Development of Mechatronics-Based Self-Propelled Intra-Row Weeder

Abstract

Background: This research presents a significant stride in precision agriculture, focusing on the development and field evaluation of a self-propelled intra-row weeder engineered using mechatronics and machine learning. The study was motivated by the need for labor-efficient and environmentally friendly weed control methods, as conventional techniques pose various challenges.

Methodology: The intra-row weeder, equipped with a crop detection and avoidance system, was developed using a sensor, servo motor, encoder, weeding tool, and a microprocessor (Arduino Uno). A crop detection and avoidance algorithm, based on the K-nearest neighbor machine learning tool, was developed and trained using a customized feature method. This facilitated the system's ability to accurately distinguish between plants and crops, a distinction that was programmed based on object height. This approach proved effective under thevarious conditions.

Result: Field performance evaluation of the weeder was conducted at different forward speeds and plant-to-plant spacing. The results revealed strong correlations between operating parameters and responses such as plant damage, weeding efficiency, performance index, and field efficiency, with R^2 values ranging from 67.87% to 83.61%. Optimal performance was achieved at a forward speed of 2.5 km·h^{-1}and plant spacing of 60 cm, yielding a field capacity of 0.041 ha.h^{-1} and field efficiency of 86.25%. This study, therefore, provides a lesslabor-intensivesolution for weed management in precision agriculture, paving the way for future innovations in the sector.

Introduction

Agriculture in India plays a crucial role in ensuring food security and providing livelihoods for a significant portion of the population (Kadiyala *et al.* 2014). However, the sector faces various challenges, including land and water scarcity, climate change, and weed infestation, which negatively impact productivity and profitability (Madhusudhan, 2015). Weeds, unwanted plants competing with crops for resources, pose a significant threat leading to yield and quality reductions, thus necessitating effective management strategies (Berge *et al.,* 2008; Slaughter *et al.,* 2008; Hamuda*et al*., 2016). In India, weed management accounts for a considerable proportion of production costs, further emphasizing the need for efficient solutions (Yaduraju and Mishra, 2018). Conventional methods like manual, chemical, and biological weed control have limitations in terms of efficiency, cost, and environmental impact, prompting the exploration of alternative approaches such as mechanical weed control (Mohanty and Mishra, 2019,52,53,54). Mechanical weed control involves using machines to uproot, cut, or bury weeds and can be performed between crop rows (inter-row) or within the crop rows (intra-row). While inter-row weed control machines are readily available, managing intra-row weeds presents a persistent challenge due to the risk of crop damage (Rao and Nagamani, 2010). Various tools, including manual, animal-drawn, and power-operated implements, have been developed for intra-row weeding, each with its advantages and limitations (Singh *et al*., 2018). Manual weeding can be labour-intensive and prone to inefficiencies, while power-operated weeders are costly and may damage crops (Slaughter *et al*., 2008). Advancements in mechanical intra-row weed control have introduced innovative solutions such as the Spring-Tine Harrow Weeder and the Brush Weeder, aiming to improve efficiency while minimizing crop damage (Kouwenhoven, 1997; Melander *et al*., 1997). However, challenges persistin intra-row weeding including the need for precise steering to avoid crop damage and limitations in compacted soils or when long-stemmed residues are present (Weide *et al*., 2008).

Recent research has focused on developing intelligent intra-row weeding systems incorporating advanced imaging, processing, and control systems Although these systems often require wide plant spacing and come with increased costs (O'Dogherty*et al*., 2007; Tillett *et al*., 2008; Fennimore *et al*., 2014). Automation and technological integration have emerged as promising avenues in weed control, offering precision and efficiency while reducing human intervention (Liakos *et al*., 2018). Studies have explored the use of sensors and machine learning algorithms for real-time weed detection and damage avoidance, aiming to overcome the limitations of existing methods (Bakker *et al*., 2009; Slaughter *et al*., 2008). The integration of non-invasive sensors with mechanical actuator systems shows potential in improving weed-plant discrimination and reducing environmental risks (Chandel *et al*., 2018).

