cutting plant stalks and corn cob breakout force and energy are important parametrs for both machine design and the parting of the stem. Crop stem cutting

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is an inevitable process in harvesting, and it is a process that can result in mechanical failure. Although it depends on the structure and strength of the plant material, the epidermis is the outermost protective tissue of stem structure. As the stem is mostly fibrous matter, the length of harvest period affects the fiber hardness and moisture content of the crop. The fiber fracture is an important part of the shear failure process (Persson, 1987; Lien and Liu., 2015).

Until now, several studies have been carried out to investigate mechanical properties of plant materials by different researchers in the worldwide for various plants and purposes such as designing a new harvest machines, designing of biomass processing equipment, chopping of plant stalk and studying how to utilize fibers of plants.

Recently, many research was directly conducted on mechanical properties with the corn plant stalk. Corn stalk is a complex material from the point of view of mechanical strength. For example, mechanical properties such as shearing resistance of corn stalk were investigated by Mani et al. (2006) and chopping of corn stalk by Igathinathane et al. (2011). Kaliyan and Morey (2009) studied the densification process of maize stover grinds by using a non-linear elasto-visco-plastic model under uniaxial compression conditions. The mechanical properties of the rind of corn stalk were studied by Chen et al. (2012), whose purpose was to maintain the rind integrity during the separation of corn stalk rind and pith. Reddy and Yang (2005) measured the tensile properties of maize stalk for determine to suitable for producing various textile products. Prasad and Gupta (1975) measured the cutting force and energy for cutting corn stalks for determine to suitable knife type at different loading combinations. Taghijarah et al. (2011) studied on shearing characteristics of sugar cane stalks as a function of the rate of the applied force. Igathinathane et al. (2010, 2011) tested corn stalks using a linear knife grid size reduction device to determine ultimate shear stress and cutting energy at different moisture content. Chen and Qu (2017) and Zhang et al. (2017) studied on physical and mechanical properties of corn stalk for to provided the data for optimizing the corresponding mechanical parameters. According to Wright et al. (2005), for successfully a designing and developing new systems requires knowledge of the mechanical properties of maize stover. A similar expression is made by Kovács and Kerényi (2019). According to this reserchers, in order to optimize the design and working parameters of agricultural machinery related to harvesting, knowledge about the physical properties and mechanical behaviour of harvest-ready maize is required. Womac et al (2005) studied on shearing characteristics of biomass for size reduction. They used A Warner-Bratzler shearing device in a universal test machine for evaluate of corn stems and cob characteristics. They were studied with different knife bevel angles (30° and 45°) at a fixed cutting speed of 254 mm/min. Biomass cutting energy was determined on a stem cross-sectional area basis (specific cutting energy, kN/m). Mean specific cutting energies for corn stover were found 28 and 34 KN/m for 30° and 45° knife bevel angles, respectively. Thus, the shallower 30° bevel angle required less cutting energy.

As can be seen from previous studies, size reduction of agricultural stalk also is an important prerequisite to produce forage and biomass energy. Size reduction/grinding is considered to be one of the most energy-intensive or energy in efficient operations (Mohsenin, 1986; The efficiency of the size reduction has typically been assessed through the amount of cutting force and energy required (Igathinathane et al.,2010; Azadbakht et al., 2015; Allameh and Alizadeh.,2016; Vu et al., 2020). It has been found that equipment using shear mode for size reduction may hold promise for improved energy efficiency (Igathinathane et al.,2010). So, there is need to improve harvesting, processing and chopping of corn stalks. In general, the cutting knife of a harvesting machine cut the plant material and separates it into different parts by external force. For this, some cutting properties need to be known. Because varieties of plants can show different characteristics each other. Therefore, plants energy needs can be also different according to variety (Sessiz et al.,2013).

