Journal of Pharmacognosy and Phytochemistry
Available online at www.phytojournal.com

E-ISSN: 2278-4136
P-ISSN: 2349-8234
https://www.phytojournal.com
JPP 2023; 12(3): 81-85
Received: 01-02-2023
Accepted: 09-03-2023

Md. Tahsin Ashraf
Department of Farm Machinery and Power Engineering, IGKV, Raipur, Chhattisgarh, India

Dr. VM Victor
Department of Farm Machinery and Power Engineering, IGKV, Raipur, Chhattisgarh, India

Corresponding Author:
Md. Tahsin Ashraf
Department of Farm Machinery and Power Engineering, IGKV, Raipur, Chhattisgarh, India

Some base cutting parameters in sugarcane harvester: A review

Md. Tahsin Ashraf and Dr. VM Victor

Abstract
India is the world's second-largest cane-growing country, after Brazil, with a 19.9% (5.16 million hectares) share in area during season 2018-19; sugarcane and sugar production were 400,157 million metric tonnes and 31.5 million metric tons, respectively. Sugarcane harvesting is a highly labour intensive operation, about 850–1000 man-hours per ha. are required for sugarcane harvesting with the traditional tools. The scarcity of labour is being felt all over the country. India needs to change the sugarcane harvesting methods from manual to mechanize. This study was conducted to determine the base cutting parameters, which play an important role in the development of sugarcane harvesters. The cutting energy is influenced by various base cutting parameters such as the physical and mechanical properties of the sugarcane stalk, cutting force, cutting speed, cutting velocity, blade angle, and blade type.

Keywords: Blade angle**,** cutting force, cutting speed, cutting velocity and sugarcane

Introduction

Sugarcane (*Saccharum officinarum* L.) is the main source of sugar in India and holds a prominent position as a cash crop. The cultivation of sugarcane dates back to the Vedic period. The most ancient reference to sugarcane is in the Atharvaveda, which is 4000 years old, and the word "sugarcane" is derived from the Sanskrit word "sarkara." Globally, it is cultivated on an area of 27.80 million hectares with an annual production of 182.70 million tonnes (OECD/FAO 2018, ISO 2018) [18]. Sugarcane constitutes around 80 percent of the total sugar produced in the world, with the rest being contributed by beet sugar and other sources such as hydrolyzed starch (Chidambaram, 2017) [8]. India is the world's largest consumer of sugar (15.6%) and the fifth largest exporter (2.8 million tonnes) (Shanthy and Ram, S., 2019) [37]. In India, 525 sugar industries are being operated, with a total installed annual sugar production capacity of about 4439 tonnes per day (Co-operative sugar, 2018).

Sugarcane cultivation covers 34.85 thousand hectares in Chhattisgarh, with production and productivity of 64.19 thousand metric tonnes (MT) and 1842 kg per hectare, respectively. In Chhattisgarh, Kawardha district has the most area (22.25), production (25.12), and productivity (1129 kg/ha) (Directorate of Agriculture, C.G., 2017–18).

Manual harvesting requires 15 to 16 labourers to cut one acre of sugarcane and takes three days. By using this machine, the problem of the labour crisis can be reduced. Comparing with manual harvesting, only 18% of the labour is required; it makes the process faster, reducing most of the harvesting time, and the labour required to operate the machine is also less (Jain *et al*. 2013) [19]. Mechanical harvesting also makes green cane harvesting possible, which reduces greenhouse gas emissions from pre-harvest burning necessitated by manual harvesting (Braunbeck *et al*., 1999) [6]. Harvester cutting mechanisms are based on two main systems: the cutter-bar cutting system and the rotating cutting system (Patil and Patil, 2013) [34]. A rotating cutting mechanism with blades is used more often than a cutter-bar cutting mechanism for thick stalks (such as sugarcane) that have more cutting resistance. The benefit of this mechanism is that rotating cutters exert high inertia and impact forces on the stem when cutting discs with diameters of up to 90 cm (Ma *et al*. 2014) [22]. Generally, sugarcane harvesters can be classified into whole-stalk harvesters and chopper harvesters. A typical whole stalk harvester system consists of a topper and a base cutter. The topper is designed to sever cane tops and then discharge the severed tops to the side of harvesting rows. The base cutter cuts cane at about 30 mm above ground level (Esquivel *et al*., 2008) [11].

