Development and testing of self-propelled type rotary forage harvester

Kabi Sankar Mahata[1], Sanjay Mochary[2*], Soumik Dey Roy[2], Rajdeep Mohanta[2]

(1. IIT Kharagpur, Kharagpur, Paschim Medinipur-721302, West Bengal, India;
2. Department of Agriculture, Brainware University, Barasat-700125, West Bengal, India)

Abstract: A study was conducted to evaluate a self-propelled rotary forage harvester designed for harvesting fodder crops like oats, guinea grass, berseem, and natural grass, particularly Napier grass during field testing. This harvester, equipped with a rotary disc cutting unit and a depth wheel for precision cutting, aims to minimize plant damage during impact cutting. It demonstrated an effective field capacity of 0.1361 ha h^{-1}, slightly lower than its theoretical capacity of 0.1749 ha h^{-1} across four observations. The harvester achieved an average harvesting efficiency of 73.64%, with 15%-wheel slip under load and 18.2% without load. The operational cost for harvesting using this rotary forage harvester was estimated at $ 29.50 ha^{-1}. Fuel consumption averaged 0.95 l h^{-1} during operation. Real-world harvesting time for one hectare was recorded at 7.34 hours, compared to the theoretical harvest time of 5.71 hours. This study underscores the harvester's capabilities in efficiently handling small fodder crops, highlighting its practical efficiency, fuel economy, and operational characteristics under real-world conditions.

Key words: rotational forage harvester, self-propelled, fodder crops, cutting unit, efficiency.

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1 Introduction

In India, raising cattle and engaging in mixed farming are fundamental aspects of rural life that are intricately woven into the country's complex social structure on a cultural, religious, and economic level. Approximately 45.76% of the labour force is still working in the agriculture and livestock industries (Anonymous, 2023a), despite the agricultural sector's contribution to the Indian economy steadily declining (from 36.4 percent in 1982–1983 to 18.3 percent in 2020–21) (Anonymous, 2023b). Similar to other crop-growing practices, the cultivation and use of fodder require tasks like seedbed preparation, crop sowing, weeding, harvesting, and so forth. Prior to feeding produced fodder crop to animals, it becomes crucial to carry out preliminary processing. High labour intensity, additional time, and energy are needed for the production, processing, and use of fodder. Forage crops must be produced and used at their best, which requires minimal, crucial, and timely operation. Fodder quality deteriorates quickly and moisture content is frequently lost when fodder production operations are delayed (Sahay et al., 2015). Mechanization makes cross-cultural interactions easier and makes seeding operations easier, which in turn provides high-quality feed (Kalamkar, 2009). In addition, high-quality fodder is needed to improve milk quality. According to Mohanty et al. (2016), mechanization is a necessary step in preserving the health of cattle and their produce. Grassland cattle farms are dynamic, hard to manage systems due to

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***Corresponding author: Sanjay Mochary.** Department of Agriculture, Brainware University, Barasat-700125, West Bengal, India. E-mail: sanjaymochary1993@gmail.com.

their susceptibility to unpredictable environmental conditions. The study conducted by Kumar and Kumar (2017) revealed that the farm's machinery utilization rate was 0.65 kw ha^{-1}, which is lower than the reported power utilization rate of 1.12 kw ha^{-1} for effective farm operations achieved by mechanization.

Due to the multiple cuts involved in harvesting green feed, more energy is needed. For gathering green fodder, a variety of equipment are available; the one used will depend on the purpose, crop kind, field size, and crop characteristics. Hand harvesting fodder crops is becoming a costly and time-consuming task. An Indian sickle must be used to physically harvest each hectare of crop standing, which takes 239.5 ± 23.2 man-hours ha^{-1} (Rao et al., 2024). It is therefore necessary to mechanize harvesting. Marginal farmers cannot afford the massive and costly harvesting equipment that is currently on the market. Two distinct types of cutting mechanisms are found in current harvesters: shear type reciprocating mechanisms and impact type rotary cutters. The revolving cutter bar is a common tool used in the harvesting of pulse and cereal crops. Disc cutters of the rotary kind are more versatile and have more potential for harvesting because of their simple yet sturdy design. The rotary cutting system's design becomes more dependable and manageable as a result of having fewer moving components. Therefore, the present study was started with the following goals in order to address the need for a rotational harvester:

(1) Creation of a forage harvester using a rotary design.

(2) To evaluate the machine's overall performance.

(3) To assess the machine's field capacity.

(4) A comparison of traditional and mechanical harvesting methods' costs.

2 Materials and method

At the Bidhan Chandra Krishi Viswavidyalaya in West Bengal, India, a rotary disc-style cutting device was intended to be constructed during 2021-2022. The geographical location of the research is at 46 meters above mean sea level, with latitude 22° 56' 46.6008" N and longitude 88° 32' 7.3176" E. Our goal was to test and adjust a forage harvester unit that was built and had four cutting blades and a rotating disk attached. The cutting unit consisted of a 45 cm diameter circular disk that extended to a 9 cm long blade tip. The rotary disc was secured to a gear box located on the cast iron main frame. The blades' ground clearance can be adjusted, ranging from 3 to 12 cm. The harvester is powered by a 3.8 kW diesel engine. From the guard to the back of the machine, the harvester's mainframe measured 198 cm in length. To move power from the engine to the cutting machine, a gear transmission system was also incorporated. It also had a depth wheel connected, which allowed the operator to control the depth of cut.