The K-Nearest Neighbors (KNN) algorithm can indeed be used for instance action with sensor detection. KNN is a popular machine learning algorithm used mostly for solving detection problems (Yang *et al.*, 2016). The KNN algorithm, when combined with advanced sensor technologies, provides a robust and efficient solution for intra-row weeding. This approach not only enhances the accuracy of weed detection but also contributes to more effective and environmentally-friendly weed management in different farming systems(Yang *et al.*, 2016). KNN can be a very effective tool for instance action with sensor detection, especially when dealing with large volumes of data and real-time monitoring requirements. However, like any machine learning method, its effectiveness can depend on the specific application and the quality of the data. It’s always important to consider these factors when choosing a machine learning method for a particular task.This method, has shown significant potential in the field of precision agriculture, particularly in the context of intra-row weeding. Intra-row weeding, the process of removing weeds within the same row as the crop, is a challenging task due to the close proximity of weeds to the main crop plant. The application of KNN in this context involves the use of sensor-based systems to distinguish between crops and weeds (Ugargol and Mahesh, 2024). One approach involves the use of textural feature analysis and morphological scanning applied to specific crops, such as sugar beet plants (Khurana and Bawa, 2020). Following this, the KNN classifier was used to classify and distinguish the weed plant from the field crop (Khurana and Bawa, 2020). The results of the weed detection were analyzed in terms of accuracy and execution time, demonstrating the effectiveness of the KNN approach (Khurana and Bawa, 2020).

Moreover, advancements in precision control in intra-row weeding have been made possible through the use of sensor-based weed detection systems (Lahre and Satpathy, 2024). These systems, equipped with GPS and RGB sensors, have shown promising results in identifying the center of a plant, regardless of lighting conditions (Lahre and Satpathy, 2024). Robots equipped with these systems have demonstrated the ability to distinguish 99.7% of crop plants in dense outdoor areas with high weed density (Lahre and Satpathy, 2024).

The non-image sensor based intra-row weed control system offers a promising solution to the challenges outlined above. Unlike traditional smart intra-row weeding systems that rely on complex imaging and costly cameras. In response to the challenges and opportunities in weed management, this study aims to develop a novel weed identification system based on plant morphology and machine learning, coupled with an intra-row weeder. The objective is to create an efficient and affordable solution that accurately distinguishes between crop plants and weeds within the row, ultimately contributing to sustainable and productive agriculture. Through the development and evaluation of this weeder, the study seeks to advance weed management strategies especially in the intra row zone for addressing weed infestation challenges in agricultural fields.

Methodology

Mechatronics setup

The self-propelled intra row weeder was conceptualized on the basis of morphological property (height) as identification parameter between crop and weed plants. The duration gap between sowing and weed growth results in canopy height difference between major plant and weed (Cordill and Grift, 2011).The sensors in the system were set at a fixed height as per the plant canopy height and the detection signal from the sensor indicated the presence of plant. The weeding tool operation was so designed that it avoids the plant after detection by sensor and again engages back for weeding after the tool crosses the pant. The tool residence time was dependent on the canopy width of the plant. The canopy width of the plant was assessed by the time the sensor detected the pant and the ground speed. The canopy height was considered as major parameter for crop/weed discrimination. The plant detection mechatronics system was implemented within the Arduino Integrated Development Environment (IDE), an open-source platform designed for electronic control systems. Through beam sensor (Autonics BEN10M-TDT) sensor was selected for the plant detection. It has separate emitter and receiver. This sensor was selected on the basis of preliminary lab experiment. This sensor has 1ms response time and can sense transparent, translucent or opaque target (Figure 1).

The designed program was uploaded onto a microcontroller. Within this program, a K-Nearest Neighbour (KNN) method was utilized to locate targeted object. The system operates as follows: The proximity sensor sends a signal to the microcontroller upon identifying an object. The microcontroller, upon receiving the signal, performs necessary computations using KNN and transmits an output signal to the servo motor. The servo motor then performs the required action based on this signal.The sensor's detection mechanism was based on the reflection from targeted object. If the signal is reflected by the object matches a pre-established limit, the servo motor moves from its current state. However, if the signal is reflected by the sensor's reflector, considered as the absence of target, the servo motor is activated to perform the necessary action. This process represents a closed-loop control system where the sensor's input and the servo motor's output are continuously monitored and adjusted by the microcontroller to achieve precise object detection (Figure 2). The process for using KNN for object detectioninvolved data collection, pre-processing, feature vector creation, training with known class labels, prediction of class labels for new instances, and integration with the Arduino platform.The feature vector includes machine speed, encoder value, delay time, hold time, and actuation time of the servo motor.

