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Design and Development of an e-Powered Inter Row Weeder for Small Farm Mechanization

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Mechanical weed control has become a more efficient and economical method over the past few years. This study presents the concept of an e-power source and a weeding mechanism to carry out the weeding operations in crop rows with a spacing of 30 cm. An e-powered mechanical inter-row weeder was designed, developed, and evaluated for sandy loam soil conditions. The result indicates that the speed of operation and weeding drum diameter significantly affected the power consumption and weeding efficiency at 1% and 5% significance levels. The average weeding efficiency, field capacity, field efficiency, and plant damage were observed as 91.68%, 0.049 ha/h, and 3.18% at the operating speed of 3 km/h. The average power consumption of the weeder was observed as 189 W. The field capacity of the developed weeder was observed to be 3–4 times more than the wheel hoe, leading to a reduction in the required manpower and cost of operations. The weeding mechanism with a combination of drum and tool reduces the chances of weed escape and enhances the weeding efficiency. Moreover, the e-drive system of the weeder significantly reduces vibration leading to improved work efficiency of the operator. Overall, the developed e-powered weeder has the potential to be an effective tool for small-scale farmers to carry out their weeding operations with less drudgery and higher efficiency.

Keywords: Eco-friendly, Field capacity, Mechanical weed control, Plant damage, Weeding efficiency

Introduction

In India, nearly half of the population makes their living through agriculture, and this is their primary source of income. In order to meet the food demands of a population of 1.7 billion by 2050, crop productivity must be increased to 400 million tons. Agricultural production systems are the most critically hampered by weeds due to their widespread and severe presence. Agricultural production systems in India are characterized by diverse climatic conditions that favour the most prevalent weeds, causing severe crop yield losses.[1] Weed control is essential to increasing yield and maximizing resource efficiency in agriculture production system.[2] There are several weed control methods available, including manual, mechanical, chemical, and biological. The manual weed control is the most effective, but also labor-intensive, tedious, and expensive.[3–6] The manual methods of weed control is accounting for one-fourth of the total labour requirement. During the peak season, crop yield is reduced by 40–60% due to shortage of labour and delayed weeding.[7,8] In addition, the chemical applications which are easy to apply and quickly effective, also pose serious health risks to crops and the environment.[9,10] The use of biological methods to control weeds can be less effective and drudgery-inducing because they attract external organisms. Mechanical methods can be a quick and effective way to control weeds because of their high throughput and efficiency.[11,12]

Weed control by mechanical means has been a sustainable option since the beginning of farming. In small farms, managing weeds is a challenge due to lack of labours, equipment, and inadequate knowledge of weed biology. The challenges of small farmers offer an innovative and appropriate approach to managing weeds. Eco-friendly technology and alternate power source are the identified mechanization gap for small farm mechanization.[13] The crop-grown area owned by small and marginal category farmers is very less which does not allow the operation of big machines due to the size of their field. The available equipment designs are region-specific, to meet the needs of various soil types, cropping systems, and available local resources.[13–15] The use of self-propelled power weeder in weeding operations has several disadvantages, which add to the

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operator's drudgery by exposing them to high levels of vibrations, which can cause dynamic disorders and vascular diseases.[13,16] The operator's work performance is affected by mechanical vibration, which causes fatigue during field operations.[17]

At present, inter-row weeding in small farms is performed manually, which requires a lot of manpower and operating time and can be quite expensive.[18,19] The application of an electrical power source is an appropriate source because of the non-existence of uncomplimentary materials. The application of e-drive vehicles for light agricultural operations can convert about 75% of the potential chemical energy within batteries to mechanical energy available at the wheels while the equivalent value for internal combustion engine vehicles is only (15%).[20,21] This technology can be used particularly for such field operations which are considered as light draft requirements. The power consumption can be reduced if the major load is substituted with a power source which will enhance the machine and the operator's performance. The small-farm mechanization has a crucial role in enhancing the productivity of agricultural systems. To achieve timely farm operations, and reduce the drudgery of the farm workers, agriculture utilizes diverse sources of farm power. The application of an e-power source for the development of a weeder reduces the drudgery involved in the weeding operation as well as eliminates the reliance of farmers on fossil fuel.[13] Recent studies have reported that walk-behind electric power units can reduce operator fatigue by 80–85%. Indian Agricultural Research Institute, has developed walk-behind electric power units that are specifically designed for weeding and inter-cultivation operations in wide-row crops above 40 cm.[21] However, the majority of crops, including seed spices, are sown at a closer spacing of 20–30 cm, and the available weeders are mainly designed for wide-spaced crops. Therefore, the objective of this study is to design an appropriate e-powered mechanical weeder for row crops spacing of 30 cm.

Materials and Methods

An e-powered weeder was designed and developed at the Department of Farm Machinery and Power Engineering, College of Technology and Engineering, MPUAT, Udaipur during 2019–2020. The main objective of the weeder was to perform the weeding operations with less drudgery and higher efficiency. Furthermore, it was designed to cause minimal damage to the crop while in operation, also make efficient use of the power source to increase the run time and produce minimal vibration for the operator.

