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RESEARCH ARTICLE

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Development of a laboratory setup simulating cabbage harvesting mechanism and optimization of torque requirement for harvesting cabbage

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Abstract

Aim of study: To develop a new type of cabbage (*Brassica oleracea* L.) harvesting mechanism in the laboratory that can be used in small-scale cabbage harvester in Indian conditions with minimum power requirement.

Area of study: Indian Institute of Technology, Kharagpur, India.

Material and methods: The mechanism consisted of a cutting unit, a pushing unit and a conveying unit. Two counter-rotating disc cutters were used as cutting devices. Cutting speed, forward speed and cutting position were considered as influential parameters for torque required to carry out the harvesting of cabbage. A full factorial design was followed for the experiment and response surface methodology was used to optimize these parameters for minimizing torque requirement for cutting and pushing the cabbage.

Main results: Torque decreased when cutting speed increased and when cutting height from the cabbage head decreased. Statistical analysis showed that cutting speed and cutting position affected the total torque significantly. The optimized cutting speed, forward speed and cutting position were found as 590 rpm, 0.25 m s^{-1} and 0 cm, respectively with a desirability of 0.995. A regression model was developed to predict the total torque for cutting the cabbage stem and it was validated against 10 datasets with a percentage of bias within 10%.

Research highlights: The mechanism developed for cabbage harvesting could successfully cut and lift the cabbage heads in the laboratory. These optimized parameters are to be followed in the field prototype cabbage harvester for its successful operation in the field.

Additional key words: cabbage harvester; cutting torque; pushing torque; response surface methodology; regression model; *Brassica oleracea*.

Abbreviatons used: AMCT (absolute maximum cutting torque); AMPT (absolute maximum pushing torque); ANOVA (analysis of variance); CAD (computer-aided design); COV (coefficient of variance); DAS (data acquisition system); DC (direct current); MS (mild steel); RSM (response surface methodology); SD (standard deviation); Std (standard).

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Introduction

Manual harvesting of cabbages (*Brassica oleracea* L.) is a very common practice in India. In this process, the cabbage head is first bent to one side and then cut with a knife. Damage may take place if the head is harvested by twisting or snapping and it also results in inconsistent stem length (Tamta et al., 2014). A considerable amount of energy is required to cut the cabbage heads from their stems in this method (Du et al., 2015, 2016). Also, rural farmers face various physical problems with this traditional method of harvesting. Biomechanical stresses in the back, neck, upper and lower limbs, bruises on hands, direct exposure to fertilizers and pesticides, and various heat-related illnesses are some of the major problems associated with this method of harvesting cabbage (Shenoi et al., 2005; Jain et al., 2018).

Research work related to harvesting of cabbage has been progressed significantly in Europe, the United States, Japan, and China (Kanamitsu & Yamamoto, 1996; Chagnon et al., 2004; Hachiya et al., 2004; Gao et al., 2015; Du et al., 2016). But in India, despite of being the second-largest producer of cabbage in the world, only a few research works have been conducted related to cabbage harvesters as cabbage is grown in small land holdings. Most of the cabbage harvesters in foreign countries need a prime mover that runs on conventional fuel. More than one operator is also required to run it in the field. In India, 86.2% of farmers are small and marginal farmers having less than two hectares of land. Because of such small land sizes and the irregular shape of fields, it is difficult to carry out field operations properly (Anonymous, 2018; Nataraj et al., 2021; Sarkar & Raheman, 2021b). According to this type of landholdings and the economic status of Indian farmers, a cabbage harvester should be developed with low power consumption and comparatively smaller size (preferably single-row) for better handling in smaller fields and with minimum damage to cabbages during cutting and conveying (Sarkar & Raheman, 2021a). Hence, it is required to develop a suitable mechanism to harvest cabbage and select the corresponding operating parameters for its efficient performance.

Research works have been carried out to study the different cutting parameters of cabbage prior to developing a cabbage harvester. Xu & Yao (2009) reported that shearing force varied as the cutting speed increased in Chinese cabbage stems. The thickness of knife edge and shearing force were positively correlated whereas smoothness of the knife edge and the shearing force were negatively correlated. Li et al. (2013) conducted single-factor and multifactor orthogonal tests to study the main influencing factors like blade types, cutting ways, cutting speeds and cutting positions on the cutting force for cabbage root. According to Du et al. (2014), the single-point clamping technique could reduce the cutting force of the cabbage root effectively, but it might increase the chance of splitting of stem. They optimized the cutting position for a Chinese cabbage harvester and the relationships between cutting forces and chemical composition were studied. Fibre content was found as the most influential parameter for cutting force. When the diameter of the cabbage stem was in the range of 30-35 mm, the minimum cutting force was observed. Du et al. (2016) studied the physical properties of Chinese cabbages which influenced the harvesting process. Indian cabbage varieties have spherical or teardrop shapes whereas Chinese cabbage has an oblong shape. It has been reported that cutting force varied when the stem diameter changed and plant height was the most important factor to design the conveying system. Zhou et al. (2017) conducted an optimization test for pulling out the cabbages in a test bed. Rotational speed, spacing of two screw poles, and their angle with the ground was considered as influencing factors to determine the efficiency of pulling out of cabbages.

From the literature review, it was found that cutting speed, cutting position and forward speed are the major influential parameters for cutting cabbage stems. Nowadays, minimization of the energy demand has been the major objective of scientists and researchers by optimizing different machine and operating parameters in different field conditions (Choudhary et al., 2021; Hensh et al., 2021; Sarkar et al., 2021). Optimization process is important to obtain the best cutting quality with minimum power input. To solve such optimization problems, there are several progressive methods available such as response surface methodology (RSM) (Danish et al., 2017; Aslantas et al., 2020; Chai et al., 2020; Vu et al., 2020; Liu et al., 2022), Taguchi method (Li et al., 2016), and artificial neural networks (ANN) (Liu B et al., 2020). Among these methods, RSM defines the effect of the independent variables, alone or in combination on the process. It also analyses the effects of the independent variables on the output and generates a mathematical model that accurately predicts the overall process (Senanayake & Shahidi, 2002). It has been successfully applied to optimize conditions in food, chemical and biological processes (Andersson & Adlercreutz, 1999; Beg et al., 2002; Özoğlu & Bayındırlı, 2002).

In this paper, a new type of cabbage harvesting mechanism has been developed in the laboratory that can be used in small-scale cabbage harvesters in Indian conditions with minimum power requirement. The influence of important parameters like cutting speed, forward and cutting position on torque requirement and cutting quality were investigated for 'Pusa Mukta' cabbage variety. As there is no in-depth research carried out on cutting Indian cabbage varieties before, this study will be beneficial to develop a cabbage harvester for cutting them.

