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Analytical design of self-propelled rotor weeder based on crop morphological parameters

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Abstract

The rising labor costs and declining availability of manual labor in agriculture have intensified the demand for mechanized weeding solutions. This study presents the design and development of an adjustable self-propelled rotor power weeder suitable for inter-row cultivation in light to medium-textured soils. The power requirement was primarily calculated based on soil resistance, blade dimensions and operational speed. A specific draft value of 25 N/cm was adopted for sandy loam soils, resulting in a total draft force of 2000 N per rotor. The calculated power requirement for four rotors was 3.555 kW (4.75 hp), with an additional 0.031 hp required for the drive wheels, summing to a total of 4.78 hp. Accounting for power losses, a 5.36 hp engine was selected. The rotor shaft was designed for a maximum tangential force of 2033.89 N, leading to a moment of 25423.74 N-cm. The rotor shaft diameter was determined to be 19 mm for solid shafts and 21.5 mm for hollow square shafts. The L-shaped blade with a triangular peg tooth was selected and stress analysis revealed a maximum equivalent stress of 146.77 MPa, well within the material limit for mild steel. A gear reduction mechanism was designed to reduce engine speed from 130 rpm to 65 rpm, ensuring optimal rotor speed and operator comfort. The developed weeder offers improved efficiency, operator ergonomics and adaptability across varied crop row spacings, making it a suitable solution for sustainable weed management in small to medium-sized farms.

Keywords: Self-propelled weeder, mechanical weeding, shaft design, blade stress and crops

1. Introduction

Agriculture continues to be the backbone of the Indian economy, providing employment and sustenance to a majority of the rural population. As per projections by the National Commission on Population, India's population is expected to increase from 1.39 billion in 2021 to approximately 1.807 billion by 2050 (Anonymous, 2021) [3]. This significant demographic expansion demands a corresponding increase in food production, which can be met through either expansion of arable land or the adoption of efficient and sustainable farming practices. Among the major constraints in crop production, weed infestation remains one of the most pressing biological challenges, as it directly competes with crops for vital resources such as water, nutrients, sunlight and space, resulting in severe yield and economic losses (NRCWS, 2007) [13].

Weeds are estimated to contribute to about one-third of total yield losses in agricultural systems, with reported reductions ranging from 29 to 70% in maize, 40 to 45% in cotton and 30 to 40% in groundnut and chilli (Mani *et al.*, 1968; Veerangouda *et al.*, 2010; Rao *et al.*, 2014) [10, 24, 15]. Under inadequate management, these losses can reach as high as 80% (Veerangouda *et al.*, 2010) [24]. Moreover, weed control is among the most labor-intensive and costly operations in Indian agriculture, accounting for approximately ₹945 per hectare nearly one-third of the total production cost and consuming 900 to 1200 man-hours per hectare (Tajuddin *et al.*, 1991; Weide *et al.*, 2008) [23, 25]. The annual economic burden from weed infestation is estimated at ₹4200 million (Natarajan, 1987) [12]. (Kanth *et al.*, 2023) [36] studied about yield losses in groundnut crop.

While mechanization has transformed agricultural operations in many developed nations, the adoption of large-scale machinery in India is constrained by the predominance of small and marginal farmers over 80% of landholdings are below two hectares. (Kanth *et al.*, 2024) [37] was analyzed the trends and patterns of farm mechanization in India.

(Rahaman *et al.*, 2025) [38, 39] addressed various factors which are affecting mechanization index and farm power availability. Conventional weeding methods, including manual labor and bullock-drawn implements, are not only time-consuming and physically demanding but also increasingly unsustainable due to labor shortages, rising wages and adverse climatic conditions. As a result, there is a growing reliance on mechanical weeders, particularly self-propelled power weeders, which offer significant labor savings, increased efficiency and reduced costs (Tajuddin, 2006; Anil *et al.*, 2014; Shekhar *et al.*, 2010) [22, 2, 18]. Also studied economic analysis and feasibility of self-propelled rotor power weeder.

