Development and performance evaluation of two-row tyned weeder for weed management in maize crop

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Abstract: Weeds significantly reduce crop yield (34%) as compared to pests (18%) and pathogens (16%). Also, weeds are one of the most significant biotic factors contributing to declining yield. Various methods are used to control weeds in row crops. Traditional methods like manual weeding are time-consuming, labor-intensive, and tedious. Chemical treatment with use of herbicides is not eco-friendly. In view of all the above problems, a two-row tyned weeder was developed for managing weeds in row crops. The developed weeder consists of a main frame, engine, tynes, wheels, and handle. Response surface methodology (RSM) along with the central composite design was used to study the effect of independent variables of forward speed (1.5, 2, and 2.5 km/h) and moisture content of soil (12%, 14%, and 16% (w.b.)) on response variables for the purpose of optimizing the operational parameters of the two-row tyned weeder. The optimized parameters for tyned weeder are forward speed of 2 km/h and moisture content of 14%. The weeding efficiency, plant damage, and field efficiency were 88.38%, 6.46%, and 81.66%, respectively, at optimized parameters. The performance parameters such as field capacity, depth, and width of operation were 0.08 hm^2/h, 55 mm, and 600 mm, respectively. The savings in cost of operation and labor for the developed two-row tyned weeder over the manual hand wheel hoe were 76.11% and 92.86%, respectively. The payback period, break-even point, labor requirement, and performance index for the developed two-row tyned weeder were 1.12 a, 104.5 h/a, 10.35 man-h/hm^2, and 410.91, respectively.

Keywords: field efficiency, maize, optimization, plant damage, RSM, weeder, weeding efficiency
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1 Introduction

The agricultural sector is the backbone of the Indian economy. The food grain production in India was 308.65 Mt in 2020–2021[1]. Maize/corn (*Zea mays* L.) is the third most important cereal crop with the highest genetic potential after wheat and rice, and it is produced across many continents globally[2]. With different variability among the soils, climate, biodiversity, and method of management, the area, production, and productivity of maize in the world were 201 Mhm^2, 1162 MT, and 5754.7 kg/hm^2, respectively[3]. Maize accounts for between 15 and 20% of daily caloric intake in more than 20 developing countries[4]. India ranks fourth in maize production, accounting for 2% of global production. The area under cultivation, production, and productivity of maize crop were 9.86 Mhm^2, 31.51 Mt, and 3195 kg/hm^2, respectively, in 2020-2021[5]. However, weeds continue to be a challenge for crops and represent a significant biotic barrier in crop production systems around the world. Weeds are plants that grow where they are unwanted and compete with crops for water, light, and nutrients[6]. Weeds could reduce crop yield by up to 34%, which is the highest compared to other biotic factors such as pests (18%) and pathogens (16%)[7].

Weeds can be managed by different methods, such as manual, chemical, mechanical, and biological. Manual methods are the simplest and most accurate but are tedious, laborious, time-consuming, and expensive[8]. Currently, village population is shifting towards the city for better livelihood, leading to labor shortages and increased labor charges. Weed management during the planting season accounts for almost 25% of the total cost of production[9-11]. One of the traditional methods of weed control is chemical, but it results in pesticide residue and soil hardening and is

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harmful for the long-term sustainability of agricultural output as well as human and animal health[12,13]. Biological weed control methods include mulching, cover crops and living mulches, soil solarization, thermal weed control, and livestock grazing. In the mulching method, the repeated application of the same mulching material to the same field results in allelopathic effects on crops due to soil changes[14]. Living mulches can also have an adverse effect on crop growth and yield because they compete for soil, water, and nutrients, increasing pest populations and the risk of disease[15]. In order to handle the flush of nutrients that solarization frequently causes, crops should be planted right away, just after the plastic is removed[16]. The flaming technique may consume a large amount of fuel and water, and there are summer usage limitations on the flame due to fire safety concerns[17]. Lastly, controlling weeds by grazing livestock can potentially harm the topsoil structures and non-target species, transfer weed seeds through dung, wool, hair, or hooves, or even result in an animal's health or liveweight decreasing[18].

Mechanical weeding is an important step in weed management in the modern world because it does not pollute the environment, increases soil aeration and temperature, alleviates labor shortages, has high output, and is a fast and efficient method[19]. Various researchers have worked on the design and development of inter-row weeders. Rahaman et al.[20] developed an adjustable, self-propelled rotary power weeder for row crops. The weeding efficiency, field efficiency, plant damage, and performance index observed were 79.49%, 80.07%, 3.4%, and 93.09%, respectively, in a maize crop at a moisture content of 13%. The cost of operation and time saved by using a power weeder over manual weeding were 74.84% and 94.51%, respectively. Gatkal et al.[21] designed and developed a two-row self-propelled rotary power weeder for narrow-spaced crops. Weeding efficiency, field efficiency, plant damage, and fuel consumption were 80.12%, 67.98%, 2.9%, and 1.6 L/h, respectively. The cost of operation and time savings of a two-row, self-propelled rotary weeder over a manual hand wheel hoe were 75.45% and 93%, respectively. Thorat et al.[22] designed and developed a ridge-profile power weeder for row crops. Weeding efficiency, plant damage, field capacity, and machine index were 91.37%, 2.66%, 0.08%, and 66.51%, respectively, at C-type blade, 200 rpm rotary speed, and (15.26±0.96)% moisture content (d.b.) for the developed ridge profile power weeder. The developed ridge profile power weeder saves time at a rate of 92.97% over manual weeding. Chaudhary et al.[23] designed and developed a multi-crop power weeder. The developed weeder was used in pearl millet and castor with row spacing of 30 cm. The highest field efficiency was observed in L-shape blade (81.02% and 86.30%), followed by the C-shape blade (76.66% and 77.28%) and J-shape blade (78.73% and 81.61%) for pearl millet and castor, respectively. Pandey et al.[24] designed and developed an e-powered inter-row weeder for row spacing of 30 cm. The average weeding efficiency, field capacity, and plant damage were observed as 91.68%, 0.049 hm^2/h, and 3.18% at the operating speed of 3 km/h. Kumar et al.[25] developed a non-powered self-propelling vertical axis inter-row rotary weeder for maize crop at operational depths of 2 and 4 cm and 15 and 30 DAS of crop growth stages. The weeding efficiency, plant damage, and field capacity were 65% to 70%, 1.98% to 5.88%, and 0.08 hm^2/h, respectively.