Design and Development of Weeder

A prototype of an e-powered weeder was designed and developed based on theoretical design calculations and functional requirements of the machine for weeding operation. The main criteria for the development of the weeder were agronomic and soil parameters such as soil type, soil resistance, crop geometry, weed density, etc. which influence weeding performance. The conceptual diagram of the weeding mechanism is presented in Fig. 1 (a). The weeder was designed to operate in walk-behind mode; this enables the operator to ease in operation during weeding. The major components of the developed weeder are the battery, DC motor with speed controller, drive wheel, the weeding mechanism (drum and tool), mainframe, transport wheel, and handle shown in Fig. 1 (b).

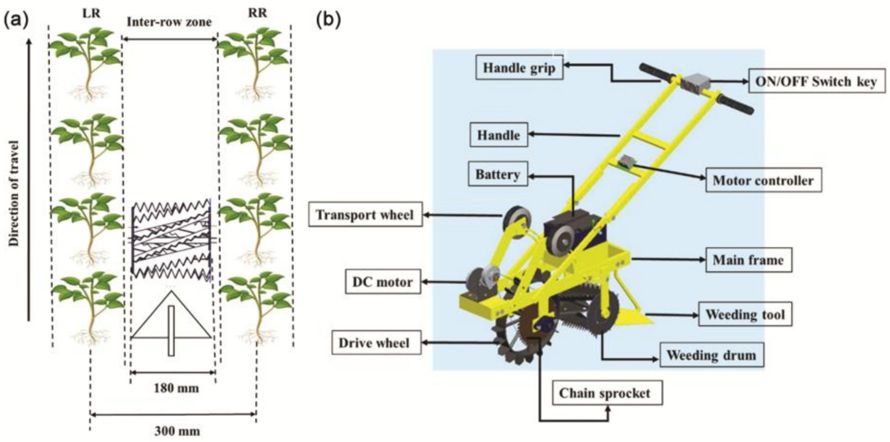

Fig. 1 — Schematic diagrams of the weeding system: (a) conceptualized weeding mechanism (LR = left row, RR = right row) and (b) computer-aided design

***Design of Weeding Mechanism*:** The weeding mechanism is a combination of a drum and a V-shape tool. The weeding drum was expected to perform two functions simultaneously shear off the soil into the small segment as well as partial weeding. The blades on the drum have a conical shape that offers a shearing effect for weeding and traction power for forward motion. Moreover, the weeding drum provides stability as well as adjusts the depth of operation. Behind the drum, a V-shaped tool penetrates the soil and cuts the weeds. The schematic view of the drum and tool is shown in Fig. 2.

***Weeding Drum*:** The geometry of the drum blade has a significant effect on the draft as well as the vertical and lateral forces acting upon the soil. Notched and plain blades have different edge shapes, but the same macro shape.[22] It is necessary to reduce the blades soil contact area to solve the problem of soil mass sticking to the blade surface.[23] Therefore, Notched blades were fabricated from a 2.5 mm thick MS sheet of 180 mm length and 45 mm width and mounted on the drum surface with the blade inclination angle of 25 degrees. The power requirements of the weeding drum were computed as follows.[23]

Maximum shearing area for one blade = $0.04 \times 0.18\ \text{m}^2 = 7.2 \times 10^{-3}\ \text{m}^2$
Effective shearing area for one weeding drum = $2 \times 7.2 \times 10^{-3}\ \text{m}^2$

Assuming that two blades shear the soil at the same time (shear stress of the soil = $5 \times 10^3\ \text{N m}^{-2}$)

Effective draft force on the weeding drum D_D = area × shear stress=72 N

***Design of Shank for Tool*:** Maximum draft force at the tip of blade = 144 N.

Taking the factor of safety of 2 for impact loading, bending load in the sweep = 144 N × 2 = 288 N

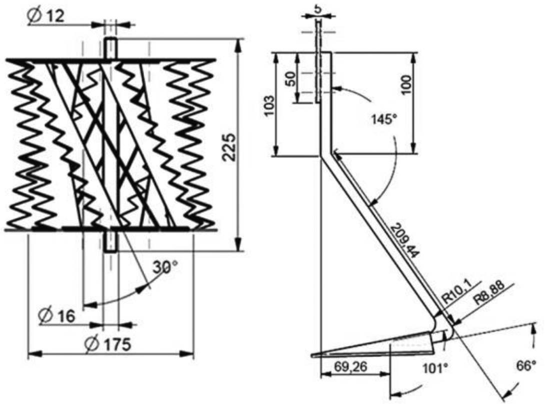

Fig. 2 — Schematic view of drum and tool

The height of the shank = 300 mm, therefore maximum bending moment M for a cantilever length of 300 mm = 288 × 300 mm = 86400 N-mm

Using the formula, $fb = MC/I$

where, fb = bending stress, N/mm^2 M = Bending moment, N-mm C = distance from the neutral axis to the point at which stress is determined.
I = Moment of inertia of section (mm^4)
$Z = I/C = M/fb$
$= 293.58\ \text{mm}^3$
Moreover, $Z= b^3/6$
$b^3 = Z \times 6$, $b = 3\sqrt{(Z\times 6)} = 9$ mm
Size of square rod = 10 mm

***Width of Tool*:** The width of the drum and tool is designed based on the minimum crop row spacing of 30 cm.[24]

$S_c = Z_f + Z_p$

where, Sc = Crop spacing, Z_f = Effective soil failure zone, cm Z_p = protection zone