Among mechanical weeders, the rotor weeder has emerged as a promising solution due to its rotating mechanism that uproots and buries weeds between crop rows with minimal crop disturbance. These machines are particularly suited for row crops and have gained popularity amidst increasing consumer demand for organic produce and non-chemical weed control solutions (Yadav *et al.*, 2018) [26]. However, the effectiveness of such weeders largely depends on their adaptability to varying field conditions, especially crop morphology, soil characteristics and weed density. Generalized designs often lead to reduced weeding efficiency, higher energy consumption and increased crop damage.

Crop morphological traits such as plant height, stem diameter, row spacing, canopy structure and root anchorage play a critical role in determining the appropriate configuration of weeding equipment (Singh and Ojha, 2019) [20]. Despite this, most current weeder designs do not incorporate crop-specific morphological parameters, resulting in suboptimal field performance (Sharma and Singh, 2019; Singh and Kaur, 2021) [16, 19]. With the rise of precision agriculture and the increasing availability of morphological data, there is a clear opportunity to develop crop-specific, adaptable mechanical weeders that integrate design and agronomic considerations (Patil *et al.*, 2020; Ali *et al.*, 2018) [14, 1].

Analytical modeling provides a scientific foundation for optimizing machine design by quantitatively linking crop morphology with mechanical parameters such as rotor diameter, blade angle, operational speed and power requirements (Kepner *et al.*, 1987; Fathollahzadeh *et al.*, 2020) [9, 6]. While some progress has been made in modeling soil-tool interactions and designing rotary tillers (Desai *et al.*, 2022) [5], few studies have focused on integrating crop morphological parameters into the analytical design of self-propelled rotor weeders. This gap highlights the need for a systematic, data-driven approach to design.

The objectives of the investigation are

- To study the morphological parameters of irrigated dry crops (chilli, cotton, maize and groundnut).
- To design the self-propelled rotor weeder based on crop morphological parameters.

2. Material and Methods

2.1 Experimental site

The present study is conducted at Madakasira, which is located in Anantapur district of Andhra Pradesh. The geographical location of the experimental site is 13° 56'58'' N and 77° 18'42'' E with an elevation of 641.6 metres above mean sea level.

2.2 Climatic conditions

The Madakasira region is considered as one of the arid areas with low precipitation of 532 mm and the maximum temperature is 35°C, whereas the minimum temperature of 23°C. The average temperature is 25.7°C. The average relative humidity is 53% and average wind speed is equal to 10.3 km h⁻¹.

2.3 Soil characteristics

The relative proportions of sand, silt and clay in a soil mass determine the texture of soil (sand 68.0%, silt 14.5% and clay 17.5%). Most of the Madakasira region is characterized by sandy loam soils with gravel.

2.4 Layout of experimental field

A field of 800 m² area was selected for the present study. It was divided into 4 plots of 200 m² of groundnut, maize, chilli and cotton crops and each plot having the dimensions of 20 × 10 m². The layout of experimental field is as shown in the Fig. 3.1. To suit the power weeder the crop spacings are selected and shown in the layout.

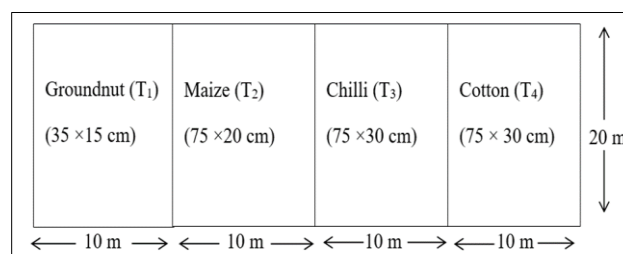


Fig 1: Lay out of experimental field

2.5 Morphological parameters of irrigated dry crops

2.5.1 Crops

The following four crops are selected for the experiment with variety of crop.

1. Groundnut, T₁ (K-9)
2. Maize, T₂ (Priya Gold 4545)
3. Chilli, T₃ (Demon F1) and
4. Cotton, T₄ (Star1, Bollgard-II SCH 234).

2.5.2 Plant Height

The plant height of the four crops were measured randomly by selecting one square metre area with the help of the measuring scale at 30 and 60 days after the sowing of the crops.

2.5.3 Width of Plant

The plant width of the four crops were measured randomly by selecting one square metre area with the help of the measuring scale at 30 and 60 days after the sowing of the crops.

