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Laboratory Investigation on Rotary Impact Cutter Blade Parameters for Multistep Cutting of Paddy Straw

Abhishek Patel, Krishna Pratap Singh and Ajay Kumar Roul
ICAR-Central Institute of Agricultural Engineering, Bhopal-462 038, India
E-mail: abhishekpatel2910@gmail.com

Abstract: The present study focused on the laboratory evaluation and optimization of the chopping unit of straw chopper cum mixture machine for paddy straw management. During the study a laboratory setup was developed for simulating the cutting process of counter-rotating blades of a chopper for cutting of paddy straw. The effect of operational parameters i.e., blade type, rotational and forward speed of the machine, and crop parameters i.e. days after harvesting (DAH) on the power requirement was observed. The response surface methodology was used to develop a statistical model to predict the torque requirement for chopping straw by front attachment of the rotary tiller. The developed model was optimized in order to minimize power required during chopping operation. The results of study showed that the cutting torque was significantly ($p \leq 0.05$) affected by the rotational speed, forward speed and DAH of the paddy straw. A straw management system (SMS) serrated blade operating at rotational and forward speed of 900 rev. min^{-1} and 1 $km.h^{-1}$ respectively with average cutting torque of 3.8 N-m was found to be optimal for cutting the paddy straw. The paddy straw chopping performed after 1-2 DAH requires minimum power. Hence, it was concluded that the optimized chopping system can be effectively used as cutting unit in rice straw incorporator.

Keywords: Blade optimization, Crop residue management, Rice straw, Straw incorporation

Rice (*Oryza sativa* L.) is one of the most important staple food, feeding more than 50% of the global population. Combine harvester leaves loose rice straw on the ground, making its collection and transportation difficult, laborious and costly. Annually, about 600 to 800 million tons of rice straw are produced in Asia; globally approximately 1 billion tons are produced. In India, 697 million metric tons of crop residue was generated from 26 crops. Approximately 60 to 70% of farmers prefer to burn the residue whereas, less than 1% of farmers incorporate in order to prepare the field for sowing of next crop. Due to a lesser window period during sowing of wheat and harvesting of rice crop, farmers choose to burn the rice residue in the field (Verma et al 2016). Rice residue collection and transportation makes ex-situ residue management economically unfeasible (Parihar et al 2023). Straw incorporation is a common practice to improve soil fertility and the yield of paddy. In general, residue retention promotes soil health, reduces soil erosion, improves soil water content and enhances crop productivity.

Paddy straw was managed using different practices such as bailing, collection and incorporated into the field (Ramulu et al 2018). Machinery like Happy seeder, zero till drill, spatial till drill, smart seeder and super seeder were popular among the farmers which results as a lack of adoption these technologies due to lack of knowledge and higher cost of the machinery (Parihar et al 2022). Generally, above said machines works horizontal shaft-based crop residue choppers with flails were commonly used to reduce the crop residues length and incorporated into the soil. The chopping blade and its design have a significant effect on crop straw chopping quality, power consumption and its operational life (Fu et al 2011). The hammer blades, straight blades and bent blades (Y-shaped and L-shaped) (Liu, 2012) are some of the commercially available blades for chopping paddy straw. The arrangement of the blade also has a significant effect on the performance and operational reliability of the straw chopper. Mountings of the blades on the rotor improves the chopping quality and helps for balancing of the straw chopper. The most commonly used blade arrangements are helical, symmetrical and staggered (Bao et al 2016).

