The Pharma Innovation Journal 2022; 11(9): 2625-2629

www.ThePharmaJournal.com

The Pharma Innovation

ISSN (E): 2277-7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2022; 11(9): 2625-2629

www.thepharmajournal.com
Received: 06-06-2022
Accepted: 30-08-2022

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Effect of cutting velocity on cutting torque of varying black gram-stem diameters at different moisture content

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Abstract
To determine the power requirement of any harvesting machine, the information about torque required to cut the plant stem is important. This study was conducted to examine the effect of peripheral cutting velocity of rotary cutting disc, stem diameter and moisture content on cutting torque requirement for cutting plant stem of black gram. A laboratory test rig consisting of a test trolley, processing trolley and vertical rotor assembly containing vertical shaft having serrated cutting disc was used to determine cutting torque. The plant stem was fixed firmly in the plant stem holder to simulate natural stand of plant stem in the field. The experimental results showed that the moisture content, plant stem diameter and peripheral cutting velocity affected the cutting torque significantly at 1% level of significance. The cutting torque increased as the diameter of plant stem of black gram up to critical peripheral cutting velocity (30 ms^{-1}), but the value decreased after critical peripheral velocity. Furthermore, torque required for cutting decreased with increasing moisture content whereas it increased with increasing stem plant diameter.

Keywords: Pulses, black gram, mechanization, harvesting, peripheral cutting velocity, cutting torque

1. Introduction

Pulses contain significantly high quality of digestible protein (20–30%) and amino acids (Darmadi *et al*., 2004) [3] and have capacity to fix the atmospheric nitrogen up to 30–40 kg N $ha^{-1}y^{-1}$ (Kebede, 2021) [7]. Pulses including green gram and black gram are beneficial for not only human beings but also for animals and soil as well as environment and favor the cultivation of subsequent crops (Pande and Joshi, 1995) [12]. Good quality seed is one of the most essential factors to enhance production and productivity of pulses. Mechanization of pulse harvesting can play a key role to get good quality seed with reduction in labor, cost and drudgery involvement apart from minimizing harvesting loss. Mechanization of pulse harvesting can be achieved only by using improved machine and to design improved machine we need the knowledge of cutting torque requirement.

The difference in the physical properties of plant stem and the cutting resistance must be identified with the aim of knowing the behaviour of material with respect to different operating conditions of harvesting and threshing. Failure in shear or impact or both is possible while acting a system of forces on the material and before shear failure, the material is essentially first compressed then bend resulted in increased work required in a cutting operation (Kepner *et al*., 1978) [8]. When critical value of pressure applied by the blade reaches; plant stem cutting completes and results in multiple modes of tissue failure (Persson, 1987) [13]. Enhanced awareness in mechanized crop harvesting and commercial use of straw has invigorated the requisite for engineering data on plant stem properties (Yore *et al*., 2002) [22].

Comparative performance of cutting elements used in the design of the harvester can be reviewed by its cutting energy requirements, cutting force and stress applied (Chakraverty *et al*., 2003) [2]. Hence, it is necessary to determine the cutting energy requirements for suitable knife design and operational parameters. A cutter bar test rig for registering the dynamic force requirement for cutting green gram and black gram plant stem was developed by Mantesh (2006). He reported that cutting force increases as increase in plant stem diameter. Many researchers have worked to know the cutting strength of the plant stem and effective parameters on cutting energy for different crops. Plant parameters that influence cutting energy and cutting force like stem structure, fibre ultimate tensile strength and fibre stiffness (Persson,

1987) [13]. Other parameters that influence cutting energy and force such as design of the knife blade, cutting material properties and mode of operation (Womac *et al.*, 2005; Ghahraei *et al.*, 2011) [20, 5]. They reported that the moisture content, plant stem diameter of the crop had significant effect on cutting energy and maximum cutting force (Yilmaz *et al.*, 2008) [21]. The peak cutting energy requirement was found to be directly proportional to plant stem diameter and inversely proportional to plant stem moisture content and cutter bar speed (Kathirvel *et al.*, 2009) [6]. Sushilendra *et al.* (2016) [17] found a positive correlation between cutting force and cutting energy with stalk area but negative correlation with cutting force and energy with cutting and reported that serrated blade cut more efficiently than smooth edge blade at same cutting velocity. The cutting speed had substantial effect on cutting torque and cutting power requirement. The rotary velocity of cutting disc was directly proportional to the specific cutting power, but the cutting torque was inversely proportional to the moisture content of plant stem (Dauda *et al.*, 2015) [4].