Turkey is one of the leading corn producers in the world with terms of climate, soil and environmental conditions. Southeastern part of Turkey is among the important corn producers. Espicially, corn is producued in Şanlıurfa, Diyarbakır and Mardin provinces and corn harvesting is performed with combine- harvester. During harvesting by a combine-harvester, maize is mainly processed by the maize header; only maize ears are threshed inside the machine. The whole plant is cut and pulled down to gather the maize ears that are conveyed into the machine, while the rest of the maize plant (stalk, leaves, husk, tassel) is chopped. The wet mass of the stalks is more significant than the wet mass of the leaves, husk and tassel (Igathinathane et al., 2010; Kovács and Kerényi., 2019).

The objective of this study was to determine cutting force and cutting energy requirements to cut corn stalk as a function of internodes of stalks along bottom to top regions. Also, breakout force and energy of the cob from stalk was to determine for four different corn varieties. The purpose is to provide a scientific basis for designing a corn and chopper machine with high efficiency and low power consumption.

Materials and Methods

Corn Stalks and Cobs

Samples of whole corn plants used in the cutting tests were obtained from farmers corn fields in the same location (location: 38.066 ° N, 40.2715 ° E) in Çınar district of Diyarbakır province. Four corn varieties, Pionner 2105, Pioner 1570, KWS and MAY75 were selected for stalk cutting and cob breakout force tests. The samples were taken during the harvesting season on 20 October 2020. In order to prevent moisture content, the samples were bagged according to variety and stored in nylon sack for 2 months in the Laboratory of Agricultural Machinery and Technologies Engineering Department until the time of tests. Before started to tests, 10 plants for each variety were selected and seperated according to stem diameters and tested for cutting force and energy (Figure 1). It has been considered that the plant stem diameters are the same as possible. To determine cob breakout force and energy, the same plan's cob was used. The corn cob used in the research had a uniform shape and size and had a mass of 293-390 g, a maximum diameter of 49-53 mm and a length of 207-295 mm.

Preparation of test material

The mechanical testes were conducted two stages. In the first stage, the stalk cutting force and energy were determinded depend on nodes. The second stage, breakout force the cob of corn from stalk were determined. The corn stalks with cobs for the mechanical tests were obtained from whole plants randomly selected and harvested by hand cutting at ground-level for each varieties during the harvesting season and then transported to laboratory for tests. Before tests, seven nodes, different diameter (cross-sectional) sizes, were prepared from the bottom sections of the stalks to top for each varieties, respectively. The diameter of the stalk decreases towards the top of the plant due to different physical properties at different heights due to cross-sectional heterogeneity. Internodes were labeled from IN1 to IN7, respectively (Figure 1). It has been taken to ensure that stem diameters and moisture contents are the same as possible. Tests were made in 9 repetitions. Nine diameter measurements were taken for each sample after which their average was calculated. Digital caliper with an accuracy of 0.01 mm was used to measure the diameter values. Average diameter values measured for each variety from the first node to the seventh node are given in the Table 2. Cutting force and cutting energy were determined based on these diameter values of stalks. The mean diameter varied between 11.28-19.00 mm from top to bottom.

After testing, the plants samples were weighed, oven dried, and reweighed to obtain moisture content. Moisture content of the samples was determined according to ASABE Standards by the oven -drying method 50 g of each sample at 105 ° C for 24 hours (ASABE Standards, Sec. 358.2, 2008). The four varieties were tested. The corn stalk moisture contents during the tests varied between 56.40% and 59.30%. It was measured as 59.30% for Pionner1570 variety, 58.00% for KWS variety, 56.40% for MAY75 variety and 57.45% for Pionner 2105 (Igathinathane et al., 2010).

The cutting and cob detachment tests

An Instron universal (Llyod LRX plus) testing machine was used to measure the cutting force, cutting energy and force-displacement. The testing frame is also shown in Figure 2. The maximum cutting speed of the machine, 5 mm s-1, was used for all tests. In the experiments, a knife with a straight cutting edge was used for all varieties. Trials were performed at 90° blade cutting angle. In the tests, the stalks were placed under the cutting platform and loaded at both ends, keeping them fixe (Figure 2). As you shown in Figure 2, The same device was used to determine the breakout force and energy of corn cobs (Figure 3).

Figure 1. The samples of corn stalk and cobs are used for experiment.