Review of some base cutting parameters

The proper mechanisation of sugarcane cutting has an important role in the entire agroindustrial process. The efficient operation of the base-cutter system has a significant impact on the quality of the process as well as on the losses of raw material and the longevity of the cane field (Max *et al*., 2012) [24]. The various base cutting parameters, such as physical and mechanical properties, cutting force and speed, cutting velocity, blade angle on cutting energy, and type of blade, which play an important role in the development of sugarcane harvesters, are discussed below

Physical properties of sugarcane

The length and diameter of the cane play a significant role in the design of both the de-topper and base cutting mechanisms. The de-topper blade assembly has to be raised or lowered to cut the top of the cane precisely to avoid the loss of the millable cane at the time of harvesting. The diameter of sugarcane varies from bottom to top and this variation depends upon the variety. The diameter of the sugarcane is determined at three different locations on the cane, *viz*., top, middle and bottom, whereas the maximum and minimum values are considered in the design of the cutting system to accommodate the variations in the sugarcane diameter.

Blackburn (1984) [5] reported that the sugarcane is a single, unbranched stem with an average height in the range of 3–4 m and a stem diameter that ranges from 3–5 cm depending on the species. Miller and Gilbert (2009) [31] described how the length and diameter of the joints vary widely with different varieties and growing conditions. Pawar (2014) [35] investigated several varieties, including MS10001, CoM0265, VSI434 and Co86032, and discovered millable cane heights in cm of 245.94-273.50, 246.96-280.83, 191.67-251.67, and 232.95-262.50, respectively; and cane diameters in cm of 3.07-3.56, 3.09-3.44, 2.81-3.31, and 2.77-3.19, respectively. Nalawade *et al*. (2017) [33] determined the physical properties of the sugarcane varieties Co86032, CoM0265 (from Indapur and Dehu, Dist. Pune, Maharashtra), and CoS767 (from Kota, Rajasthan). The length and weight of sugarcane stalks varied with variety, as did the average diameter and internode length of the stalk, which decreased from the bottom to the top of the stalk. (Ashraf *et al*., 2016) [3] evaluate the various physical parameters of the different varieties (Co-80036, Co-86032, COVSI-9805, Co-8014 and COM-0265) of sugarcane as measured in the farmers' field, such as length, diameter and node distance of the sugarcane crop. Sugarcane length ranged from 2000 to 3000 mm, diameter ranged from 30 to 50 mm, and node-to-node distance ranged from 50 to 170 mm. The parameters depend on their variety, soil type and climatic condition.

Mechanical properties of sugarcane

Sugarcane harvesting requires research into the mechanical properties of sugarcane stalks. (McNulty and Mohsenin, 1979) [25]. The properties of the cellular material that are important in cutting are compression, tension, bending, shearing, density and friction. These properties depend on the species, variety, stalk diameter, maturity, moisture content, and cellular structure (Bright and Kleis, 1964; Persson, 1987) [7, 36]. Taghijarah *et al*. (2011) [41] carried out research to determine the shearing characteristics of sugar cane stalks. It was found that shearing stress varied from 3.03 to 4.43 MPa. The specific shearing energy ranges from 37.42 to 64.25 MJ mm-2. Yadav *et al*. (2004) [45] studied the designs of sugarcane cutter planters, namely the IISR Lucknow designed ITI and Khalsa PE 630. It was found that the cutting force required to cut sugarcane setts varied from 12.2 to 106.57 N, depending upon the diameter of the cane. The cutting force varied from 29.14 to 106.57 N in the cylindrical cutting mechanism and from 12.2 to 81.20 N in the rotary cutting mechanism. Taghinezhad *et al*. (2012) [43] studied the mechanical cutting properties of sugarcane stalks using a universal testing machine and a linear blade and size reduction device to determine the effect of sample orientation with respect to the cutting element and quantify the possible cutting energy reduction. It found that the mean specific cutting energies of cane stalks at 0°, 45° and 90° orientations for internodes were 4.368, 6.978 and 10.021 kN m-1 respectively and for nodes at 0° and 90°, they were 6.458 and 15.812 kNm-1, respectively. Also, other parameters of mechanical cutting such as ultimate stress, energy and peak force were presented and the results showed a significant difference between orientation, nodes and internodes in mechanical cutting properties. Suleiman Samaila *et al*. (2012) [40] developed a machine that calculates the energy requirement for cutting and topping sugarcane. The apparatus consisted of a crank, sprocket, chain, flywheel, flange, front hub, spindle, frame and base support. It was found that 15.71 joules and 23.83 joules were needed for cutting the top and base of the sugarcane, respectively. Bastian *et al*. (2014) [4] studied the mechanical properties of sugarcane stalks for variety CO-86032, *viz*., bending resistance, cutting resistance, penetration resistance and crushing resistance. It was found that the Young's modulus of the sugarcane stalks was 86 MPa. The specific cutting resistance varied between 1764.56 and 957.48 k-Nm-2, penetration resistance ranged from 29.74 kN-m-2 to 56.33 kN-m-2 and the crushing force varied from 0.75 kN to 1.53 kN. For a diameter range of 40 mm to 50 mm, the maximum cutting force for single cane was 2.7 kN at the bottom and 1.04 kN at the top.

