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ORIGINAL RESEARCH

Paddy straw collector-cum-chopper for in situ paddy straw management: A sustainable approach

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Abstract

Purpose The study was devoted to conceptualize, develop and evaluate a collector-cum-chopper for *in situ* paddy straw degradation at the farmer's field level. The intention was to increase the amount of straw cut at size below 5 cm for nutrient recycling.

Method A paddy straw collector-cum-chopper comprised of three sub-systems *i.e.* straw collection and conveying unit, straw chopping device and discharging mechanism was designed and developed. The performance evaluation, economic assessment of paddy straw collector-cum-chopper and fertility status of soil was recorded.

Results The results revealed that operating the machine at 40% moisture content, forward speed 3 kmph and 40 cm height of cut resulted into percentage of paddy straw <5 cm, 5-10 cm, 10-15 cm and > 15 cm as 63.5 %, 8.12 %, 6.44 % and 17.92 percent. At such a condition, it consumed 5.78 lh^{-1}, 7.82 kWh-ton^{-1} energy at 2.06 $tonnesh^{-1}$ productivity. The operating cost was Rs.694.6 h^{-1}, break-even point 556 hours per annum, annual utility 1146 tonnes, pay-back period 1 year and unit cost of paddy straw chopping as Rs.58.44 per tonne. The mixing of the treated paddy straw with the soil bolstered NPK and organic carbon by 64.61%, 48.36%%, 74.32% and 54.54% with respect to 38.37%, 34.91%, 38.69%, 43.33% treated paddy straw kept above the soil.

Conclusion The study provides an opportunity to bolster nutrient content of the soil, restrict the dependence on hazardous chemical fertilizers and protect the environment.

Keywords *In situ* degradation, Productivity, Fertility status, Straw chopper, Cost economics

Introduction

Indo-Gangetic plains cover an area of 26 million hectares in Rice–Wheat cultivation system in South Asia and China (Muzamil et al. 2021; Choudhary et al. 2018) with 90% area generating more than 500-550 million tonnes of crop residues annually (Janaiah and Hossain 2003). With the expected increase in the global rice demands by 28% in 2050 (Zhang et al. 2021) and mechanization of the agricultural system picking up, more than 75% of the rice crop is harvested with the help of combine harvesters (Bisen and Rahangdale 2017). The crop is harvested at 30-40 cm height to save energy and complete the operation within stipulated time. However, the harvesting of the

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combine harvested paddy results in the generation of loose straw (5 tha^{-1}) and standing stubbles (7 tha^{-1}) constituting a total of 12.5 tha^{-1} (Singh 2002). The straw interferes with the working of the subsequent machinery and induces limitations. The farmers often resort to burning of the paddy straw to prepare the field in record time. The burning of paddy straw causes the loss of renewable organic source (Singh and Singh 2001) and contributes to global warming by the release of greenhouse gases (Badrinath et al. 2006; Kumar et al. 2023). Moreover, the burning robs the soil from essential nutrients, kills beneficial micro-organisms and severely affects the human health (Muzamil et al. 2013).

The problem of paddy straw management is multifaceted with lack of appropriate machinery to handle the standing stubbles and loose straw after combine operation, bulky volume, slow degradation rate, harbouring of pathogens and weed problems (Devevre and Horwath 2000) and direct relation with the poor yield caused by short-term negative effect on nitrogen immobilization (Pandey et al. 2009). The best alternative is to reduce the size of the paddy straw below 5 cm and incorporate with the soil through rotavator (Muzamil et al. 2021). The size reduction is a cumbersome job owing to flexible and supple nature of the paddy straw. The conversion of paddy straw into nutrient rich compost demands a size reduction within 1.27–7.62 cm (Luis et al. 1993).

The existing choppers have failed to achieve the objective of size reduction. Moreover, the developed machines have huge power consumption, rendering them unsuitable for normal use. It is imperative to utilize biological tools to enhance the rate of degradation of paddy straw. The activities of soil microorganisms play a major role in nutrient recycling and organic matter decomposition. The bolstering of physical, chemical and biological health of soil is interrelated with crop residue recycling (Shrivastava et al. 2018). The main objective of the study was to develop a mechanical interface to reduce the particle size of paddy straw below 5 cm, apply the recommended dose of the inoculum and mix the ingredients with the soil to assess the impact on parameters governing the soil fertility. The size reduction and incorporation of the paddy straw with the soil can help to prepare the soil for wheat cultivation. *In situ* degradation of rice straw can be a safe alternative option for appropriate disposal of waste, ensuring the recycling of the nutrients (Banger et al. 1989) for the ecological benefit and economic feasibility (Taiwo 2011). The nutrient status of the soil can get bolstered, burning incidents may reduce and dependence on hazardous and costly chemical fertilizers may subside. This, in turn, can help farmers monetarily and ensure protection of soil biodiversity.

Materials and methods

The design parameters of the paddy straw collector-cum-chopper were finalized on the basis of mathematical calculations and preliminary experiments. The machine comprised of reciprocating cutter bar, chain conveyor, chopping rollers, trapezoidal discharge and inoculum tank, Fig. 1. The developed prototype was tested in combine harvested field. The machine was operated and the chopped paddy straw was treated with inoculum prepared from *Aspergillus awamori, Trichoderma viride, Phanerochaete chrysosporium* and *Aspergillus nidulans* @1000 g per tonne of the material (Muzamil et al. 2015). The treated chopped paddy straw was mixed with soil in one treatment and allowed to decompose on the top of the soil in other treatment. The experiments were replicated thrice to confirm the validity of the results.