To achieve an optimum weeding and field efficiency with minimum plant damage, several studies have centered on prediction techniques for the most efficient and effective application. There are three methods for prediction: computer software and models, mathematical equations, and regression equations. The computer model and simulation tool reduce the cost and time of field experiments by predicting several parameters. One statistical and mathematical technique for analyzing and optimizing independent variables in a variety of operations is the response surface methodology (RSM). Moreover, the RSM would be used in this sector to study the effect of numerous factors and their interactions on output variables[26].

It is observed from the literature cited above that most of the existing weeders available are of rotary unit type, which compact the soil. Moreover, the optimization of operational parameters and the validation of experimental results of weeders in narrow-row crops have not been verified by any researcher. Also, much less work has been done on tyned weeders in row crops, and tyne does not compact the soil as well. Presently, there are no effective tyned weeders available in India for narrow-row crop weeding for maize crop. In view of the above problems, this study developed a two-row tyned weeder for weed management in maize crop. The tyned weeder was developed with the goal of achieving high weeding and field efficiency with minimum plant damage, fuel consumption, and time savings and no soil compaction. Furthermore, the performance of the developed tyned weeder was evaluated in a maize crop field.

2 Materials and methods

2.1 Experimental site

A two-row tyned weeder was developed and evaluated at the Department of Farm Machinery and Power Engineering, Aditya College of Agricultural Engineering and Technology, Beed, Maharashtra, India, during October 2023. A detailed description of the experimental field and the canopy attributes of the maize crop is presented in Table 1.

Table 1 Details of experimental field plot and canopy attributes of maize crop

Parameter	Value
Variety	Ganga-II
Crop type (rainfed/irrigated)	Irrigated
Plot size/m	50 × 50
Row spacing/mm	300
Plant spacing/m	0.9
Plant height/mm (mean ± SD)	800 ± 0.15
Plant width/mm (mean ± SD)	220 ± 0.19
Date of sowing	October-2023

2.2 Crop and soil parameters

Maize crop (variety: Ganga II) was selected for the experiment, and the weeding operations were carried out 30 d after sowing (DAS). The crop parameters, i.e., row-to-row distance (300 mm), plant height (800 mm), plant canopy (220 mm), and weed density (72 weeds/m^2 area), were measured during the field performance of a tyned weeder. Bulk density of soil was estimated using core cutter method (Figure 1) at the desired depth for different soil moisture contents. The bulk density of soil was determined by Equation (1)[27]:

$$\text{Bulk density} = \frac{\text{Mass of soil sample (M)}}{\text{Volume of cylinder (V)}} \tag{1}$$

Soil resistance is one of the most important factors that affects the power requirement of a tyned weeder. A digital cone penetrometer (DIK 0500 model and Daiki Rika Kogyo manufacturer, USA) (Figure 2) was used to measure soil resistance before and after field operations. Furthermore, a digital moisture meter (ATO-MM-PMS710 model and ATO manufacturer, USA) (Figure 3) was used for the estimation of soil moisture content

Figure 1 Core cutter

Figure 2 Digital cone penetrometer

during the field performance evaluation of the tyned weeder. The digital moisture meter probe is inserted into the soil and senses the moisture content of the soil, which is directly displayed on the monitor. The moisture contents of 12%, 14%, and 16% (d.b.) were selected as the three levels of moisture content for the field performance of the tyned weeder.

Figure 3 Soil moisture meter

2.3 Requirements for development of tyned weeder

1) Easy to operate for a long period of time without pain or discomfort.

2) The weeder gives maximum weeding and field efficiency with minimum plant damage.

3) The developed weeder should be lightweight and portable.

4) It should be made from local materials to reduce the cost of manufacturing.

2.4 Major components of developed two-row tyned weeder

The major components of the developed tow-row tyned weeder are illustrated in Figure 4. The description of the major components is given below:

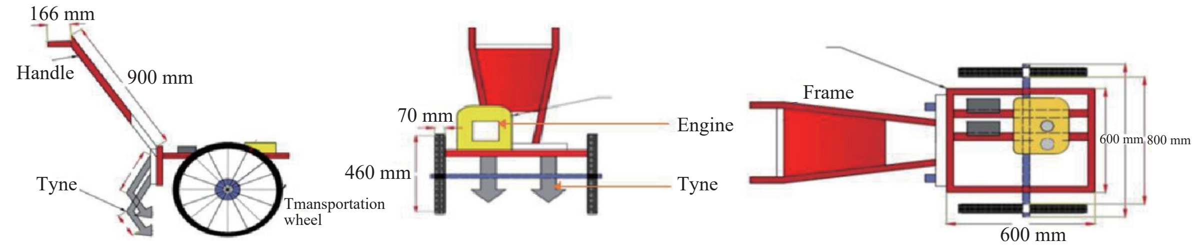


Figure 4 Isometric view of computer-aided design model of two-row tyned weeder

2.4.1 Main frame

It is made of a mild steel 600 mm long and 50 mm wide. Some holes were made to support and accommodate the engine, weeding unit, and transport wheel. The total weight of the weeder was approximately 60.45 kg with all components including the engine.

2.4.2 Power source

It is required for the forward movement of the tyned weeder. A 3.5 kW engine was selected for the weeder.

2.4.3 Handle

The overall length of the handle was 1066 mm with two bends from the point of attachment and a height of 750 mm from ground level. It is used for balancing tyned weeders during field operations. A round pipe is used for the handles with the required dimensions, and the accelerator is fitted to the handle, which is connected to the carburetor by wire.

2.4.4 Wheel

The tyned weeder is fitted with tires having diameter and width of 560-710 mm and 38-51 mm, respectively. During the field operation, these wheels provide traction and stability to the tyned weeder.

2.4.5 Wheel shaft

It is the shaft on which the wheels are mounted. The wheel shaft was selected as 900 mm long and 4.5 mm wide.

2.4.6 Tynes

They are used for removing weeds in rows of crops. A sweep-type blade was used in the developed tyned weeder.

2.4.7 Transmission system

To transmit engine power to the wheel shaft through a chain and sprocket, a light-weight dog clutch was directly connected with the engine shaft. The developed tyned weeder consists of a 5 hp engine to give forward speed.

2.4.8 Power requirement calculations

Soil resistance has a considerable effect on the power requirement of a weeder. Also, width of cut and speed of operation influence its power requirement. For calculating the power requirement of the weeder (Equation (2)), the following assumptions were made based on the available literature[21]:

1) Maximum soil resistance was taken as 6000 kgf/m^2.

2) The speed of operation of the weeder was considered as 1.5 to 2.5 km/h.

3) Total width of coverage of tyned weeder was 500 mm.

4) The depth of operation was considered as 30 to 50 mm.