Several researchers have developed flail type blade system in order to chop different kinds of crop residues. Manes et al (2016) introduced a trail-type chopper that has a cutting unit with flail blades to harvest the paddy straw and a chopping unit with fixed blades to chop straw delivered by the cutting unit. Zhang (2014) designed a fixed-blade cylindrical straw chopper that has the functions of paddy straw pickup, cutting, stubble cleaning and soil incorporation. Li and Li (2001) also studied the blade arrangement by comparing the behavior of rotor dynamic balance to reduce the vibration of the straw chopper. Based on the literature cited above it can be seen that the most of the paddy straw chopping systems having a flails type blade which seems to impart excessive vibration and noise during working (Ji et al 2003, Tu et al

2003). It was also seen that very limited scientific data is available on the vertical shaft mounted blades used for chopping of paddy straw. Therefore, present study was formulated to study the different blade types i.e. SMS serrated, cutter bar and SMS plain blade mounted on vertical shaft and operating at different rotational and forward speeds for the paddy straw samples taken at different DAH, through laboratory experiments. The parameters under study were optimized and selection of blade in order to minimize the torque requirement.

MATERIAL AND METHODS

The paddy straw (*c.v. Kranti*) used in this work was provided by the ICAR-CIAE Bhopal. The straw bunch from the field was collected on three different days after harvesting of paddy by the combine harvester. Paddy straw bunches with a height of 35-40 cm were placed over the bunch holder for experimentation. The experiments were conducted on the same day (M_1), fifth day (M_2) and tenth day (M_3) after harvesting, respectively. The moisture content of the paddy straw was 35 (M_1), 26 (M_2) and 17% (M_3) for 0, 5 and 10 DAH, respectively.

Experimental setup: The CAD model of the laboratory setup for cutting torque measurement was drawn in CREO 3.0 software as shown in Figure 1. The laboratory setup required for the simulation and prediction of cutting torque to cut the paddy straw is shown in Figure 2. The developed chopping unit consisted of two vertical counter-rotating shafts, each having a pair of flanges with four blades. The blades were equally spaced in the flange. The cutting width was 340 mm for a single rotor, therefore the total cutting width was 630 mm with an overlapping of 50 mm was provided between two rotors. The mechanism had horizontal and vertical adjustments.

The present research work carried out in an indoor soil bin consists of a tool carriage trolley, linear movement transmission system and data logging system. Even though the soil was not a part of this experimental study, it was used to keep the straw bunch holder in front of the tool carriage system and can easily be controlled by the control panel during the cutting process.

An AC motor (3.7 kW) was used to supply the power required for the blade through a V-belt pulley mechanism. The motor had a double V groove pulley to accommodate two V belts for both shafts. One shaft was connected directly while the other was connected in cross belt for the counter-rotation mechanism of the setup. The chopped paddy straw was pushed inwards by counter rotation of blades. A torque transducer (HBM T22/kNm) was connected on the AC motor shaft to measure the torque required to cut the paddy straw (Fig. 1). The data was recorded using HBM data logger (MX840B, 8 channel). The straw bunch holding device was made of MS flat with a circular pipe of diameter 40 mm and was welded at a space of 200 mm between the two bunches. Similarly, three rows were fabricated to hold the bunches. The rotating and forward speeds of the designed cutting setup were controlled using the control panel.

Experimental design: An optimization study was conducted for selection of suitable cutting blade for paddy straw cutting unit. Three different types of blades namely SMS serrated, cutter bar and SMS plain blades with a thickness of 4 mm were used in this study. The independent parameters used in this study were forward speed, rotational speed and moisture content (M_1, M_2, and M_3) in terms of days after harvesting. The Central Composite Rotatable Design (CCRD) along with Response surface methodology (RSM) was used for optimization of machine and operational parameters. The minimum and maximum values for these variables were selected after the preliminary experiments. The range of rotational speed and forward speeds were between 500 to 900 rev/min and 1 to 2 km.h^{-1}, respectively. A total of 48 experimental combinations were obtained for each type of blade by conducting six experiments at the center point and replicating three times at factorial and axial points. The statistical analysis in this study was done using Design-Expert software (version 13.1). The sequential model sum of squares (SMSS), lack of fit test and coefficient of determination (R^2) were considered for selection of an appropriate model. In numerical optimization, the solution was obtained as a point with maximum desirability.