Traditionally, harvesting and threshing of black gram crop is done by manually i.e. harvesting is done either by uprooting or using sickle in India (Maharana *et al.*, 2018) [10]. Harvesting of pulse crop can be done manually with or without cutting tools (Singh and Singh, 1978; Pitra and Gite, 1980; Salkini *et al.*, 1983; Kulkarni and Sirohi 1985; Maharana *et al.*, 2018; Tiwari *et al.*, 2017) [16, 14, 15, 9, 10, 18]. Manual harvesting is labour intensive, time-consuming, expensive and involves human drudgery. The shortage of labour and bad weather during season often results in delayed harvesting. Timely harvesting of the pulse crop is essential to minimizes losses and achieve quality produce. Manual harvesting of green gram and black gram involves 200–240 man-h per hectare (Maharana *et al.*, 2018) [10]. These crops are harvested manually with sickle or by uprooting. Tully (1984) [19] estimated that manual harvesting with hand pulling cost around 50–56% of total lentil production cost.

It has been reported that in some areas uprooting of crops such as green gram and black gram are performed by contract basis by the available work force of the village and they charge about 50–60% of the crop as a wage for uprooting and transporting to owners threshing yard in Odisha (Maharana *et al.*, 2018) [10]. To overcome the drudgery associated in manual harvesting and costly manual farm labour, suitable mechanical harvesting is the only option left for viable cultivation of pulses. Pulses stand second in the Odisha and their share has increased in the past decade from 14.8 to 22.3%. Green gram, black gram, and arhar covered 826, 435 and 129 thousands hectares; respectively in 2016–2017 (Anonymous, 2021) [1]. Black gram is one of the principal pulse crops in Odisha.

With the above facts in mind, the cutting torque requirement for cutting plant stem of black gram (variety: OBG-38) was studied. The specific objective of the study was to examine the effect of moisture content, peripheral speed of rotary cutting disc and stem diameter on cutting torque requirement for cutting plant stem of black gram.

2. Materials and Methods

Determination of cutting torque required to cut stem of black gram was performed at the test soil bin in the Department of FMPE, CAET, OUAT, Bhubaneswar. A laboratory test rig consisting of a test trolley, processing trolley, vertical rotor assembly and plant stem holder. Vertical rotor assembly consists of vertical shaft having serrated cutting disc. The system has a provision of varying forward speed, rotor speed, and height of cut. An experiment was designed as 3-factors complete randomised design with three replications to determine cutting torque required to cut black gram (Table 1) and analysis was done by using statistical software MSTATC (version: Mstat 5.4).