2.5.4 Root Length

The root length of the four crops were measured by randomly uprooting the plants in the selected one square metre area with the help of the measuring scale at 30 and 60 days after the sowing of the crops.

2.6 Design of adjustable self-propelled rotor power weeder

2.6.1 Calculation of power requirement for rotors

To calculate the power requirement for self-propelled power weeder, the soil resistance force is a major factor to consider

for power calculation based on type of soil, similar way two more factors such as size of blade engaging with soil surface and speed of operation are also taken into consideration for power calculations. Certain assumptions are made to estimate power requirement, i.e., speed 1 to 1.2 km/h. specific draft is 25 N/cm for a light medium soil i.e., sandy loam soil, (Pandey, 1994) ^[33]. The maximum width of cut by blade is 20 cm and depth of cut is 4 cm. The belt-pulley power transmission efficiency is 70 to 75%. For weeding operation, the minimum required revolutions are 150 at which maximum tangential force will act (Niyamapa and Chertkiattipol, 2010) ^[32].

The furrow cross-section cut by weeder = Width of cut, cm × Depth of cut, cm = 20 × 4 = 80 cm², Draft of weeder = Specific draft, N/cm × Furrow cross section, cm² = 25 × 80 = 2000 N, Total power requirement for one rotor of weeder in kW, is calculated according to (Thorat *et al.*, 2014) ^[35] using Eq.1.

$$\text{Total power} = \frac{\text{Draft} \times \text{Speed}}{\text{Efficiency}} = 0.88 \text{ kW} \quad (1)$$

Total power requirement for 4 rotors is = 0.888 × 4 = 3.555 kW ≅ 4.75 hp

2.6.2 Calculation of power requirement for drive wheels

Power required for wheels is 23.12 watts (0.031 hp) was considered for the design of power weeder as given by Pandit *et al.* (2016) ^[34] and as shown in Eq.2.

The total required power for self-propelled power weeder is calculated by

$$P_{\text{Total}} = P_{\text{Blade}} + P_{\text{Wheels}} = 4.78 \text{ hp} \quad (2)$$

Considering power losses through various ways, a higher value of 5.36 hp was selected for present study, which is equivalent to 4.0 kW.

2.6.3 Design of rotor shaft

The rotors maximum tangential force should be taken into account while designing the rotor shaft. Using Eq. 3, it was determined that the maximum tangential force of the blades occurs at the lowest tangential speed. Using given by (Bernacki *et al.*, 1972) ^[28].

$$K_s = C_s \frac{75N_C \eta_C \eta_Z}{u_{\min}} \quad (3)$$

Where, K_s = Maximum tangential force, kg, C_s = Reliability factor which is equal to 1.5 for non-rocky and 2 for rocky soils, N_C = Power of engine, hp, η_C = Traction efficiency (it's value for the forward rotation of rotor shaft is 0.9), η_Z = Coefficient of reservation of engine power which is between 0.7-0.8 and $u_{\min}$ = Minimum tangential speed of blades, m/s.

The tangential peripheral speed, $u_{\min}$ was calculated by using the Eq.4.

$$u_{\min} = \frac{2\pi NR}{6000} = 1.963 \text{ m/s} \quad (4)$$

Where, N = Revolutions of rotor, rpm and R = Radius of rotor, cm.

By using Eq.3. $K_s = 207.40 \text{ kg}$ (2033.89 N)

The maximum moment on the rotor shaft (M_s) is calculated by the Eq.5.

$$M_s = K_s \times R = 2592.5 \text{ kg cm}, (25423.74 \text{ N cm}) \quad (5)$$

For design of rotor shaft or any other shaft the yield strength (σ_y) should be from 530 to 784 MPa. The rotor shaft was made from alloy steel. Using Eq.6. The allowable stress on rotor (τ_{all}) was calculated according to (Mott, 1985) ^[31].

$$\tau_{\text{all}} = \frac{0.577k\sigma_y}{f} = 210.60 \text{ MPa} \quad (6)$$

Where, k = Coefficient of stress concentration is 0.75, f = Coefficient of safety is 1.5, τ_{all} = Allowable stress on rotor shaft, kg/cm and σ_y = Yield stress, 730 MPa.