2.1 Adaptation and construction of a self-propelled rotating feed harvester

2.1.1 Functional requirement

Forage crops that are shorter than 70 centimetres in height must be able to be harvested by the self-propelled type rotating forage harvester. Before the harvester, a protective guard is positioned to keep crop debris from becoming stuck and suffocating the cutting disc. Still, the blades on the rotating disc need to be sharp enough to avoid losing power and flattening the fodder. The fodder crop is cut at a specific height with the aid of the depth wheel. A mechanism for changing the field's size ought to be included.

2.1.2 Principle of operation

The concept of impact cutting serves as the foundation for the self-operated rotary type fodder harvester's construction. A revolving circular disc that is fastened to a frame at a particular height above the ground makes up the cutting unit. The front of the apparatus weighs more than the rear because of the protection and cutting unit. A 15 kg counterweight balance is fastened to the rear to help balance the weight as a consequence. To adjust the cutting height of the fodder crop, a depth wheel is attached for ease of use. Harvesting crops with little damage to the plants is our goal when using impact cutting. The stainless-steel cutting disk is attached to the cast carbon steel blades. The gear box is attached to it at the front of the harvester. The highest recommended rpm for the blade's rotation is possible. Between 62.83 and 194.78 m s^{-1} is the range at which the blades rotate.

2.1.3 Factor of safety and strength of the material of construction

For optimal field performance, the self-operated rotary type forage harvester may operate in low undulating fields at a working speed of roughly 3.07 km h^{-1}. Under these operating conditions, there will be less chance of an unplanned engine failure and less slippage. The weight of the equipment would affect its convenience of use, especially when using it in shifts.

2.1.4 Specific moisture content of soil

The machine was designed to be used in fields that were low lying and undulating, with light to medium soils that had 20% or less moisture. In these conditions, the tire would slip and crash to the ground. A maximum particular soil resistance needs to be assumed, per the adjustment. While making modifications to the machine, the following factors were taken into account:

(1) The machine features a rotating cutting unit attachment and a 3.8 kW engine.

(2) It is estimated that the procedure would be carried out at a speed of 3.07 km h^{-1}.

(3) Its design and construction should be simple enough for local craftspeople to modify and maintain it with ease.

(4) The rotary forage harvester is utilized in crop fields with light to medium textured soil and low moisture content (around 10% to 20%).

(5) The machine should be reasonably priced so that the average farmer may purchase one.

(6) Attachments that required little upkeep should be included.

1. Drive gear lever, 2. 6.5 Hp engine, 3. Frame, 4. Guard Plate 5. Rotary cutting disc 6. Main frame, 7. Gear box, 8. Accelerator, 9. Belt Drive 10. Wheel, 11. Counter weight, 12. Pulley

Figure 1 Components of the self-propelled type rotary forage harvester

2.2 Self-propelled type rotary forage harvester and its components

The terms and parts listed below are necessary for the self-propelled type rotary forage harvester to meet the functional specifications:

2.2.1 Engine

A 3.8 kW single cylinder diesel engine produced by Greaves Ltd. powers the forage harvester. The engine is air-cooled. The flywheel's rated maximum rotating speed is 188.5 m s^{-1}. The engine can hold five liters of fuel in its tank.

2.2.2 Transmission system

The system of belts and pulleys transfers engine power. The power transmission system in this instance featured a B-type pulley. With a diameter of 10.16 cm, the engine pulley is coupled to the clutch pulley to transfer power to the gearbox. Through a revolving shaft, the cutting disc and gear box are connected. The gear box is 20 × 18 × 15 meters. The wheel axle driven pulley was attached to the engine pulley and installed on the reduction gear shaft. With a diameter of 30.48 cm, the axle wheel driven pulley rotates the axle at a lower speed.

2.2.3 Control unit

The primary gear system, the accelerator, the engine stop button, and the gear system that drives the cutting unit are all part of the control unit. Near the handle bar is where all of the control mechanisms are located. The direction of travel of the rotary harvester can be manually adjusted by us.

2.2.4 Wheel

A pair of pneumatic Wheels is used to drive the forage harvester. The diameter of the wheel is 53.5 cm and the diameters of the rim is 33.5 cm.

(a) Wheel track: Wheel track is the measurement made at the point of ground contact between the median planes of wheels or tracks on the same axle.

(b) Turning space: Turning space is the diameter of the circle, measured in centimetres and represented by the outermost point of the rotary harvester during its shortest turn.

2.2.5 Cutting unit

The cutting unit is made up of a guard and a rotary disk to which four blades are attached. It is coupled to a gearbox by a revolving shaft. The harvester is positioned in front of the gear box. To prevent crop debris from becoming lodged and suffocating the cutting disc, the harvester is equipped with a guard in front of it.

(a) Cutting width: the separation between the spots where the tips of two blades mounted to opposing discs are attached is measured. The rotary harvester has a 63 cm cutting width.

(b) Cutting disc height: The measurement in centimetres of the lowermost portion of the cutting disc above the surface the harvester is standing on. Minimum and maximum values need to be measured when the height is adjustable.

(c) Effective width of cut: The actual cutting width, measured in centimetres when using the harvester in the field. The operating width of cut for this machine is 57 cm.