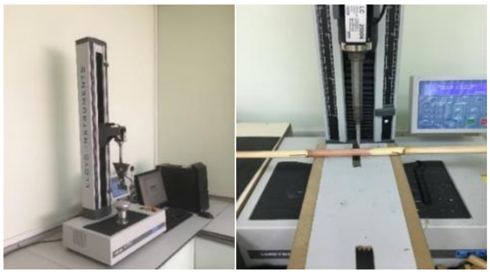

Figure 2. Universal testing device used in cutting experiments.

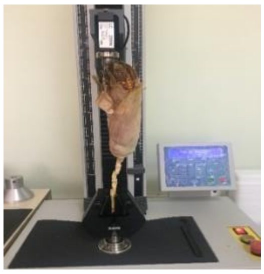

Figure 3. Universal test device used in cob breakout force experiments.

The stalk cutting energy and cob detachment energy was calculated by measuring the surface area under the force-deformation curve via material testing machine by using a Nexygen data analysis computer program (Yore et al., 2002; Chen et al., 2004; Kocabıyık and Kayışoğlu, 2004; Nazari et al., 2008; Ekinci et al., 2010; Hassan-Beygi et al., 2010; Zareiforoush et al., 2010; Heidar and Chegini, 2011; Sessiz et., 2013; Ozdemir et al., 2015; Ozdemir and Sessiz, 2018; Nowakowski, 2016; Pekitkan et al., 2018; Oztürk et al., 2017 Sessiz et al.,. 2018). A computer data acquisition system recorded all force-displacement curves during the cutting process.

Experimental design and data analysis

Statistical procedure of this study was planned as a completely randomized block design. Independent variables were selected internode number and crop variety. Dependent variables were peak stalk cutting force, cob detachment force. Cutting force and energy properties were determined with nine replications and nine internodes of stalks and cob detechman force from stalks for four varieties. Analysis of variance (ANOVA) was performed to examine the main effects of experimental factors and their interactions. The means were compared at the 1 and 5 % levels of significance using the Tukey multiple range tests in JMP software, version 11.

Results and Discussion

Corn stalks cutting force-deformation characteristics

Cutting energy of a plant stem can be estimated from the relationships between the force of cutting the stem and the displacement of the knife (force–displacement curves) (Chen et al., 2004). Typical force-time characteristics of corn stalks (left side) and cop detachment force from plant (right side) in this study are shown in Figure 4. The force-time curves (force–displacement curves) is shown that, at the beginning, cutting force and breakout force increased from zero at the moment of initial contact between the knife and the stem, and then decreased due to the failure in stem structure (collapse of the hollow core). The compression continued along with cutting as the knife moved. When the force reached to peak point, cutting operation took placed. Then, the force dropped as the cutting was completed. That is, the first peak correspond to the biological yield point at which stalk damage was initiated. The second peak (upper yield) corresponds to maximum force (Figure 4). After reaching the upper yield, the force suddenly decreases with the displacement increasing. After, the second low peak, cutting or detachment has occurred.

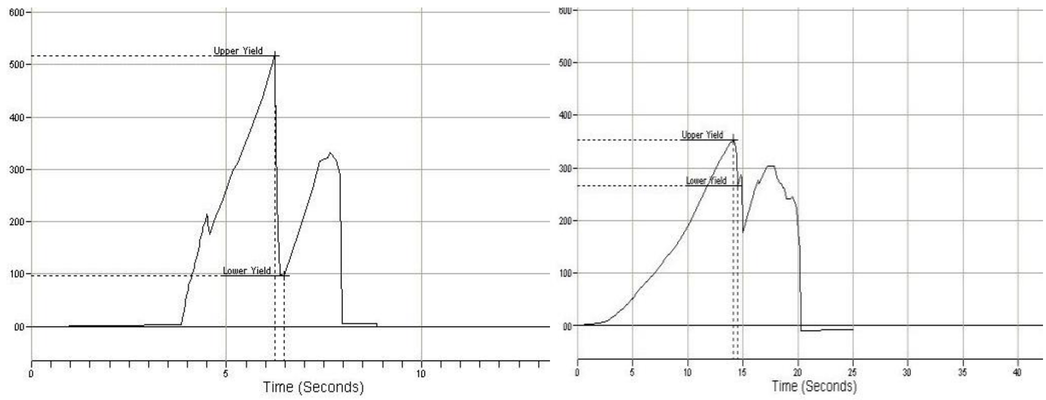

Figure 4. Typical force-deformation characteristics of corn stalks (left side) at various nodes and cop break force (right side).