Cutting force and cutting velocity

Cutting forces and cutting speeds required to cut plant materials play a significant role in designing energy efficient equipment. To determine the operating characteristics of a knife-type sugarcane base cutter, (Persson, 1987) [36].

Gupta and Oduori (1992) [15] investigated the relationship between cutting force and system parameters, including blade oblique angle, cutting disc tilt angle, and blade cutting velocity. It was found that the desired blade cutting velocity ranged from 13.8 to 18.4 m/s (The power consumption will increase extensively when the velocity is more than 19.4 m/s); The desirable blade oblique angle was between 20° and 50°; and the recommended operating tilt angle was from 25° to 50°.

According to Song *et al*. (2006) [38], forward speed has the greatest influence on the cutting force requirement of the base cutter, followed by blade oblique angle, cutting disc tilt angle, and the number of blades installed on the cutting disc. They derived an experimental equation to calculate the cutting force needed with particular system parameters such as machine forward speed, blade cutting velocity, and cutting disc tilt angle. This equation has the potential to be used for further research on new base cutter adjustments, modifications, and developments.

Liu *et al*. (2007) [21f] carried out experiments on three parameters of the base cutter: blade cutting velocity, disc tilt angle and blade oblique angle. The study showed that the blade cutting velocity influenced the unit cutting force the most, with a generally linear relationship between them. When the cutting velocity is higher, the required unit cutting force will be higher. Srivastava *et al.* (2007) [39] study concluded that cutting disc tilt angle and blade oblique angle also influenced the cutting force, but to a lesser extent compared to blade cutting velocity. As the knife continues to advance, the fibres in the stem are deflected and eventually fail in tension. Mathanker *et al*. (2015) [13] showed that cutting power increases with increasing cutting speed. The lowest average cutting power was at a 60° oblique with an average cutting speed of 7.9 m/s.

Blade angle and blade design on the cutting energy

(Gupta & Oduori, 1992) studies on effect of blade angle and blade design on the cutting energy. A blade peripheral velocity of 13.8 m/s, oblique angle of 35^0, and a tilt angle of 27^0 were optimum for a revolving knife-type sugarcane base cutter.

Clementson & Hansen (2008) [9] The cutting force required for cutting sugarcane stems depended on the blade design and a difference of 26% was reported between the two designs tested. A cutting blade oriented parallel to a corn stalk (00) compared to perpendicular (900) resulted in a significant reduction in the specific cutting energy to one-tenth for internodes and about one-fifth for nodes (Igathinathane, *et al*., 2010) [17]. Optimal knife edge angle, shear angle, oblique angle, and rake angle were 250, 400, 400, and 400, respectively, for Kenaf stems (Ghahraei, Ahmad, Khalina, Suryanto, & Othman, 2011) [14]. Hammer mills performed better than knife mills represented by various cutting mechanisms for energy cane size reduction (Miao, Grift, Hansen, & Ting, 2011) [30].

Mello and Harris (2000, 2003) [28-29] evaluated the performance of a base cutter disc fitted with blades having smooth and serrated cutting edges. They observed that the blades with serratedcutting edges caused less damage to the cut stems than the smooth-edged blades.