The crop protection zone was assumed as 3 cm,

$Z_f = Sc - Zp = 30 - (3 \times 2) = 24$ cm

(Protection zone is multiplied by 2 since the protection zone has to be provided on both sides of the crop)

Also $Z_f = W + 2d \tan \varphi_s$

W= cutting width of sweep, cm, d = depth of weeding, φs = angle of internal friction which ranges between 10 to 30 depending upon the type of soil

Let $\varphi_s = 20^\theta$ d = depth of weeding be = 4.5 cm, putting these values in the equation, we get

$24 = W + 2 \times 4.5 \times \tan 20^\theta$
W = 180 mm

The apex angle (2θ) is the included angle formed between the two cutting edges

$\theta = 90 - \varphi_w$

where, φ_w = Angle of friction between weeds and cutting edge and it id ranges between 30 to 56 (φ_w assume = 36)
Therefore, apex angle = 2 × 35 = 72°

***Draft of Tool*:** The draft force necessary to pull the tool for weeding operation. The draft force of the weeding tool was calculated as:[26]

$D_T = W \times d_w \times S_R = 144$ N

where, D_T = Draft force of the weeder tool (N), d_w is the depth of weeding (cm), W is the width of cut (cm) and SR is the specific soil resistance (N/cm^2). The specific drafts of sandy and silt loam soil ranges from 2-5 N/cm^2.(25,26)

Total draft force requirement of the weeding mechanism $D_f = D_D + D_T = 216$ N

Motor Size Calculations for Weeder: The developed system has to work with soil, thus determination of tractive force is necessary to select the size of the motor. Tractive force (T_f) is expressed as the sum of draft force (D_f), rolling resistance (Rr), and acceleration force (A_f).

$T_f = D_f + R_r + A_f$

The total draft force, D_f = 216 N was taken from the calculation. The total tractive force included the total draft force and rolling resistance and acceleration force. The safety factor of 1.2 was considered.

Rr (rolling resistance) = $\mu_c \times W_g$

W_g is the gross weight of the machine and μ_c is the coefficient of rolling resistance, The rolling resistance force Rr (51 N) is calculated as.[27]

$\mu_c = 0.04 + 1.2/Cn$
$C_n = (CI\ bd)/W = 12.11$
$\mu_c = 0.13$

where, CI = Cone Index (kPa); b = wheel width (m); d = wheel diameter (m); W = Vertical load (kN);

$R_r = 0.13 \times 40 \times 9.81 = 51$ N

The acceleration force (A_f) = m × a

where, m and a are the weight and acceleration of the system

$a = v/t$
v = speed of drive wheel (0.69 m/s),

The speed of the drive wheel was calculated based on the average speed of the operator (2.5 km/h) while operating walk behind in comfortable mode under row crop conditions as reported in previous studies.[13,21]

t = time required to achieve maximum speed (2 seconds)

As the estimated weight of the drive wheel system putting the value of m and So, $A_f = 13.8$ N

Total tractive force $T_f = 216 + 51 + 13.8 = 281$ N

Now the power P of the driving motor was calculated as:[28]

$P = (T_{fm} \times S)/3.6 = 195$ W

where, S is the average speed of operation (2.5 km/h)

Considering the efficiency of DC motor = 75% (multiplying factor 1.33)

Thus motor power required = 260 W

The brushed DC motor available in the market had a power rating of 250–350 W with the rated speed of 350 RPM. Therefore the maximum torque M_t of the driving motor was calculated using the following equation

$M_t = (60 \times P)/(2 \times 3.14 \times RPM) = 9.54$ N-m

Power Transmission System: The chain-sprocket drive system was selected for the transmission of power from the motor to the drive wheel shaft. The sprockets of the motor and drive wheel were placed 350 mm apart. To get a speed ratio of 5.33, a small sprocket with 9 teeth for the motor shaft and 48 teeth for the drive wheel shaft was provided based on the operational speed of the drive wheel system.

Drive-Wheel Shaft: A single-drive wheel system was adopted to get a minimum radius of turn and better maneuverability. The diameter of the drive wheel is based on a minimum ground clearance requirement of 100 mm. The size of drive wheel was kept large in size of 300 × 50 mm fitted with pegs to get better traction for weeding operation. The large sprocket was mounted on the traction wheel driveshaft, which had 48 teeth. The length of the shaft was taken as 225 mm according to the track width changes required during weeding. The drive wheel shaft is subjected to both combined twisting and bending moments.

Total weight on drive wheel system = 392 N, Reduction ratio at chain drive = 48/9 = 5.33

Torque transmitted by shaft (T) = torque at motor shaft × reduction at chain drive = 51 N-m

Load on drive shaft due to chain drive (Qv) = Ft × sin a = 69.11

Therefore, the Maximum bending moment (M) in the shaft was calculated

M = (Weight on wheel × overhung) + (Qv × overhung) = 42650 N-mm

Ultimate tensile strength (MPa) = 560 (IS carbon steel of grades 40 C 8)

Allowable shear stress τs = 42 MPa (as per ASMM)

Equivalent twisting moment $T_e = \sqrt{(M^2+T^2)} = 57.12$ N-m

Now, Equivalent twisting moment $T_e = \pi/16 \times [d]^3 \times \tau_s$

where, d = diameter of the shaft in mm. Now putting the values of T_e and τ_s in the equation we got

$$d = 19.06 \text{ mm} \approx 20 \text{ mm}$$

***Mainframe and Handle*:** The mainframe was developed to accommodate all the components of the system and provides support to the DC motor, batteries, transmission system, drive wheels, weeding drum and tool, and handle. Two MS flats each 700 × 50 × 8 mm were used to fabricate the mainframe of the weeder. The length of the handle was calculated based on the average standing elbow height of male/female operators as given below.