Material and methods

Measurement of the physical properties of cabbage

To design the laboratory setup for the cabbage harvesting mechanism, a measurement of the physical properties of the cabbage head was required. The most important physical properties (Fig. 1) measured in this study to develop the laboratory setup were: head weight (kg), head height (mm), head diameter (mm), stump diameter (mm), leaf stem length (mm), stump length (mm), feeder leaf diameter (mm), spacing of leaves (mm), and feeder leaf angle

Table 1. Physical properties of cabbage.

Physical properties	Max	Min	Mean	Variance	SD	COV
Head weight (kg)	1.67	0.83	1.18	0.06	0.26	21.63
Head height (mm)	182	135	158	206.6	15.15	9.57
Head diameter (mm)	178	154	165.5	55.41	7.84	4.75
Stump diameter (mm)	29	20.5	24.36	4.97	2.35	9.65
Leaf stem length (mm)	78	60	68.35	39.7	6.64	9.71
Stump length (mm)	81	65	71.9	31.09	5.88	8.07
Max. feeder leaf diameter (mm)	472	367	427.7	1428.8	39.85	9.31
Feeder leaf angle (˚)	56	25	36.1	57.29	7.97	22.1

SD: standard deviation. COV: coefficient of variance

(°). A total of 10 samples were taken for the measurement. The dimensions of the cabbages are given in Table 1 and the dimensions of the laboratory setup were decided based on these parameters. The moisture content of the cabbage stem at the time of harvesting was 38% (dry basis).

Laboratory setup

A laboratory setup was developed at the Agricultural and Food Engineering Department of IIT Kharagpur to measure the torque required to cut and push a cabbage head. The setup consisted of a main frame, a plant holding frame, and a processing trolley (Fig. 2).

Main frame and plant holding frame

The main frame or rail was constructed to hold the processing trolley and the plant holding frame. A C-channel (70×40×40 mm) was used to make a rectangular frame of 4000 ×900 mm. The rail was kept 400 mm above the ground surface for ease of operation.

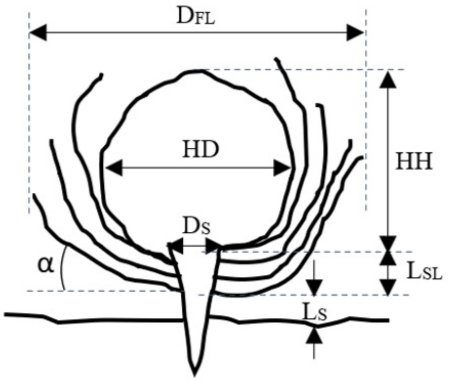

Figure 1. Physical properties to be measured. DFL, feeder leaf diameter; LSL, leaf stem length; DS, stump diameter; HD, head diameter; LS, stump length; HH, head height; α, feeder leaf angle.

A rectangular frame (2100 × 820 mm) with an arrangement to hold the cabbage plants was fabricated from a mild steel (MS) angle (25 × 25 × 3 mm) as shown in Fig. 2. The frame had provisions to hold the stems of three cabbage plants at a distance of 600 mm, thus it exactly simulated the standing cabbage in the field. A semicircular clip of radius 15 mm (the maximum diameter of a cabbage stem at the harvesting stage is 29 mm) was attached to the MS angle to hold the cabbage. A provision was made in the clamp to loosen or tighten the stem depending on the stem diameter of the cabbage plants.

Processing trolley

The processing trolley consisted of a cutting unit, a pushing unit, and a conveying unit (Fig. 3). The processing trolley moved over the rail powered by a direct current (DC) motor. The cabbage plants held in the plant holding frame were pushed back to a conveyor after cutting and the cabbage was then conveyed to a storage unit through a conveyor belt.

— *Cutting unit.* In our experiment, the concept of support cutting was adopted instead of free cutting. In free cutting, cutting of the cabbage stem relies on the inertia of stem; the stem can easily be damaged in the later stage of the cutting process (Bethel & Harger, 2014). By contrast, support cutting provides an extra support point while the stem is being cut, thus reduces the required cutting force and power consumption (Zhang et al., 2017). Moreover, the extra support increases the resistance of the stem to bending resistance, reduces deflection, and improves cutting quality (Geng, 2011; Lu et al., 2013). Based on these findings, two counter-rotating discs were used to cut the cabbage stems. During the cutting process, two serrated blades (outer diameter 300 mm, inner diameter 290 mm, thickness 1.25 mm and number of teeth100) cut cabbage stems from both sides at the same time, thus avoiding the deflection of the cabbage stem caused by the impact of blade. An overlap of 3 mm and a clearance of 2 mm were provided between the two blades to ensure complete and smooth cutting of the stems.

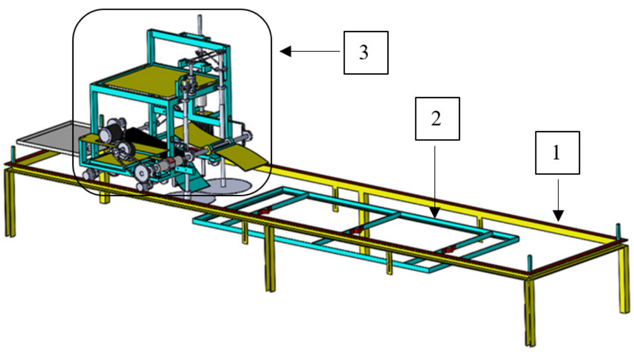

Figure 2. Computer-aided design (CAD) model of laboratory setup. 1, main frame; 2, plant holding frame; 3, processing trolley.

The literature review showed that rotation of the blade from 400 to 600 rpm could be suitable for cutting cabbage stem efficiently (Du et al., 2016). So, for the selection of motor for cutting, the following calculation was done: desired speed (maximum) = 600 rpm; cutting force (max) = 230 N (Du et al., 2016); disc diameter = 30 cm; cutting torque = (230×0.15) = 34.5 Nm; speed reduction = 3:1; and motor torque = 11.5 N-m.

As the required speed is higher, the DC motor (850W, 48V, 3000 rpm, 60 Nm) would be suitable for this purpose as it meets both speed and torque requirements.

A counter-rotating arrangement was made with the help of two cycloid type of gears to rotate the cutting discs in opposite directions. Four 12 V 18 Ah batteries were used in series to supply power to this motor. The speed of the motor was controlled by using a motor controller and speed regulator. A torque transducer (HBM T22/100 N-m) was placed between the DC motor and the shaft to measure the cutting torque.