The width of coverage of tyned weeder = Number of tynes × distance covered by each tyne = 2 ×250 mm = 500 mm

$$\text{Power requirement of weeder}\,(p_d) = \frac{SR \times d \times w \times v}{75} \tag{2}$$

where, SR = soil resistance, kgf/m^2; d = depth of cut, mm; w = effective width of cut, mm; v = speed of operation, km/h.

Hence, power requirement (P) is estimated as:

$$P = \frac{6000 \times 55 \times 500 \times 1.5}{75 \times 10^6} = 2.25\ \text{kW(Take factor of safety 1.5)}$$

$$P = 2.25 \times 1.5 = 3.375\ \text{kW} \cong 3.50\ \text{kW}$$

The power for the tyned weeder used for weeding operations was calculated as 3.50 kW with all major factors considered, such as speed, soil resistance, etc. Hence, a single-cylinder, 2-stroke petrol engine of 3.50 kW air-cooled engine was used in the tyned weeder. The isometric view and technical specifications of the engine are shown in Figure 4 and Table 2, respectively.

Table 2 Technical specification of the developed two-row tyned weeder

Particulars	Specification
Engine	Air-cooled, 2-stroke
Starting system	Recoil
Fuel	Petrol engine
Clutch	Dog clutch
Size of tire/mm	560 to 710 × 38 to 51
Overall dimension/mm (Length×width×height)	1400 × 650 × 750
Main frame/mm (D×W)	600 × 50
Fuel tank capacity/L	3.5
Starting	Recoil starts
Total weight of weeder/kg	45
Engine weight, kg	17
Recommended speed, rpm	300 (Adjusted)

2.5 Design of sweep blade

For self-propelled tyned weeders, a sweep-type blade was selected for weeding operations because of its lower draft force and higher performance index compared to straight and curved blades[28]. The following assumptions were taken into consideration for the design of the sweep blade:

1) Row to row spacing for maize crop 600 mm[29].

2) Depth of cut 55 mm[30].

3) Zone of crop protection 150 mm.

4) Angle of internal friction 25°[31].

The width of the cut of a sweep-type tyne was calculated using Equation (3)[31].

$$S_c = Z_f - Z_p \tag{3}$$

where, S_c is row spacing, mm; Z_f is effective soil failure zone, mm; Z_p is zone of crop protection, mm;

$$Z_f = S_c - Z_p$$

$$Z_f = 600 - (2\times 150) = 300 \text{ mm}$$

The effective soil failure zone was calculated using Equation (4)[31]:

$$Z_f = (W + 2d\tan\phi_s + 2(W_1 + 2d\tan\phi_s) \tag{4}$$

where, W is the width of full sweep, mm; W_1 is the width of half sweep, mm;

$$300 = (W + 2\times 55\times \tan 25^\circ + 2(W_1 + 2\times 55\times \tan 25^\circ)$$

$$W = 249.5 \cong 250 \text{ mm}$$

So, the width of the sweep tyne was selected as 250 mm.

2.6 Design of shank of tyned weeder

For self-propelled tyned weeders, a square shank was designed. For designing the shanks, the following assumptions were considered:

1) Unit draft of soil 0.006 kg/mm² [32].

2) Width of sweep 250 mm[33].

3) Depth of soil 55 mm[20].

4) Factor of safety 2[31].

5) Maximum force for impact loading 2.

Height of shank for maize crop 500 mm[31].

The draft is calculated using Equation (5).

$$Draft = Soil\ resistance \times Cross\ sectional\ area \text{ of cut} \tag{5}$$

$$Draft = 0.006\times 1/2\times 250\times 55$$

$$Draft = 41.25 \text{ kg}$$

The maximum draft for sweep type tyne was 41.25 kg.

Total draft for two-tyne = 2×41.24 = 82.5 kg

Bending force in sweep tyne=Draft × Factor of safety × Maximum force for impact loading

$$\text{Bending force insweep tyne} = 41.25\times 2\times 2$$

$$\text{Bending force in sweep tyne} = 165 \text{ kg}$$

Maximum bending moment for cantilever length of 500 mm= 165 kg ×500 mm

Maximum bending moment for cantilever length of 500 mm= 82500 kg·mm

Bending stress was calculated by Equation (6)[31].

$$f_b = \frac{MC}{I} \tag{6}$$

where, f_b is bending stress, kg/mm²; M is bending moment, kg·mm; C is distance from neutral axis to the point at which stress is determined; I is moment of inertia, mm⁴;

$$Z = \frac{I}{C} = \frac{M}{f_b}$$

$$Z = \frac{82\,500}{30} = 2750 \text{ mm}^3$$

$$Z = \frac{b^3}{6}$$

$$b^3 = Z\times 6 = 2750\times 6$$

$$b = \sqrt[3]{2750\times 6}$$

$$b = 25.45 \cong 25 \text{ mm}$$

A length of 500 mm and a width of 25 mm mild steel square shank were selected for the developed tyned weeder.

2.7 Developed two-row tyned weeder

The developed two-row tyned weeder consisted of a main frame, power source, handle, wheel, wheel shaft, tyne, and transmission system. The main frame was made up of an iron angle to which other components of the tyned weeder were attached. A power source was mounted on the main frame, which drives the tyned weeder. Handle is used for balancing of weeder during field operation. An accelerator was fitted on the handle to control the forward movement of the tyned weeder. A transmission system (chain and sprocket) was used for the transmission of power from the engine to the wheel shaft. Tynes made of mild steel are the main actual working parts of a weeder, which are used for removing weeds in row crops. Wheels are used for transportation and movement of the tyned weeder during field operations. Several experiments were carried out to evaluate the developed tyned weeder for removing weeds (Figure 5) in maize crop. Its performance was tested at three levels of forward speeds and moisture contents of 1.5 km/h, 2 km/h, and 2.5 km/h and 12%, 14%, and 16% (d.b.), respectively.

Figure 5 Developed two-row tyned weeder

2.8 Optimization of operational parameters

Central composite design was used to determine the number of experimental runs. Three responses were recorded for each experimental run, i.e., weeding efficiency, plant damage, and field efficiency. Table 3 shows the treatment combination of two factors (2), each with three levels (3) and three replications (3); a total of treatment of 13 runs were conducted (Table 3) with response surface methodology (RSM) design expert software. The bulk density and soil resistance were observed during each treatment of the experiment (Table 4).

Table 3 Experiment design for the field study

Independent parameters	Level	Replication	Dependent parameters
1. Speed of operation	3 (1.5, 2, and 2.5 km/h)	3	1. Weeding efficiency (%) 2. Plant damage (%) 3. Field efficiency (%)
2. Moisture content	3 (12, 14, and 16% (d.b.))		