Average standing elbow height of farm worker = 100 cm

Distance of operator from handle mounting on frame (for operator height of 95 – 100 cm) = 112 cm

Therefore angle of inclination (θ_h) with horizontal:[24] (Fig. 3).

$\tan(\theta_h) = 410$

Now $\sin(\theta_h) = 76.66/ L_h$

where, L_h = Length of handle

$L_h = 76.66/ \sin 410 = 116.9$ cm

A standard MS rectangular pipe 1180 × 25 × 15 mm was used to fabricate the handle of the weeder. A handle of T-type was selected for the development of the weeder.[26] The length of the handle was determined based on the average standing elbow height of male and female operators. So that it could accommodate 5 to 95% of the operators. Two standard MS rectangular conduit pipes 600 × 20 mm were used to fabricate the handle with an adjustable operating height ranging from 95 to 105 cm from the ground. A plastic handgrip of 600 mm long and 35 mm outer diameter was provided for easy grip and handling of the weeder. Handle height and length were made adjustable to ensure the operators comfort.

Based on the design and calculation a 350-watt brushed DC motor with a 24-volt supply was selected for the weeder development. The DC motor with gear reduction produces more torque and can rotate clockwise or counter-clockwise by reversing input control wires of the motor. The rated speed of the motor after a gear reduction was measured as 350 rpm. The motor has an efficiency of more than 75%. The weeder has been equipped with two transport wheels to facilitate its transportation to and from the field (Fig. 1b). The technical specifications for the e-powered weeder are described in Table 1.

Electrical Connection for e-Powered Weeder

A block diagram of the developed e-powered weeder is presented in Fig. 4 wherein the motor controller is connected to a 24 V, 24 Ah battery pack comprising two 12 V batteries in series. The connection between the battery pack and the motor controller was established using AWG 12-size wires. To prevent the battery from draining when the weeder (TWDS) is not in use, a main switch was provided to stop the power flow. The motor controller was connected to the key switch, throttle position sensor (TPS), battery charge level indicator, brake, and motor. The key switch was mainly used to instantly turn on/off the motor controller. To evaluate the

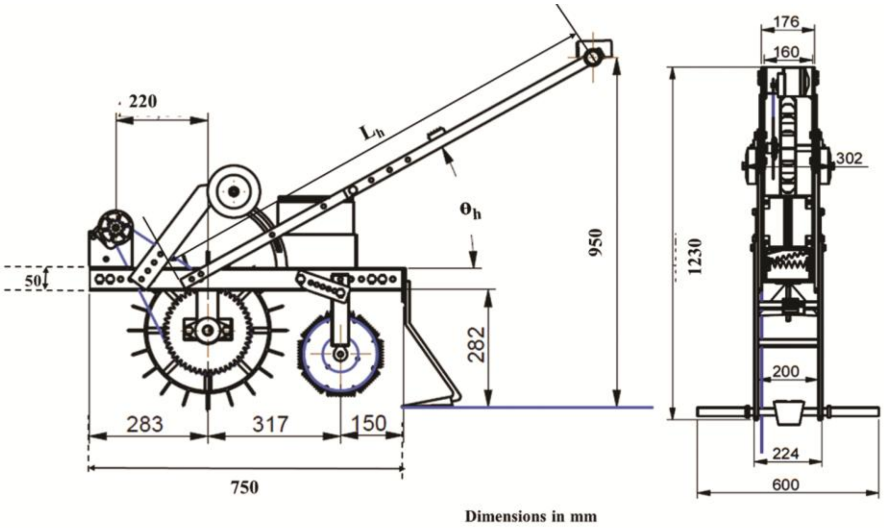

Fig. 3 — Main frame and handle with all major components

Table 1 — Technical specifications of developed e-powered weeder

Sl. No.	Particulars	Details
1.	Overall dimensions, mm (L × W × H)	765 × 250 × 950
2.	Weight, kg	45
3.	Size of the drive wheel (D × W), mm	300 × 50
4.	Handle dimension (L × W), mm	1180 × 200
5.	Size of T- type grip of the handle, (L × D), mm	20 × 600
6.	No. of blades on the drum	10
7.	Sweep angle, degree	72°
8.	Size of the weeding tool, (L × W× T), mm	120 × 180 × 4
9.	Number of weeding tools	1
10.	Cutting width, mm	180
11.	Maximum weeding depth, mm	45
12.	DC motor withspeed controller	24-V, 350 W
13.	Speed reduction ratio from the motor to the drive wheel	5.33
14.	Batteries	2, 12-V, 24-Ah
15.	Energy meter	LCD, 0–20 A, 6.5–100 V
16.	Throttle position sensor	0–4 A, 0–24 V
17.	Turning radius, mm	450–700
18.	Transport wheel	2