— *Pushing unit.* It consisted of a pusher and a DC motor. The DC motor rotated the pusher with a speed reduction of 2:1 through the chain and sprocket transmission.

$$\text{Maximum pushing force: } F = (\mu\times m\times g)$$

where, μ = coefficient of friction of cabbage head with the belt material (from the experiment it was found as 0.364); m = maximum weight of cabbage head (kg); and g = gravitational acceleration (m s^{-2}).

$$F = (\mu\times m\times g) = (0.364\times1.67\times9.81) = 5.96 \text{ N}$$

Considering the head height of the cabbage, the length of the pusher plate was taken as 350 mm. So, the torque required at the pusher end = (5.96×0.35) =2.086 Nm.

Speed reduction = 2:1, factor of safety 3, and assuming a transmission efficiency of 80%:

$$\text{The required motor torque for pusher} = \frac{(2.086\times3)}{(2\times0.8)} = 3.91 \text{ Nm}$$

For this purpose, a 250 W DC motor (24 V, 8 Nm rated torque) was found to be suitable. Two 12 V 12 Ah batteries were connected in series to power the DC motor. The pusher had two plates (300×200 mm) with 180° intervals. The pusher plate was actuated by the operator using a push button switch.

The surfaces of the plates were made curved according to the surface of a cabbage head so that it could easily push and lift the cabbage heads to the conveyor belt. Two pusher plates were attached to the pusher shaft. A 30 teeth

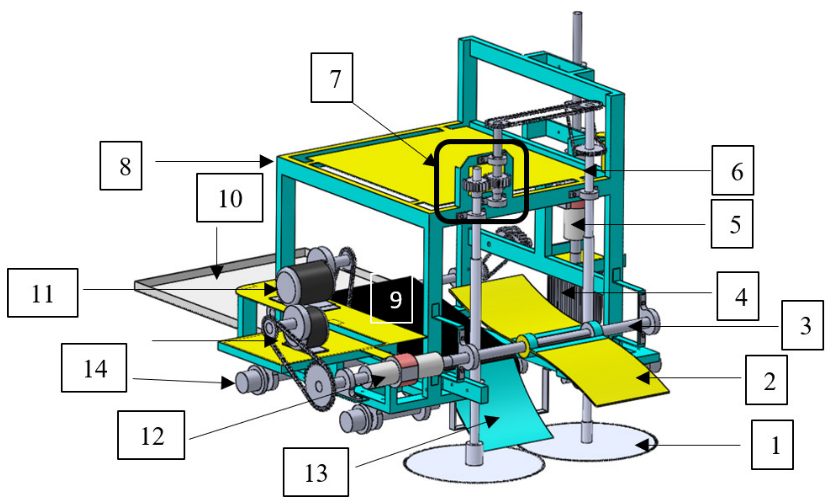

Figure 3. Computer-aided design (CAD) model of processing trolley: 1, cutting disc; 2, curved plate for pushing; 3, pusher shaft; 4, direct current (DC) motor for cutting; 5, torque transducer for cutting torque; 6, cutting shaft; 7, counter-rotating arrangement; 8, frame; 9, conveying belt; 10, tray; 11, DC motor for propelling and conveying; 12, torque transducer for cutting torque; 13, inclined plate; 14, roller.

Table 2. Experimental plan for laboratory test.

	Low level	High level
Independent parameters		
Cutting speed (rpm)	400	600
Forward speed (m s^{-1})	0.22	0.32
Cutting position from bottom leaf (cm)	0	2
Dependent parameters		
Torque required for cutting (Nm)		
Torque required for pushing (Nm)		

sprocket was mounted at the end of the shaft and a torque transducer (HBM T22/100 N-m) was attached to measure the torque required to push the cabbage as shown in Fig. 3. The rpm of the pusher was fixed based on the forward speed and spacing of the cabbage plants. The speed of the pusher needed to be neither so fast that the cabbage heads were damaged nor so slow that the next cabbage plant was missed. Considering that cabbage plants were spaced 60 cm apart and the average walking speed of operator at 1 km h-1, the motor was selected to run at 65 rpm.

— *Conveying unit.* It consisted of two pulleys, a conveyor belt, and a curved plate placed between the conveyor belt and the cutting disc. After cutting, cabbages were pushed to a conveyor belt and then these cabbages were moved to a storage tray attached at the rear of the processing trolly. Based on the availability in the market, the diameters of the front and rear pulleys were 7.5 cm and 5 cm, respectively, with a center-to-center distance of 100 cm. The conveyor belt was made of rubber and the width was chosen as 30 cm. The rear pulley i.e., the driving pulley for the belt was powered by the propelling shaft using a chain and sprocket. As the direction of the pulley was to be opposite to the forward motion of the processing trolley, a counter-rotating arrangement was provided between propelling shaft and rear pulley shaft using two spur gears of the same size. The relation between conveyor belt speed and forward speed was established using the following equations (Du et al., 2016):

$$\frac{\pi n_B D_B}{60} > \frac{V_m}{cos\alpha} \quad (1)$$

$$\frac{\pi n_B D_B}{60} > \frac{\pi n_r D_r}{60 \times cos\alpha} \quad (2)$$

$$\frac{n_B}{n_r} > \frac{D_r}{D_B cos\alpha} \quad (3)$$

where n_B is the rotating speed of the belt roller, rpm; n_r is the rotating speed of the propelling shaft; D_B is the diameter of the rear belt pulley, mm; V_m is the forward speed, m s^{-1}; α is the angle between transverse belt and ground in degrees; D_r is the roller diameter of processing trolley.

From the experiment, the angle of friction between the cabbage and the belt material was found as 19.5°. Hence, the angle between the transverse belt and ground (α) was taken as 15°. Based on the availability in the market, the pulley diameter and roller diameter were selected as 50 mm and 60 mm, respectively. So, in our experiment, α = 15°; D_B= 50 mm; D_r = 60 mm.

From Eq. (3), $n_B/n_r > 1.24$. So, the speed ratio between propelling shaft and rear belt pulley shaft was chosen as 1.5 (sprocket on propelling shaft of 15 teeth and sprocket on rear belt pulley shaft of 10 teeth).

A DC motor was used to supply the power for both propelling and conveying. The selection of the motor was made such that it would be capable of field prototype also. The calculation for the selection of a motor is as follows (Brixius, 1987):

$$Motion\ resistance\ of\ one\ wheel = \left[\left(\frac{1}{B_n} + 0.04 + \frac{0.5\,s}{\sqrt{B_n}}\right) \times W_g\right] \quad (4)$$

$$B_n = \frac{CIbd}{W_g}\left[\frac{1+5\delta/h}{1+3b/d}\right] \quad (5)$$

where B_n = mobility number, s = slip (%), CI = cone index (kN m^{-2}), W_g = dynamic load on one wheel (N), b = unloaded tyre section width (m), d = unloaded tyre diameter (m), h = tyre section height (m), δ = deflection (m).