Design considerations for individual components of Paddy straw collector-cum-chopper

The design was such that both the standing stubbles and loose straw will get collected, chopped and laid in the form of windrow. Also, the recommended dose of inoculum will be applied in one go.

Straw collection and conveying unit

Reel design

The imperative function of the reel was to deliver the stalks to the cutting unit, holding them upright during cutting and convey them to the chopping rollers. The reel executed complex motion, both translational motion along with the machine moving at a speed V_m and a rotational motion around its own axis.

u = R ω (1)

Where, ω = angular velocity of the reel and R = radius of the reel

When u is greater than final velocity V_m, the trajectory of the reel is a trochoid.

Reel index

Reel speed index is related to the ratio of reel peripheral speed to forward travel speed. It varied from 1.25 to 1.5. The rotational speed of 72 rpm was selected on the basis of preliminary experiments to divert the standing stubbles towards cutter bar.

Rotational velocity of the reel

$$\omega = \frac{2\,\pi\,N}{60} = \frac{2\,\pi\,x\,72}{60} = 7.53 \text{ rad/s}$$

Peripheral speed of the reel with 23cm radius of the reel

u = R ω = 0.23 x 7.53 = 1.731 m/s

Distance with magnitude equal to header advance per radian of reel rotation, R_o

R_o = V_m / ω = 1.384/ 7.53 = 0.183 m = 18.3 cm

The deflection angle calculated = 54°

$$\omega t = \sin^{-1}\frac{R_O}{R}\sin\theta + \frac{\pi}{2} - \theta$$

$$= \sin^{-1}(\frac{18.3}{23}\sin 54) + 90 - 54 = 76.06^{\circ} \quad (2)$$

Angular displacement (α) between successive tine bars

$$\alpha = \omega t - \cos^{-1}(\frac{Z_r}{R} + \cos\omega t)$$

$$= 76.06 - \cos^{-1}(\frac{17.3}{23} + \cos 76.06) = 69.31^{\circ}$$

The number of tyne bars (n) on the reel,

$$n = \frac{2\pi}{\alpha} = \frac{2x\,180}{69.31} = 5 \quad (3)$$

Selection of appropriate chain drive

The velocity ratio of chain drive

$$V = \frac{Speed\ of\ the\ driver\ (N_1)}{Speed\ of\ the\ driven\ (N_2)} = \frac{200}{95} = 2.10$$

The number of teeth on smaller sprocket for velocity ratio 2 is 27. Number of teeth on the larger sprocket or gear $T_2 = T_1 x \frac{N_1}{N_2} = 27\ x\ \frac{200}{95} = 56$ (4)

Helical corrugated cutting blades

In order to increase the coefficient of friction and grip the paddy straw (Fig. 2), corrugated helical shaped blades were selected with 80 mm height, 75 mm base and 35 mm top width. The failure of the plant depends on moisture content, loading rate and internode position (Muzamil et al. 2016). The blades were attached to the straw bruising cylinders with nuts and bolts. Therefore, Volume = $\frac{a+b}{2}\ x\ h\ x\ L = \frac{35+75}{2}\ x\ 80\ x\ 50$

= 2.2 x 10^{-4} m^3 (5)

The total weight of knives

= ρVgn = 7850 x 2.2 x 10^{-4} x 9.81 x (14x19 + 4 x19)

= 5.8 kN

Diameter of shaft of the bruising cylinder

The maximum diameter of the shaft carrying the bruising cylinder was determined by (Sharma and Aggarwal 1998) as

$$d^3 = \frac{16}{\pi\,\delta}\sqrt{(M_t K_t)^2} + \sqrt{(M_b K_b)^2} \quad (6)$$

Where, δ = allowable stress = 40 x 10^{6} N/m^2

M_t = torsional moment = 2192Nm

M_b = bending moment = 26.63 Nm (Maduka 1988).

K_t, K_b = fatigue and shock factor for torsional and bending moments (1.5 and 1.0)

$$d^3 = \frac{16}{\pi\ x\ 40\ x\ 10^6}\sqrt{(2192\ x\ 1.5)^2} + \sqrt{(26.63\ x\ 1.0)^2}$$

d = 75 mm

Permissible twist in the torsional rigidity of the shaft

The torsional deflection was determined by using the torsion equation given by (Khurmi and Gupta 2005) as $\theta = \frac{TL}{jG}$ (7)

Where, θ = angle twist in radians

T = 2192 x 10^3 N-mm = torque

G = modulus of rigidity for shaft material, N/ mm^2 (G = 84 x 10^3 N/mm^2)

L = length of the shaft, mm

j = Polar moment of inertia of the cross sectional area about the axis of rotation

$j = \frac{\pi}{32} d^4 \,; j = \frac{\pi}{32} (50)^4$ = 6.13 x 10^5 mm^4

$$\theta = \frac{2192 \; x \; 10^3 \; x \; 1000}{2.52 \; x \; 10^5 \; x \; 84 \; x \; 10^3} = \; 0.0425 \; ^{O}$$

$$\theta = 0.0425 \; x \frac{\pi}{180} \; = 0.0074 \; radians$$

The permissible amount of twist should not exceed 0.25 ^{O} per metre length of shaft (Khurmi and Gupta 2005). The calculated twist of 0.0425 ^{O} (0.00074 radians) for the designed shaft was within the safe limit.

Design of the hopper

The shape of discharging hopper was selected as trapezoidal to converge the chopped materials into compact rows of desired width, Table 1.