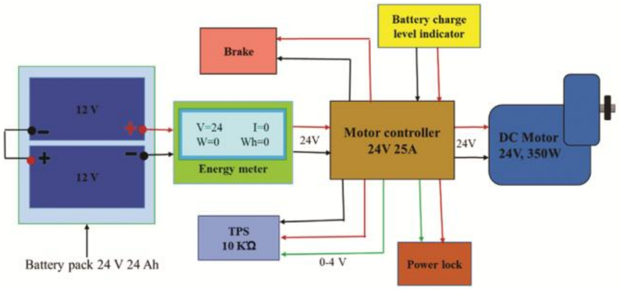

Fig. 4 — Block diagram of the electrical connection for e-powered mechanical weeder

current and power consumption of the weeder during the study, an energy meter was also used. A throttle position sensor (TPS) is a specially designed potentiometer (10 K) where a specific biasing voltage (4 V) is provided from the main controller unit and outputs voltage (0 to 4 V) corresponding to the angle of the throttle, which is supplied to the controller where it is processed to deliver a corresponding voltage (0 to 24 V) to change the speed of the motor. The throttle positioning sensor, supplies a corresponding throttle position voltage to the controller to control the motor's speed. The TPS provided enables variable speed control in the weeder, and uses only the power required for the given load.

Table 2 — Experimental plan for the fieldstudy of the developed weeder

Independent variables	Level of variables	Value
1. Diameter of drum, mm	D_1	150 mm
	D_2	175 mm
	D_3	200 mm
2. Speed of operation, km/h	S_1	2.0 km/h
	S_2	2.5 km/h
	S_3	3.0 km/h
Dependent variables		
1. Weeding efficiency, %		
2. Plant damage, %		
3. Effectivefield capacity, ha/h		
4. Power consumption, W		

Field Evaluation of Developed Weeder

The field experiments were conducted in seed spices crops such as fenugreek and coriander 30 days after planting when the fields were infested with weeds. Soil parameters, including moisture content, bulk density, and cone index were measured at different locations before the experiment. A digital soil moisture meter, a digital cone penetrometer, and a core cutter were used to measure these parameters. Several crop parameters were measured at various locations before experiments including row spacing, plant height, canopy width, and weed height. To prevent crop damage, the developed weeder operated between the crops and passed at the centre of rows to maintain a safety zone. The experimental plan for the field performance study of the weeder is presented in Table 2. The field performance study of the developed weeder was also compared with the wheel hoe.

The different machine performance parameters such as weeding efficiency, plant damage, field capacity power consumption, and vibration were recorded and calculated by using the following formulae.

Weeding Efficiency: To calculate the weeding efficiency, the average values of the numbers of weeds before and after each weeding operation were counted:[7,14]

$$WE = \frac{(W1 - W2)}{W1} \times 100$$

where, WE= weeding efficiency of the weeder (%), W_1 = number of weeds before the weeding operation, and W_2 = the number of weeds after the weeding operation.

Plant Damage: The percentage of damaged plants, as a quality of work, is calculated by the following equation:[29]

$$\mathrm{Pd} = \left[\, 1 - \left(\frac{Qd}{\mathrm{Qp}}\right) \right] \times 100$$

where, P_d = percentage of plant damage, Q_D = number of plants in 10-meter row length after weeding, and Q_P = number of plants in 10 m row length before weeding.

Effective Field Capacity: Effective field capacity (F_C) was calculated by the following equations.[30,31]

$$\mathrm{Fc} = \frac{\mathrm{A}}{[Tp + Tn]} \times 100$$

where, F_C = actual field capacity (ha/h), T_p and T_n productive time, and non-productive time. Total working time includes effective time, time lost for turning, minor adjustment, rest time etc.

Statistical Analysis:

The experiments were conducted using a Factorial Randomized Block Design (RBD) to investigate the effect of independent parameters on weeder performance. A total of 9 treatments have been carried out with three replication of each parameter. The statistical analysis was performed using SAS (9.3) software to determine the significance of independent variables.

Results and Discussion

The field experiment was carried out in sandy loam soil. The machine was operated in fenugreek, and coriander (30 cm of row spacing) crops during the Rabi season. The experimental trials were conducted on a 30-day-old crop. The average value of soil moisture content, bulk density, and cone index was measured as 14.83% (d.b), 1.59 g/cc (d.b), and 406.3 Kpa, respectively. The average value of plant height, plant canopy width, plant population, and weed count was recorded as 15.85 cm, 14.8 mm, 62.2, and 95.5 as presented in Table 3. The developed prototype was operated with a safety zone to avoid plant damage.