It was assumed that the total weight of the harvester would be 180 kg. The other parameters for the pneumatic tire were, b = 10 cm; d = 41 cm; h = 11 cm; δ = 1.02 cm.

$$B_n == \frac{700 \times 1000 \times 0.10 \times 0.41}{90 \times 9.81}\left[\frac{1 + 5(\frac{0.0102}{0.11})}{1 + 3(\frac{0.10}{0.41})}\right] = 27.40$$

Motion resistance of one wheel = 75.97 N.

Motion resistance of two wheels = (75.97×2) N = 151.94 N.

Torque required for the wheel shaft for propelling = (151.94×0.195) Nm = 29.63 Nm, (static loaded radius of the wheel = 0.195 m).

The required torque (T) for conveying was computed under the assumption that maximum two cabbages could be conveyed at the same time on the conveyor belt and the formula is given below:

$$T = \frac{1}{2}D(F + \mu \cdot m \cdot g \cdot cos\theta) \quad (6)$$

Table 3. Parameters for model verification (Liu et al., 2022).

Terms	Expression	Remarks
R^2	$R^2 = \frac{SS_{Res}}{SS_T}$	Close to 1.0 is ideal.
$R^2_{adjusted}$	$R^2{}_{adj} = \frac{1 - SS_{Res}/(n-p)}{1 - SS_T/(n-1)}$	Close to 1.0 is ideal.
PRESS	$PRESS = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$	The value should be small.
$R^2_{predicted}$	$R^2{}_{pred} = 1 - \frac{PRESS}{SS_T}$	No more than 0.2 discrepancy between R^2_{adj} and R^2_{pred} should be expected.

SS_{Res} = square sum of error; SS_T= total sum of squares; f = number of distinctly different factor combinations; p = number of parameters; n = experimental number; y_i = observed value; $\hat{y}_i$ = predicted value.

where D = diameter of pulley (m), F= external force (N), μ = friction coefficient (0.354), m = mass of load (3.34 kg), g = gravity acceleration (9.8 m s^{-2}), and θ = inclination of conveyor belt (15˚). The torque requirement for the driving shaft of conveyor becomes 0.35 Nm. This driving shaft was run at a speed 1.5 times higher than the speed of the wheel shaft.

Torque requirement at wheel shaft for conveying, T = 0.28 Nm.

Total torque requirement = (29.63+0.28) Nm = 29.91 Nm.

The speed ratio between the motor and the wheel shaft was 8:1 and assuming a transmission efficiency of 80% and factor of safety 3, the required motor torque,

$$T = \frac{(29.91 \times 3)}{(0.8 \times 8)} = 14.02\, Nm$$

Hence, a 650 W DC motor (24V, 15 Nm rated torque) is suitable for propelling and conveying.

Torque measurement

The torques required for cutting and pushing were measured by using a T22/100 Nm torque transducer (HBM Darmstadt Germany). The nominal sensitivity of the torque transducer was 5 V and 8 mA with a composite error of ±0.3 and an excitation voltage (DC) range of 11.5-30 V (Upadhyay & Raheman, 2020).

The torque transducer was calibrated before starting experiments by applying known torque and the corresponding outputs were acquired through a Data Acquisition System (DAS). The calibration setup used for the torque transducer is shown in Fig. S1 [suppl]. The same procedure was repeated several times and the calibration curve was drawn as shown in Fig. S2 [suppl]. From the calibration result, it was observed that the output torque varied linearly with the input torque with a high value of the coefficient of determination (R^2 = 0.99).

Experimental plan

In the cabbage harvesting process, machine parameters like cutting speed (rpm), forward velocity of the harvester, and cutting position of the cabbage stem are known to influence the torque requirement for cutting and pushing. Preliminary trials were carried out to find the minimum cutting speed required for cutting the cabbage stems. It was found that at speed of cutting disc below 400 rpm, the cutting resistance offered by the stem was enough to stop the rotation of the disc. Cutting speed, forward speed and cutting position from the bottom leaf were taken as independent variables in these experiments.

The rotating speed of the cutting unit was varied from 400 to 600 rpm (Chagnon et al., 2004; Du et al., 2016). Since the unit to be developed is for a human-operated walking-type cabbage harvester, the average forward speed was kept in the range from 0.22 m s^{-1} to 0.33 m s^{-1}. The cutting position was considered as the distance between the cabbage head bottom and the cutting point (Fig. 4). It was varied between 0 cm to 2 cm (Li et al., 2013; Du et al., 2014).

The experimental plan for conducting different tests is given in Table 2. In the experiment (Fig. S3 [suppl]), QuantumX data acquisition system (DAS) was used which had 8 channels for acquiring data (Fig. S4 [suppl]). The transducer was connected to the DAS through a commercially available 15-pin 3-row D-type connector. The DAS was connected to the laptop through Ethernet. During operation, excitation voltage was supplied by the DAS to the transducers which in turn produced output signals, which were acquired through the DAS and saved in a laptop. The power supply to the DAS was provided by a 12 V, 7 Ah battery. The recorded data from the torque transducer were stored on a laptop through the Catman Easy software. The

Table 4. ANOVA for the effect of forward speed, cutting speed and cutting position on total torque requirement.

Sum of source	Squares	df	Mean square	F value	p-value Prob > F
Model	33.77	6	5.63	150.25*	< 0.0001
A-Cutting speed	13.07	1	13.07	349.03*	< 0.0001
B-Forward speed	0.15	1	0.15	4.09	0.0561
C-Cutting position	20.52	1	20.52	547.93*	< 0.0001
AB	4.033E-003	1	4.033E-003	0.11	0.7460
AC	3.675E-003	1	3.675E-003	0.098	0.7572
BC	9.075E-003	1	9.075E-003	0.24	0.6277
Residual	0.79	21	0.037		
Lack of fit	0.79	20	0.039		
	Pure error	0.000	1	0.000	
	Cor total	34.55	27		

df: degrees of freedom. Cor total: corrected total. *: significant at 95% confidence interval

graphs were updated in real-time during each run and corresponding data were saved in a particular format for further processing in spreadsheets or other software.

Optimization for minimum torque requirement

The RSM was followed to design the experiment and optimize the operational parameters. RSM is a collection of mathematical and statistical techniques and it helps to develop and optimize a process (Liu G et al., 2020; Hensh & Raheman, 2021; Liu et al., 2022). This method allows evaluation of the effects of multiple factors and their interaction on one or more response variables.