The selection of blade was done based on the minimum cutting torque measured by the torque sensor for cutting paddy straw. The frictional torque produced during idle operation of the setup prior to and during each experiment was added to calculate the actual torque required for cutting the straw. The effect of design factors on the response parameters was evaluated using analysis of variance and regression analysis with a second-order polynomial model. Paired t-test was used for validating the predicted model value.

Total power requirement: The total power requirement for the cutting of the straw bunch was calculated according to the given equation 1 & 2. It is the combination of frictional and cutting power which was corresponding to the frictional (T_f) and cutting torque (T_C).

$$T_t = T_f + T_c \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$P = \frac{2 \times \pi \times N \times T_t}{60} \quad \ldots\ldots (2)$$

Where, P = power, Watt; N = blade rotation per mint; T = cutting torque, Nm,

RESULTS AND DISCUSSION

The actual torque required to cut the paddy straw versus time is shown in Figure 4. The figure showed that the SMS serrated blade has a very less cutting torque (12.25 Nm) than the cutter bar blade (17.67 Nm) followed by SMS plain blade (20.01 Nm).

The quadratic model was selected and all the models were significant (Table 1). The models were capable to represent the variability of the data set to capture the effect of design factors over the response parameters. The lack of fit was found non-significant indicating the model efficiently estimated the response parameters. The cutting torque obtained from the blades A, B and C through the test runs during the experiment and the predicted values accessed by quadratic models followed linear relationship. The curve indicates a good fit to the model and it sufficiently covers the design factors within the experimental range. The deviation of observed and estimated straw cutting torque values was found to be acceptable and a good agreement with R^2 values 0.99, 0.97, and 0.95, respectively indicates the accuracy of the selected models.

Effect of operating parameters on cutting torque for different types of cutting blades: The forward speed, blade rotational speed and days after harvesting have significant effect on the cutting torque for all types of blades. The cutting torque increased significantly as the forward speed increased for all types of blades whereas it decreased as the rotational speed increased and decreased with increase in days after harvesting. The increase of forward speed and DAH, cutting torque increased from 4.5 to 6.7 Nm (Fig. 5). It may be due to the interacting time being less at high forward speed (Sahoo and Raheman 2020). The increase in days after harvesting (DAH) from 0 to 10 days the cutting torque also increased from 6.06 to 8.64 Nm because of the reduction in moisture content of the straw. At the same time, the increment in rotational speed of the blade from 500 to 900 rev/min caused a reduction in cutting torque from 7.1 to 5.5 Nm. It may be due to high impact when the rotational speed increased, the stems were cut without flattening or crushing with a low resistive force from the paddy stem. The cutting process was accomplished by a large resistive force from the paddy stems with flattening and crushing at lower rotational

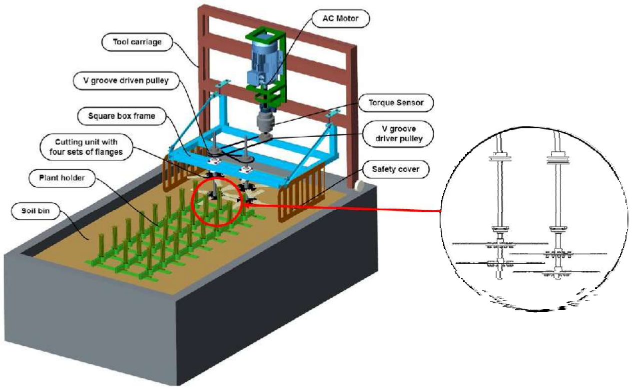

Fig. 1. Detailed specification of cutting torque setup representation by CAD model

Fig. 2. a) Laboratory setup for cutting torque measurement, Paddy straw bunch in plant holder (b) before cutting and (c) after cutting