The volume of the hopper was determined as

$$V \; = \; \frac{h}{3} \left(A_1 + \; A_2 \; + \; \sqrt{(A_1 \; x \; A_2)} \right) \quad (8)$$

Where, V = volume of the hopper, m^3

A_1 = area of the top, m^2

A_2 = area of the base, m^2

A_1 = L x B = 1.53 x 1.53 = 2.34 m^2

A_2 = L x B = 0.5 x 0.5 = 0.25 m^2

Therefore, $V \; = \; \frac{h}{3} \left(A_1 + \; A_2 \; + \; \sqrt{(A_1 \; x \; A_2)} \right)$

$= \frac{0.77}{3} \left(2.34 + \; 0.25 + \; \sqrt{(2.34 \; x \; 0.25)} \right)$ = 0.86 m^3

Table 1 Design values of paddy straw collector-cum-chopper

Parameter	Value	Significance
Number of tyne bars on the reel	5	To divert the standing paddy stubbles towards the cutter bar
Total weight of the knives	5.8 kN	To reduce the side of the paddy straw and ensure the stability of the reciprocating cutter bar
Volume of the hopper	0.86 m^3	To discharge the chopped paddy straw uniformly in a windrow for *insitu* degradation

Evaluation procedure

The performance of the developed prototype of paddy straw collector-cum-chopper was tested in a combine-harvested field (Fig. 3) as per plan of experiment, Table 2. The samples were dried, segregated and weighted at regular intervals to determine the weightage of the particle size < 5 cm, 5 – 10 cm, 10 – 15 cm and > 15 cm, Fig. 4. The chopped paddy straw in the windrow was treated with inoculum prepared from *Aspergillus awamori*, *Trichoderma viride*, *Phanerochaete chrysosporium* and *Aspergillus nidulans* at the rate of 1000 g per tonne of the material. The treated chopped paddy straw was mixed with the soil using rotavator in treatment T_1 and kept above the soil in treatment T_2. A single pass of the rotavator was used after every 10 days (turning frequency) to mix the chopped treated paddy straw with the soil.

Table 2 Plan of experiment for the evaluation of paddy straw collector-cum-chopper

Experiment	Parameter	Levels	Response
1	Moisture content	3 (30, 40 and 50%)	• Size of cut, cm • Power requirement, kW
	Forward speed	3 (2,3 and 4 kmph)	• Energy, kWh-ton^{-1} • Chopper productivity, ton-h^{-1}
	Stubble height	3 (30,40 and 50 cm)	• Fuel consumption, lh^{-1}
2	T_1: Treated paddy straw mixed with the soil T_2: Treated chopped paddy straw kept above the soil		• Nitrogen, kgha^{-1} • Phosphorus, kgha^{-1} • Potassium, kgha^{-1} • Organic carbon, %

Performance evaluation parameters

1. Fuel consumption

The fuel consumption was measured by top-up method. Initially the tank was the filled to the top and the operation was carried out. After the operation, the difference in the fuel level was used to measure fuel consumption.

2. Power requirement

It was calculated according to principles and assumption of Hunt (1983) and Embaby (1985). The power consumption (kW) was measured with the help of Fuel consumption (lh^{-1}), density of the fuel (kgm^{-3}), calorific value (kcalkg^{-1}), 427 as thermo mechanical equivalent (kgm-kcal^{-1}), Mechanical efficiency of engine (η_m) and Thermal efficiency of the engine (η_{th}).

$$P = \frac{FC\ x\ \rho\ x\ CV\ x\ 427\ x\ \eta_m\ x\ \eta_{th}}{3600\ x\ 75\ x\ 1.36} \quad (9)$$

3. Energy

The energy requirement of paddy straw collector-cum-chopper was calculated as the ratio of power consumption to the machine productivity.

$$Energy\left(\frac{kWh}{ton}\right) = \frac{Power\ consumption\ (kW)}{Machine\ Productivity\ (\frac{ton}{h})} \quad (10)$$

4. Length of chopped paddy straw

An arrangement was made to collect the chopped straw for every 12 m distance. The straw was weighted by means of digital weighting balance and dried. Out of total quantity, about 500 g of sample was segregated manually and measured on percent weight basis with size <5 cm, 5-10 cm, 10-15 cm and beyond 15 cm.

5. Measurement of N, P, K and organic carbon

The parameters depicting fertility status of the soil – nitrogen, phosphorus, potassium and organic carbon was measured with Kjeldahl apparatus, spectrophotometer, flame photometer and muffle furnace (Muzamil et al. 2021). The soil fertility status parameters were measured with chopped and treated paddy straw placed on the surface and incorporated with the soil for comparative evaluation.

Statistical analysis

The experiments were conducted as per the plan of experiment and LSD design was used in planning the experiment. The results were analysed by Duncan multiple range test to test the significance of the treatments at 5 % level of significance and 1 % level of significance.

Cost estimation parameters

The cost calculation involves the fixed and operating cost (Mohiuddin et al. 2022) of prime mover (tractor) and paddy straw collector-cum-chopper to ensure that the paddy straw management remains economically feasible. It also included the comparison of the manual paddy straw management with the operation of developed machine. It included the cost saving, capacity to handle the paddy straw effectively, breakeven point (PBP), annual utility (AU) and payback period (PBP) of paddy straw collector cum chopper. The indices serve as hallmark of acceptance by the custom hiring agencies and farmers.