In our experiment, a three-factor three-level full factorial design was followed to set the order of run (Table S1 [suppl]) in Design-Expert 7.0.0 (Stat-Ease, Inc., USA) software. The torque required for cutting and pushing the cabbage was the response in this experiment. The optimization process involves estimation of coefficients, prediction of responses and checking the acceptability of the developed model. The response Y is represented by Eq. (7):

$$Y=f\left(x_1,x_2,x_3,\ldots\ldots,x_n\right)\pm E \qquad (7)$$

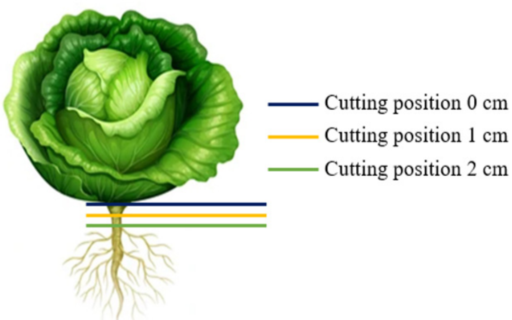

Figure 4. Different cutting positions of a cabbage stem.

where, f is the response function, $x_1 \ldots x_n$ are the independent variables, and E is the experimental error (Balasubramani et al., 2013; Rashidi et al., 2021). The response function (f) largely depends on the nature of the relationship between the response and the independent variables. The two-factor interaction model is represented by Eq. (8):

$$y=\beta_0+\sum_{i=1}^{n}\beta_i x_i+\sum_{i=1}^{n-1}\beta_{ij}x_i x_j+E \qquad (8)$$

where, y is the predicted response; β_0 represents the intercept or regression coefficient; β_i and β_{ij} represent the linear and interaction coefficients, respectively; x_i and x_j are the coded values of the process variables; and E is the experimental/residual error.

The mathematical model obtained from the RSM approach was validated using various statistical parameters i.e., coefficient of determination (R^2), adjusted R^2 (R^2adj) and predicted R^2 (R^2pred). The expressions used for model verification are given in Table 3 (Liu et al., 2022). The value of R^2 describes up to what extent the model can perfectly estimate the experimental data points and the R^2adj measured the amount of variation about the mean explained by the model.

Data analysis

Analysis of variance (ANOVA) is a very useful tool to evaluate the significance of different independent variables and their interactions with the magnitude of measured parameters (Upadhyay & Raheman, 2018; Nataraj et al., 2021). The outcome of ANOVA is the 'F statistic'. This ratio shows the difference between the within-group variance and the between-group variance, which ultimately produces a figure which allows a conclusion about whether there is a significant difference between the groups or not. The larger

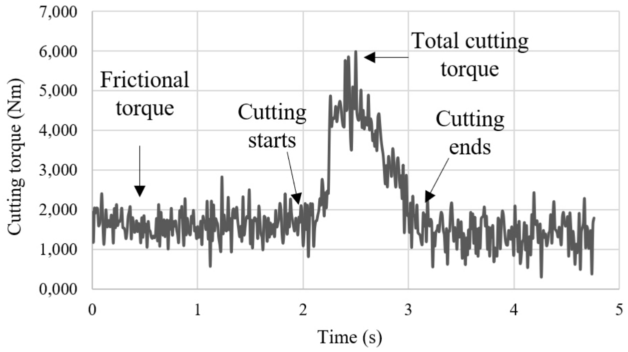

Figure 5. A typical torque vs time curve for cutting the cabbage stem.

F-value denotes a more significant effect of the corresponding coefficient (Yi et al., 2010; Behera et al., 2018). The model terms are significant only when the values of p are lower than 0.05. Values of "Prob > F" lower than 0.05 indicate that the model terms are significant. In our experiment, ANOVA of total torque required (for cutting and pushing) was performed in Design Expert 7.0.0 software and individual effects of cutting speed, forward speed and cutting speed and their interaction effect were studied.

Results and discussion

Torque required for cutting and pushing the cabbage

The data acquired by the DAS during the cutting and pushing operation were displayed in the excel spreadsheet as torque vs. time curve. The real-time torque data for cutting and pushing are shown in Fig. 5 and Fig. 6, respectively. The total cutting torque is the sum of frictional torque and absolute maximum cutting torque (AMCT). From this plot, the absolute maximum cutting torque of the cabbage stem was obtained using Eq. (9):

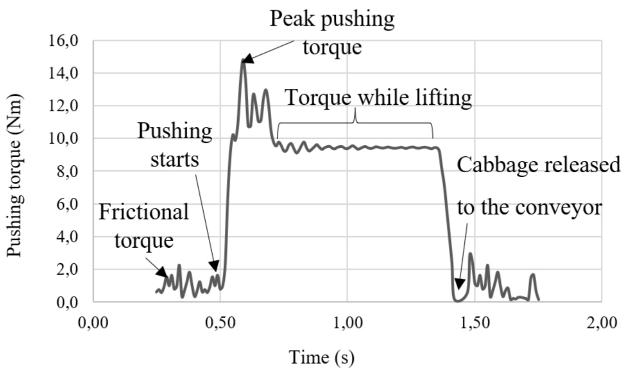

Figure 6. The variation of torque required for pushing the cabbage with time.

$$T_C = T_{tc} - T_{fc} \quad (9)$$

where T_C = absolute maximum torque required for cutting, Nm; T_{tc} = total maximum cutting torque, Nm; and T_{fc} = frictional torque for cutting, Nm.

Similarly, the total pushing torque is the sum of frictional torque and absolute maximum pushing torque (AMPT). While pushing the cabbage head, initially the torque increased to a peak when the pusher plate was in contact with the cabbage head and then it reduced and got flattened when the cabbage head was being pushed to the inclined plate. When it was released on the conveyor belt the torque requirement was again reduced as shown in Fig. 10. From this plot, the absolute maximum torque required for pushing of cabbage stem was obtained by using Eq. (10):

$$T_P = T_{tp} - T_{fp} \quad (10)$$

where TP = absolute maximum torque required for pushing, Nm; T_{tp} = total maximum torque required for pushing, Nm; and Tfp = frictional torque required in pushing, Nm.

The variations of absolute maximum torque required for cutting and pushing at each combination are graphically represented in Fig. 7. It shows that the maximum and minimum torque required for cutting were 3.49 Nm and 4.46 Nm, respectively. It increased with a change in the cutting position. At the cutting speed of 500 rpm and forward speed of 0.27 m s^{-1}, the cutting torque increased by 9.42% and 11.6% when the cutting position changed from 0 cm to 1 cm and 0 cm to 2 cm, respectively. High cutting torque values were observed when the cutting position changed from 0 cm to 2 cm. This could be due to the increase of the strength of the stem with an increase in distance from the bottom of the head (Du et al., 2016). With an increase in the cutting speed, the torque required for cutting was reduced. At the forward speed of 0.22 m s^{-1} and cutting position at 1 cm, the torque required for cutting decreased by 4.61% and 12.24% when the cutting speed changed from 400 cm to 500 rpm and 400 rpm to 600 rpm, respectively. It could be due to the fact that at higher speed the cabbage stem offered less resistance (Persson, 1987). Stems cut at different cutting positions are shown in Fig. 8.