Machine speed was taken with four classes as 1, 1.5, 2 and 2.5 km·h^{-1}. Encoder value was correlated with ground wheel diameter for determination of the speed of operation.The delay time in terms of the encoder reading (Y), which was the time lag between instant the sensor detect the plant and the instant servo motor was actuated to remove the weeding tool from the line of action.It was calculated using Equation 1 by assuming that the weeding tool was removed from the line of action just 5cm before the plant to avoid plant damage (PD).

Encoder value for one complete rotation = 2400

Encoder value for actuation of servo motor (and weeding tool) before 0.05m of targeted plant

$$Y = \frac{X-0.05}{\pi D} \times 2400 \qquad \ldots (1)$$

Where, X: distance between the sensor position and weeding tool position, m; D: Diameter of ground wheel of weeder, m.

An additional parameter, the holding time (Z), was crucial in preventing plant damage and was computed using Equation 2. The holding time was the time during which the weeding tool was in raised position before it is reengaged for weeding operation. The system was designed in away that the weeding tool remained in raised position from 0.05 m prior to 0.05 m post the plant position.The holding time was determined in terms of the encoder valuecorresponding to a total travel distance of plant canopy width plus 0.1m.

$$Z = \frac{(t \times S + 0.1) \times 2400}{\pi D} \ldots (2)$$

Where, t: time during which the sensor remained in front of the plant, s; S: speed of operation, m/s.

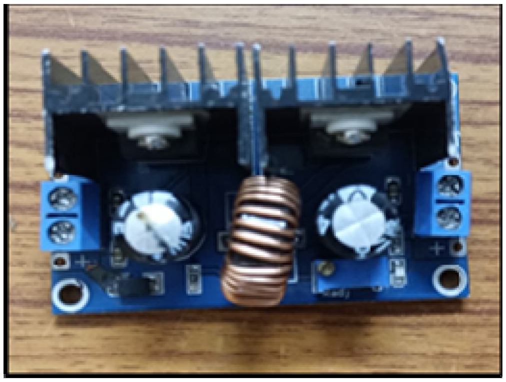
The actuation time is the instant when the weeding tool is reengaged for weeding. This was determined in terms of the corresponding the encoder value (R).

Encoder value for repositioning of cutting tool $(R) = Y + Z$ ...(3)

This repositioning of cutting tool was the time where the cutting tool comes at its neutral position (0 degree). The cutting tool was set as to move in (0 to 45 degree). After completion of task (which is plant detection and removal of weed), the cutting tool comes it'sneutral position.During training several feature vectors collected along with their corresponding class labels. Each class label represents parameters related to object. These were added as examples to the KNN classifier using the add Example() function.

To make a prediction for a new instance (i.e., to detect an object), feature vectors were created from current sensor readings. The KNN algorithm was used to find the k training examples that are closest to this feature vector in the feature space. The class label of the new instance was then set to be the most common class label among these k examples.

Action Based on Prediction: Once predicted classes are defined, servo motor takes action based on it.



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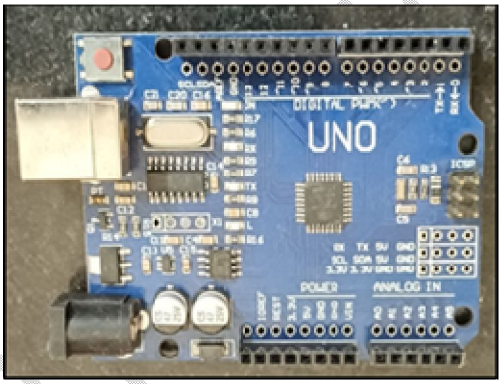

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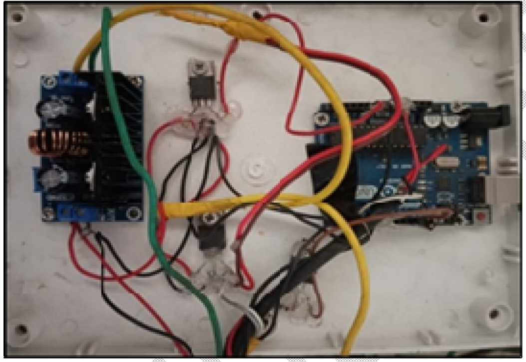

(c)