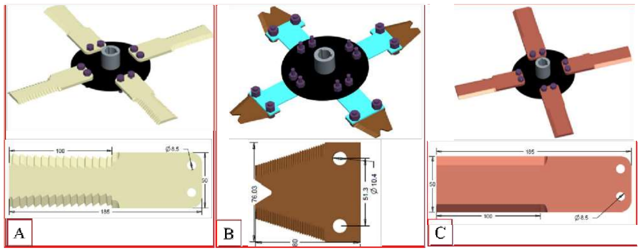

Fig. 3. Placement and dimensions of different blades A) SMS Serrated, B) Cutter bar and C) SMS Plain blade

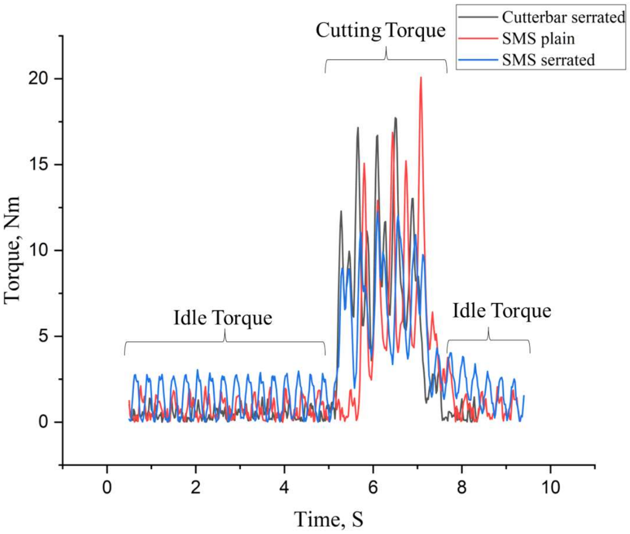

Fig. 4. Torque v/s travel time curve for different blade

speeds. The influence of each parameter on the cutting torque required by the SMS serrated blade was less followed by the cutter bar and the SMS plain blade.

Combined effect of independent parameters on the cutting torque: The combined effect of independent parameters on the response was observed from the 3D response surface plots (Error: Reference source not found) by keeping the third value at the center point. The blue and red color shows the minimum and maximum values of cutting torque. The regression analysis revealed that cutting torque was significantly affected by the interaction of independent parameters. The cutting torque of all three types of blades were greatly affected by the interactions between forward and rotational speed as well as the rotational speed with DAH.

SMS serrated blade: The cutting torque was increased constantly from 5.6 to 7.2 Nm with an increase in forward speed from 1 to 2 km h^{-1} at a constant rotational speed of 500 rev/min whereas, it decreased from 5.6 to 3.8 Nm by increasing rotational speed 500 to 900 rev/min at a forward speed of 2 km h^{-1} (Fig. 5A). Lower forward speed of 1 km.h^{-1} and maximum rotation of blade 900 rev/min had minimum