Stalk cutting force and energy depending on the variety

Measured mean cutting force and energy data for each varieties are given in Table 1. As can be seen from the table, the cutting force requirement of the varieties was statistically different. While, no difference was found between MAY 75 and Pioneer 2105 varieties, cutting force were found statistically different ($p < 0.01$) among the other varieties. The highest cutting force requirements were found in MAY75 as 504.79 N and Pioneer 2105 as 537.80 N, followed by Pioneer 1570 as 464.60 N and KWS as 409.50 N varieties, respectively. The lowest value was obtained in the KWS variety. Similar results were found for cutting energy values. While, there were no found difference between MAY 75 and Pioneer 2105 varieties, cutting energy requirements were found statistically different ($p <0.01$) among the other varieties. The highest cutting energy requirements were found in Pioneer 2105 and MAY75 varieties, followed by Pioneer 1570 and KWS variants, respectively. The lowest value was obtained in the KWS variety as 3.83 J.

Table 1. Mean cutting force and cutting energy

Varieties	Cutting Force* (N)	Cutting Energy Nm (Joule)
MAY 75	504.79 a	5.25 a
Pioneer 2105	537.80 a	5.15 a
Pioneer 1570	464.60 b	3.89 b
KWS	409.50 c	3.83 b
LSD	19.00	0.231

*means followed by the same letter in each column are not significantly different by Tukey multiple range tests at the 5% level.

Stalk cutting force and energy depending on the internodes (diameter)

The cutting force and energy values depending on the internodes (diameter) obtained from the average values for all varieties are given in the Table 2. As can be seen from the Table, there is no difference between the diameters of internodes of the varieties. The diameters of the internodes were almost the same. Therefore, only the average values of all varieties have been taken into account.

Table 2. Mean diameter values for each variety depending on the number of internodes.

Internodes	Diameter of nodes			
	Pioneer 2105	Pioneer 1570	KWS	MAY75
N1	18.70	19.66	19.06	18.59
N2	17.76	18.40	18.44	18.33
N3	16.83	17.47	17.85	17.87
N4	16.16	17.00	17.10	17.26
N5	14.88	15.26	16.63	16.32
N6	13.78	12.86	12.95	13.30
N7	11.25	10.74	11.23	11.90

As can be seen from the Table 3, as the internodes thickness (diameter) decreased from the bottom to the top, the cutting force and cutting energy requirement were decreased from bottom to top internode for all varieties. While the highest cutting force values varied between 806.00 N and 203.00 N, the cutting energy varied between 7.91 Joules and 1.56 Joules depend on internodes. The difference between internodes was found statistically significant. While the highest cutting force and cutting energy values were obtained at the first node, which is the lowest node, 806.00 N and 7.91 Joules, these values decreased as the diameter decreased from the bottom to the top. This effect is in agreement with a previous study on maize stalks, in which both the cutting energy and maximum cutting force were directly proportional to cross-sectional area (Prasad and Gupta, 1975). The effect of stem diameter on the maximum cutting force and cutting energy is consistent with Chen et al. (2004), who reported that both the cutting energy and maximum cutting force are directly proportional to the cross-sectional area of hemp stalk. The results have shown that the cutting strength and cutting energy related to plant physical and mechanical properties (Igathinathane et al., 2010). Similar results were reported by Yore at al. (2002) for rice straw, by Chen et al. (2004), Kronsberg et al. (2011) for hemp stalk, by Alizadeh et al. (2011) for rice stem, and by Ghahraei et al. (2011) for kenaf stems, by Sessiz at al. (2013) for olive sucker, by Ozdemir at al. (2015) for grape sucker, by Sessiz at al. (2015) for cane of some different grape variety, by Öztürk et al. (2017) for soybean stem. These results also are in agreement with Aydin and Arslan (2018) who determined shearing force and energy for shoot of cotton plant at different height of plant. Also, similar results were observed for cotton stalk by Pekitkan et al. (2018). Proper equipment design to accomplish the cutting will maintain the quality of the harvested product while minimizing the force and energy needed to accomplish the task (Srivastava et al., 2006; Sessiz et al.,2019).