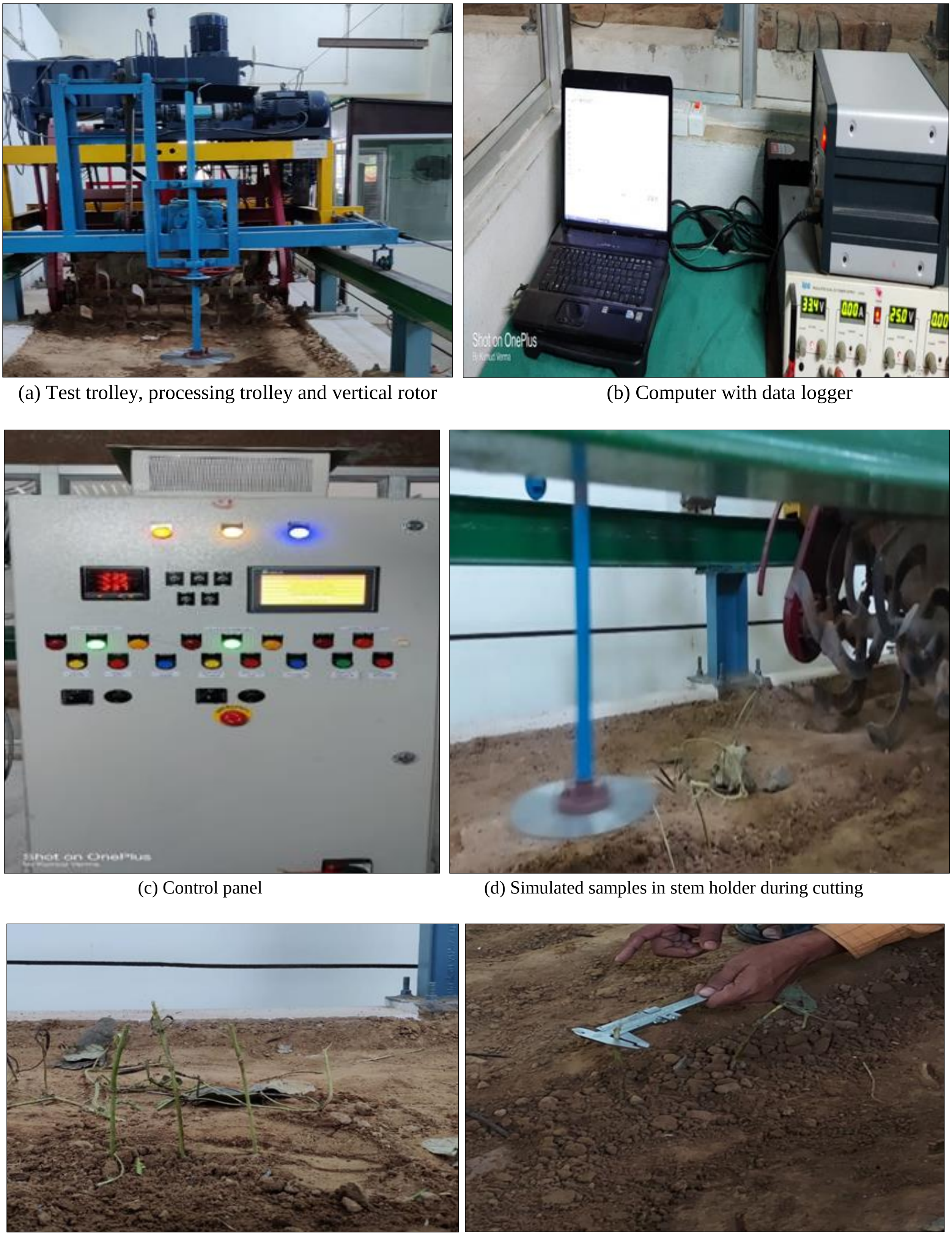
Table 1: Experimental design for determining cutting torque for black gram crop

Independent variables		Reasons for selecting the levels	Observed variables
Variables	**Levels**		
Moisture content of crop, % (wb)	M_1= 35–38	Black gram moisture content of crop varies from 35–45% (wb) at the time of harvesting.	Cutting torque, Nm
	M_2= 38–42		
	M_3= 42–45		
Peripheral cutting velocity, ms^{-1}	V_1 = 20	Plants are cut sharply only higher than a specific velocity (critical velocity).	
	V_2 = 25		
	V_3 = 30		
	V_4 = 35		
Diameter of plant stem, mm	D_1 = 3	Cutting force requirement is directly related to plant stem diameter.	
	D_2 = 4		
	D_3 = 5		

Plants of black gram (Variety: OBG-38) were uprooted from the EB-2 field of OUAT, Bhubaneswar (20°15’48” N 85°48’34” E) and brought to the laboratory in sealed plastic bags and experiments were conducted on the same day. Experimental stet-up of the test soil bin of CAET, OUAT, Bhubaneswar (Fig. 1a) was used for the experiment. The plants were fixed in diameter hole of 3, 4, and 5 mm into plant stem holder and placed under soil of stationary bin. Having been adjusted the rotary cutting disc of vertical rotor assembly at proper cutting height, the required motor speed (5 hp, AC and rpm of 1400) and forward speed (0.3 ms^{-1}) of the processing trolley were adjusted and fixed. Power of motor was transmitted to input shaft of vertical rotor assembly through V- belt (1:1 gear ratio), then power was transmitted to shaft of bevel gear arrangement shaft (1:1.5 gear ratio) having a gear box (2:1 gear ratio) through belt and pulley. After that power was then transmitted to the rotor shaft by V-belt and pulley arrangement through which rotary cutting blade (1:3 gear ratio) was attached as well as vertical rotor assembly was connected with processing trolley by means of nut and bolts. Owing to this arrangement vertical rotor assembly gets forward speed and rotary cutting disc gets rotary speed resulted in to cut the plant stem placed under soil of stationary bin and diameter of plant stem was recorded using vernier calipers (Aerospace; 300×0.02 mm). The torque required to drive the rotor shaft of motor was measured, which was displayed on the monitor through data acquisition system (GTDL350 data logger with provision for 8 channels and multi-scan plus multi-fold software; Joo Shinn Corporation, Kyeonggi-do, Korea) which was noted down. The torque required to drive rotary blade was calculated using equation 1.