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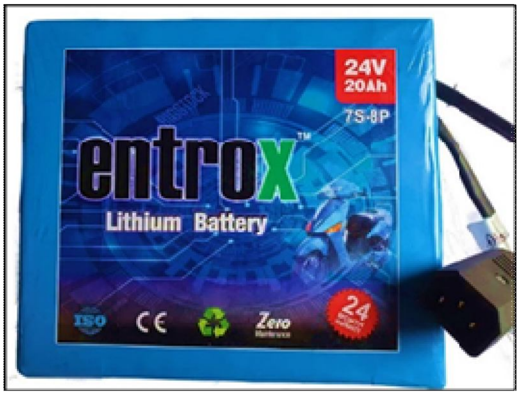


(g)

Figure 1. Electronic components of the developed intra-row weeder (a) voltage regulator (b) Arduino uno and (c) circuit for object detection and (d) proximity sensor (e) servo motor (f) encoder and (g) battery

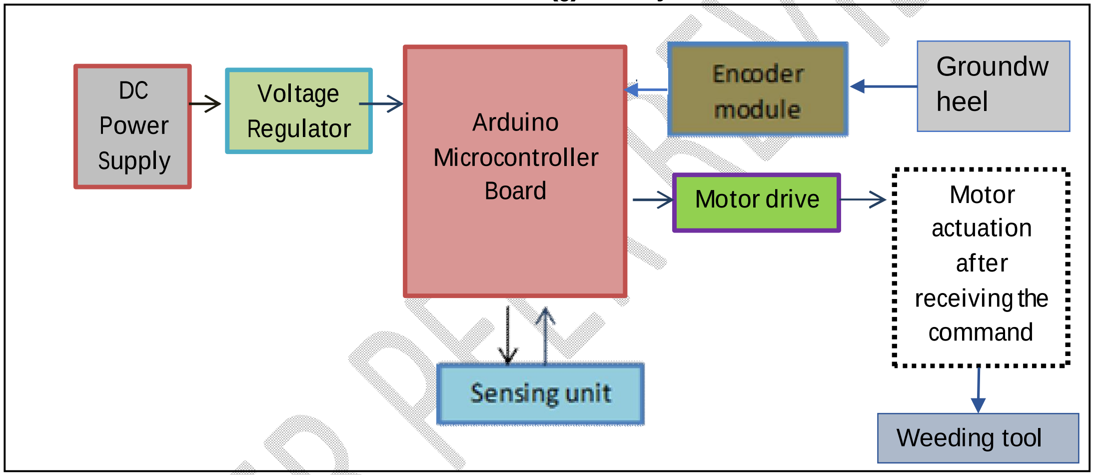


Figure 2. Block diagram of the weed control unit

Development of self-propelled intra row weeder

Tractive force and power requirement of the weeder

The total tractive force (FT) required for the weeder's operation is a cumulative sum of three distinct forces: the rolling resistance force (R), the draft force of the weeding tools (D), and the acceleration force (A). The rolling resistance force (R) is hypothesized to act horizontally at the point of contact between the wheel and the ground, specifically at the wheel contact patch. The estimation of the weeder's rolling resistance was conducted in accordance with the methodology proposed by Redrouthu and Das (2014).

$$R = \mu_r \times W_g \ldots(4)$$

$$\mu_r = 0.04 + \frac{1.2}{C_n} \ldots(5)$$

$$C_n = \frac{CIbd}{W} \ldots(6)$$

Where, *R*: Rolling resistance force, N; μ_r: Coefficient of rolling resistance, W_g: Gross weight of the weeder, N; C_n: Wheel numeric; *CI*: Cone Index, kPa; b: width of wheel, m; *d*: diameter of wheel, m and *W*: vertical load on wheel, N.

Taking gross weight (Wg) = 65kg, the vertical load on each wheel (W) = 318.83 N.

Assuming CI = 500kPa for wet stubble soil (Reece, 2002) and taking b = 0.035m and d = 0.4m, the C_n = 21.95, μ_r = 0.95 and R = 605.77 N were determined.

The total draft force (D) of the weeder was due to the draft of the weeding tool. The weeder had four inter row and one intra row weeding tool. The total draft was estimated as below.