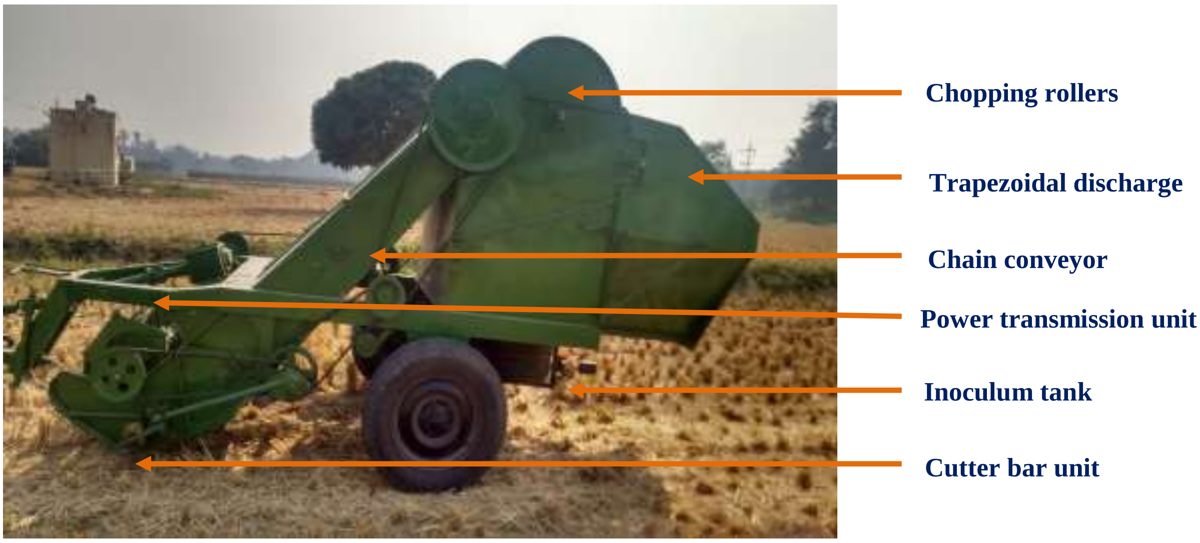


Fig. 1 Components of paddy straw collector-cum-chopper (Muzamil et al. 2021)

Fig. 2 Harvesting and densifying mechanism of collector-cum-chopper

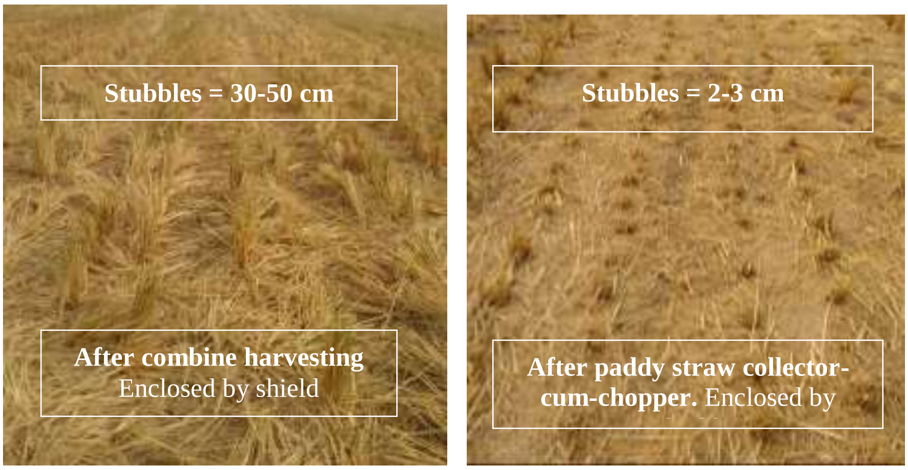


Fig. 3 Field conditions before and after paddy straw collector-cum-chopper

Fig. 4 Drying, segregation and weighing of chopped paddy straw

Results and discussion

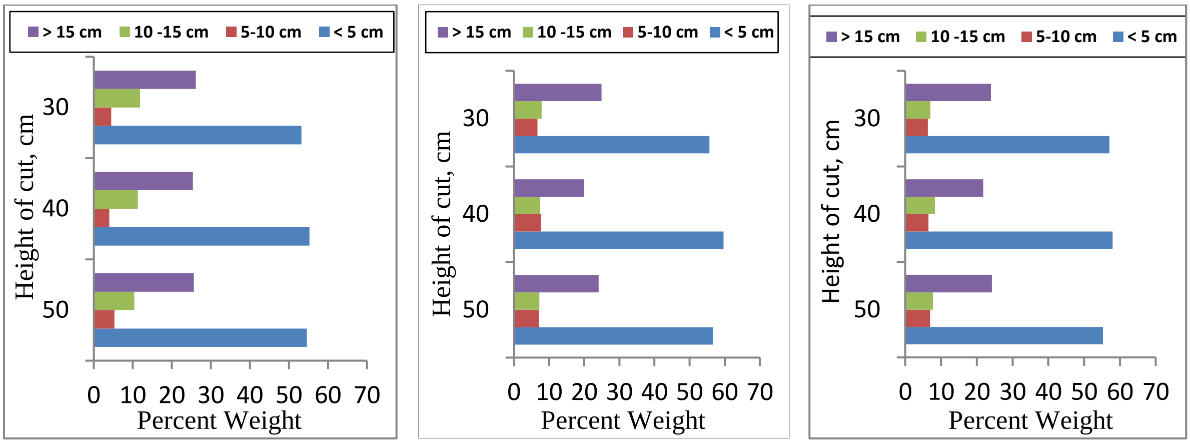
Effect of moisture content on size of cut