$$T_R = \frac{T_M}{V_R}$$

Where,
T_M = Motor torque, Nm
T_R = Rotor torque, Nm
V_R = Velocity ratio



(a) Test trolley, processing trolley and vertical rotor

(b) Computer with data logger

(c) Control panel

(d) Simulated samples in stem holder during cutting

(e) Simulated sample after cutting

(f) Measurement of stem diameter

Fig 1: Experimental stet-up of test soil bin

3. Results and discussion

3.1. Analysis of variance (ANOVA)

The analysis of variance (ANOVA) was conducted considering moisture content of crop (MC, 39.2, 41.4 and 42.9%, (wb)), plant stem diameter (PSD, 2.95, 3.97 and 4.96 mm) and peripheral cutting velocity (PCV, 20, 25, 30, and 35, ms^{-1}) as dependent variable and torque required for cutting as a depended variable. The results from the ANOVA analysis in mentioned in Table 2. It is evident from the Table 2 that moisture content of crop, plant stem diameter and peripheral cutting velocity affected the torque required for cutting crop significantly at 1% level of significance. However, the combined effect of moisture content of crop and plant stem diameter as well as plant stem diameter and peripheral cutting velocity was found to be non-significant. This may be due to opposite effect of concerned variables on torque required for cutting by peripheral cutting velocity.

Table 2: Analysis of variance results of the experiment

Sl. No.	Source	DF	SS	MS	F-value	p-value
1.	MC	2	5.86	2.93	24.12	0.00
2.	PSD	2	299.1	149.54	1230.97	0.00
3.	MC×PSD	4	1.15	0.29	2.37	0.06
4.	PCV	3	6.49	2.16	17. 99	0.00
5.	MC×PCV	6	0.01	0.00	0.01	
6.	PSD×PCV	6	0.03	0.05	0.44	
7.	MC×PSD×PCV	12	0.00	0.00	0.00	
8.	Error	72	8.75	0.12		
9.	Total	107	321.66			

3.2. Effect of plant stem diameter (PSD) and moisture content (MC) on cutting torque

The effect of moisture content (MC) of crop and plant stem diameter on torque requirement for cutting for the black gram crop (BCG) has been presented in Fig. 2. The average torque required for cutting was found to be 6.64, 6.34 and 6.076 Nm at moisture contents of 39.4, 41.2 and 42.7% (wb), respectively. Similarly, the average torque required for cutting was observed to be 4.26, 6.45, and 8.33 Nm against diameters of 2.94, 3.96 and 4.97 mm.

As evident from Fig. 2, torque required for cutting decreases with increasing moisture content whereas it increased with increasing stem plant diameter. It might be due to less hard pith or less stiffness of fibre to be cut at higher moisture content than at lower moisture content. It is due to pass larger cross-sectional area by disc for larger plant stem diameter. Similar results were also reported by Dauda *et al.* (2015) [4].

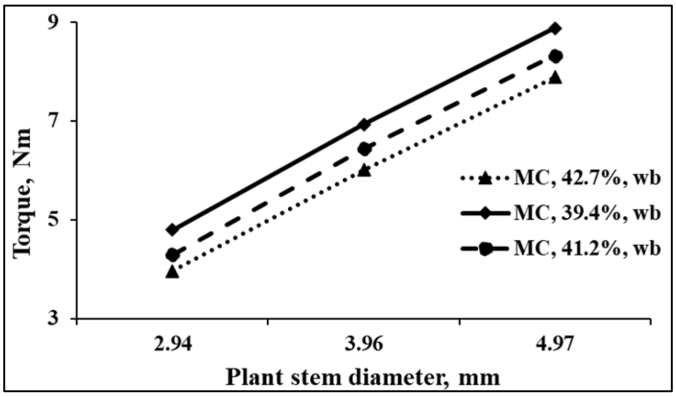


Fig 2: Effect of plant stem diameter on torque required for cutting at different moisture content.