The required shaft diameter was calculated by using Eq.7.

$$d = \sqrt[3]{\frac{16M_s}{\tau \pi}} = 1.844 \text{ cm} = 18.44 \text{ mm} \quad (7)$$

The rotor shaft diameter was selected higher value as 19 mm to balance variable loads during operation for solid shaft and for hollow square shaft shown in Fig.5 the diameter is taken as 21.5 mm.

2.6.4 Design of rotor blade

The type of blade, the number of blades and the functionality of the rotary weeder all affect the rotor blade design. The L-shape blade with triangular peg tooth was selected and as shown in Figure 2 was considered for the power weeder according to the working condition. The dimensions of the blade are width (4 cm), thickness (0.6 cm) and cutting width i.e., length of blade (20 cm). Thus, total length of a single gang is 40 cm. The number of rotor flanges (i) was calculated using Eq.8 given by (Mandal *et al.*, 2015) ^[30]. Where, b = Working width, cm and b_i = Distance between the flanges on the rotor, cm.

$$i = \frac{b}{b_i} = \frac{80}{20} = 4 \quad (8)$$

Six number of blades were considered on each of the flange ($Z_e=6$), the total number of blades was obtained using Eq.9

$$N = i \times Z_e = 4 \times 6 = 24 \quad (9)$$

The soil force available at each blade (K_e) is calculated using Eq.10. Given by (Mandal *et al.*, 2015) ^[30]

$$K_e = \frac{K_s C_p}{i Z_e \eta_e} = 103.7 \text{ kg} (1016.94 \text{ N}) \quad (10)$$

Where, K_s = Maximum tangential force, kg, C_p = Coefficient of tangential force, (taken as $C_p = 2$), i = Number of flanges (4), Z_e = Number of blades on each side of the flanges (6) and η_e = Obtained through dividing the number of blades which act jointly on the soil by total number of blades (1/6).

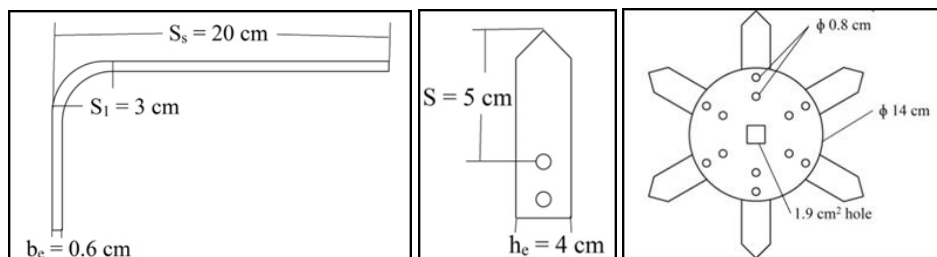


Fig 2: Design of blade indicating with dimensions

The blade dimensions are illustrated in Figure 2. The values of b_e , h_e , S_s , S_1 and S were considered as 0.6, 4, 20, 3 and 5 cm duly. By considering blade shape, the bending stress (σ_{zg}), shear stress (τ_{skt}) and equivalent stress (σ_{zt}) are calculated using Eq. 11, 12 and 13 given by (Bernacki *et al.*, 1972) [28]. The blade dimensions are fixed based on crop row-to-row distance and also on the blade orientation. Where, b_e = Thickness of the blade, h_e = Width of the blade, S_s = Total length of the blade, S_1 = Curvature of the blade and S = Distance from the edge of blade supporter to the first hole of blade supporter.

$$\text{Bending stress } (\sigma_{zg}) = 6 \frac{K_e S}{b_e h_e^3} = 32.406 \text{ MPa} \quad (11)$$

$$\text{Shear stress } (\tau_{skt}) = \frac{3K_e S_1}{(b_e - 0.63) b_e^3} = 71.576 \text{ MPa} \quad (12)$$

$$\text{Equivalent stress } (\sigma_{zt}) = \sqrt{\sigma_{zg}^2 + 4\tau_{skt}^2} = 146.77 \text{ MPa} \quad (13)$$

The calculated values of stresses were bending stress (32.406 MPa), shear stress (71.576 MPa) and equivalent stress (146.77 MPa), while for mild steel material (Thorat *et al.*, 2014) [35] calculated stresses were bending stress (85.40 MPa), shear stress (167.65 MPa) and equivalent (346.0 MPa) respectively.