The quality of final product is an important parameter to evaluate the performance of size reducing equipment. The cutting length suitable to enhance degradation for nutrient recycling should be ≤ 5 cm (Metwally et al. 2006). At lower forward speed of 2 kmph, the highest percent weight of chopped straw size < 5 cm, 5-10 cm, 10-15 cm and >15 cm was 59.64 %, 7.66 %, 7.42 % and 19.94 % at 40 % moisture content and 40 cm height of cut, Fig. 5. The reciprocating cutter bar of paddy straw collector-cum-chopper was able to grip the stubbles, comparatively better than 30 % and 50 % moisture content. When forward speed was increased to 3 kmph, the percent weight of chopped straw size < 5 cm, 5-10 cm at 40 % moisture content increased to 63.5 %. The forward speed of 3 kmph was appropriate to prevent the accumulation of the paddy straw at the reciprocating cutter bar. At highest forward speed of 4 kmph, it was observed that the paddy straw choked the reciprocating cutter bar, resulting in reduction in chopped straw size < 5 cm to 57.02 % at 40 % moisture content. In general, the percentage of chopped straw < 5 cm increased with the reduction of moisture level from 50 % to 40 % and increase in forward speed from 2 kmph to 3 kilometre per hour. The analysis with Duncan multiple range test revealed that impact of 40%moisture content was higher than 30 and 50% moisture content.

Effect of moisture content on power and energy consumption

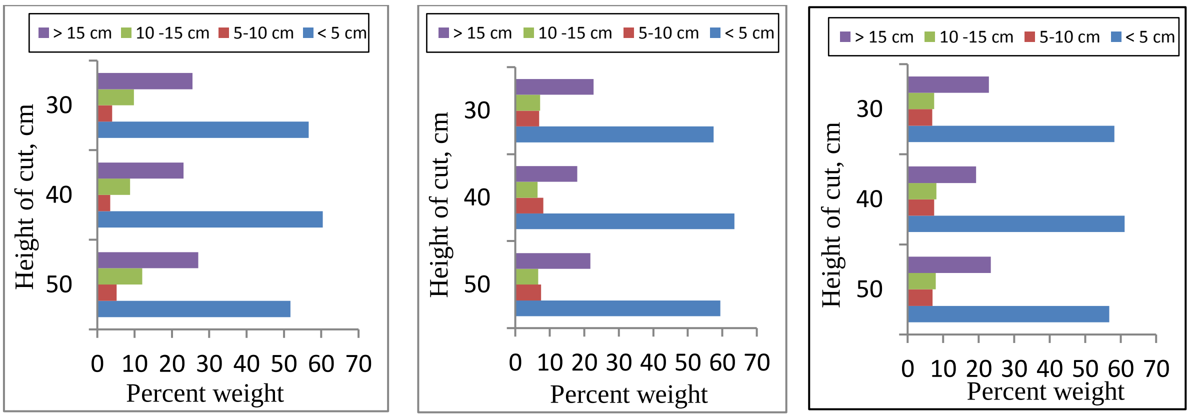
The energy consumption is directly related to the cost per unit operation and governs the adaptability and acceptance of the machine among the farmers. When paddy straw collector-cum-chopper operated at 2 kmph forward speed in a field of stubbles with 50 % moisture content, the power and energy consumption varied from 13.95 - 13.67 kW and 8.74 -7.95 kWh-ton^{-1} for stubble height 50-30 cm, Fig. 6. The highest power and energy consumption of 19.32 kW and 9.99 kWh-ton^{-1} was associated with height of cut of 50 cm operating at 4 kilometre per hour. It was observed that power and energy consumption increased with the increase in forward speed. When moisture content of paddy straw was 40% operating at forward speed of 2 kmph, the power and energy consumption varied from 13.78-13.5 kW and 9.43-8.05 kWh-ton^{-1} at stubble height of 50-30 cm. The smooth flow of stubbles and loose paddy straw led to reduction in power and energy consumption at 40 % moisture content in comparison to 50 % moisture content. At lower moisture content of 30 % and operating speed of 2 kmph, the paddy straw collector-cum-chopper consumed 13.61-13.11 kW power and 11.61-9.23 kWh-ton^{-1} energy for size reduction of paddy straw at height of cut of 50-30 centimetre. With the increase in forward speed, it was found that more power and energy was required to operate the machine, ranged from 16.14-15.20 kW, 9.5-

8.41 kWh-ton^{-1} and 18.23-17.31 kW and 11.01-9.92 kWh-ton^{-1} at forward speed of 3 kmph and 4 kilometre per hour. The Duncan analysis showed that lower power and energy consumption occurred at moisture content of 40%, forward speed of 3 kmph and height of cut of 40 cm.