The torque required to push the cabbage was observed to be higher at a speed of 400 rpm and it decreased with an increase in cutting speed. At the forward speed of 0.27 m s^{-1} and cutting position at 1 cm, the torque required to push the cabbage decreased by 2.67% and 9.23% when the cutting speed changed from 400 rpm to 500 rpm and 400 rpm to 600 rpm, respectively. At lower speeds, the higher resistance offered by the cabbage stem caused some amount of deflection of cutting discs which resulted in some uncut portion at the middle of the stem (Fig. 9a). Hence, some extra torque was needed to break this portion while pushing and lifting the cabbage. This could be the probable reason for higher torque requirement in pushing the cabbage

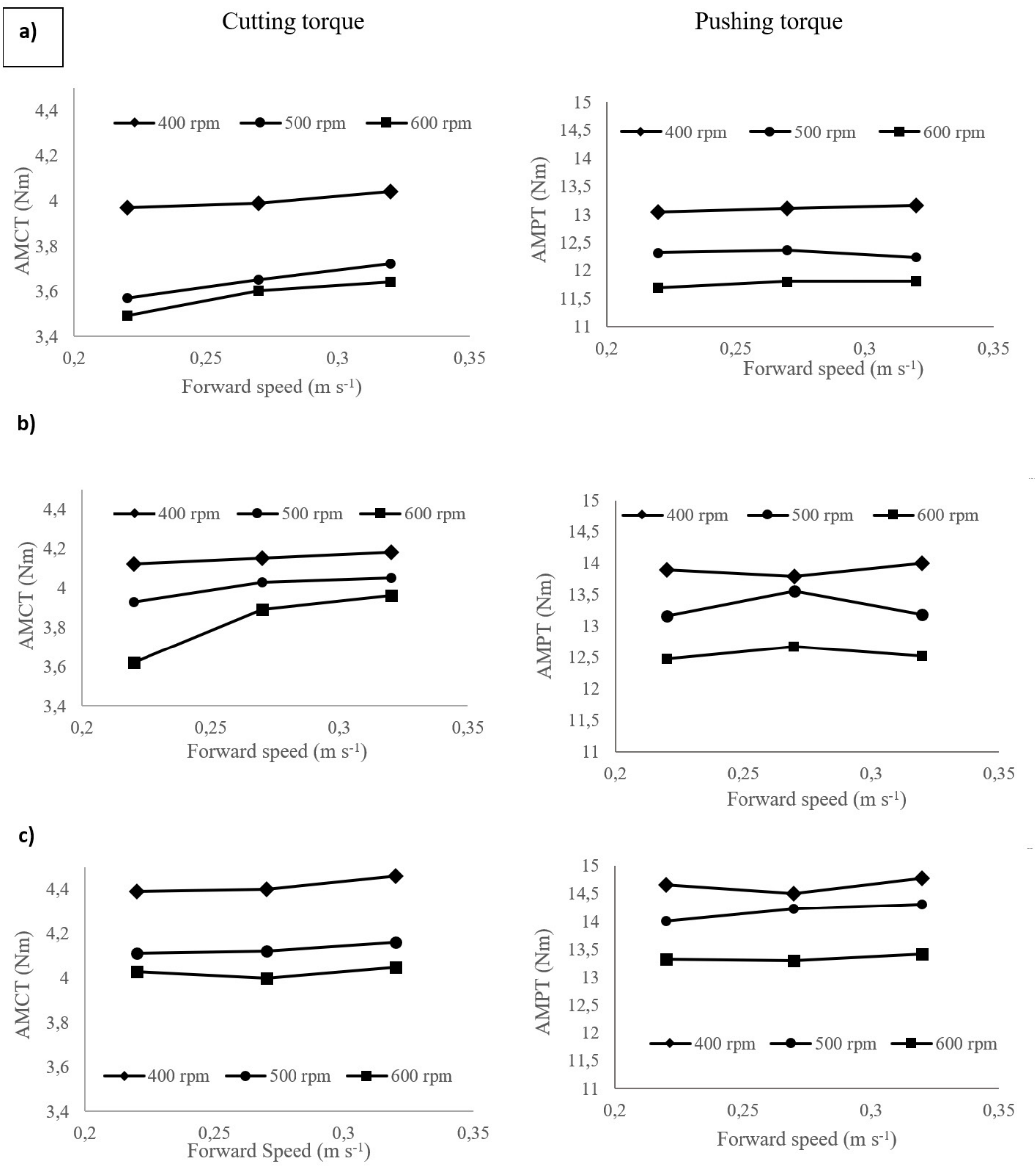

Figure 7. Variation of absolute maximum cutting torque (AMCT) and absolute maximum pushing torque (AMPT) at different combinations of operating parameters: (a) cutting position 0 cm; (b) cutting position 1 cm; (c) cutting position 2 cm.

at lower cutting speed. Change in torque requirement for pushing the cabbage heads was observed when cutting position increased or decreased. Higher torque was required to push the cabbage head when the cutting position was increased from 0 to 2 cm. At cutting speed of 500 rpm and forward speed of 0.27 m s^{-1} the torque required to push increased by 8.84% and 15.71% when cutting position changed from 0 cm to 1 cm and 0 cm to 2 cm, respectively. At the higher cutting position, the extended portion of the cabbage stem created some obstacle in the space between the inclined plate and cutting discs and some extra torque was needed to overcome this resisting force. When the cutting position was at 0 cm, the cabbage bottom had no extended stem, hence, a smooth pushing operation was observed (Fig. 9b).

Analysis of total torque requirement

The ANOVA for total torque requirements in cutting cabbage heads is given in Table 4. The larger F-value implies a more significant effect of the corresponding coefficient (Yi et al., 2010; Behera et al., 2018). The model terms are significant only when the values of p are < 0.05. Table 4 shows that the model F-value was 150.25, i.e., the model was significant. Values of "Prob > F" lower than 0.05 indicate that the model terms are significant. In this case, cutting speed (A) and cutting position (C) are significant model terms. Forward speed (C) did not affect the total torque requirement significantly. Values > 0.10 indicate that the model terms are not significant. All the interaction effects (AB, AC and BC) of the model

Figure 8. Stems cut at different positions: 1, cut at 0 cm from head bottom; 2, cut at 1 cm from head bottom; 3, cut at 2 cm from head bottom.

were not significant in this experiment at 95% confidence interval.