2.6.5 Design of the power transmission system

Power transmission system for the self-propelled rotor power weeder is designed based on rotor and engine speeds. The coefficient of power transmission (i_c) for the power weeder was calculated using Eq.14. given by (Hemad *et al.*, 2010) [29].

$$i_c = \frac{n_d}{n_a} = \frac{65}{130} = 0.5 \quad (14)$$

Where, i_c = Coefficient of power transmission, n_d = Rotational speed of the power weeder rotor, rpm and n_a = Rotational speed of the power weeder engine, rpm. To achieve the projected coefficient of speed alteration of 0.5 at full engine speed, a power transmission system should be chosen for this design. The 130 rpm is reduced to 65 rpm because which is comfortable for walking speed for operator.

3. Results and Discussion

3.1 Morphological parameters of irrigated dry crops

3.1.1 Chilli crop

At 30 days, chilli plants had an average height of 14.2 cm, a plant width of 9.8 cm and a root length of 6.3 cm, indicating the establishment of early vegetative structures. By 60 days, the height increased to 35.6 cm, plant width to 22.4 cm and

root length to 12.8 cm, showing a significant enhancement in both shoot and root growth. The height more than doubled, suggesting favorable environmental conditions and good genetic potential. Similarly, the increased plant width reflects canopy expansion, which is essential for maximizing photosynthesis. The doubling of root length over the period indicates a healthy root system capable of supporting continued above-ground growth. Overall, chilli showed balanced and vigorous development, ideal for transitioning into reproductive stages.

3.1.2 Cotton crop

At 30 days, cotton plants measured 18.5 cm in height, 12.3 cm in width and had a root length of 8.1 cm. By 60 days, plant height rose to 42.7 cm, width to 25.6 cm and root length to 14.2 cm. The growth in height and width suggests good vegetative development, critical for setting up a strong framework for boll production later. Although root elongation was moderate compared to other crops, the root length nearly doubled, indicating reliable soil anchorage and water uptake capacity. The broad canopy at 60 days enhances light interception, which supports biomass accumulation. These growth trends confirm that cotton is progressing well through its vegetative phase.

3.1.3 Maize crop

Maize exhibited rapid growth, reaching 32.1 cm in height, 16.7 cm in width and 10.5 cm root length at 30 days. By 60 days, these values increased sharply to 78.3 cm in height, 34.2 cm in width and 21.6 cm in root length. This nearly 2.5-fold increase in height is characteristic of maize's fast vertical development during early stages. The plant width also doubled, reflecting substantial leaf expansion, vital for efficient light capture and energy synthesis. Root length growth mirrors the shoot development, indicating strong below-ground support to meet the crop's high water and nutrient demands. Maize is clearly on a vigorous growth trajectory, well-prepared for the onset of reproductive stages.

3.1.4 Groundnut crop

Groundnut plants recorded 12.6 cm in height, 14.5 cm in width and 7.4 cm in root length at 30 days. By 60 days, these values grew to 25.4 cm, 30.3 cm and 13.9 cm respectively. Although plant height was the lowest among the crops, the wide canopy at both stages shows groundnut's typical horizontal growth habit. The more than twofold increase in width supports soil shading and weed suppression, which are agronomic advantages. The steady increase in root length is critical for nutrient absorption and nitrogen fixation. Groundnut's overall development reflects a healthy vegetative phase, setting the foundation for flowering and peg formation.