Table 4 Soil parameters measured during weeding operation of tyned weeder

Run	Forward speed/ $km \cdot h^{-1}$	Moisture content/ %(w.b.)	Bulk density/ $kg \cdot m^{-3}$	Soil resistance/ $kg \cdot m^{-2}$
T1	2	14	1630.32	3589.65
T2	2.5	16	1600.50	3534.25
T3	1.5	12	1650.38	3621.72
T4	2	16	1602.48	3541.68
T5	2	14	1631.62	35.82.69
T6	2.5	12	1649.33	3618.75
T7	1.5	14	1627.34	3586.47
T8	2	14	1629.48	3581.64
T9	2	14	1626.49	3582.48
T10	2	14	1632.87	3589.65
T11	2	12	1647.95	3616.48
T12	1.5	16	1602.54	3548.74
T13	2.5	14	1633.42	3580.29

Optimization of various parameters was carried out with Design Expert Version 7 software[5]. A regression analysis was solved with a second order polynomial model in Equation (7):

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i=1}^{k-} \sum_{j=i+1}^{k} \beta_{ij} X_i X_j \tag{7}$$

where, Y is desired value for response; β_0 is intercept; β_i, β_{ii}, β_{ij} are constants of linear, quadratic, and interaction coefficients; X_i, X_j are levels of process variables.

Analysis of variance (ANOVA) was carried out to confirm the fitted mathematical model. Three-dimensional response surface plots were used to represent the interaction and influence of variables on weeding operation of tyned weeder. The operational parameters were optimized by setting limits, goals, and by importance.

Design expert numerical optimization will maximize, minimize, or target a single or combination of two or more responses. The program uses five possibilities (None, maximize, minimize, target, in range or equal to) for a "Goal" to construct desirability indices. Desirability varies between zero and one for any given response. The program combines individual desirability into a single number and then searches for the greatest overall desirability. A value of one represents the ideal case, and zero indicates that one or more responses fall outside the desirable limits[34].

2.9 Performance parameters

To evaluate the performance of the developed two-row tyned weeder, the following performance parameters were evaluated in the maize field.

2.9.1 Weeding efficiency

Weeding efficiency was calculated using Equation (8)[35]:

$$\text{Weeding efficiency}(\%) = \frac{W_1 - W_2}{W_1} \times 100 \tag{8}$$

where, W_1 is number of weeds counted per unit area before weeding operation; W_2 is number of weeds counted in same unit area after weeding operation.

2.9.2 Plant damage

Plant damage was calculated using Equation (9)[35]:

$$\text{Plant damaged}(\%) = \left(1 - \frac{q}{p}\right) \times 100 \tag{9}$$

where, p is number of plants in a 10 m row length of field before weeding; q is number of plants in a 10 m row length of field after weeding.

2.9.3 Field efficiency

The field efficiency was calculated using Equation (10)[35]:

$$\text{Field efficiency}(\%) = \frac{\text{Actual field capacity,}}{\text{Therotical field capacity, ha/h}} \times 100 \tag{10}$$

where, $\text{Actual field capacity} = \frac{S \times W}{10} \times E$

$$\text{Therotical field capacity} = \frac{S \times W}{10}$$

where, S is speed of travel, km/h; W is theoretical width of cut of the implement, mm; E is field efficiency, %.

2.9.4 Performance index

The performance index was calculated using Equation (11):[22]

$$\text{Performance index (PI)} = \frac{FC \times (100 - PD) \times WE}{\text{Power (Kw)}} \tag{11}$$

where, FC is field capacity, hm^2/h; PD is plant damage, %; WE is weeding efficiency, %.

2.10 Fuel consumption

The fuel consumption was determined by top fill method. Firstly, the tank was filled to full capacity before operation on leveled ground. After, the field performance of weeder and amount of fuel needed to fill the tank gives the fuel consumption of that test run, and it is expressed as liters per hour (L/h). The fuel consumption is calculated using Equation (12)[36]:

$$\text{Fuel consumed (L/h)} = \frac{v}{t} \tag{12}$$

where, V is volume of fuel consumed, L; T is total operating time, h.

2.11 Depth and width of operation measurement

Using a steel scale, the vertical distance between the horizontal soil surface and the dugout bottom was measured to determine the depth of operation. The average depth of operation was calculated using the values of five randomly selected locations. For measurement of width of operation, a measuring tape was used. The horizontal length of the cut formed by two weeding cones perpendicular to the row was used as a measurement for the operation width of cut. The average width of the cut during the operation was calculated using the values of five randomly selected locations.

2.12 Cost of operation

The initial cost of tyned weeder and manual hand wheel hoe was Rs. 32 000 (INR) and Rs. 3180 (INR), respectively. Total cost of operation was calculated following the straight-line method[37], and the performance of the developed two-row tyned weeder was compared to the hand weeding method, i.e., manual hand wheel hoe. Fixed cost of weeder was computed considering the salvage value of 10%, interest 7%, insurance, taxes (2% of average purchase price of weeder), and housing cost (1.5% average price of weeder). The operating cost of the weeder includes fuel cost (INR. 97/L), operator wages (INR 350/d), repairs, and maintenance charges (10%).

2.13 Statistical Analysis

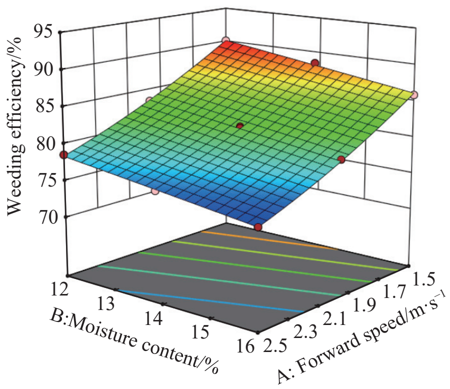
Analysis of variance (ANOVA) was performed using the central composite technique of Design Expert 10.0.2 software (version 10, Statease Inc., Minneapolis, USA) software. To determine the relationship between the responses and model validation, several statistical parameters such as correlation coefficient of determination (R^2), predicted R^2, and adjusted R^2 were used. The analysis of variance (ANOVA) was performed to determine the significance of the quadratic model at the level of 0.05.