2.2.6 Depth control wheel

The rotary harvester cannot function smoothly without a depth control wheel. There is a depth control wheel on the frame. The wheels measure roughly 17.78 cm in diameter. Rubber and mild steel are used to make it. The wheel's purpose is to regulate the forage crop's cut height. The depth adjustment lever, allows you to change the depth of cut. It is a revolving device fastened to the depth control wheel's structure.

2.3 Specifications for self-propelled type rotary forage harvester

The details of the harvester's specifications, including the dimensions of its various components and the type and power of the engine, are presented in Table 1.

2.4 Testing of self-propelled type rotary forage harvester

There were four forward speeds that the self-propelled type rotary feed harvester was tested at: 2.86, 3.05, 3.17, and 3.2 km h^{-1}.

2.4.1 Location

The Self-propelled Type Rotary Forage Harvester performance evaluation trials were conducted in a field close to the Agricultural Engineering Faculty, Bidhan Chandra Krishi Viswavidyalaya in West Bengal, India (22° 56' 46.6008" N, 88° 32' 7.3176" E). There are many kinds of grass sown in the field. The following supplies were utilized to include the experiment:

(a) Developed Self-propelled Type Rotary Forage Harvester, Engine Model – Greaves Ltd.

(b) Raw materials & measuring instruments

(c) Tachometer

(d) Stopwatch

(e) Pegs

(f) Vibration meter

2.4.2 Instrumentation used

To record various observations, the experiment was carried out using the instruments that are mentioned below.

Table 1 Specifications for self-propelled type rotary forage harvester

	Parameters	Specifications
General Information of Engine	Name and Address of the Manufacturer	Greaves Ltd. Plot J2, M.I.D.C, Chikalthana, Aurangabad, Maharashtra, India
	Model	1523
	Year of Manufacturing	10/2005
	Serial No.	D-0-02760
Specifications of Engine	Engine Speed (m s^{-1})	
	Maximum Speed at no load (m s^{-1})	194.77
	Maximum Speed at load (m s^{-1})	183.25
	Low Idle Speed (m s^{-1})	62.62
	No. of Cylinder	1
	Fuel System	
	Fuel Tank Capacity (l)	5
	Provision for Draining Sediments/ Water	Filter → Pump → Injector
	Displacement (cm^3)	325
	Stroke (mm)	78
	Lubrication Oil Consumption (g h^{-1})	13
	Dry Weight (kg)	43
	Max Torque In NM	29.03 N-M
	Specific Fuel Consumption (g kW^{-1} h^{-1})	275.4 - 295.4
	Oil Sump Capacity (l)	1
Harvesting Attachments	Cutting Unit	
	Type of Material	Stainless Steel
	Diameter of Rotary Disc (cm)	45
	Working Width of Cut (cm)	63
	Effective Width of Cut (cm)	57
	No. of Blades	4
	Type of Blades	Swing Type
	Type of Material	Carbon Steel
	Length of Blades (cm)	9
	Guard Sheet	
	Length (cm)	90
	Width (cm)	45
	Material Used	Cast Iron
Operating Controls	Controls on the RHS of the Operator	Engine Kill Switch Gear Lever for Drive Gear Lever for Cutting Unit
	Controls on LHS of the Operator	Accelerator
Wheel System	Diameter of the Wheel (cm)	53.34
	Diameter of the Rim (cm)	33.5
	Type of Wheel	Pneumatic
Colour of the Rotary Harvester	Colour	Orange

2.4.2.1 Electronic balance

After harvesting, the weight of the fodder was measured using an electronic scale with a sensitivity of 0.01 g. The electronic balance had a 1200 g capacity. The mass was measured with an accuracy of ± 0.5 percent in grams.

2.4.2.2 Measuring tape

Three-meter-long steel tapes were used to measure and mark the field. Plant height and cut height were also measured using the steel foot rule. When measuring length in meters, the measuring stopwatch's accuracy was 0.5%.

2.4.2.3 Stop watch

A Swiss-made gallet stopwatch, with an accuracy of at least 1/10 of a second and up to 30 minutes, was used to record the operating time during the test. Moreover, the measurement accuracy of the stopwatch was 0.2 percent.

2.4.2.4 Tachometer

A computerized photo-cum-contact tachometer with a 0.05 percent accuracy was used to assess the engine and rotary disc's rotating speed. Notable were the highest and lowest values. When expressing rotational speed in rev min^{-1}, the measurement's accuracy was 0.5%.

2.4.2.5 Vibration meter

Portable vibration meters are typically furnished with a memory that allows them to store measurements. Most vibration meters have an integrated data logger, which collects and stores vibration measurement data over time. With this approach, exact data on vibration measurement can be obtained.

2.4.3. Parameters for observation and estimation

(a) A randomly chosen and marked 28.2 m × 14 m plot was selected.

(b) A selection of grass varieties was made.

(c) Performance evaluation was carried out at four different speeds.

(d) Plant characteristics, such as plant population (number-m^{-2}) and stubble length (cm), were measured.

(e) Actual operating time was documented throughout the performance review, and time loss was separately tracked.

(f) A measure was taken of fuel use.