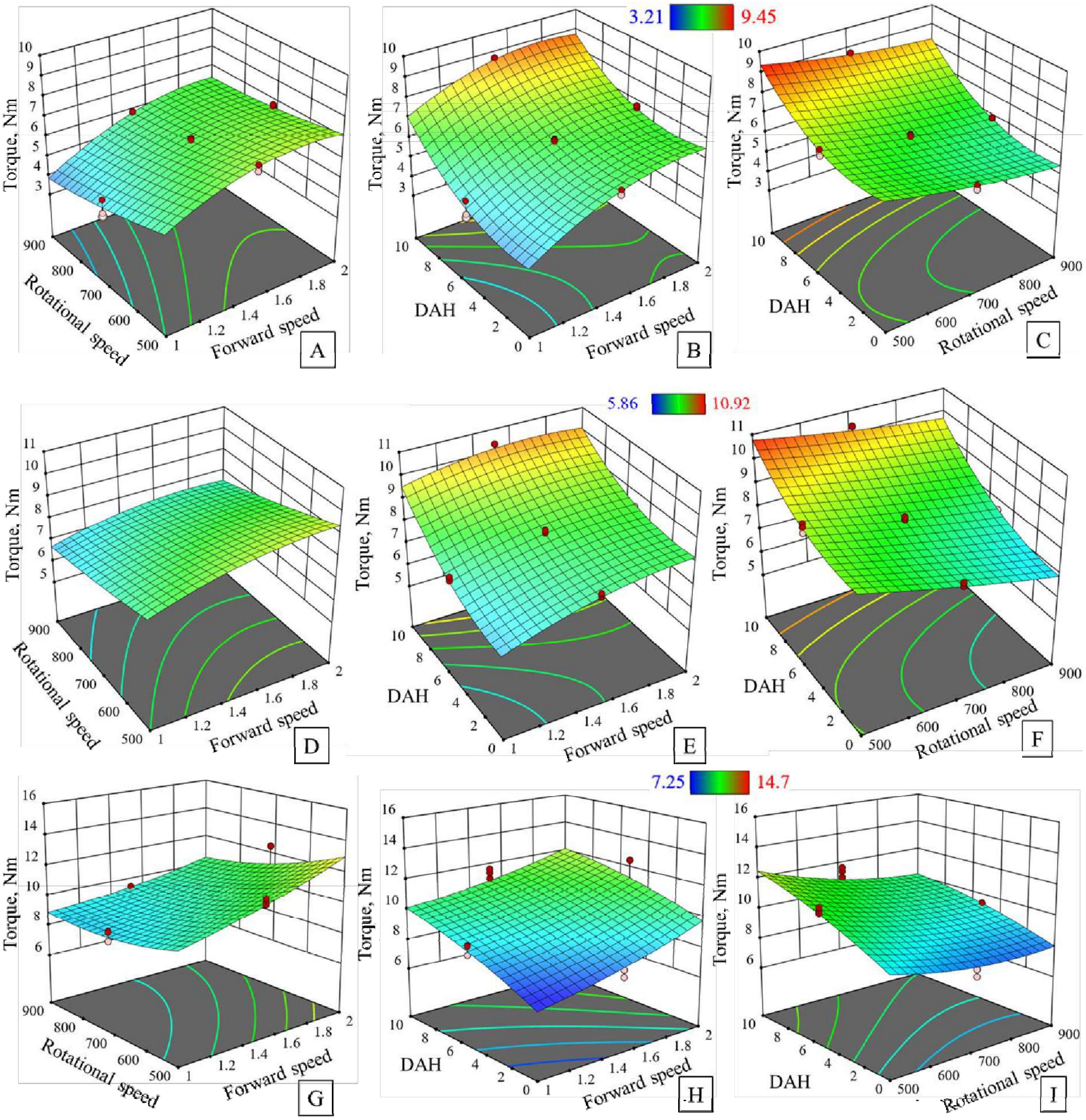

Fig. 5. Response surface curve for cutting torque by SMS serrated (A, B, C), cutter bar (D, E, F) and SMS plain (G, H, I) blade

cutting torque of 3.8 Nm. Interaction effect of forward speed and DAH (Error: Reference source not found B) by keeping the third parameter fixed in-between values, the cutting torque was minimum (4.1 Nm) and increased up to 6.6 Nm at forward speed from 1 to 2 km h^{-1} at 0 DAH, whereas in extreme values of the parameter (2 km h^{-1} forward speed and 10 DAH) cutting torque was maximum 8.89 Nm. Similarly in the interaction of DAH and rotational speed (Error: Reference source not found C) by keeping the forward speed constant at mid value, the cutting torque was decreased from 6.9 to 5.5 Nm at 0 DAH, whereas the cutting torque increased from 6.9 to 9.5 Nm at 500 rev/min for increase in DAH from 0 to 10, respectively.