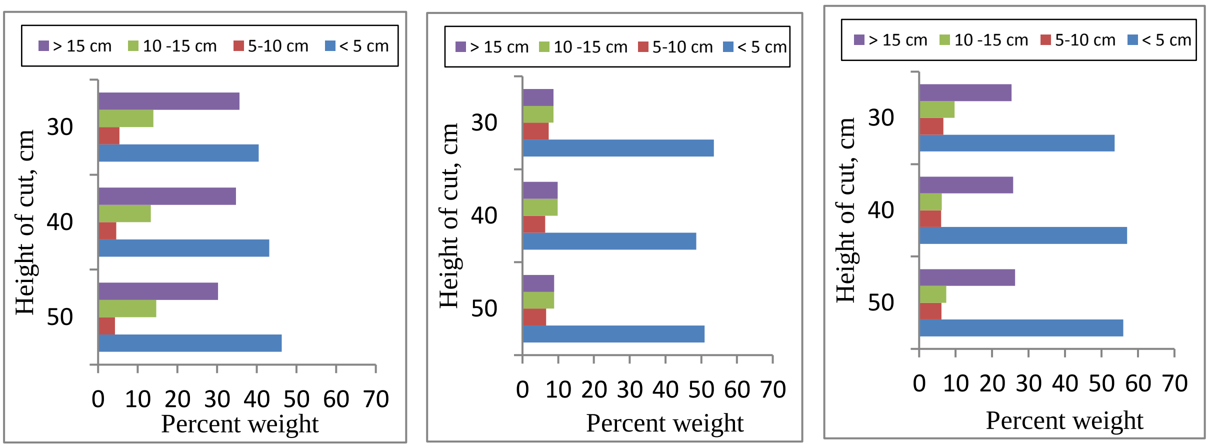
50 % Moisture content   40 % Moisture content   30 % Moisture content

A: Size of cut at forward speed of 2 kmph



50 % Moisture content   40 % Moisture content   30 % Moisture content

B: size of cut at forward speed of 3 kmph



50 % Moisture content   40 % Moisture content   40 % Moisture content

C: size of cut at forward speed of 4 kmph

Fig. 5 Variation in size of cut at different forward speed, moisture content and height of cut

Effect of moisture content on chopper productivity

The productivity of the machine gives rough idea about the capability to chop large quantities of paddy straw in shortest possible time. At 50 % moisture content, the maximum and minimum productivity of paddy straw collector-cum-chopper operating at 50 cm height of cut was 2.10 $tonh^{-1}$ and 1.59 $tonh^{-1}$ at forward speed of 3 kilometre per hour. At 40 cm and 50 cm height of cut, the maximum productivity of 2.13 $tonh^{-1}$ and 2.15 $tonh^{-1}$ and minimum productivity of 1.72 $tonh^{-1}$ and 1.73 $tonh^{-1}$ was observed at 3 kmph and 2 kilometre per hour, Fig. 7. At 40 % moisture content and 50 cm height of cut, the maximum and minimum productivity was found to be 2.04 $tonh^{-1}$ and 1.77 $tonh^{-1}$ at forward speed of 3 kmph and 4 kilometres per hour. At 30 % moisture content with 50 cm height of cut, the maximum productivity of 1.80 $tonh^{-1}$ occurred at 3 kmph and minimum productivity of 1.65 $tonh^{-1}$ at 4 kilometre per hour. The moisture content, forward speed and interaction between forward speed and height of cut was found to be significantly influencing machine productivity at 1 % level. The low productivity was mainly due to accumulation of soil on the cutter bar that reduces its efficiency to chop the standing stubbles.

Effect of forward speed and height of cut on fuel consumption

The fuel consumption has a bearing on the cost of operation of the machine. The fuel consumption of paddy straw collector-cum-chopper operated in paddy straw field with moisture content of 50 % and height of cut of 50 cm increased from 5-6.92 lh^{-1} as the forward speed increased from 2-4 kilometre per hour. The maximum fuel consumption of 6.92 lh^{-1} with a standard deviation of 0.08 occurred at forward speed of 4 kmph and 50 cm height of cut. When the height of cut was 40 cm, the fuel consumption increased from 4.96-6.67 lh^{-1} with the increase in forward speed. Similar trend was observed with height of cut of 30 cm. The maximum fuel 6.48 lh^{-1} with standard deviation of 0.1 was consumed at forward speed of 4 Kmph and height of cut of 30 cm, Table 3. The fuel consumption increased with the increase in forward speed. The maximum fuel consumption at 40 cm and 30 cm height of cut was 6.36 lh^{-1} and 6.2 lh^{-1} with standard deviation of 0.13 and 0.14 at forward speed of 4 kilometre per hour.

Effect on nutrient recycling of soil

It was observed that NPK and organic content in treated chopped paddy straw mixed with the soil increased by 64.61% (110.6 – 182.0 $kgha^{-1}$), 48.36% (42.8 – 63.5 $kgha^{-1}$), 74.32% (1068.4 – 1862.5 $kgha^{-1}$) and 54.54% (0.33 – 0.51%), respectively. The increment in NPK concentrations can be attributed to the reduction in size, thereby providing more area for the microbes to act. The increase in the microbial growth may have resulted in the reduction in molecular weight of organic matter and degradation in short period of time. In case of treated paddy straw above the soil, NPK and organic content increased by 38.37% (106.34 – 147.53 kg ha^{-1}), 34.91% (35.8 – 48.3 kg ha^{-1}), 38.69% (1057.6 – 1466.8 kg ha^{-1}), 43.33% (0.3 – .43%), Fig. 8. Liu et al. (2014) recommended that paddy straw incorporation can improve soil fertility in terms of an increase in 11.1% nitrogen, 12.2% phosphorus and 13.0% potassium. The statistical analysis revealed that operational parameters of moisture content, forward speed and height of cut were significantly ($p<0.05$) influencing the bolstering of nutrient proportion of soil.

Optimization of operating parameters

The optimization of the functional parameters of paddy straw collector-cum-chopper was carried out through Design expert analytical software, Table 4. At optimum conditions, power consumption was 16.14

kW with energy demand of 7.82 kWh-ton^{-1} generating a productivity of 2.06 tonnes h^{-1} consuming fuel @ 5.78 litre per hour and percentage of straw < 5 cm 63.5 per cent on weight basis.