(g) Field efficiency (FE, %), actual field capacity (AFC, ha h^{-1}), theoretical field capacity (TFC, ha h^{-1}), and the work rate (ha h^{-1}) stated above were computed with their assistance.

2.4.4. The purpose of the experiment was to evaluate the performance and ascertain

(a) AFC

(b) TFC

(c) FE

(d) Total time loss during turning

(e) Harvesting efficiency.

2.5 Theoretical considerations

2.5.1 During and after the operation, following observations were recorded

(a) Area covered

(b) Time of Operation

(c) Time lost in turning

(d) Wheel Slip

(e) Fuel Consumption

(f) Vibration

(g) Plant Height.

A comparison of forage harvesting by machine and by hand was also conducted. All of the machine was brought up to working order before the test began. Prior to the test, the self-propelled type rotary harvester underwent all required pre-checks.

2.5.2 Theoretical field capacity

TFC is a simple calculation involving speed and width with efficiency set at 100%. It is calculated from the following equation (Hanna and Hanna, 2016):

$$X = \frac{A \times B}{10} \quad (1)$$

Where, X is the theoretical field capacity (ha h^{-1}), A is the width of coverage (m) and B is the speed (km h^{-1}).

A machine's TFC cannot be sustained for extended periods of time. TFC is severely reduced by interruptions like turning times and breakdowns. Since the TFC is the greatest attainable capacity at a given speed, it can be used as a benchmark for assessing the operator's or machine's performance.

2.5.3 Actual field capacity

AFC is the actual average rate of coverage by the machine it is expressed as ha h^{-1}.

$$Y = \frac{Q}{T} \quad (2)$$

Where, Y is the actual field capacity (ha h^{-1}), Q is the area of plot (ha) and T is the total time taken (h).

2.5.4 Field efficiency

FE is the ratio of AFC to TFC. Failure to use the machine's entire operational breadth and several additional interruptions, such as malfunctions, waiting, turning, etc., are explained by FE.

$$Z = \frac{Y}{X} \times 100 \quad (3)$$

Where, *Z* is the field efficiency (%), *X* is the theoretical field capacity (ha h^{-1}) and *Y* is the actual field capacity (ha h^{-1}).

2.5.5 Turning loss

During the harvester's first and second test runs, the amount of time it takes to make the smallest turn possible for the appropriate turning condition is known as turning loss. Seconds are used to express it.

2.5.6 Wheel slip

Wheel slip refers to the ratio of the harvester's theoretical distance to its actual distance, or the differential between the two. It is expressed as percentage. According to Wong (2022) and Zhu et al. (2022),

$$S_w = \frac{Dt - Da}{Da} \times 100 \quad (4)$$

Where, S_w is the wheel slip (%), D_t is the theoretical distance (m) and D_a is the actual distance (m).

2.5.7 Plant height

The height of the plant from its base at the ground level to its top hen the plant is straightened. It is expressed in centimetres.

2.5.8 Stubble length

The length of plant stalk attached to the ground immediately after harvesting. It is generally expressed in centimetres.

2.5.9 Fuel consumption

By utilizing the conventional method, the fuel consumption was determined. After filling the graded cylinder with a known quantity of fuel, the technique was run with the rotary harvester on a level surface to obtain the final measurement of the cylinder. One consideration was the cost of the gasoline utilized over a given period of time. Fuel consumption is expressed in litres.

2.5.10 Harvesting efficiency

Harvesting efficiency was calculated based on the number of forage crops counted before harvesting & the no. of actual forage plants left after harvesting operation (Jalu et al., 2020).

$$M = \frac{W_1 - W_2}{W_1} \times 100 \quad (5)$$

Where, M is the harvesting efficiency (%), W_1 is the number of forage crop before harvesting, and W_2 is the number of forage crop after harvesting.

2.6 Ergonomic considerations

2.6.1 Vibration measurement

(a) The rotary harvester's functionally essential assemblies and components must have their mechanical vibration amplitude measured using an appropriate vibration measuring device. To park the rotary harvester, utilize a level concrete platform.

(b) The rotor harvester sub-assemblies must make the observations while operating at the field-recommended no load engine speed. It is important that the tire pressure matches the manufacturer's suggested pressure.

2.7 Cost of operation

2.7.1 Fixed costs

2.7.1.1 Depreciation

It is the machine's diminishing worth as time goes on. Although the machine's sale price at the end of its useful life would determine true depreciation, depreciation can be approximated using the straight-line method, as described below, based on several computing techniques (Hunt, 1963).

$$D = \frac{C - S}{L \times H} \quad (6)$$

Where, D is the depreciation per hour, \$ h^{-1}; C is the capital Investment, \$; S is the salvage value, 10% of capital; H is the number of working hours per year; and L is the life of machine (self-propelled type rotary forage harvester) in years.

2.7.1.2 Interest

Interest is calculated on the average investment of the machine taking into consideration, the value of machine in first and last year.

$$I = \frac{C + S}{2} \times \frac{i}{H} \quad (7)$$

Where,

I= Interest per year.

i = % rate of interest per year.

2.7.1.3 Housing

Housing cost is calculated on the basis of the prevailing rates of the locality the housing cost is taken as 1% of the initial cost of the machine per year.

2.7.1.4 Insurance

Insurance charge is taken on the basis of the actual payment to the insurance; it is taken as 0.5% of the initial cost of the machine per year.