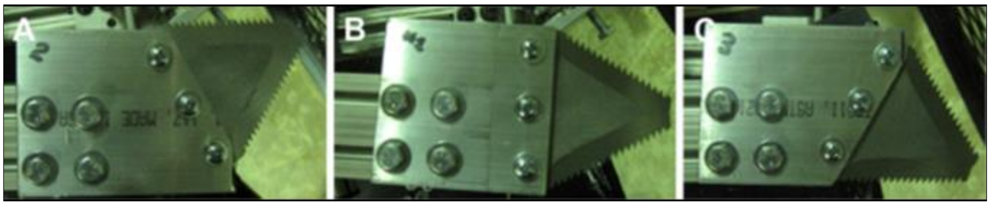

Fig 1: Serrated cutting blade mounted at different oblique angles representing: straight cut (0°) (A), 30° oblique cut (B), and 60^o oblique cut (C). (Johnson *et al.*, 2012) [20]

In addition, serrated blades with a short serrated pitch of 3 mm required less cutting energy than smooth-edged blades. The blade shape (i.e., forward or backward curved) and serrated pitch are considered important design features for serrated blades. Toledo *et al*. (2013) [44] reported that cutting blades tilted from the perpendicular axis of the base cutter produced less cane damage and that serrated blades, in combination with industry-standard base cutter discs, produced a desirable cutting height in the range of 0 to 100 mm.

Habib *et al*. (2002) [16] conducted a study of the effect on angle of the knife edge, and the plant material to the moisture content. Due to the impact of moisture content, the cutting energy consumed in the harvesting process is much lower than the energy consumed in the crushing process.

Type of cutting blade (Plane and Serrated type cutting blade)

Frazzetta, (1988) [13]. To investigate the effect of blade shape on cutting ability, Mello and Harris (2001) [27] carried out a series of lab-based cutting trials for smooth-edge and serrated blades. It was found that serrated blades have good cutting ability and are efficient in cutting force and energy consumption. Because the serrated blade cutting process involved a combination of slicing and direct cuts, cutting force was reduced compared to that with smooth-edge blades (Mello and Harris, 2000) [28]. Further, Mello and Harris (2003) [29] conducted geometric parameter studies of serrated blades, which included two important factors: the length of the serration pitch (the distance from a point on one projection to the same point on an adjacent projection) and geometric shape (Forward or backward curvature). Because the serrated blade cutting process involved a combination of slicing and direct cuts, cutting force was reduced compared to that with smooth-edge blades (Mello and Harris, 2000) [28]. Further, Mello and Harris (2003) [29] conducted geometric parameter studies of serrated blades, which included two important factors: the length of the serration pitch (the distance from a point on one projection to the same point on an adjacent projection) and geometric shape (forward or backward curved). They carried out a two-factor experiment to test two kinds (forward and backward curved) of serrated blades with different pitches (3 and 7 mm), examining the cutting energy spent for cane cutting. It was concluded that the forward blade with a 3 mm pitch has the best result among the configurations evaluated (Mello and Harris, 2003) [29]. Higher energy efficiency with smaller pitches could be because more projections per unit length make penetration easier and cutting more effective.

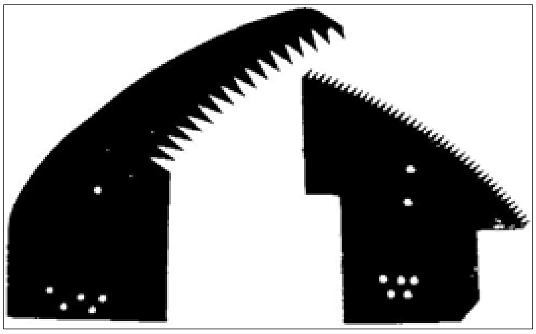

Fig 2: Forward and backward with 15 mm and 7 mm pitches in serration (Mello and Harris, 2001) [27]

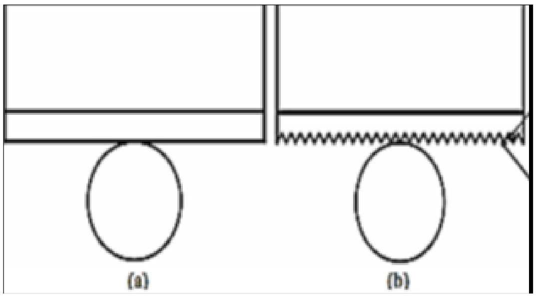

Fig 3: (a) Cutting by the smooth-edged blade; (b) cutting by the serrated blade. (Frazzetta, 1988) [13]

Momin *et al*. (2017) [32] studied the effects on sugarcane cut quality of four base cutter blade designs: a conventional straight blade, a 30° angled blade, a serrated blade, and a straight blade with laser cladding on its underside. Blades of each type were installed at a 45° angle on a base cutter fitted to a John Deere 3520 sugarcane harvester.