Cob breakout force and energy depend on the varieties

The change in the force and energy of breakout the cob from the stalk depend on the varieties are given in the Table 4. As can be seen from the Table, Tukey test results showed that there were no significant differences among the varieties in terms of both breakout force and breakout energy. However, the highest values were obtained as 382.7 N and 15.50 J in Pioneer1570 variety, while the lowest values were obtained as 319.0 N and 9.830 J in Pionner 2105 variety.

Table 3. Cutting force and energy requirements depending on the stalk internodes

Internode	Diameter (mm)	Cutting force* (N)	Energy consumption of stalk (J)
1	19.00	806.00 a	7.91 a
2	18.23	722.00 b	6.67 b
3	17.50	610.00 c	5.87 c
4	16.88	450.00 d	4.37 d
5	15.77	354.00 e	3.14 e
6	13.22	270.00 f	2.21 f
7	11.28	203.00 g	1.56 g

*means followed by the same letter in each column are not significantly different by Tukey multiple range tests at the 5% level.

Table 4. Cob breakout force and energy depend on the varieties

Variety	Cob breakout force* (N)	Cob breakout energy (J)
Pioneer 1570	382.70 a	13.50 a
KWS	352.00 a	11.33 a
MAY 75	332.00 a	10.93 a
Pioneer 2105	319.00 a	9.830 a
LSD	3.95	2.07

*means followed by the same letter in each column are not significantly different by Tukey multiple range tests at the 5% level.

Conclusion

In this study, cutting force and energy requirement of corn stalk at different internode and cob breakout force and energy were examined for Pionner 2105, Pioner 1570, KWS and MAY 75 corn varieties. According to test results, as the internodes thickness (diameter) decreased from the bottom to the top, the cutting force and cutting energy requirement were decreased from bottom to top internode for all varieties. The cutting force requirement were found statistically different among varieties. While the highest cutting force requirement was found in MAY75 variety as 504.79 N and Pioneer 2105 as 537.80 N, the lowest values were obtained in the KWS variety as 409.50 N. Similar results were found for cutting energy values. While, there were no found difference between MAY 75 and Pioneer 2105 varieties, cutting energy requirements were found statistically different ($p<0.001$) among the other varieties. The highest cutting energy requirements has been found in Pioneer 2105 and MAY75 varieties, followed by Pioneer 1570 and KWS variety, respectively. The lowest value was obtained in the KWS variety as 3.83 J.

The difference between internodes was found statistically significant. The highest cutting force and cutting energy values were obtained at the first node as 806.00 N and 7.91 Joules, these values decreased as the diameter decreased from the bottom to the top. The cutting force values varied between 806.00 N and 203.00 N, the cutting energy varied between 7.91 Joules and 1.56 Joules depend on internodes.

Tukey test results showed that there were no significant differences among the varieties in terms of both breakout force and breakout energy. However, the highest values were obtained as 382.7 N and 15.50 J in Pioneer1570 variety, while the lowest values were obtained as 319.0 N and 9.830 J in Pioneer 2105 variety.

Compliance with Ethical Standards

Conflict of interest

The authors declared that for this research article, they have no actual, potential or perceived conflict of interest.

Author contribution

The contribution of the authors to the present study is equal. All the authors read and approved the final manuscript. All the authors verify that the Text, Figures, and Tables are original and that they have not been published before.

Ethical approval

Not applicable.

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No financial support was received for this study.

Data availability

Not applicable.

Consent for publication

Not applicable.

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