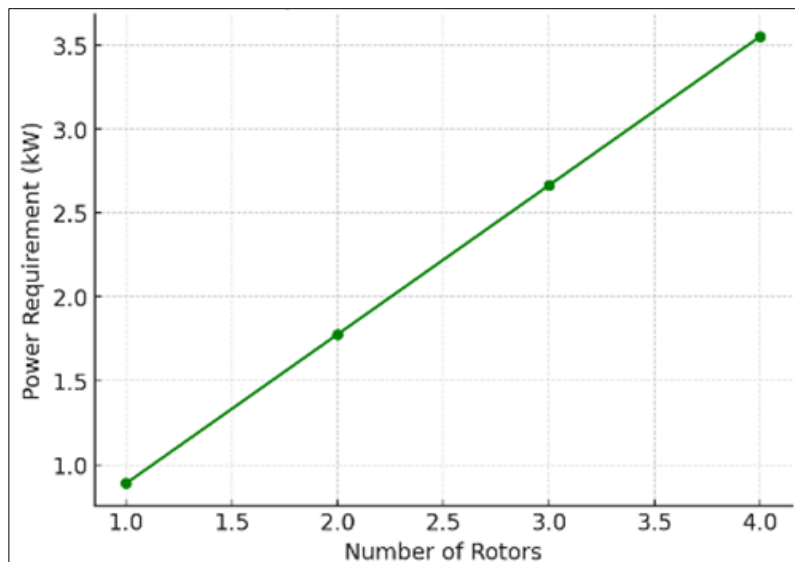


Fig 3: Power requirement with respect to number of rotors

3.2 Analysis of adjustable self-propelled rotor power weeder

3.2.1 Power requirement with respect to number of rotors: The power requirement for the rotor system was calculated considering a specific draft of 25 N/cm for sandy loam soil, a blade width of 20 cm and a depth of cut of 4 cm. This results in a furrow cross-sectional area of 80 cm². The draft force is thus 2000 N. At an operational speed of 1.2 km/h (0.33 m/s) and accounting for a belt-pulley transmission efficiency of 70%, the power requirement per rotor is approximately 0.88 kW. For a four-rotor configuration, the total power requirement is 3.55 kW (4.75 hp). The above graph (Figure 3) illustrates the linear relationship between the number of rotors and the total power requirement, emphasizing the need for appropriate engine selection based on the number of rotors used. This graph displays a clear linear relationship between the number of rotors and power consumption. As rotors increase from 1 to 4, power requirements rise proportionally from approximately 0.9 kW to 3.5 kW. This indicates that each additional rotor requires a consistent amount of additional power. This is crucial for optimizing power source selection and ensuring efficiency in the power weeder's design.

3.2.2 Moment (Torque) with respect to shaft diameter

The rotor shaft was designed to withstand the maximum tangential force, which occurs at the lowest tangential speed. Using the formula provided by Bernacki *et al.* (1972) [28], the maximum tangential force (K_s) was calculated as 207.40 kg (2033.89 N). The maximum moment on the rotor shaft (M_s) was thus 2592.5 kg-cm (25423.74 N-cm). Considering a yield strength (σ_y) of 730 MPa for alloy steel and a safety factor of 1.5, the allowable stress (τ_{all}) was calculated as 210.60 MPa. The required shaft diameter was determined to be 18.44 mm and a higher value of 19 mm was selected for the solid shaft to balance variable loads during operation. The above curve (Figure 4) illustrates how shaft diameter must increase as the moment (torque) on the shaft increases. Starting at 15 mm diameter at 10,000 N-cm, the shaft diameter grows to 19 mm at 26,000 N-cm, with the slope decreasing at higher moments. As torque increases, the shaft diameter must also increase to prevent mechanical failure. This relationship follows engineering principles for maintaining structural integrity under increasing loads. The relationship suggests a nonlinear rise, crucial for designing shafts that can withstand field stresses in weeder operations.