Optimization for minimum torque requirement

RSM was used to study the three-dimensional response plots, which were generated from the effects of the three variables on the total torque. Figs. 10-12 demonstrate the interactions between the variables in three-dimensional response surface plots. These plots reveal that the RSM generated a nearly flat surface plot. Hence, a linear relationship was suggested between independent and response variables. For example, when the cutting position was 1.8 cm, the total torque increased with a decrease in cutting speed and an increase in forward speed (Fig. 10). The contour map shows that the variation rate of total torque along the direction of cutting speed was higher than that of forward speed, which indicates the greater influence of cutting speed on total torque than forward speed. When the forward speed was 0.27 m s^{-1}, total torque decreased when cutting position decreased and cutting speed increased. A minimum torque was observed in the cutting speed range of 550 rpm to 600 rpm and 0 cm to 0.5 cm cutting position (Fig. 11). The maximum torque was reached when the cutting speed was between 400 rpm to 450 rpm and the cutting position was between 1.5 cm to 2 cm. The contour map shows the influence of both cutting speed and cutting position on total torque. The rate of variation of total torque along the direction of cutting speed was similar to that of cutting position. The variation of total torque with forward speed and cutting position when the cutting speed is fixed at 450 rpm is shown in Fig. 12. It indicates that the total torque decreased with the decrease in the cutting position. The contour plot shows a very low variation of total torque with a change in forward speed.

The most important part of the experiment was to obtain the optimized parameters for minimum torque requirement. The optimum operating conditions for the minimum torque requirement for cutting cabbage stems were 590 rpm cutting speed, 0.25 m s^{-1} forward speed and 0 cm cutting position with desirability of 0.995. At this operating combination, experimental total torque and predicted total torque were found as 15.7 Nm and 15.33 Nm, respectively. The percentage of bias was calculated by Eq. (11) and it was computed to be 2.36%.

$$P_{bias} = \frac{|Experimental\ value - Predicted\ value|}{Experimental\ value} \times 100\% \quad (11)$$

Model development and its validation

Based on the test results, the total torque value can be expressed by the regression equation (Eq. 12), obtained following the Design expert 7.0.0.

$$T = 20.64 - 9.69 \times 10^{-3} \times A - 0.54 \times B + 0.83 \times C + 0.55\,BC \quad (12)$$

where, T is the total torque (Nm), A is the cutting speed (rpm), B is the forward speed (m s^{-1}), and C is the cutting position (cm).

The R^2 (0.977), predicted R^2 (0.965), adjusted R^2 (0.971) and coefficient of variation of the developed model were computed with the help of the equations from Table 5. Here, the high R^2 value indicates that the regression model suited the data well. So, the model can predict the total torque for

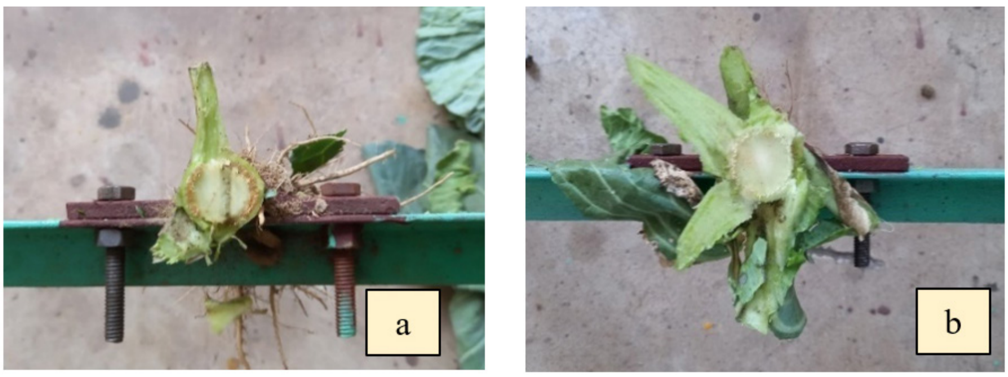

Figure 9. Cross section of cabbage stem after cut: a) at a cutting speed of 400 rpm, b) at a cutting speed of 600 rpm.

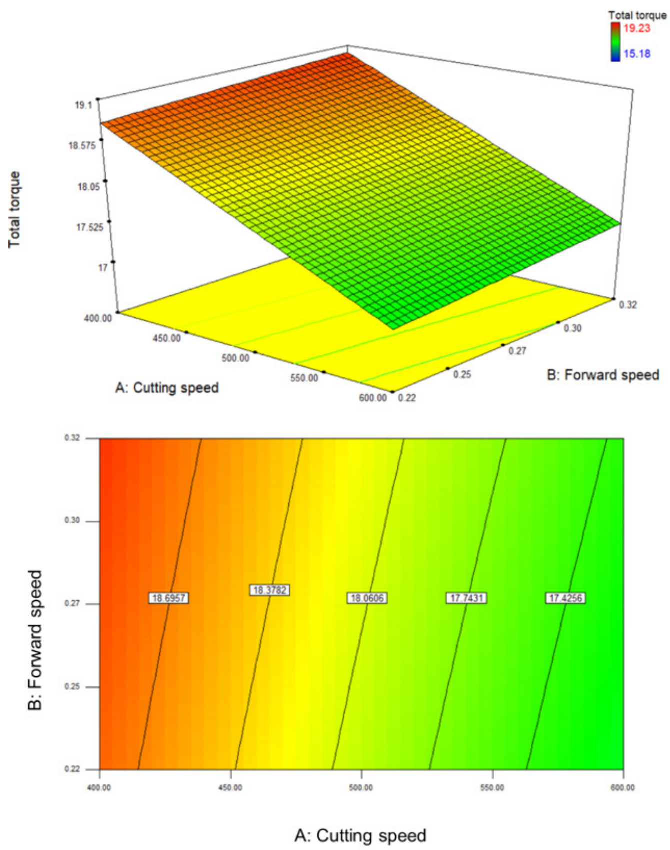

Figure 10. Two-factor interaction (A, cutting speed and B, forward speed) plot on response surface (total torque).