2.7.1.5 Taxes

Taxes are calculated on the basis of the actual taxes paid per year; it is taken as 1.5% of the initial cost of the machine per year.

2.7.2 Variable costs

2.7.2.1 Fuel costs

Based on the harvester's actual fuel usage, fuel costs are determined. It is given in l h^{-1}. Using the delivery 7 return pipe, the independent fuel measuring cylinder was fastened. Direct measurements were made of the fuel use.

Fuel consumption costs = rate of fuel × fuel consumption.

2.7.2.2 Lubrication costs

Charges for lubrications should be calculated on the actual consumption, the lubricants costs varies between 25% to 35% of the fuel costs.

2.7.2.3 Repair and maintenance costs

Costs of repair and maintenances 7% of the initial cost of the machine per year.

2.7.2.4 Wages and labour costs

Wages are calculated on the basis of actual wages of the workers. It was generally taken \$3.57 day^{-1}.

2.7.2.5 Total costs of operation

The total costs of operation per hour of the developed rotary harvester for forage crops can be calculated by summation of total fixed cost per hour.

Total costs per hour = fixed costs per hour + variable costs

3 Results and discussion

3.1 Field evaluation

The field performance of the harvester, including the actual time taken to harvest, TFC, AFC and FE, is shown in Table 2.

3.1.1 Calculation of total time loss

Avg. length of the field = 28.2 m

Width of the field = 14 m

Therefore, Area = 28.2 m × 14 m = 394.8 m^2

Speed of E_1 = 2.86 km h^{-1}

Speed of E_2 = 3.06 km h^{-1}

Speed of E_3 = 3.17 km h^{-1}

Speed of E_4 = 3.2 km h^{-1}

Average forward speed of the implement = $\frac{\text{Sum of all the forward speeds}}{\text{No.of Experiments}}$ = 3.07 km h^{-1}

Working width of cut = 0.57 m

Now, for a plot of 1 ha,

Area covered in 1h = avg. speed (km h^{-1}) × width (m) = $\frac{3.07 \times 0.57}{10}$ = 0.1749 ha

Time needed to harvest 1 ha field = $\frac{1}{0.1749}$ = 5.71 hr

No. of turns = $\frac{14}{0.57} - 1$ = 24 turns (approx.)

Avg. time consume in 1 turn = 9.2 s

Total time loss in 24 turns = 9.2 × 24 = 221 s (approx.) = 3 min 41 s

Total time required by the rotary harvester = time needed to harvest + time loss in 24 turns = (33.1 × 25) s + 3 min 41s = 17.4 min.

The efficiency and speed benefits of mechanical harvesting over human labour can be seen by comparing the time required to harvest one hectare of fodder crop by a self-propelled rotary harvester and by hand harvesting. From the above calculation it can be interpreted that the rotary harvester takes 5.71 hours in theory, but it actually takes 7.34 hours. On the other hand, harvesting by hand takes 240–256 hours, or 30–32 man-days (Sahay et al., 2015). Even with the little discrepancy in real versus theoretical time for the rotary harvester, it is still far faster than harvesting by hand. This pace of harvesting is made possible by mechanized methods since they are more reliable, more efficient, and require less labour from humans. On the other hand, manual harvesting requires more time to complete due to variances in labour productivity, weariness, and skill levels. Overall, the research highlights the efficiency gains attained by mechanization in agricultural practices and emphasizes the significant time-saving advantages of employing a self-propelled rotary harvester over human harvesting techniques.

Table 2 Data collected from the field

Parameters	Observation 1	Observation 2	Observation 3	Observation 4	Mean Results
Distance Covered (m)	28	29	27.3	28.5	28.2
Actual Time (s)	35.3	34	31	32	33.1
Turning Loss (s)	10	9	12	8	9.75
Forward Speed (km h^{-1})	2.86	3.06	3.17	3.2	3.07
Fuel Consumption (ml)	11	12	11.5	10.5	11.25
Working width of cut (m)	0.57	0.57	0.57	0.57	0.57
Theoretical Field Capacity (ha h^{-1})	0.163	0.175	0.1806	0.1824	0.1749
Actual Field Capacity (ha h^{-1})	0.1268	0.1383	0.1302	0.1462	0.1353
Field Efficiency (%)	77.7	79.02	72.1	80.15	77.79
Fuel Consumed (l)	0.011	0.012	0.0115	0.0105	0.0112
Area (ha)	0.0016	0.00165	0.0156	0.00162	0.0016
Fuel Consumption (l ha^{-1})	6.875	7.26	7.37	6.48	7
Time of Operation (s)	35.3	34	31	32	33.07
Fuel Consumption (l h^{-1})	0.93	0.98	1	0.88	0.95

The efficiency and speed benefits of mechanical harvesting over human labour can be seen by comparing the time required to harvest one hectare of fodder crop by a self-propelled rotary harvester and by hand harvesting. From the above calculation it can be interpreted that the rotary harvester takes 5.71 hours in theory, but it actually takes 7.34 hours. On the other hand, harvesting by hand takes 240–256 hours, or 30–32 man-days (Sahay et al., 2015). Even with the little discrepancy in real versus theoretical time for the rotary harvester, it is still far faster than harvesting by hand. This pace of harvesting is made possible by mechanized methods since they are more reliable, more efficient, and require less labour from humans. On the other hand, manual harvesting requires more time to complete due to variances in labour productivity, weariness, and skill levels. Overall, the research highlights the efficiency gains attained by mechanization in agricultural practices and emphasizes the significant time-saving advantages of employing a self-propelled rotary harvester over human harvesting techniques.