Weeding Efficiency

The F value of weeding efficiency as given in Table 4 shows that model (F = 9.74) was found significant at 1% level of significance with a coefficient of determination (R^2 = 0.81), standard deviation (SD = 9.1) and coefficient of variance (CV = 11.88). The graphical representation of the effect of independent parameters on weeding efficiency is given in Fig. 5. It can be observed that the individual effect of diameter and speed was significant while the interaction effect was non-significant on weeding efficiency. The least significant difference ($LSD_{p=0.5}$ =

Table 3 — Soil and crop parameters of experimental field

Sl No	Parameters	Minimum	Maximum	Mean ± S.D
1.	Soil moisture content, % d.b	12.9	18.40	14.83 ± 2.27
2.	Bulk density, g/cc (d.b)	1.56	1.67	1.59 ± 0.05
3.	Cone Index, (Kpa)	245	621	406.3 ± 128.41
4.	No. of plants/m^2	49	76	62.20 ± 8.55
5.	Weeds count/m^2	60	121	95.50 ± 18.5
6.	Height of plants, cm	13	19	15.85 ± 2.16
7.	Plant canopy width, cm	10	19	14.8 ± 2.65
8.	Height of weeds	13	22	16.35 ± 2.51

Table 4 — Statistical analysis (ANOVA) of various parameters

Source	DF	F-Value			
		Weeding efficiency, %	Plant damage, %	Field capacity, ha/h	Power consumption, W
Model	8	9.74^{**}	1.40^{NS}	27.50^{**}	16.64^{**}
Error	18	—	—	—	—
Corrected Total	26	—	—	—	—
Speed (S)	2	18.53^{**}	3.65^{*}	108.02^{**}	30.63^{**}
Diameter(D)	2	20.12^{**}	1.55^{NS}	0.82^{NS}	35.17^{**}
Interaction (S*D)	4	0.16^{NS}	0.19^{NS}	0.58^{NS}	0.38^{NS}
$LSD_{(p=0.05)}$		4.69	1.24	0.0026	10.81
R^2		0.81	0.38	0.92	0.88
Mean		76.63	2.95	0.04	180.97
SD		9.10	1.33	0.01	26.32
CV%		11.88	45.06	18.41	14.55

**Significance at 1% level, *Significance at 5% level, ^{Ns} Non-significance, ^{SD}Standard deviation R^2 Coefficient of determination CV = Coefficient of variance, %

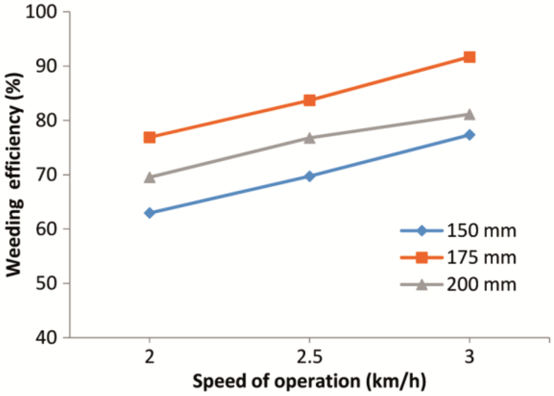

Fig. 5 — Effect of forward speed on weeding efficiency for different drum diameter

4.69) comparisons indicate that levels of independent parameters were also affected significantly. The higher values of weeding efficiency indicate better performance of the weeding system. The result shown in Fig. 5 depicts that the average value of the weeding efficiency increased with an increase in the forward speed of the operation. Weeding efficiency was also observed higher for mean values of drum diameter, the reason for increased values could be the lower rolling resistance and higher weed cutting or uprooting action. These results are following the findings of other researchers. The overall mean value of weeding efficiency was observed 80 percent. The highest weeding efficiency of 91.68% was observed for a drum diameter of 175 mm at the forward speed of 3 km/h which was about 34.10% higher than the minimum weeding efficiency observed for a drum diameter of 150 mm at 2 km/h speed. The weeding mechanism with the drum and tool together, the possibility of weeds escaping in between the row reduced, and the weeding efficiency of the weeder increased. The variations in weeding efficiency were due to the undulating surface and the weed population. Overall the mean drum diameter of 175 mm and forward speed of 3 km/h recorded a maximum weeding efficiency, of 91.68%. Also it was observed that the higher forward speeds lead to a higher weeding efficiency. This was mainly due to the higher rotational speed of the weeding drum resulting higher number of weeding actions.

Plant Damage

The F value of plant damage (PD) is as given in Table 4 shows that model (F = 1.40) was found non-significant at 5% level of significance with a coefficient of determination (R^2 = 0.38), standard deviation (SD =1.33) and coefficient of variance (CV = 45.06). It can be seen that the individual effect of speed and diameter as well as the interaction effect was found non-significant on plant damage. The least significant difference ($LSD_{p=0.5}$ = 1.24) indicates that levels of independent parameters were non-significant. The lower values of plant damage indicate better performance of the weeder. As can be observed from Fig. 6, the plant damage increases momentarily with an increase in forward speed. The minimum plant damage was observed at the forward speed of 2 km/h. The average plant damage of 3.18 was observed at the speed of 3 km/h. The overall mean value of plant damage was observed 2.54%. These results are in accordance with the findings of other researchers.[5,29]