Cost economics

The developed paddy straw collector-cum-chopper has 2.06 th^{-1} productivity with annual utility of 1146 t and breakeven point of 556 hours per annum, Table 5. The money spent on the machine can be recovered within a span of one year. The unit cost of paddy straw management was calculated as Rs. 58.44 per tonne.

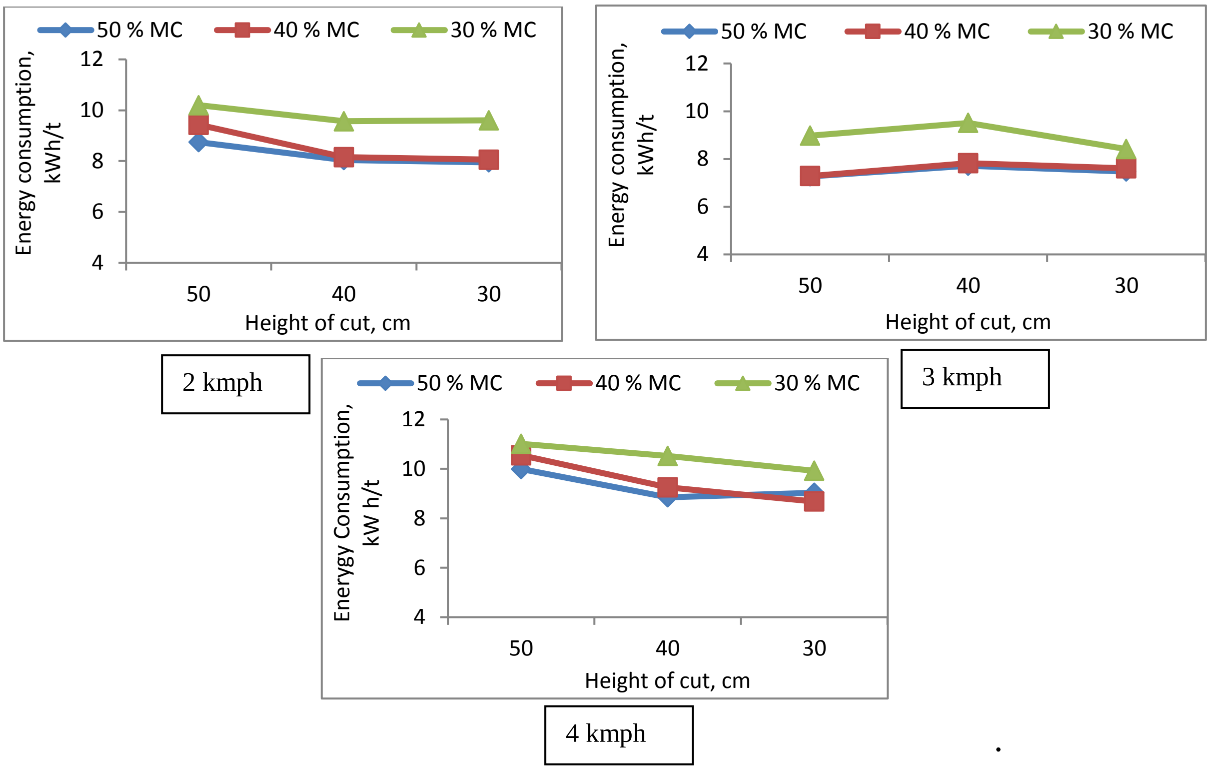


Fig. 6 Variation in power and energy consumption at different moisture content and forward speed

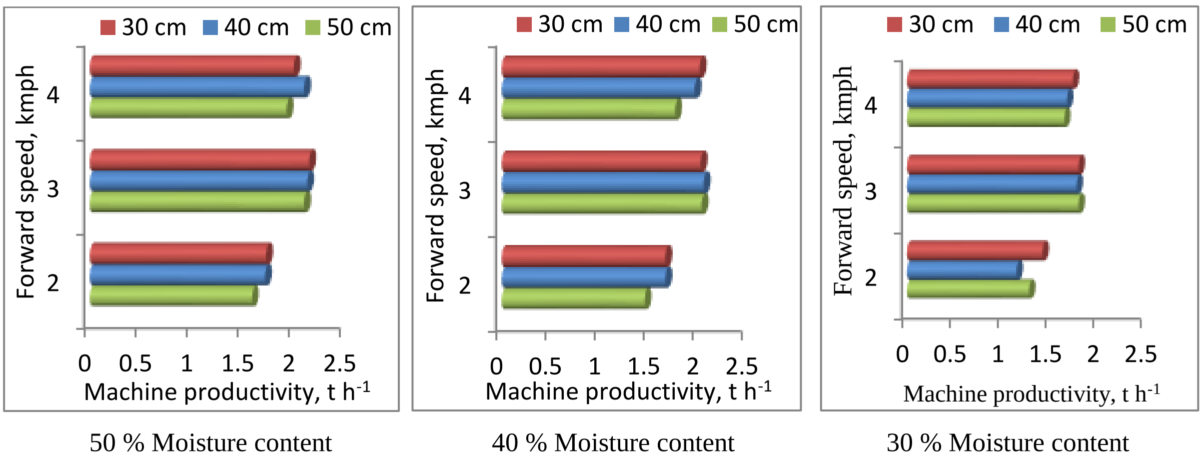


Fig. 7 Productivity of paddy straw collector-cum-chopper at different height of cut and moisture content