3 Result and discussion

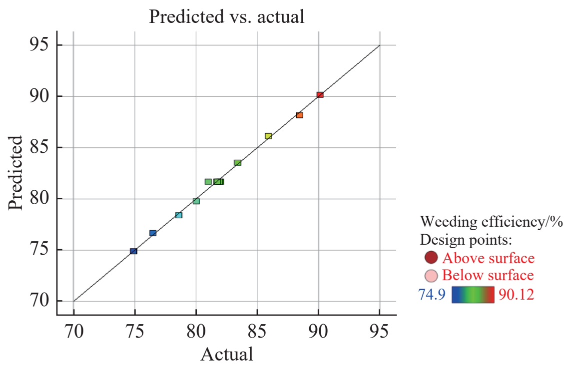
The performance of the developed two-row tyned weeder and manual hand wheel hoe was evaluated after 30 d of sowing on a maize field at the College of Agricultural Engineering and Technology, Beed, Maharashtra, India. The type of soil was black soil with a bulk density and soil resistance of 1600-1650 kg/m^3 and 3534.25-3621.72 kg/m^2, respectively. The average depth and width of cut of the developed tyned weeder were 55 mm and 500 mm, respectively. The developed tyned weeder was operated at three forward speeds and moisture contents of soil at 1.5 km/h, 2 km/h, 2.5 km/h, and 12%, 14%, and 16%, respectively. The performance parameters, i.e., weeding efficiency, field efficiency, plant damage, cost of operation, and time savings, were calculated for the developed tyned weeder, and the results were compared with the manual hand wheel hoe.

3.1 Effect of forward speed and moisture content on weeding efficiency

The highest and lowest weeding efficiency were 95.12% and 82.7% at forward speeds and moisture contents of 1.5 km/h (12%) and 2.5 km/h (16%), respectively. The weeding efficiency at a forward speed of 1.5 km/h and moisture content of 12%, 14%, and 16% was 92.12%, 93.45%, and 90.70%; at 2 km/h and 12%, 14%, and 16%, it was 92.47%, 88.45%, and 85.90%; at 2.5 km/h and 12%, 14%, and 16%, it was 90.01%, 85.14%, and 82.7%, respectively (Figure 6). From the above result, it was found that the increase in forward speed and moisture content decreases the weeding efficiency. The reason for decreasing weeding efficiency with increasing forward speed is that the tyned weeder was difficult to handle during field operations at high forward speed, resulting in the weeder going out of row and weeds remaining in that position. Also, with the increased moisture content, the weeding efficiency decreased because at high forward speeds the tyned weeder gets stuck in the ground, which results in a decrease in weeding efficiency. A similar result was reported by Kachhot et al.[38], with the highest weeding efficiency (90.24%) and lowest plant damage (7.40%). The weeding efficacy of the developed tyned weeder in a rice crop was 61.5%-71.3%[39]. Figure 7 shows the before and after field operation performed by two-row tyned weeder. Hence, with minimum plant damage and high weeding and field efficiency, a forward speed of 1.5 km/h and a moisture content of 12% (d.b.) were considered optimal parameters.



a.



b.

Figure 6 Effects of forward speed and moisture content on weeding efficiency

From the ANOVA (Table 5), it was observed that the linear terms of forward speed (*A*) and moisture content (*B*) were found to be highly significant (p<0.05) and quadratic terms A^2, B^2, and intersection of *AB* were found to be non-significant (p>0.05). From Figure 6 it was observed that the forward speed (*A*) and moisture content (*B*) had a negative effect on weeding efficiency.

The lack of fit test was found to be non-significant (p>0.05) for weeding efficiency, indicating that the developed model was

a. b.

Figure 7 Maize field before (a) and after (b) weeding operation

Table 5 ANOVA on effect of forward speed and moisture content on weeding efficiency of maize crop

Source	*df*	Sum of squares	Mean square	*F*-value	*p*-value
Model	5	221.58	44.32	334.70	< 0.0001*
Forward speed *A*	1	198.49	198.49	1499.15	< 0.0001*
Moisture content *B*	1	21.28	21.28	160.74	< 0.0001*
AB	1	0.0676	0.0676	0.5106	0.4980NS
A^2	1	1.52	1.52	11.48	0.0116NS
B^2	1	0.0015	0.0015	0.0111	0.9189NS
Residual	7	0.9268	0.1324		
Lack of fit	3	0.3031	0.1010	0.6479	0.6242NS
R^2			0.9958		
Adjusted R^2			0.9929		
Predicted R^2			0.9822		
Adeq precision			61.77		
Std. dev.			0.3639		
Mean			82.02		
C.V. %			0.4437		

Note: *df*: degree of freedom; *p<0.05: significant; NS: Not significant. The same below.

adequate for predicting the weeding efficiency of tyned weeder accurately. The R^2 must not be less than 0.8 for fitting the regression model[26]. The higher coefficient of determination R^2 was 0.996, indicating 99.6% variability of the response, which indicated that this model can be considered significant for predicting the experimental results. The predicted R^2 of 0.9822 is in reasonable agreement with the adjusted R^2 values of 0.9929, i.e., a difference less than 0.2. A signal-to-noise ratio greater than 4 is preferred for the quantification of adequate precision. The model ratio of 61.77% for weeding efficiency indicates adequate signal. By using this model, the design region can be accessed. The model shown in Equation (12) was used to represent the variation of weeding efficiency, and the model was also used for further analysis. The graphical representation (Figure 6b) shows that the actual values are in line with the predicted values determined by the models. The response variable, i.e., weeding efficiency, meets the requirements for prediction criteria, and it can be concluded that the ANOVA table for the weeding efficiency values is reliable. The design points above and below the surface indicate that the models predicted results for weeding efficiency of 74.9% and 90.12%, respectively.

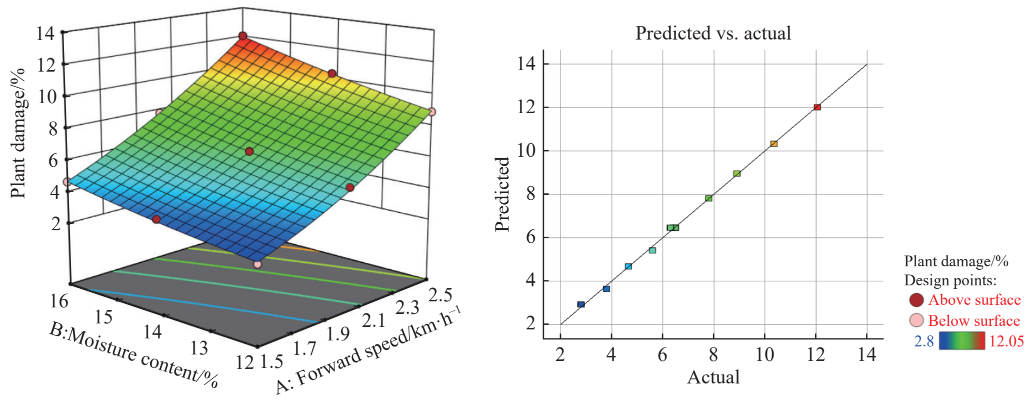
The final regression Equation (13), (excluding non-significant term) depicting the effect of independent parameter on weeding efficiency of tyned weeder for weeding in maize in terms of coded factors is:

$$\text{Weeding efficiency}(\%) = 81.68 - 5.75A - 1.88B - 0.741A^2 \quad (13)$$

Therefore, higher values of R^2 and adequate precision indicate that this model can be considered significant for model Equation (13) to predict the behavior of weeding efficiency of tyned weeder in maize crop. The CV of weeding efficiency for tyned weeder was 0.4437, which indicates the reliability of the conducted experiment[40].