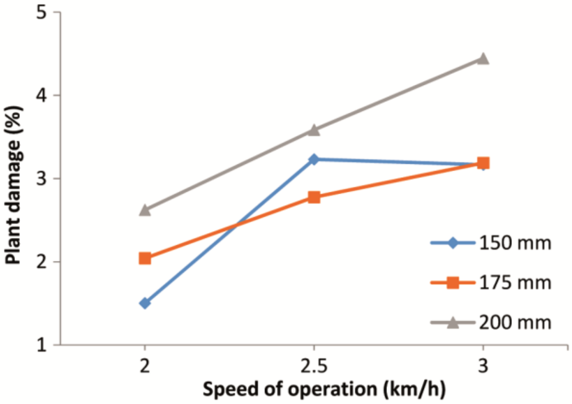

Fig. 6 — Effect of forward speed on plant damage for different drum diameter

Effective Field Capacity

The F value of field capacity as given in Table 4 shows that model (F = 27.5) was found significant at 1% level of significance with a good coefficient of determination (R^2 = 0.92), standard deviation (SD = 0.01) and coefficient of variance (CV = 18.41). The statistical analysis shows that the individual effect of diameter and speed was significant while the interaction effect (D × S) was non-significant for effective field capacity. The forward speed significantly affects field capacity at 1% level of significance whereas the drum diameter shows a nonsignificant effect. The diameter does not affect the field capacity because there is a non-significant difference between the widths of the cut. The least significant difference ($LSD_{p=0.5}$ = 0.0026) comparisons indicate that levels of independent parameters were also affected significantly at 5% level of significance. The higher values of field capacity indicate better efficiency of the weeding

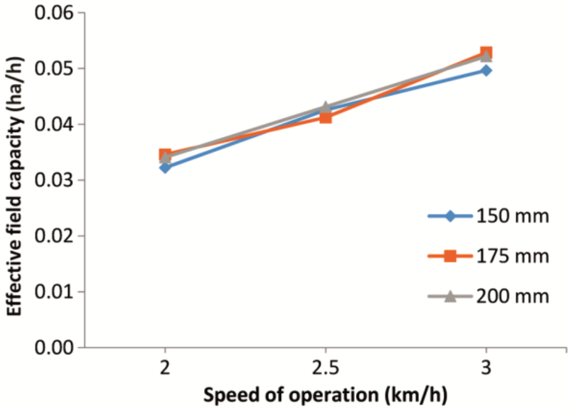

Fig. 7 — Effect of forward speed on effective field capacity for different drum diameter

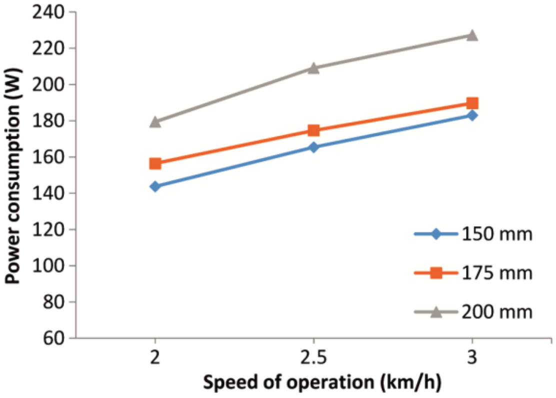

Fig. 8 — Effect of forward speed on power consumption for different drum diameter

system. As per the result shown in Fig. 7, the highest field capacity was observed at the speed of 3 km/h for the drum diameter of 175 mm. Since the developed weeder operated in walk-behind mode the average speed of the operator should not be more than 3 km/h for comfortable and safe operation. The effective field capacity of the developed weeder was observed higher than the manual tools reported.[26] The variations in field capacity were also reflected in field efficiency which was due to field condition, moisture content, and operating skill. The main reason for the higher output of the machine is due to the minimum workload on the operator and turning losses. The weeder performance results trend is similar to earlier studies.[13,22] The turning radius of the developed weeder was found to be a minimum of 450 mm. The single-drive wheel system provides less turning radius and added better maneuverability that may directly benefit the field capacity of the weeder. The combination of the weeding mechanism and single-drive wheel system used in the weeder minimized turning loss, improved traction, and increased maneuverability.

Power Consumption

The F value of power consumption as given in Table 4 shows that model (F = 16.64) was found significant at 1% level of significance with a good coefficient of determination (R^2 = 0.88), standard deviation (SD = 26.32) and coefficient of variance (CV = 14.55). The graphical representation of the effect of independent parameters on power consumption is given in Fig. 8. It can be observed that the individual effect of diameter and speed was significant while the interaction effect was non-significant on power consumption. The least significant difference ($LSDp_{=0.5}$ = 10.81) comparisons indicate that levels of independent parameters were also affected significantly. In this study, lower values of power consumption indicate better performance of the weeder. The result shown in Fig. 8 depicts that the average value of power consumption increases significantly as the speed and diameter increase. The reason for increased power consumption could be the higher draft force, soil bulk density, and moisture content of the soil. These results are in accordance with the findings of other researchers.[13] Overall mean value of power consumption was observed 180.97 W. It was also observed that drum diameter D_1 consumed less power than drum diameter D_2 and D_3.

Fig. 9 — Field view of the weeding operation

The field view of weeding operation with the developed weeder in row crops shown in Fig. 9.