$D = R_s \times d_w \times (4 \times W_{inter} + W_{intra})$...(7)

Where, R_s: unit soil resistance, N.m^{-2}; d_w : depth of weeding, m; W_{inter} : width of cut of inter row weeding tool, m and W_{intra} : width of cut of intra row weeding tool, m. Taking R_s = 49050 N.m^{-2}, d_w = 0.025, m; W_{inter} = 0.08 m and W_{intra} = 0.05 m, the draft of the weeder was estimated to be 453.7 N. The acceleration force was required to accelerate the weeder from rest to the working speed. The acceleration force was calculated as below

$$A = m \times a \quad ...(8)$$

Where, m and a are the mass and acceleration of the weeder. Assuming a working speed of 2.5 km·h^{-1} and time required for the acceleration to be 2s, the acceleration force was estimated to be 23N

Hence the tractive force, F_T = 605.77 + 453.7 + 23 = 1082.4 N

The power requirement of the weeder was calculated as below:

$P = \frac{F_T \times S}{3.6} \times f_s$...(9)

Where, P = Power requirement, W; S = Speed of operation, km·h^{-1}and f_s = factor of safety

Assuming speed of operation of 2.5 km·h^{-1}and factor of safety of 2, the power requirement was estimated to be 1503.3 W. The engine power requirement was estimated with a transmission efficiency of 90% to be 1670.4 W or 2.24 hp. Therefore, a 2.5 hp (Honda GX- 100) petrol engine was selected for the weeder.

Servo Motor size calculations for intra row weeding tool

The weeding tool side wise retraction movement was powered by the servo motor. The motor torque requirement depends on the soil resistance force of cutting tool and the moment arm i.e. the length of the tool shank (Figure 3). The torque of the driving motor was determined through the following calculation (Bugday and Karali, 2019).

$$T = F \times L$$

Where, T: Torque, N-m; F: soil resistance force on the weeding tool, N; L: length of shank, m

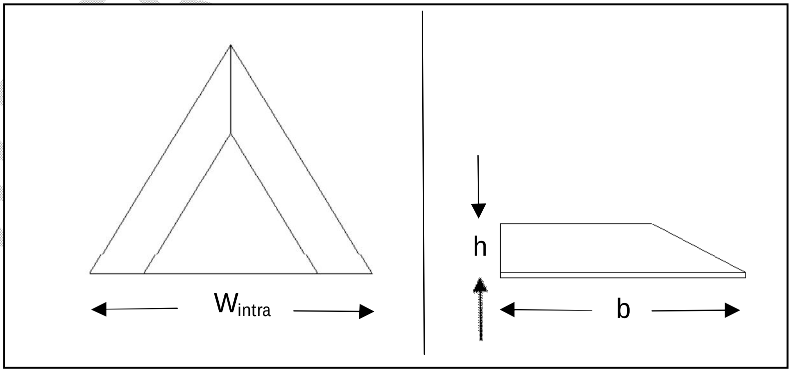


Figure 3 Schematic diagram of intra row weeding blade

The soil resistance depends on the area of soil disturbance and the soil unit draft. The area of soil disturbance is equal to the cross-section area of the tool in a longitudinal plane, which is duck foot type in shape. Hence, the soil resistance force (F) can be calculated by following formula (Ovsyannikov and Kalinin, 2018):

$$F = \frac{1}{2} \times b \times h \times k \quad ...(10)$$

$$F = \frac{1}{2} \times 0.045 \times 0.01 \times 49050$$

$$F = 11.04 \text{ N}$$

Where, *b*: blade thickness, m; h: Height of blade, m; k = unit soil resistance ($N.m^{-2}$).
Taking L = 35 cm, the maximum torque T of the driving motor was calculated using Eq. 9 and found to be 3.86 N-m or or 39.4 kg-cm. Therefore, a servo motor of 60 kg-cm torque was used in the weeder.

Design of inter row weeding tool

The selection of the weeder's tine is essential for uprooting weeds at the desired depth without causing harm to the crops. The depth of weeding depends on factors such as the crop variety and soil moisture level. For effective weed removal operation, a sweep-type inter row cutting blade was chosen. Biswas and Yadavs (2004) reported that the sweep blade demonstrated superior performance compared to straight and curved blades, exhibiting minimal draft force per unit working width and achieving the highest performance index. When designing the sweep blade, considerations were made for chilly crop with row spacing of 30-40 cm, weeding depth 2-5 cm and a total crop protection zone of 5 cm. The cutting width of the sweep-type tine was determined using the formula proposed by Sharma and Mukesh (2010).