3.2 Effects of forward speed and moisture content on plant damage

The plant damage at a forward speed of 1.5 km/h and moisture content of 12%, 14%, and 16% were 2.80%, 3.80%, and 4.65%; at 2 km/h and 12%, 14%, and 16%, it was 5.60%, 6.43%, and 7.80%; and at 2.5 km/h and 12%, 14%, and 16%, it was 8.90%, 10.25%, and 12.05%, respectively. The lowest and highest plant damage were 2.80% and 12.05% at forward speeds and moisture contents of 1.5 km/h (12%) and 2.5 km/h (16%), respectively (Figure 8). These results indicate that increasing the forward speed of the weeder and moisture content of the soil increased plant damage. The reason for increasing plant damage with increasing forward speed is that the tyned weeder was difficult to handle during field operations at high forward speed; as a result, the tyned weeder went directly on the plant, which led to plant damage. Also, with the increased moisture content, the plant damage was increased because with moisture content the tyned weeder gets stuck in the ground and directly goes on the plant, which also results in plant damage. Similar results were also found by several researchers. When forward speed increased from 1.6 to 2.0 km/h, plant damage increased from 3.61 to 4.89%[30]. Weeding operations were difficult above 13.52% (d.b.) moisture content due to soil adhesion[41].



a. b.

Figure 8 Effects of forward speed and moisture content on plant damage

The ANOVA (Table 6) shows that the linear terms of forward speed (A), moisture content (B), and the quadratic terms A^2, B^2, and intersection of AB were found to be highly significant (p<0.05), while quadratic term B^2 was non-significant (p>0.05). From Figure 8, it was observed that the forward speed (A) and moisture content (B) had a positive effect on plant damage.

The lack of fit test was found to be non-significant (p>0.05) for plant damage, indicating that the developed model was adequate for predicting the plant damage of tyned weeder accurately. The R^2 must be not less than 0.8 for fitting the regression model[26]. The higher coefficient of determination R^2 was 0.999, indicating 99.86% variability of the response, which indicated that this model can be considered significant for predicting the experimental results. The predicted R^2 of 0.99 is in reasonable agreement with the adjusted R^2

values of 0.997, i.e., the difference is less than 0.2. A signal-to-noise ratio greater than 4 is preferred for the quantification of adequate precision. The model ratio of 105.88 for plant damage indicates an adequate signal. By using this model, the design region can be accessed. The model shown in Equation (13) represents the variation of plant damage. The graphical representation (Figure 8b) shows that the actual values are in line with the predicted values determined by the models. The response variable, i.e., plant damage, meets the requirements for prediction criteria, and it can be concluded that the ANOVA table for the plant damage values is reliable. The design points above and below the surface indicate that the models predicted results for plant damage of 2.80% and 12.05%, respectively.

Table 6 ANOVA on effect of forward speed and moisture content on plant damage of maize crop

Source	*df*	Sum of squares	Mean square	*F*-value	*p*-value
Model	5	77.24	15.45	968.89	< 0.0001*
A-Forward speed	1	67.00	67.00	4202.06	< 0.0001*
B-Moisture content	1	8.64	8.64	541.87	< 0.0001*
AB	1	0.4225	0.4225	26.50	0.0013*
A^2	1	0.7723	0.7723	48.44	0.0002*
B^2	1	0.0653	0.0653	4.10	0.0826NS
Residual	7	0.1116	0.0159		
Lack of fit	3	0.0861	0.0287	4.50	0.0902NS
R^2			0.9986		
Adjusted R^2			0.9975		
Predicted R^2			0.9900		
Adeq precision			105.88		
Std. dev.			0.1263		
Mean			6.78		
C.V. %			1.86		

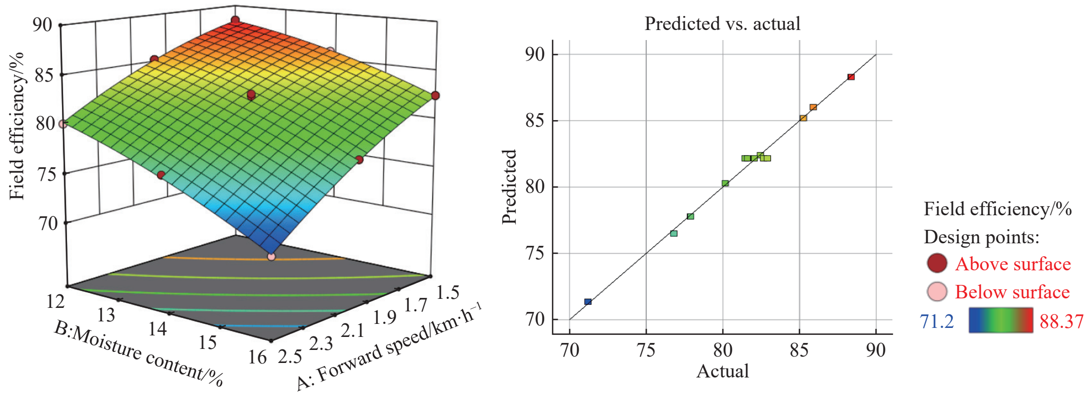
The final regression Equation (14), (excluding non-significant term) depicting the effect of independent parameter on plant damage of tyned weeder for weeding in maize in terms of coded factors is:

$$\text{Plant damage}(\%) = +6.46 - 3.34A - 1.2B + 0.325AB + 0.528A^2 \quad (14)$$

Therefore, higher values of R^2 and adequate precision indicates that this model can be considered significant for model Equation (14) to predict the behavior of plant damage of tyned weeder in maize crop. The CV of plant damage for tyned weeder was 1.86, which indicates the reliability of the conducted experiment[40].