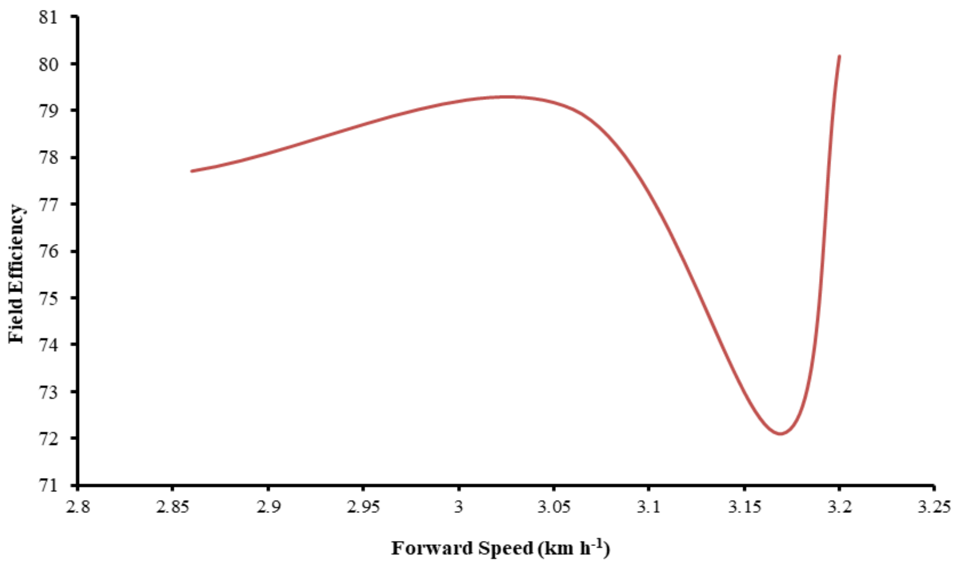

Figure 2 Forward speed vs field efficiency

3.1.2 Calculation of TFC, AFC, FE and fuel consumption

Theoretical field capacity (X) = $\frac{A \times B}{10} = \frac{0.57 \times 3.07}{10}$ = 0.1749 ha h^{-1}

Actual field capacity (Y) = $\frac{Q}{T} = \frac{394.8 \times 60}{17.4 \times 1000}$ = 0.1361 ha h^{-1}

Actual time required to harvest 1 ha of field = $\frac{1}{0.1361}$ = 7.34 h

Field efficiency (Z) = $\frac{Y}{X} = \frac{0.1361}{0.1750}$ = 77.8%

Fuel consumption = $\frac{\text{Fuel consumed (lt)}}{Area(ha)}$

Total fuel consumed during harvesting of 14×28.2 m^2 plot = 280 ml.

So, fuel consumption for 1 ha (or 10000 m^2) of land = $\frac{280}{14x28.2}$ x 10000 ml = 7.01 litres.