3.3. Effect of peripheral cutting velocity (PCV) and moisture content (MC) on cutting torque

The effect of moisture content of crop and peripheral cutting velocity (PCV) of rotary cutting disc on torque required for cutting crop is illustrated in Fig. 3. The average torque required for cutting crop was found to be 6.07, 6.37, 6.73 and 6.28 Nm at peripheral cutting velocities of 20, 25, 30, and 35 ms^{-1}, respectively.

It is evident from Fig. 3, the torque required for cutting crop decreased with increasing moisture content of crop whereas it increased with increasing peripheral cutting velocity up to 30 ms^{-1} subsequently the torque required for cutting crop decreased as increased of peripheral cutting velocity. It indicates that 30 ms^{-1} is the critical peripheral cutting velocity in test soil bin condition for cutting black gram crop. Similar results were reported by Dauda *et al*. (2015) [4].

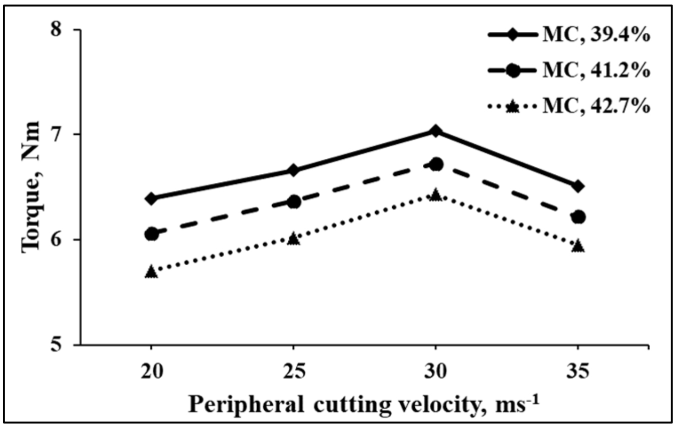


Fig 3: Effect of peripheral cutting velocity on toque required for cutting at different moisture content.

3.4 Effect of plant stem diameter (PSD) and peripheral cutting velocity (PCV) on cutting torque

Figure 4 illustrates that the torque required for cutting increases with increasing plant stem diameter whereas it increased with increasing peripheral cutting velocity up to critical peripheral cutting velocity after that the required cutting torque decreased as increased of peripheral cutting velocity. Similar results were also obtained by Dauda *et al.* (2015) [4].

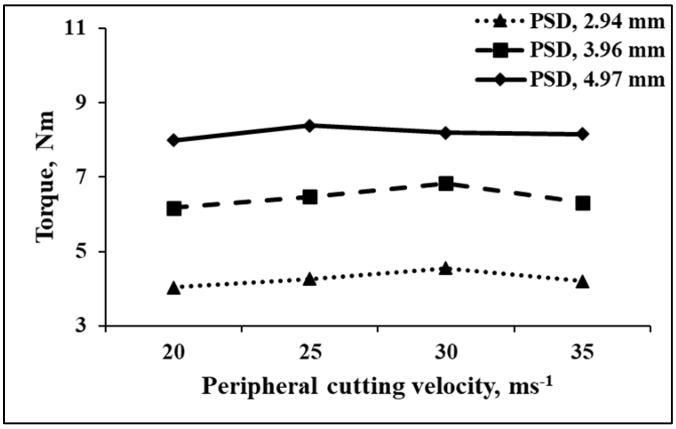


Fig 4: Effect of Peripheral cutting velocity on torque required at different plant stem diameter.

4. Conclusions

The study evaluated the torque requirement for cutting the black gram stems at different moisture content (39.4, 41.2 and 42.7% (wb)), plant stem diameter (2.94, 3.96 and 4.97 mm) and peripheral cutting velocity (20, 25, 30, and 35 ms^{-1}). The experimental results showed that the required cutting torque increased as the diameter of plant stem of black gram up to critical peripheral cutting velocity (30 ms^{-1}), but the value decreased after critical peripheral velocity. Furthermore, torque required for cutting decreases with increasing moisture content whereas it increased with increasing stem plant diameter. The moisture content of crop, plant stem diameter and peripheral cutting velocity affected the torque required for cutting crop significantly at 1% level of significance.

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