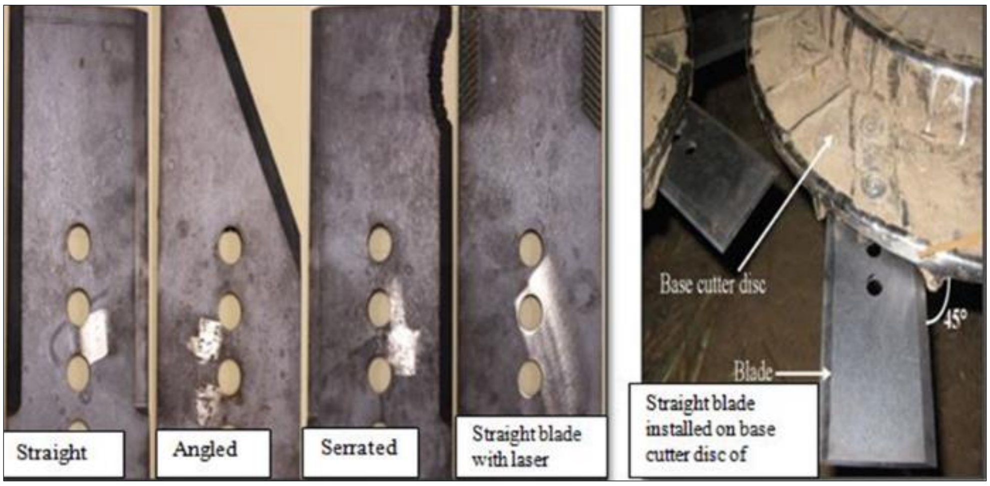

Fig 4: Four blade designs used in the experiments (Momin *et al*., 2017) [32]

In this study, the extent of stem and root system damage was classified into nine categories: (1) an undamaged stem, not uprooted; (2) an undamaged stem, partially uprooted; (3) an undamaged stem, uprooted; (4) a partially damaged stem, not uprooted; (5) a partially damaged stem, partially uprooted; (6) a partially damaged stem, uprooted; (7) a severely damaged stem, not uprooted; (8) a severely damaged stem, partially uprooted and (9) a severely damaged stem, uprooted. The highest percentage of stems damaged during harvest (approx. 38%) and the highest percentage of root systems damaged (approx. 36%) occurred with the angled blade. The percentages of undamaged stems for the straight, angled, serrated, and laser-clad blades were 76.9%, 62.1%, 83.1%, and 72.3%, respectively; partially damaged stems were 11.25%, 21.97%, 11.29%, and 17.73%, respectively; and severely damaged stems were 11.9%, 15.9%, 5.65%, and 9.9%, respectively. Except for the angled blade, all the blades cut almost 80% of stems without affecting the root system, and only 5% of stems were uprooted. The results of this study classified the levels of stem and root system damage occurring in the field during harvesting and their effects on ratooning for four base cutter blade designs.

Conclusion

This study understood the requirements for the design and development of a sugarcane harvester. On the basis of the information obtained from the study, the various base cutting parameters, such as physical and mechanical properties, cutting force and speed, cutting velocity, blade angle on cutting energy, and type of blade, could thus be inferred.

1. The study was carried out on the different varieties of sugarcane, such as CO-80036, CO-86032, COVSI-9805, CO-8014, and CO-0265. Sugarcane varieties ranged in length from 2000 to 3000 mm and diameter from 30 to 50 mm.
2. The maximum cutting force for single cane at the bottom was 2700 N and at the top was 1040 N and the crushing force varied from 750 N to 1530 N for a diameter range of 40 mm to 50 mm. The average shear strength was 3.64 MPa, varying from 3.03 to 4.43 MPa.
3. A serrated-edge blade cuts better than a smooth-edge blade, and a serrated-edge blade with a shorter pitch uses less energy.
4. Cutting force and cutting velocity were in a proportional relationship when the blade cutting velocity was less than 618 rpm.
5. The desired tilt angle could be in the range of 25° and 50° and the desired oblique angle could be between 20° and 5°.
6. The optimal combination of parameters was a blade cutting velocity of 13.8 m/s.
7. The angled blade, cut almost 80% of stems without affecting the root system, and only 5% of stems were uprooted.

Higher energy efficiency with smaller pitches could be because more projections per unit length make penetration easier and cutting more effective.

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