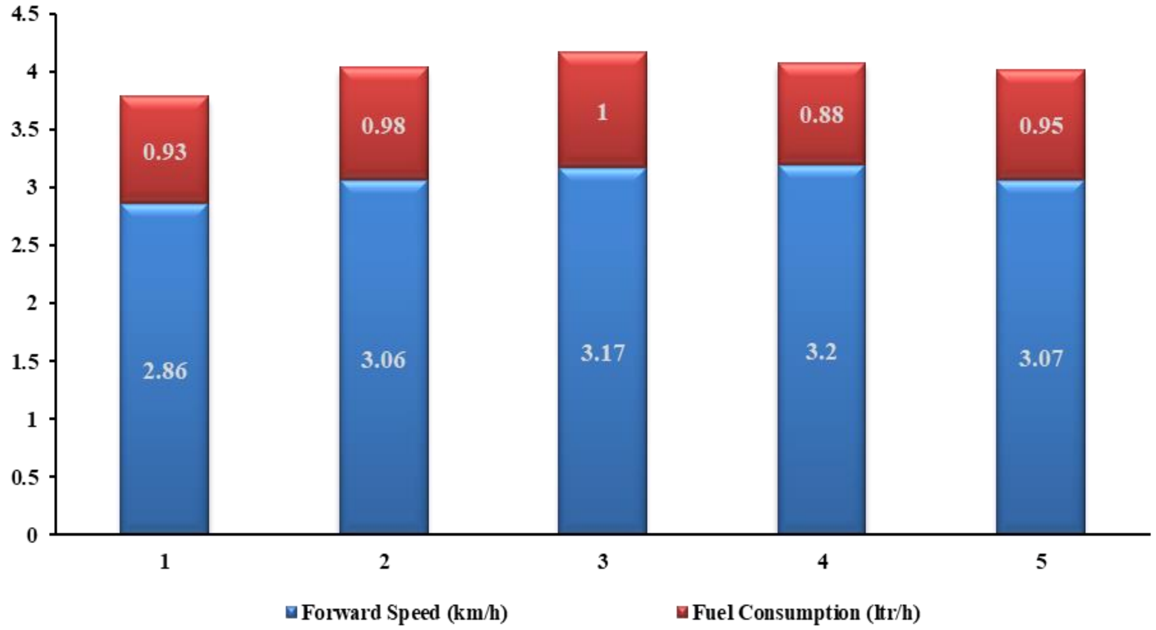

Figure 3 Forward speed vs fuel consumption

Theoretically, the self-propelled rotary forage harvester can harvest one hectare in 5.71 hours per hectare. A hectare's real harvesting time is 7.34 hours due to time losses in turning, which add 1.63 hours to the total. 3.07 km h^{-1} is the average forward speed. The percentage of theoretical capacity realised in actuality is reflected in the harvester's FE, which stands at 77.80%. When operational delays are considered, the AFC is 0.1361 ha h^{-1}, whereas the TFC, or the ideal area harvested per hour, is 0.1749 ha h^{-1}. This performance data shows the harvester's effectiveness and efficiency in actual operations.

An AFC of 0.1393 ha h^{-1}was observed on average at a forward machine speed of 3.07 km h^{-1}. Using a self-propelled rotary harvester, the average FE for grass-forage was found to be 77.8% when all time losses were considered. While developing and testing a harvester for dwarf napier grass, Desrial and Ridha (2020) also discovered a 75.01% FE. The FE of mechanical and manual harvesting was reported by Nikam et al. (2017) to be 72.36% and 54.67%, respectively. According to these results, harvesting by machine is far more efficient than harvesting by hand.

It was discovered that 7.01 liters of fuel would theoretically be consumed by one hectare of land. Khar and Ahuja (2007) discovered similar outcomes.

3.1.3 Wheel slip

S_w (%) = $\frac{Dt-Da}{Da} \times 100$

Theoretical distance covered for 1 rotation of wheel = $\pi \times D = \pi \times 0.533$ = 1.67 m.

Wheel slip %, average wheel slip percentage, revolutions, and covering distance are just a few of the metrics that reflect how a wheeled vehicle performs when it is loaded and unloaded. When the vehicle is loaded, it travels a little farther, but the total number of revolutions is almost the same. More weight distribution results in better traction and efficiency, as evidenced by the wheel slip percentage decreasing when the car is loaded. Another finding that lends credence to this observation is that the vehicle performs better overall when loaded, as seen by a lower average wheel slip percentage. These results are consistent with the laws of friction and weight distribution, which state that extra weight increases tire grip and decreases slippage, thereby increasing the vehicle's overall effectiveness and efficiency in a variety of applications.

Table 3 Wheel slip

Load	10 Revolutions	1 Revolution	Wheel Slip (%)	Average Wheel Slip (%)
	13.4	1.34	19.8	
Covering distance Without Load (m)	13.6	1.36	18.6	18.2
	14	1.4	16.2	
	14.2	1.42	15	
Covering distance With Load (m)	14	1.4	16.2	15
	14.4	1.44	13.8	

3.1.4 Harvesting efficiency of rotary forage harvester

M (%)

$$= \frac{W_1 - W_2}{W_1} \times 100$$

$$= \frac{129 - 22.5}{129} \times 100 = 73.64\%$$

A harvesting efficiency of 73.64% for a self-propelled rotary harvester signifies its capability to harvest nearly three-quarters of the available crop, showcasing several scientific advantages over manual harvesting. These advantages stem from the machine's consistent performance, higher speed, labour-saving potential, reduced crop loss, and precision. Unlike manual labour, which can vary in efficiency due to factors like skill level and fatigue, machines operate consistently, ensuring a steady and reliable harvest. Moreover, the speed of machine harvesting enables farmers to cover more ground in less time, optimizing the harvest window and potentially increasing overall productivity. Additionally, the reduced reliance on manual labour leads to labour savings and decreased costs. Furthermore, the precision of modern harvesting machines minimizes crop damage and ensures that only ripe crops are harvested, maximizing yield and reducing waste. Therefore, the high harvesting efficiency of a self-propelled rotary harvester underscores its scientific superiority over manual harvesting methods.

3.2 Calculation of cost of operation of self-propelled type rotary forage harvester

3.2.1 Fixed costs

Capital = $891.90

Salvage Value = $89.19

Depreciation cost = $0.54 h^{-1}

Insurance Cost = $0.33 h^{-1}

Housing+ Taxes = $0.21

Total fixed cost = $1.07 h^{-1}

3.2.2 Variable costs

Fuel Consumption Cost = $1.38 h^{-1}

Oil/Lubrication Cost = $0.41 h^{-1}

Repair & Maintenance Cost = $0.42 h^{-1}

Labor charge per hour = $0.75 h^{-1}

Total Variable Cost = $2.95 h^{-1}

Operating Cost = Fixed Cost + Variable Cost ($ h^{-1}) = 1.07 + 2.95 = $4.02 h^{-1}

Total cost for harvesting 1 ha of land = $4.02 h^{-1} × 7.34 h = $29.50

3.3 Cost calculation for manual harvesting

Amount paid to the labour for one day = $ 3.57

Total man-day required to harvest forage crop from 1 ha of land = 23

Total cost for harvesting 1 ha of land = $3.57 × 23 = $82.11

3.4 Cost comparison

Amount saved by utilizing a self-propelled type rotary forage harvester in 1 ha = (Amount spent by using the old manual method - cost of operation by using a rotary harvester) = $ (82.11-29.50) = $52.61.