3.3 Effects of forward speed and moisture content on field efficiency

The field efficiency at a forward speed of 1.5 km/h and moisture content of 12%, 14%, and 16% was 88.37%, 88.90%, and 82.45%; at 2 km/h and 12%, 14%, and 16%, it was 85.25%, 81.65%, and 77.90%; and at 2.5 km/h and 12%, 14%, and 16%, it was 80.15%, 76.80%, and 71.20%, respectively. The highest and lowest field efficiency were 88.37% and 71.20% at forward speeds and moisture contents of 1.5 km/h (12%) and 2.5 km/h (16%), respectively (Figure 9). From the above result, it was found that when increasing forward speed and moisture content, the field efficiency was decreased. At high forward speed, the tyned weeder’s balance in row crop was difficult, resulting in the tyned weeder going out of row, resulting in a loss of time, and decreased field efficiency. Also, with the increased moisture content, the field efficiency decreased because at high forward speeds the tyned weeder gets stuck in the ground, which results in a loss of time to get the tyned weeder back in the row, which leads to decreased field efficiency. A similar result was reported by [42] at increasing forward speeds of 0.9, 1.1, and 1.44; the field efficiency decreased by 73%, 69%, and 63%, respectively. Weeding operations were difficult above 13.52% (d.b.) moisture content due to soil adhesion[41].



a. b.

Figure 9 Effects of forward speed and moisture content on field efficiency

From the ANOVA (Table 7), it was observed that the linear terms of forward speed (A) and moisture content (B) were found to be highly significant (p<0.05), while quadratic terms A^2, B^2, and intersection of AB were found to be non-significant (p>0.05). From Figure 9 it was observed that the forward speed (A) and moisture content (B) had a negative effect on field efficiency.

The lack of fit test was found to be non-significant (p>0.05) for plant damage, indicating that the developed model was adequate for predicting the field efficiency of tyned weeder accurately. The R^2 must be not less than 0.8 for fitting the regression model[26]. The higher coefficient of determination R^2 was 0.9921, indicating 99.21% variability, which indicated that this model can be considered significant for predicting the experimental results. The predicted R^2 of 0.9822 is in reasonable agreement with the adjusted R^2 values of 0.9865, i.e., a difference less than 0.2. A signal-to-noise ratio greater than 4 is preferred for the quantification of adequate precision. The model ratio of 49.23 for field efficiency indicates adequate signal. By using this model, the design region can be accessed. The model shown in Equation (14) was used to represent the variation of plant damage, and the model was also used for further analysis. The graphical representation (Figure 9b) shows that the actual values are in line with the predicted values determined by the models. The response variable, i.e., field efficiency, meets the requirements for prediction criteria, and it can be concluded that the ANOVA table for the field efficiency values is reliable. The design points above and below the surface indicate that the models predicted results for field efficiency of 71.20% and 88.37%, respectively.

Table 7 ANOVA on effect of forward speed and moisture content on field efficiency of maize crop

Source	*df*	Sum of squares	Mean square	*F*-value	*p*-value
Model	5	226.24	45.25	176.57	< 0.0001*
A-Forward speed	1	136.04	136.04	530.88	< 0.0001*
B-Moisture content	1	82.29	82.29	321.12	< 0.0001*
AB	1	2.30	2.30	8.96	0.0201NS
A^2	1	2.25	2.25	8.77	0.0211NS
B^2	1	1.27	1.27	4.94	0.0617NS
Residual	7	1.79	0.2563		
Lack of fit	3	0.1808	0.0603	0.1494	0.9248NS
R^2			0.9921		
Adjusted R^2			0.9865		
Predicted R^2			0.9822		
Adeq precision			49.23		
Std. dev.			0.5062		
Mean			81.44		
C.V. %			0.6216		

The final regression Equation (15), (excluding non-significant term) depicted the effect of independent parameter on plant damage of tyned weeder for weeding in maize in terms of coded factors as:

$$\text{Field Efficiency}(\%) = 82.16 - 4.77A - 3.70B - 0.75AB - 0.90A^2 \tag{15}$$

Therefore, higher values of R^2 and adequate precision indicate that this model can be considered significant for model Equation (15) to predict the behavior of field efficiency of the tyned weeder in maize crop. The CV of field efficiency for tyned weeder was 1.86, which indicates the reliability of the conducted experiment[40].

3.4 Optimization of operational parameters for developed tyned weeder

After analyzing the polynomial equation, a central composite of Design Expert 10.0.2 software (version 10, Statease Inc., Minneapolis, USA) was used to determine the optimum conditions for weeding of tyned weeder in maize crop. The three dependent parameters of weeding efficiency, plant damage, and field efficiency and their desirable range have to be ascertained with an optimum level of forward speed and moisture content. Considering the desirable range of the weeding efficiency, plant damage and field efficiency optimum levels were received. The operational parameters were optimized by setting goals and assigning importance to them (Table 8). Numerical optimization gave solutions for weeding efficiency, plant damage, and field efficiency. The operational parameters contributing to these solutions were forward speed 2 km/h and moisture content of soil 14% (w.b.) with desirability of 0.72. The contour plot (Figure 10) shows a representation of the response plotted against a combination of factors, showing the relationship between the response and factors.

3.5 Validation of optimized performance parameters

The weeding experiment for tyned weeder was conducted at the optimum levels of independent parameters, i.e., forward speed 2 km/h and moisture content 14% (w.b.) of tyned weeder to check the adequacy of model equations for predicting the response values.

Table 8 Optimum solutions for various field parameters and validation of model for different response variables

Constraints	Goal	Predicted values	Experimental values	Importance	Prediction error/%
Independent parameters					
Forward speed, km/h	Max	2.16	2	5	-
Moisture content % (w.b)	In range	13.94	14	3	-
Dependent parameters					
Weeding efficiency, %	Max	88.38	89.36	5	1.10
Plant damage, %	Min	6.46	6.23	5	3.56
Field efficiency, %	Max	81.66	82.12	4	0.56
Desirability			0.72		

The mean values were obtained from actual experiments and values predicted by the model (Table 8). Under the optimized conditions, the predicted values of weeding efficiency, plant damage, and field efficiency were very close to experimental values (field values) (Table 8). The percent variation of predicted values and actual values for the response variables was less than 10%, hence the developed model can be considered reliable for experimental results[40]. These results indicate the suitability of the model in optimizing the weeding experiment for field performance parameters.