Cutter bar blade: The cutting torque was increased constantly from 8.2 to 9.5 Nm with an increase in forward speed 1 to 2 km.h^{-1} at a rotational speed of 500 rev/min whereas, it decreased from 8.1 to 7.0 Nm by increasing rotational speed 500 to 900 rev/min at a forward speed of 2 km.h^{-1} (Error: Reference source not found D). At a lower forward speed of 1 km h^{-1} and a maximum rotation of blade 900 rev/min had minimum cutting torque. Interaction effect of forward speed and DAH (Error: Reference source not foundE) by keeping the third parameter fixed in-between values, the cutting torque was minimum 6.7 and increases up to 8.2 Nm at forward speed from 1 to 2 km h^{-1} at 0 DAH, whereas in extreme values of parameter (2 km h^{-1} forward speed and 10 DAH) the cutting torque was maximum of 10.1 Nm. Similarly in the interaction of DAH and rotational speed by keeping the forward speed kept fixed at mid value, the cutting torque was decreased from 8.8 to 6.9 Nm at 0 DAH, whereas at constant 500 rev/min the cutting torque increased from 8.8 to 10.7 Nm in the variable range of DAH from 0 to 10, respectively.

Table 1. Analysis of variance of different types of blades for cutting torque

Source	df	F-value		
		SMS Serrated	Cutter bar	SMS plain
Model	9	436.48*	190.03*	75.10*
Forward speed (A)	1	1184.51*	189.92*	225.92*
Rotational speed (B)	1	453.70*	404.75*	103.07*
DAH (C)	1	1807.04*	951.46*	292.17*
AB	1	53.34*	8.37*	21.56*
AC	1	39.63*	31.38*	5.13**
BC	1	8.42*	28.22*	11.28*
A^2	1	152.61*	23.50*	2.81^{NS}
B^2	1	8.53*	1.11^{NS}	9.02*
C^2	1	291.05*	79.35*	4.03^{NS}
Lack of Fit	5	1.21^{NS}	2.13^{NS}	2.45^{NS}
R^2	-	0.99	0.97	0.95
CV, %	-	2.51	2.46	4.46

* = Significant at p≤ 0.01, **= Significant at p≤ 0.05, NS= Non-significant, df= degree of freedom, R^2= coefficient of determination, CV= coefficient of variance

SMS plain blade: The cutting torque was increased constantly from 9.7 to 12.8 Nm with an increase in forward speed from 1 to 2 km h^{-1} at 500 rev/min whereas, it decreased from 9.7 to 8.8 Nm by increasing rotational speed from 500 to 900 rev/min at a forward speed of 2 km.h^{-1} (Fig. 5G-I). The cutting torque was minimum at the forward speed of 1 km.h^{-1} and the blade rotations of 900 rev/min. Interaction effect of forward speed and DAH (Error: Reference source not found H) by keeping the third parameter fixed in between range, the cutting torque was minimum 6.9 Nm and increased up to 9.7 Nm at forward speed of 1 to 2 km.h^{-1} at 0 DAH, whereas in extreme values of the parameter (2 km.h^{-1} forward speed and 10 DAH) cutting torque was maximum of 12.2 Nm. Similarly in the interaction of DAH and rotational speed (Error: Reference source not foundI) by keeping the forward speed kept fixed at mid-value in the range of the variable, the cutting torque was decreased from 9.0 to 7.9 Nm at 0 DAH, whereas at constant 500 rev/min, the cutting torque increased from 9.0 to 12.4 Nm in the variable range of DAH from 0 to 10, respectively.

Total power requirement: The power required for cutting of paddy straw by different types of blades was calculated by Eq. 2 and determined the effect of rotational speed on cutting power (Fig. 6). The result showed a good agreement between the rotational speed of the blade and cutting power with an R^2 value greater than 0.9. As the rotational speed of