$$S_c = Z_f + Z_p \ldots(11)$$

Where, S_c: row plant spacing, cm; Z_f: effective soil failure zone, cm; Z_p: crop protection zone, cm

$$30\,cm = Z_f + 2 \times 5\,cm$$

$$Z_f = 10\,cm$$

The protection zone was multiplied by two since the protection zone has to be provided on both sides of the crop. The effective soil failure zone was calculated by using the formula by Sharma and Mukesh (2010).

$$Z_f = [W + 2 \times d \times \tan \emptyset_s] \ldots(12)$$

$$10 = W + 2 \times 2.5 \times tan(30)$$

$$= 8\,cm$$

Where *W*: width of sweep, and *d*: depth of weeding and $\emptyset_s$: angle of internal friction (assumed as 30°). So, the width of the sweep was taken 80 mm for inter row weeding tool and 55 mm for intra row weeding tool as per the canopy width. While designing the sweep, the apex angle, and condition for easy undercutting of the weeds by the sweep blade were considered. The sweeps were attached to the shank with the help of a nut and bolt.

The total working width of weeder with extended inter-row shaft is 40 cm, therefore, number of inter row weeding tool that can be provided:

$$= \frac{40}{8}$$

$$= 5$$

So, four inter row weeding tool and one intra row weeding tool with full sweep type can be provided.

Apex angle of blade

The apex angle (2θ) is the included angle formed between the two-cutting edge. The apex angle was determined by Eq. 13 (Varshney et al. 2005).

$$\theta = 90 - \emptyset_w \ldots(13)$$

Where $\emptyset_w$= angle of friction between weeds and cutting edge and it ranges between 30 to 50°
Let $\emptyset_w$ = 50,
Therefore, apex angle = $2 \times 60 = 120$

Design of the shank

The shank was designed to have proper fixing on the tool frame of the engine-operated weeder (Figure 4). Four inter row weeding shanks of the weeder were fitted on the main frame of the weeder and one intra row weeding shank is connected to the servo motor with the help of bolt and nut arrangement. The tool shank length could be adjusted for varying the depth of operation. The maximum draft (D) of one weeding tool

$$D = \frac{P}{N_t} \ldots(14)$$

Where, D: maximum draft, N; P: total tractive force requirement for weeder, N and N_t: no. of weeding tools

Taking P = 1082.4 N and N_t= 5, therefore D was found as 216.48 N. Maximum draft at tip of sweep tool was 216N. Taking factor of safety as 2 and taking 2 times of maximum draft for impact loading.

Bending load on sweep = 216×2×2 = 864 N

Maximum bending moment for inter row weeding tool's length of 40cm = $M_b = D \times L$

= 34560 N-cm

Maximum bending moment for intra row weeding tool's length of 35cm = 30240

The bending moment (M) for a rod of circular cross-section is related to the bending stress(σ) and the section modulus (Z). Bending stress was determined in the Eq. 15 (Sharma and Mukesh, 2010).

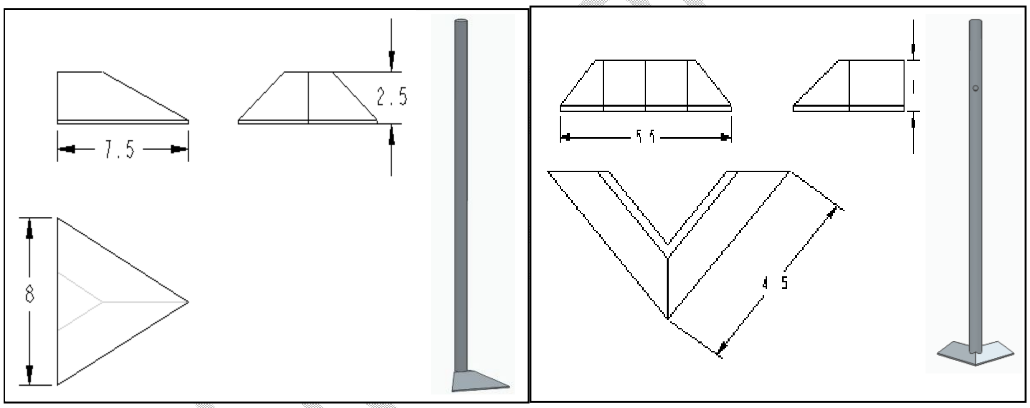
$$M = \sigma \times Z \quad ...(15)$$

For a circular rod, the section modulus (Z) is given by:

$$Z = \frac{\pi \times d^3}{32} ...(16)$$

Where, M_b: maximum bending moment, N.cm; σ: bending stress, MPa; Z: section modulus of the shank, cm^3 and d: diameter of rod of mild steel, cm.