Battery Backup Time

The battery backup time decreased with an increase of current consumption from 4.24 to 17.18 A at this load, the power requirement varied from 105 to 406 W. The weeder consumed 1.66 to 3.72 A during no-load conditions whereas, in the weeding operation, the average current consumption was 5.65 to 9.07 A (143 to 227 W). The effect of operational speed and drum diameter on battery run time during the weeding operation is depicted in Fig. 10. The weeder was observed to have maximum run time of 3 hours with the drum diameter of 175 mm and operating at the speed of 3 km/h. As the drum diameter and operating speed increased, power consumption also increased, leading to a decrease in battery run time. The results are in agreement with the findings of researchers.[21]

Charging Time for the Battery: The charging current for the battery should be 10% of the Ah rating, Therefore, the charging current for a 24 Ah battery = 2.4 A

The total current required to charge the battery (assumed 40% losses) = 2.4 × 1.4 = 3.36 A

Charging time for a 24 Ah battery = 24/3.36 = 7.14 h

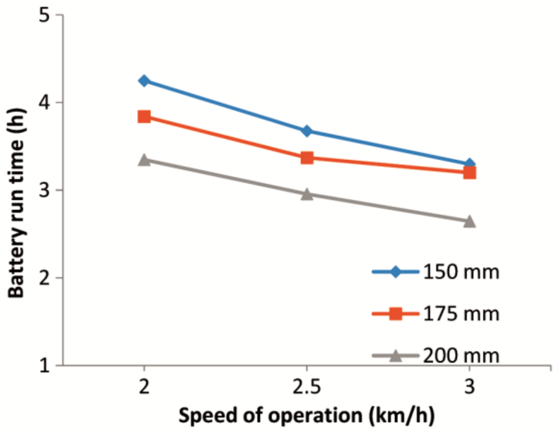

Fig. 10 — Effect of forward speed on battery run time for different drum diameter

Hence full charging of the battery required 3–4 A current supply for 6–7 hours. The battery can also be charged by using a solar panel of 200 W capacities.

Mechanical Vibration

The electric drive system of the weeder enables the reduction of the peak value of acceleration. During no-load and load conditions the hand vibration was measured at the operational speed of 3 km/h. The maximum value of vibration under both no-load and load conditions was observed at 1.62 m/s^2 and 2.73 m/s^2 as shown in Table 5. The overall vibration among all three axes (x, y, and z) during the weeding operation was observed to be 2.54 m/s^2 which was comparatively less than the existing power weeder.[17] The daily vibration exposure value ranges between 1.85 m/s^2 to 2.89 m/s^2 with an average value of 2.37 m/s^2. In all the cases the daily vibration exposure was found to be less than the Exposure Limiting Value (ELV) of 5 m/s^2.(17,32) The instrument set up for the measurement of vibration of the power weeder is shown in Fig. 11.

Comparative Evaluation

The comparative evaluation of the prototype was conducted with the wheel hoe for seed spice crops. From the Table 6, it is observed that the developed weeder reduced the amount of human effort required

Fig. 11 — Instrument set-up for vibration measurement in the field

Table 5 — Vibration characteristics of the developed weeder

		Max	Min	AV	SD	CV, %
No load condition						
	x	2.15	1.28	1.68	0.32	19.05
	y	1.12	0.70	0.90	0.17	18.89
	z	1.58	1.09	1.39	0.19	13.67
	AV	1.62	1.02	1.32	0.23	17.20
Load condition						
	x	2.60	2.29	2.48	0.12	4.84
	y	1.25	1.10	1.20	0.06	5.00
	z	4.33	3.68	3.93	0.25	6.36
	AV	2.73	2.36	2.54	0.14	5.40
Daily vibration exposure		2.89	1.85	2.37	0.44	18.70

Table 6 — Comparative performance evaluation of the developed weeder with wheel hoe

Parameters	Developed weeder	Manual wheel hoe
Effective field capacity	0.049	0.015
Weeding efficiency, %	91.68	93.36
Plant damage, %	3.18	0.57
Total man power required for weeding, Man-h/ha	20.41	66.67
Cost of operation, ₹. /ha	1168.37	2166.67

during the weeding operation. Additionally, the weeding drum also pulverized the upper layer of soil, which resulted in the benefit of plant root growth. Furthermore, the developed weeder was performing weeding operations significantly faster as compared to the wheel hoe. The developed weeder had a field capacity 3–4 times higher than the wheel hoe. The cost of the weeding operation with the weeder was found minimum of ₹1168/ha because of the high field capacity of the weeder. In comparison with wheel hoe weeding, the manpower requirement of the weeder was reduced by 65–70%. The developed weeder reduced the cost of weeding operation by 45–50 percent over manual wheel hoe. It was also observed that the weeder with the tool alone was insufficient to perform effective weeding operations. This ultimately led to increased power consumption and reduced weeding efficiency. The weeder consumed about 210 W of power while using only the sweep-type blade, and the weeding efficiency and plant damage were observed to be 74% and 12.5%, respectively. Therefore the use of drum supports was necessary to maintain a uniform depth of operation and stability during weeding. However, using a combination of drum and tool approach was observed to be more effective than using the tool alone.

Conclusions

The present study shows that the forward speed of the developed weeder has significant effects on weeding efficiency, plant damage, effective field capacity, and power consumption at 1% and 5% levels of significance, but the interaction effect was not significant. The drum diameter has a significant effect on weeding efficiency and power consumption at 1% level of significance. The developed weeding mechanism (combination of drum and tool) performed better for D2 (175 mm) drum diameter at the forward speeds of 3 km/h. The field capacity of the developed weeder was observed to be 3–4 times more than the wheel hoe. The developed weeder led to a significant reduction in the required manpower for weeding, which ultimately reduced the cost of operation. Further field testing is required under different soil and crop conditions to refine its performance and adaptability. The developed weeder will be suitable for small-scale farmers.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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