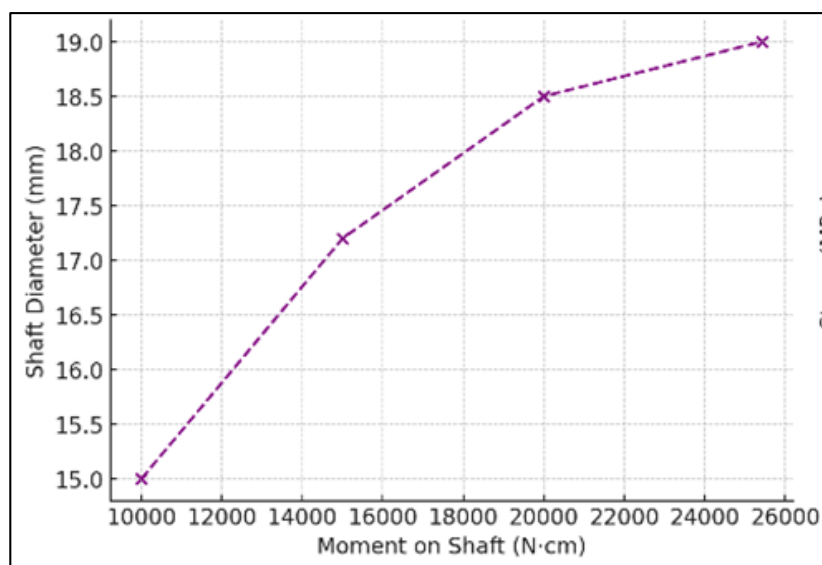


Fig 4: Moment on the shaft with respect to shaft diameter

3.2.3 Different types of stress distribution pattern on blade

An L-shaped blade with a triangular peg tooth was selected for the power weeder. The blade dimensions are width, thickness and length was 4, 0.6 cm and 20 cm respectively. With six blades on each of the four flanges, the total number of blades is 24. The soil force available at each blade (K_e) was calculated as 103.7 kg (1016.94 N). The bending stress (σ_{zg}), shear stress (τ_{skt}) and equivalent stress (σ_{zt}) were calculated as 32.406 MPa, 71.576 MPa and 146.77 MPa, respectively. These values are within acceptable limits for

mild steel material. The above graph (Figure 5) compares bending, shear and equivalent stress acting on the blade. This bar chart compares three critical stress types on the weeder blade are bending stress (32 MPa, blue), shear stress (72 MPa, yellow) and equivalent stress (140 MPa, red). The equivalent stress, being highest, would be most critical for material selection and safety factor calculations in the blade design. This graph helps evaluate blade material suitability and predict failure, ensuring structural reliability under field conditions.

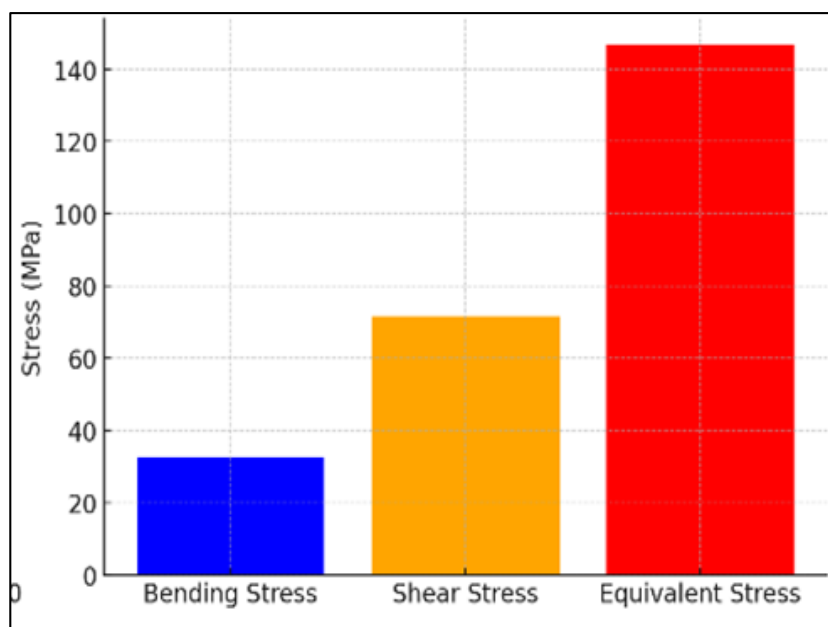


Fig 5: Different types of stress distribution on blade

3.2.4 Power transmission system effectiveness with respect to rotor speed

The graph (Figure 6) demonstrates how transmission efficiency decreases linearly as rotor speed increases. From approximately 75% efficiency at 60 RPM to 65% at 130 RPM, this negative correlation highlights the system's mechanical limitations at higher speeds, potentially due to increased friction and vibration. This inverse relationship

indicates greater mechanical losses at higher speeds. It emphasizes the importance of maintaining optimal rotor speed to enhance energy efficiency and performance in the self-propelled power weeder. The power transmission system was designed based on rotor and engine speeds. The coefficient of power transmission (i_c) was calculated as 0.5, reducing the engine speed from 130 to 65 RPM, which is comfortable for the operator's walking speed.