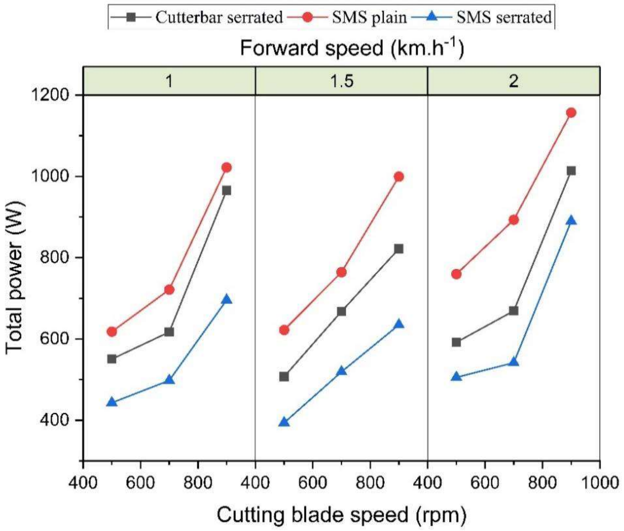

Fig. 6. Total cutting power vs. cutting blade rev/min at a different rotational speed

Table 2. Optimized values of selected SMS serrated blade of design parameters and responses

Design parameters	Goal	Lower	Upper	Optimum value
Forward speed, km.h^{-1}	in range	1	2	1
Rotational speed, rev/min	in range	500	900	900
DAH	in range	0	10	1.24
Torque (Response)	minimize	3.21	9.45	3.214

Table 3. Model validation using paired t-test for cutting torque for SMS serrated blade

Response	Predicted	Actual value ± SD	Standard error	Mean difference	t_{cal}
Torque, Nm	3.21	3.26 ± 0.52	0.03	0.045	0.271

h_0: $\mu_0 = \mu_1$, $t_{cal} < t_{tab}$ at $p<0.01$, h0 was accepted

the blade increased from 500 to 900 rev/min, the power requirement also increased and thereafter reduced within the variable range in all blade types and results followed the study of Sahoo & Raheman (2020). In the present study, a minimum cutting power of 0.62 kW requirement was observed in the SMS serrated blade and hence, it was selected for the optimization of design variables.

The increase in forward speed from 1 to 2 km h^{-1} and rotational speed from 500 to 900 rev/min, the total cutting power was also increased. There was a significant effect on the total power of the three blades when rotational speed varying from 500 to 900 rpm at 1 km.h^{-1} forward speed. The SMS serrated blade required less power to cut the paddy straw than the cutter bar followed by the SMS plain blade. Similarly, the increasing trend of total power requirement was observed for all three blades with a change in forward speed and rotational speed from 1.5 to 2 km h^{-1} and 500 to 900 rev/min, respectively. It was concluded from the Figure 6 that the total power was minimum at a forward speed of 1 km h^{-1} followed by 1.5 and 2 km h^{-1}. It may be due to the amount of paddy straw chopped would be less at a forward speed of 1 km h^{-1} compared to 1.5 and 2 km h^{-1}.

Optimization and model validation: The constraints range of different independent parameters with optimized values are shown in Table 2. The minimization of torque required was the target while optimizing the parameters. The optimization of the selected blade was carried out based on the input parameters such as rotational speed, forward speed, and DAH. The numerically optimized results had a desirability of 0.98 when a second order model equation was used. A two-tailed t-test was used to compare the model projected value to the actual values under the optimization settings, which indicates no significant difference (Table 3). The the established model to forecast the responses of cutting the paddy straw by SMS serrated blade can be used after harvesting along with the specified design parameters.

CONCLUSION

The operational parameters had a significant effect on the torque and power requirement for the cutting purpose. A minimum torque of 3.8 N-m and total cutting power of 0.62 kW were observed at 900 rev/min on the 0th DAH for the SMS serrated blade followed by the cutter bar and SMS plain blade for cutting the paddy straw. The validation of the developed model to estimate the torque required for the cutting of paddy straw exhibit a good agreement between the actual and estimated torque with an accepted R^2 value. The rotational speed should be more than 700 rev/min for the effective cutting of paddy crops, whereas, the forward speed should be within 1.5 km.h^{-1} to obtain a proper cutting quality with minimum torque. The study will help in selection of suitable blade with optimized operational parameters for development of an efficient cutting system of chopping cum incorporation unit for in situ management of paddy straw.

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