Therefore, machine performance is far more economical and time-efficient for improved fodder harvesting techniques. Thus, employing a rotating forage harvester that is self-propelled will save money and time.

According to the information provided, mechanical harvesting has a substantially lower operating cost than manual harvesting. This suggests that harvesting with machinery is more economical than with human effort. Machine harvesting may have lower operating costs because of things like increased productivity, less manpower needed, and maybe quicker harvesting periods. Therefore, it would probably be more cost-effective for farmers or agricultural enterprises to choose machine harvesting over manual harvesting.

3.6 Measurement of Vibration

Crank angle is converted from time domain for vibration analysis. The crank angle determines both the knocking limit and the control of mechanical loads. The start of the fuel injection pressure results in a rapid rise in the cylinder gas, which in turn creates an increase in pressure that vibrates the engine block during testing. It is well known that the combustion process in diesel engines initiates at multiple points within the cylinder. This situation caused the engine block to vibrate irregularly and to suddenly increase in pressure.

Table 4 Vibration measured at arm with load and unload condition along X-axis, Y-axis and Z-axis

Engine Speed (rpm)	Vibration of Arm without load (m s^{-2})			Vibration of Arm with load (m s^{-2})		
	X	Y	Z	X	Y	Z
600	12	13.6	11.5	23.2	17.9	15.5
790	40	54	23	54.2	44.2	21.7
1416	84.9	102.8	86.8	92.6	95.3	72.4
1860	87	72.8	87.2	96.8	86	93.3

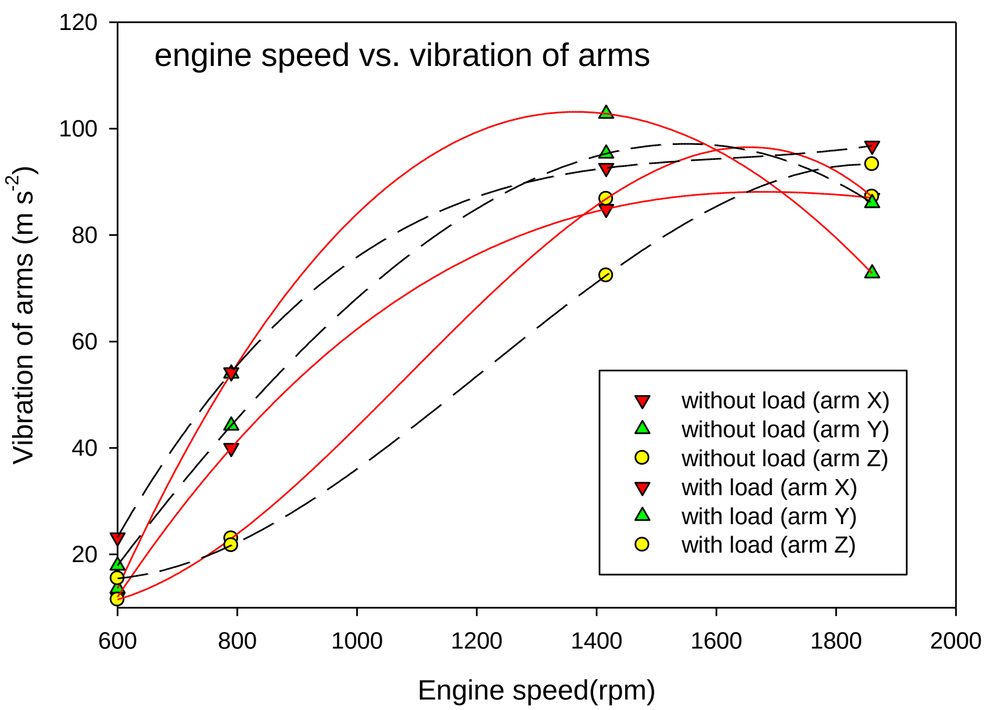

Figure 4 Engine speed vs vibration of arms (the dotted line denotes a load condition, while the red line indicates no load situation)

Therefore, the engine counterbalances the vibration of the engine when it rotates at a greater rpm than a sudden one (>1416 rpm i.e., 148.28 m s^{-1}) caused by the emission of excessive exhaust gas. It can be one of the potential causes of the vibration decrease at the maximum rpm, or 1860 rpm (i.e., 194.77 m s^{-1}).

4 Conclusion

The investigation allows for the drawing of the following important conclusions. The depth control wheel allows for height adjustment of the cut, and the actual width of the covered area is approximately 0.57 meters. It spans 10 to 17 centimetres. With an average forward speed of 3.07 km h^{-1}, the FE of the designed self-propelled type rotary forage harvester was determined to be 77.8%. Average harvesting efficiency of 82.75% is achieved, with 15% slippage under load and 18.2% slippage under no load during operation. The rotary forage harvester has an observed maximum TFC of 0.1806 ha h^{-1} and a minimum of 0.1630 ha h^{-1}; the AFC is 0.1393 ha h^{-1}. The rotary forage harvester operation cost $29.50 ha^{-1} to harvest. The machine used 0.95 litres of fuel per hour on average. A one-hectare area may be harvested in 5.71 hours theoretically and 7.34 hours really by this machine.

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