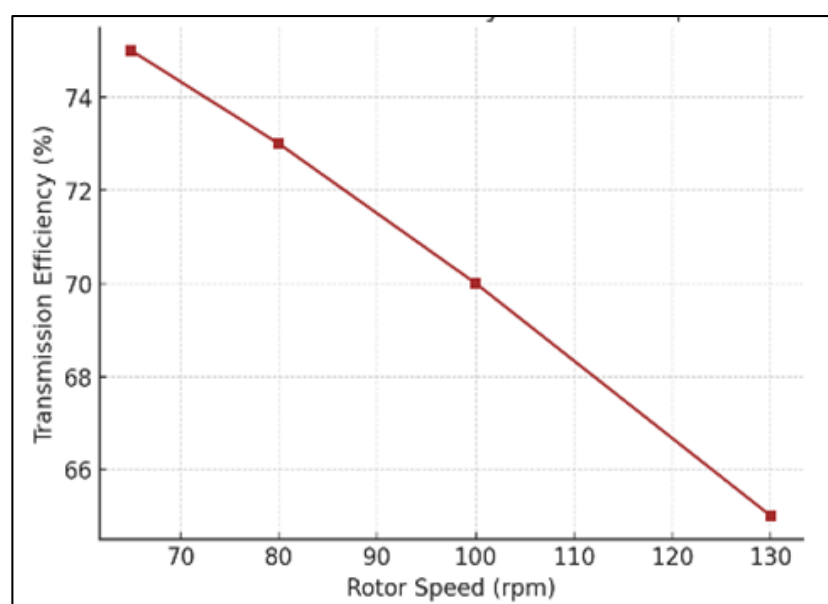


Fig 6: Transmission efficiency with respect to rotor speed

3.2.5 Estimated drive wheel power requirement

The above graph shows breaking down the total power (5.36 hp) among rotors, wheels and mechanical losses. The power allocation in the system are 88.6% goes to the rotors (green), 10.5% is lost in transmission (red) and only 0.9% powers the wheels (white). This distribution emphasizes that the majority of power is appropriately directed to the primary weeding function. This breakdown aids in understanding energy utilization and identifying areas for improving efficiency in machine design. The power required for the drive wheels is minimal, estimated at 23.12 W (0.023 hp). Therefore, the total power requirement for the self-propelled power weeder is approximately 4.78 hp. Considering various power losses, a higher value of 5.36 hp (4.0 kW) was selected for the present study.

Table 1: Power requirement for different components

S. No.	Component	Power Requirement
1.	Single Rotor	0.88 kW
2.	Four Rotors	3.55 kW
3.	Drive Wheels	0.023 kW
4.	Total	3.573 kW
5.	Selected Engine Power	4.0 kW (5.36 hp)

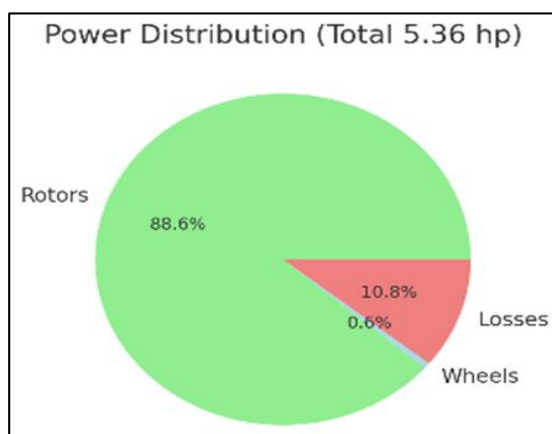


Fig 7: Power distribution pattern of self-propelled power weeder

4. Conclusion

The design and development of the adjustable self-propelled rotor power weeder have been successfully accomplished, considering various factors such as soil resistance, blade dimensions, operational speed and power transmission efficiency. The calculated power requirements and stress analyses ensure the reliability and efficiency of the weeder in field operations. The selected engine power of 4.0 kW (5.36 hp) provides adequate performance while accommodating potential power losses. The rotor shaft and blade designs meet the necessary strength requirements, ensuring durability and effective weeding performance. Overall, the developed power weeder is expected to enhance weeding efficiency, reduce labor requirements and improve productivity in agricultural practices.

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Competing Interests

The authors have declared no conflict of interests exist.

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