Table 3 Variation in fuel consumption with forward speed and height of cut

Moisture content (%)	Height of cut (cm)	Forward speed (kmph)	Straw collected (kg) Mean ± SD	Fuel consumption ($l\ h^{-1}$) Mean ± SD
50		2	7.98±.14	5.0±0.07
50	50	3	9.6±0.99	6.0±0.04
50		4	6.98±0.85	6.92±0.08
50		2	8.6±0.16	4.96±0.08
50	40	3	8.9±0.37	5.90±0.11
50		4	7.6±0.54	6.67±0.12
50		2	8.6±0.23	4.9±0.06
50	30	3	8.96±0.49	5.76±0.05
50		4	7.23±0.73	6.48±0.1
40		2	7.31±0.26	4.94±0.11
40	50	3	9.43±1.16	5.90±0.09
40		4	6.4±0.90	6.7±0.11
40		2	8.39±0.25	4.9±0.08
40	40	3	8.6±0.39	5.78±0.11
40		4	7.12±0.64	6.53±0.12
40		2	8.38±0.19	4.84±0.13
40	30	3	8.59±0.34	5.61±0.17
40		4	7.33±0.54	6.31±0.12
30		2	6.43±0.14	4.88±0.26
30	50	3	7.5±0.61	5.78±0.19
30		4	5.98±0.46	6.53±0.13
30		2	5.79±0.32	4.82±0.15
30	40	3	6.87±0.43	5.61±0.1
30		4	6.1±0.10	6.36±0.13
30		2	7.1±0.08	4.7±0.18
30	30	3	7.53±0.39	5.44±0.12
30		4	6.3±0.47	6.2±0.14

Table 4 Optimization of the operational parameters

Parameters	Levels	Optimum conditions
Height of cut	30, 40 and 50 cm	40 cm
Moisture content	30, 40 and 50 %	40 %
Forward speed	2, 3 and 4 kmph	3 kmph

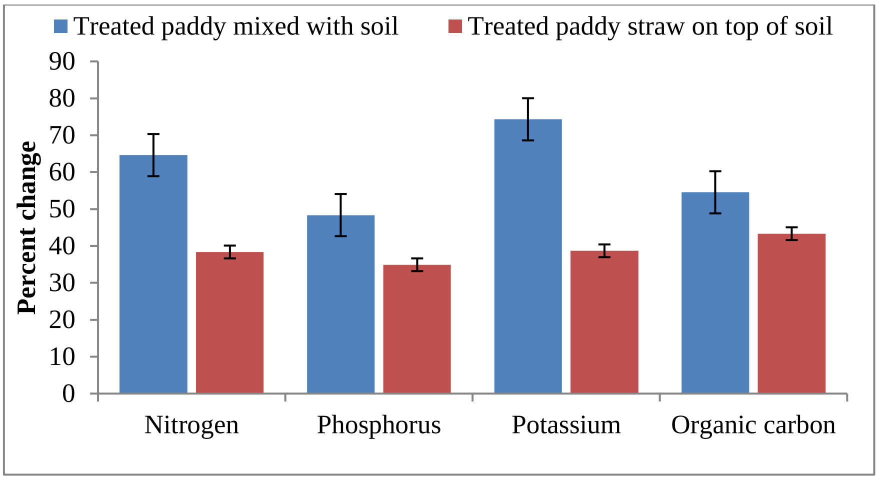


Fig. 8 Percent change in soil fertility status parameters

Table 5 Appraisal of cost attributes of paddy straw collector-cum-chopper

Parameter	Value	Importance
Operating cost of tractor and paddy straw collector-cum-chopper, Rsh^{-1} (fixed cost + variable cost)	694.5	It provides an idea about the cost of the operation per unit time.
Break event point, hours per annum	556	It defines the limit above which the operation of paddy straw management will be profitable.
Annual utility, tonnes	1146	It is the benefit accrued from each rupee invested.
Payback period, year	1	It is the time limit in which the invested money will be re-covered.
Unit cost of paddy straw manage-ment, $Rs.ton^{-1}$	58.44	It is an essential parameter to decide the custom hiring rate of paddy straw collector-cum-chopper.

Conclusion

The individual components of Paddy straw collector-cum-chopper Viz. cutting, conveying, chopping and discharging system worked satisfactorily to ensure size reduction for efficient paddy straw management at farmer's field level. At optimum working condition of 40% moisture content, forward speed of 3 kmph and 40 cm height of cut, the percentage of paddy straw < 5cm, 5-10 cm, 10-15 cm and > 15 cm were 63.5 %, 8.12 %, 6.44 % and 17.92 percent. The response parameters were fuel consumption 5.78 lh-1, energy requirement 7.82 $kWh\text{-}ton^{-1}$ and productivity of 2.06 tonnes per hour. The cost economics revealed an operating cost of Rs. 694.6 per hour, break-even point of 556 hours per annum, annual utility of 1146 tonnes, pay-back period of 1 year and unit cost of paddy straw chopping as Rs. 58.44 per tonne. The mixing of the treated paddy straw bolstered the nitrogen, phosphorus, potassium and organic content by 64.61%, 48.36%%, 74.32% and 54.54% with respect to 38.37%, 34.91%, 38.69%, 43.33% treated paddy straw above the soil. Thus, a window of opportunity for custom hiring through private owners, government agencies, state corporations and cooperative societies exists to to get rid of the menace of paddy straw burning and associated environmental pollution.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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