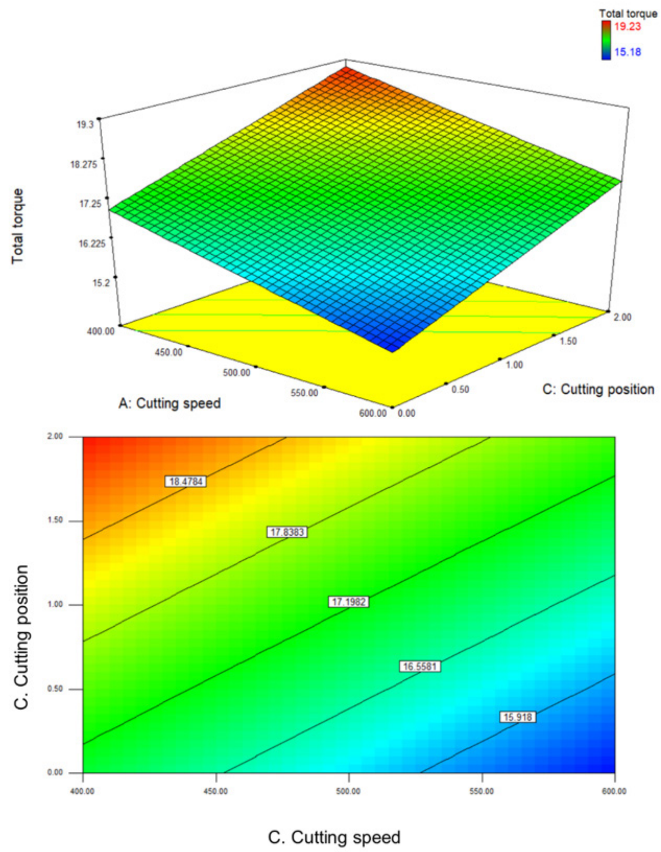

Figure 11. Two-factor interaction (A, cutting speed and C, cutting position) plot on response surface (total torque)

cabbage cutting and pushing under the influence of cutting speed, forward speed, and cutting position. The "R^2pred" is in reasonable agreement with the "R^2adj". "Adeq Precision" measures the signal-to-noise ratio. It compares the range of the predicted values at the design points to the average prediction error. Ratios greater than 4 indicate adequate model discrimination. In our case, a ratio of 41.589 was found which indicates an adequate signal. So, this model can be used to navigate the design space.

To verify the accuracy of the above-developed model, three combinations of cutting speed, forward speed and cutting position which were not used in the model setup were selected along with 9 data from the test set (Table S2 [suppl]). The computed total torques were compared with the measured values from the experiment. The measured and predicted total torque values were plotted in Fig. 13, which fits well with the linear regression lines ($R^2 > 0.84$). The P_{bias} between experimental and predicted values for all runs were within 10%, indicating perfect estimations of total torque requirements.

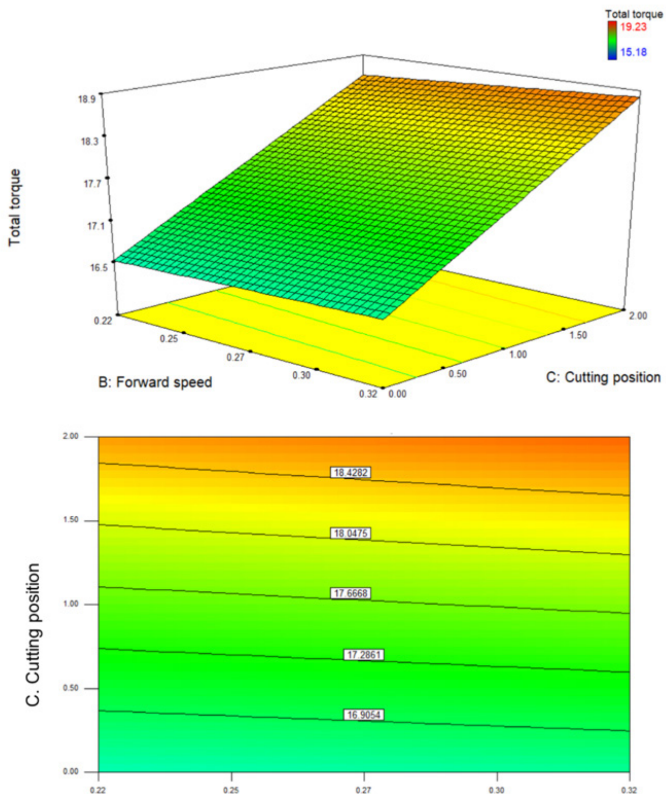

Figure 12. Two-factor interaction (B, forward speed and C, cutting position) plot on response surface (total torque).

Conclusion

A simulated cabbage harvesting mechanism for a small-scale cabbage harvester was developed in the laboratory.

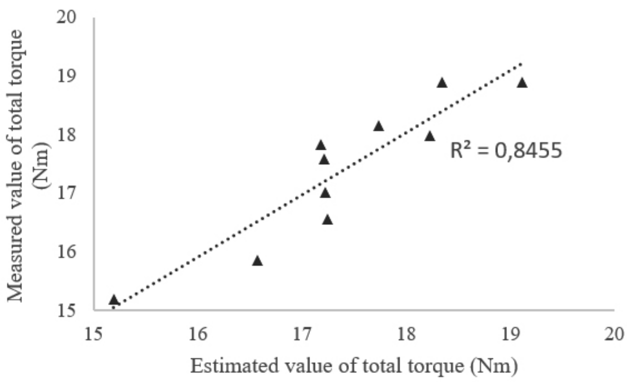

Figure 13. Comparison of measured and estimated total torque required for cutting the cabbage stem.

In addition, experiments on cutting and pushing an Indian cabbage variety were carried out. Cutting speed, cutting position and forward speed were considered as influential input variables. It was observed that the torque required to cut as well as push the cut cabbage increased with a decrease in cutting speed. Also, at lower cutting speeds improper cutting of cabbage stem was observed. Torque for cutting and pushing the cabbages were found to be minimum when the cabbage stem was cut nearer to the stem and were increased with an increase in cutting height i.e., distance from the head. Statistical analysis (ANOVA) showed that only cutting speed and cutting position had a significant effect on the total torque (cutting and pushing) requirement. Forward speed and other interaction effects didn't affect the total torque requirement significantly. Optimization for minimum torque requirement was carried out and the optimized cutting speed (rpm), forward speed and cutting position were found as 590 rpm, 0.25 m s^{-1} and 0 cm, respectively with a desirability of 0.995. A regression model was developed to predict the total torque required for cutting the cabbage stem. R^2, Adj R^2, and Pred R^2 of the model were found as 0.977, 0.970 and 0.965, respectively. This model was validated against experimental data and percentage of bias (P_{bias}) was found to be within 10%.

The mechanism developed for cabbage harvesting could successfully cut and lift the cabbage heads in the laboratory. The optimum values of input variables will be followed in a field prototype cabbage harvester for its successful operation in the field.

Authors´ contributions

Conceptualization: P. Sarkar, H. Raheman.
Data curation: P. Sarkar
Formal analysis: P. Sarkar
Funding acquisition: Not applicable.
Investigation: H. Raheman.
Methodology: P. Sarkar, H. Raheman.
Project administration: Not applicable.
Resources: H. Raheman.
Software: P. Sarkar.
Supervision: H. Raheman.
Validation: Not applicable.
Visualization: Not applicable.
Writing – original draft: P. Sarkar
Writing – review & editing: H. Raheman.

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