Industrial Crops & Products 112 (2018) 396–401

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

Mechanical properties of cotton shoots for topping

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ARTICLE INFO

Keywords:
Cotton
Topping
Shearing
Mechanical properties
Water content

ABSTRACT

Cutting the shoots of cotton plants (topping) at about 10–20 cm from the top of plants is a cultural practice, which may offer advantages to improve yield and yield components in cotton production. The cutting forces of plant stalks were reported in the literature, which help understand the mechanical properties of stalks for a cultivar of field crops. However, the shearing characteristics of cotton shoots have not been addressed yet. The objective of this study was to determine some physical and mechanical properties of cotton (*Gossypium hirsutum* L.) shoots. The test specimens were obtained from two different plant segments, i.e. 0–15 cm (Segment A) and 16–30 cm (Segment B) from the top of cotton plants, in 21 plots in an ongoing cotton topping study. The samples were collected from each plot and were subjected to shearing test using a universal test machine in the laboratory. In Segment A, average shoot diameter, shearing force, water content, maximum shearing stress, and specific shearing energy were determined to be 4.35 mm, 73 N, 72%, 4.94 MPa, and 0.069 J mm^{-2}, respectively. In Segment B the same parameters were 5.79 mm, 121 N, 64.8%, 4.65 MPa, and 0.078 J mm^{-2}, respectively. The difference between the Segment A and B was significant at 5% level for shearing stress while all others parameters showed differences at 1% level. Although displacement at the bioyield point was similar in both sampling locations, the maximum shearing force requirement was more (121 N) in Segment B compared with Segment A (73 N) suggesting that topping should be done as high as possible from the ground to complete the topping process with low energy consumption. In terms of cutting energy requirement, it was concluded that the topping should be done as early as possible from 100 to 120 days from the planting.

1. Introduction

Cotton production (*Gossypium herbaceum* L., *G. arboretum* L., *G. hirsutum* L.) and cotton based industry is of utmost importance for cotton producing countries due to limited segments that can produce cotton in the world. However, the costs might be high depending on cultural practices during the production and harvesting operations. In addition to tillage, drilling, fertilizing, spraying, and irrigation operations, cotton topping is another cultural practice that should be done during the vegetation period (Obasi and Msaakpa, 2005; Renou et al., 2011; Yaşar, 2013).

Cutting the shoots of cotton plants (topping) increases the yield and quality of cotton and improves the earliness, limiting the vegetative growth of the plant and improving the development of generative organs of the cotton plants (Kittock and Fry, 1977; Dong and Han, 1996, Ma et al., 1983; Xu et al., 2001; Dai et al., 2014; Yang et al., 2008). Topping after 100–115 days from the planting not only increased the boll yield, but also improved ginning (separating the cotton lint from the seeds) efficiency and lint length, increased the number of opened bolls whereas factors such as short lint rate, lint strength, spinning index, lint homogeneity, and lint strain did not change (Kittock and Fry, 1977; Yaşar, 2013). Topping the cotton shoots result in reduced plant height and the number of stalk nodes (Obasi and Msaakpa, 2005).

The number of pests such as *Helicoverpa armigera* Hübner, *Earias* spp., and *Diparopsis watersi* Rothschild was reduced in cotton plants that were subjected to topping (Renou et al., 2011). The effect of pruning was also studied. Compared with non-pruning, extensive pruning (concurrent removal of vegetative branches and the main-stem leaves below the first fruiting branch at squaring) increased the net revenue (7.9%) through improved cotton yield whereas intensive pruning (removal of vegetative branches, topping, and continuously excising old leaves, growth tips of fruiting branches, excessive buds and empty fruit branches) reduced the net revenue (3.5%) because of increased labor costs (Dai et al., 2014).

Physical and mechanical properties of plants and their residues are important to relate the findings to harvesting machines used for stalk removing following the cotton lint harvesting operations as well as to produce biomass (Du and Wang, 2016). Plant properties are dependent

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https://doi.org/10.1016/j.indcrop.2017.12.036
Received 25 December 2016; Received in revised form 14 December 2017; Accepted 15 December 2017
0926-6690/

on their water contents. Cotton stalks showed average cutting resistance of 26.5, 18.79, and 11.54 MPa at 11.15, 16.22, and 21.92% water contents (Eissa et al., 2008). Gupta et al. (2007) studied the mechanical properties of cotton stalks in relation to stalk cutter and determined the cutting force and the tensile strengths during compression at two different water contents (55.5% and 61%). Cutting forces varied from 33.63 and 64.82 N at 55.5% and 30.12 and 56.14 N at 6%1, respectively, suggesting lower cutting resistance in drier cotton stalk samples. In another study, cutting force of cotton stalks at different heights from the ground varied from 20.3 and 30.4 N with an average cutting force of 26.7 N (Kaplan, 2007). Sonde et al. (2015) found average tensile and compressive strength for cotton stalks with the ranges of 0.34–0.23 MPa and 7.24–5.5 MPa, respectively at water contents from 9.58% to 16.0%.