Taking σ = bending stress (56 MPa for mild steel), diameter of inter row weeding tool is found to be 1.6 cm and intra row weeding tool is found to be 1.4 cm.



(a) (b)

Figure 4. Schematic diagram: (a) inter row cutting blade and (b) intra row cutting blade

Therefore, inter row and intra row weeding tool were made from MS circular round rod material of 55 cm × 1.6 cm size and 35 × 1.4 cm was quite safe and the size was available in the market.

Design of power transmission system

Selection of sprocket size

Average forward speed of the machine was considered as: 2.50 km·h^{-1}= 41.67 m.min^{-1}

Diameter of ground wheel was taken as: 40.0 cm

Therefore, required RPM of ground wheel (N) to get 2.5 km·h^{-1}

$$V = \pi \times D \times N = 3.14 \, x \, 0.40 \, x \, N \qquad ...(17)$$

Where, S: forward speed, m.min^{-1}, D: Diameter of ground wheel, m

Therefore,

$$N = \frac{41.67}{3.14 \times 0.40} = 33.17 \, say \, 33$$

Rated engine speed, RPM: 3600

Speed reduction ratio of gear box used was 40:1

Therefore, speed of output shaft of gear box = $\frac{3600}{40}$ = 90

Hence, required speed reduction from gear box shaft to drive wheel shaft = $\frac{90}{33}$ = 2.72 i.e., 2.72: 1
Sprocket size to get 2.72: 1
Sprocket on gear box shaft = 14 teeth
Sprocket on ground wheel shaft = 14× 2.72 = 38 teeth

Calculation of Chain Length

For the purpose of power transmission from the gear box to the ground wheel, a roller chain (08B with a pitch of 12.70 mm) has been selected. Conforming to established design principles, it is recommended that the minimal center-to-center distance between the smaller and larger sprockets be maintained within the prescribed range of 30 to 50 times the pitch of the chain. Therefore, a center distance equivalent to 30 times the pitch of the chain was taken to suit machine design dimensions.

Center distance (x) between the sprockets,

$$x = 30 \times p = 381mm$$

Simultaneously considering the initial sag in the chain, an adjustment was applied by decreasing the center distance value within a range of 2 to 5 millimeters

∴Correct center distance

$$x = 381 - 2 = 379\,mm$$

The length of chain was calculated by using the following equation given by Khurmi and Gupta (2005).

$$K = \frac{T_1+T_2}{2} + \frac{2x}{p} + \left[\frac{T_2-T_1}{2\pi}\right]^2 \times \frac{P}{X} \text{...(18)}$$

Where, *K*: Number of chain links; *X*: Center to center distance between tow sprockets, mm; T_1: Number of teeth in drive sprocket; T_2: Number of teeth in driven sprocket, and *P*: Chain pitch, mm. The number of chain links was found as 88.

Putting the values in equation 19.

Chain length was calculated by using the following relationship,

$$L = \text{K} \times \text{P} = 88 \times 12.70 = 1118\text{mm} = 1.118\text{ m} \qquad \text{...(19)}$$

Drive wheel design

The function of the wheel is to provide required traction for movement of the weeder. The type of drive wheel to be used depends on the ground conditions. Verma (1986) suggested diameter of ground wheels 22.5 to 40 cm for animal operation and 40 to 60 cm for power operation. Diameter of the ground wheel for the weeder was taken as 40 cm. The wheel of the weeder was made from 3 mm thick and 35 mm wide MS flat sheet. The maximum shear strength (τ_{max}) of sheet metal is 80 MPa. Each wheel was provided with eight spokes made from mild steel rods with a diameter of 16 mm and length of 190 mm welded to the rim and hub at the center of the wheel that served as bushing or shaft bearing, at equal intervals.