3.6 Comparative performance and economic analysis of tyned weeder and manual hand wheel hoe

The calculated performance and economical parameters for two-row tyned weeder and manual hand wheel hoe (Table 9) show that using a two-row tyned weeder required only 10.35 man-h/ha of labor, compared to 145 man-h/hm^2 when using manual hand wheel hoe in maize field. The performance parameters such as speed of operation, field capacity, weeding efficiency, plant damage, field efficiency, and depth of operation of the tyned weeder and manual hand wheel hoe were 1.5 km/h, 0.08 hm^2/h, 95.12%, 2.80%, 88.37%, 55 mm, and 1 km/h, 0.05 hm^2/h, 97.04%, 2.10%, 90.25%, 40 mm, respectively. Similar results were reported by forward speed of 1.5 to 2 km/h[22] and 2.45 km/h[43], field capacity was 0.018 hm^2/h and 0.05 hm^2/h[43], weeding efficiency was 77.4%[38] and 88.62%[43], plant damage was 4.5% [38], depth of operation was 40-50 mm[43], and width of operation was 600 mm[43]. The cost of weeding operations for the developed tyned weeder and manual hand wheel hoe were

Table 9 Comparative performance and economic analysis of tyned weeder and manual hand wheel hoe

Particular	tyned weeder	Manual hand wheel hoe
Speed of operation/ km·h^{-1}	1.5	1
Field capacity, hm^2·h^{-1}	0.08	0.05
Weeding efficiency/%	95.12	97.04
Plant damage/%	2.80	2.10
Field efficiency/%	88.37	90.25
Depth of operation/mm	55	40
Fuel consumption/L·h^{-1}	1.3	-
Cost of operation/Rs·h^{-1}	122	35.60
Cost of operation, Rs/ha	1233	5162
Saving in cost of operation over manual/Rs·hm^{-2}	3929	-
Saving in cost of operation over manual/%	76.11	-
Payback period/a	1.12	-
Break-even point/h·a^{-1}	104.5	-
Labor requirement man-h·hm^{-2}	10.35	145
Saving in labor requirement/%	92.86	-
Performance index	410.91	-

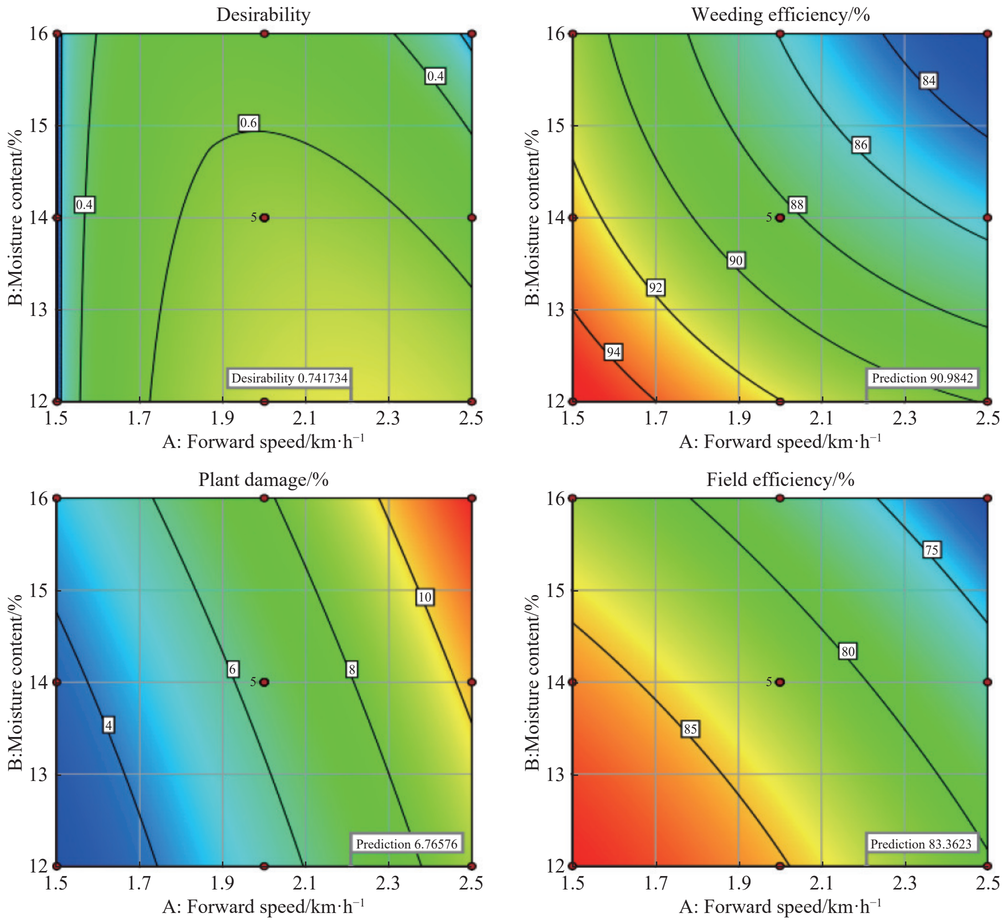


Figure 10 Contour graph for desirability, weeding efficiency, plant damage, and field efficiency for tyned weeder

1233 and 5162 INR/hm^2, respectively. The savings in cost of operation and labor of the developed tyned weeder over the manual hand wheel hoe were 76.11% and 92.86%, respectively. The payback period, break-even point, labor requirement, and performance index for the developed two-row tyned weeder were 1.12 a, 104.5 h/a, 10.35 man-h/hm^2, and 410.91, respectively.

4 Conclusions

A two-row tyned weeder was developed for row crops, and it was evaluated in a maize field at different forward speeds and moisture content of soil. From the above study, the following conclusions were drawn:

1) The optimized parameters for the tyned weeder were 2 km/h forward speed and 14% moisture content.

2) The weeding efficiency, plant damage, and field efficiency were 88.38%, 6.46%, and 81.66%, respectively, at optimized parameters.

3) The performance parameters of field capacity, depth, and width of operation were 0.08 hm^2/h, 55 mm, and 600 mm, respectively.

4) The savings in cost of operation and labor of the developed tyned weeder over the manual hand wheel hoe were 76.11% and 92.86%, respectively.

5) The payback period, break-even point, labor requirement, and performance index for the developed two-row tyned weeder were 1.12 a, 104.5 h/a, 10.35 man-h/hm^2, and 410.91, respectively.

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Author Contributions

Narayan R. Gatkal: Conceptualization, Investigation, Methodology, Experimental work, Data curation and Interpretation, Original manuscript writing, Design of experiment, Manuscript review and editing; **Mohini S. Shelke:** Methodology, Experimental work, Data curation; **Sachin M. Nalawade:** Experimental work, Data curation and interpretation, Manuscript review and editing; **Ramesh K. Sahni:** Manuscript review and editing, Supervision, Resources and Validation; **Akinbode A. Adedeji:** Manuscript review and editing; **Tomáš Najser**: Supervision and language correction; and **Kateřina Beňová:** Project administration and Coordination. All authors have read and agreed to the published version of the manuscript.

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