Liu et al. (2012) studied the biomechanical properties of miscanthus stems and showed that the specific cutting energy of 87.5 mJ mm^{-2} with flat blade could be reduced to 66.1 mJ mm^{-2} using a serrated blade. For alfalfa (*Medicago sativa* L.) stems, maximum shearing stress varied between 0.4 and 18.0 MPa depending on water content (Halyk and Hurbult, 1968). Shearing stress and shearing energy was 16 MPa and 12.0 mJ mm^{-2}, respectively for field grasses (*Poaceae*) (McRandal and McNulty, 1980). For hemp (*Cannabis sativa* L.), average values of maximum force and total cutting energy were 243 N and 2.1 J, respectively (Chen et al., 2004).

Some research determined the effect of cutting height and water content on mechanical properties of sunflower (*Helianthus annuus* L.) stalks (Uğurluay et al., 2005; Kocabıyık and Kayışoğlu, 2004). These studies found that shearing stress reduced with increasing cutting height from the ground. Cutting force of sunflower stalks were between 23.9 N and 33.6 N and increased with increasing stalk water content (Kayişoğlu et al., 1999). Studies on mechanical properties of maize (*Zea mays* L.) plant focused on dry maize stalks to relate the findings to harvesting and biomass operations. The maximum cutting force and the cutting energy was different at different internodes of dry maize stalks of varying thickness (Ingathinathane et al., 2010).

It can be concluded from the published literature that mechanical properties of plants such as maize, sunflower, wheat (*Triticum aestivum* L.), and field grasses, mostly were determined using dry stalks and residues. Topping of cotton shoots has been applied as a cultural practice in different countries both manually and mechanically. However, physico-mechanical properties of cotton shoots have not been published to date, which may be used to estimate the energy needed for mechanical topping machines.

The objective of this study was to determine the physical (plant height, diameter, and cross-sectional area) and mechanical properties (force-deformation relationship, shearing energy, and specific shearing energy) of cotton shoots of cotton cultivar DP 499 to get insight on improved topping conditions.

2. Materials and methods

A cotton topping study was initiated to design and build a cotton topper and test the prototype machine at three different tractor ground speeds and three different rotational speeds of the cutting knifes at two different cutting distances from the top of cotton plants to determine the optimum tractor and cutting speeds. The number of total tractor operations were 18 and the number of total plots was 21, including three control plots for the mechanical topping experiment. Since there was no treatment differences among the plots, control plots were not needed in the study indeed. These three plots were included to increase the number of samples for testing as the number of samples was equal to the number of plants in the current study.

The current study focusing on physical and mechanical properties of cotton shoots is a part of ongoing project to develop the aforementioned cotton topper. The cotton cultivar grown for the experiments was DP-499 (*Gossypium hirsitum* L.) produced widespread in the Southeast part of Turkey. Some properties of the cotton cultivar used in this study were given in Table 1. The experimental field is located 20 km from Dicle University, near Diyarbakır-Turkey.

Table 1
Characteristics of DP 499 cotton cultivar used in the study (Aytekin, 2009).

Factor	Property
Earliness	Medium
Boll type	Medium and elliptic
Ginning efficiency	44–45%
Number of seeds	11,000 seed kg^{-1}
Plant height	Long, elongated
Fiber length	28–30 mm
Fiber strength	38–40 g tex^{-1}
Machine harvest	Suited
Other	Resistant to lodging in storm and rain

The diameter of the cotton stem decreases from the roots to the shoots at the top of plants. Due to smaller stem diameters towards the top of plant, cross-section at a given plant height also varies proportionally, changing the mechanical properties at different heights. The samples were taken from two different heights, namely at 0–15 cm (segment A) and 16–30 cm (segment B) from the top of cotton plants (Fig. 2). The widths of plants at peak were measured from edges of uppermost two extended leaves. To determine the mechanical properties of cotton shoots, the samples were collected randomly near the middle part of each plot avoiding the first and fourth rows to eliminate side effects on the plants.

The cotton plant from each plot was manually cut at 35–40 cm and were immediately taken to the laboratory. The sampling was done at 110 days from the planting from 9:00 am to 10:00 am in the same day. The leaves were removed in the laboratory from the shoots and then the stem samples were separated into two segments corresponding to the segment A and B. Average shoot diameter was calculated by measuring the diameter of a shoot with three replications at about the shearing point near the middle section of a test specimen. The specimens were used for testing in their original size and shape under fresh conditions. Therefore, the sampling of cotton shoots and the testing was done successively without storing the samples for testing. The water content of each sample was determined using a standard method (ASABE Standards, 2008) before the shearing tests were conducted.

A materials testing machine (Lloyd LRX Plus) was used to determine the cutting forces of the cotton shoot samples (Fig. 1). The testing machine is equipped with a cutting blade that was set to a loading rate of 0.35 mm s^{-1} for the experiments. The test machine comprises an AC

Fig. 1. Experimental test device for cutting the samples and the computer used in the study.