According to Bhandari (2010), the shear stress on the wheel was calculated from given equation:

$$\tau = \frac{T \times r}{Z} \text{...(20)}$$

The torque on wheel was calculated from the given equation:

$$T = \frac{W_d}{2} \times F_T$$

$$Z = \frac{\pi}{32} \cdot ({W_d}^4 - (W_d - 2t)^4)$$

$$\tau = \frac{T \times r}{\frac{\pi}{32} \cdot ({W_d}^4 - (W_d - 2t)^4)}$$

Where, τ: Shear stress on the wheel, kPa; *T*: the torque produced by the wheel, Nm; *r*: the distance from the center to the point where shear stress is to be calculated, m; *Z:* polar moment of inertia (Z) is related to the outer diameter (W_d) and the inner diameter (W_i) of wheel; F_T: total tractive force, N and *t*: thickness of the wheel

The thickness of wheel was calculated by following given equation:

$$t = \frac{W_d - W_i}{2}$$

Taking, F_T = 1082 N; W_d = 0.4 m, the torque produced at one wheel is 216.4 N.

Taken as W_d = 0.4 m, W_i = 0.397m, so thickness of wheel was found as 0.003m.

Therefore, the shear stress on wheel was found as 293548.45 N.m^2 or 293.54 kPa.

The shear stress of the wheel was compared with the maximum allowable shear stress of the metals, 293.54 kPa and τMax, 80 MPa. Hence, the wheel was safe from failure under the designed loading conditions.

Design of handle

The handle of the weeder should be designed to be adjustable for different heights of the male/female workers. The adjustable handle should help the operator of the weeder to operate the machine comfortably. Two handles were provided at the rear of the machine which were attached to the mainframe. The length of the handle was calculated based on the average standing height of the operator. Therefore, angle of inclination (θ_h) of the handle with the horizontal was calculated by following relation (Sharma and Mukesh, 2010).

$$\tan\theta_h = \frac{a_1}{a_2} \ldots(21)$$

Where, a_1: height of the center of wheel to the elbow, cm; a_2: horizontal distance of wheel center from the operator in operating condition normal to the elbow line

Taking, a_1 = 80 cm and a_2 = 40 cm

$$\theta_h = \tan^{-1} 2 = 63.43$$

$$\sin\theta_h = \frac{80\text{ cm}}{L_h}$$

Therefore,

$$L_h = 89.44\ cm$$

Therefore, the height of the designed handle was kept 90 cm from the ground level.

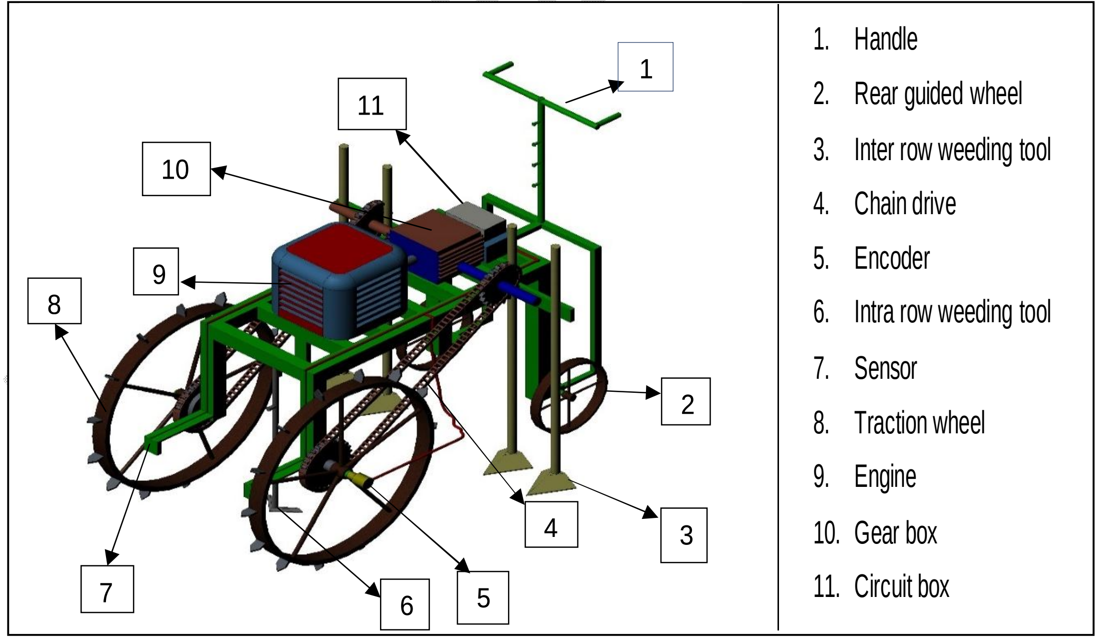
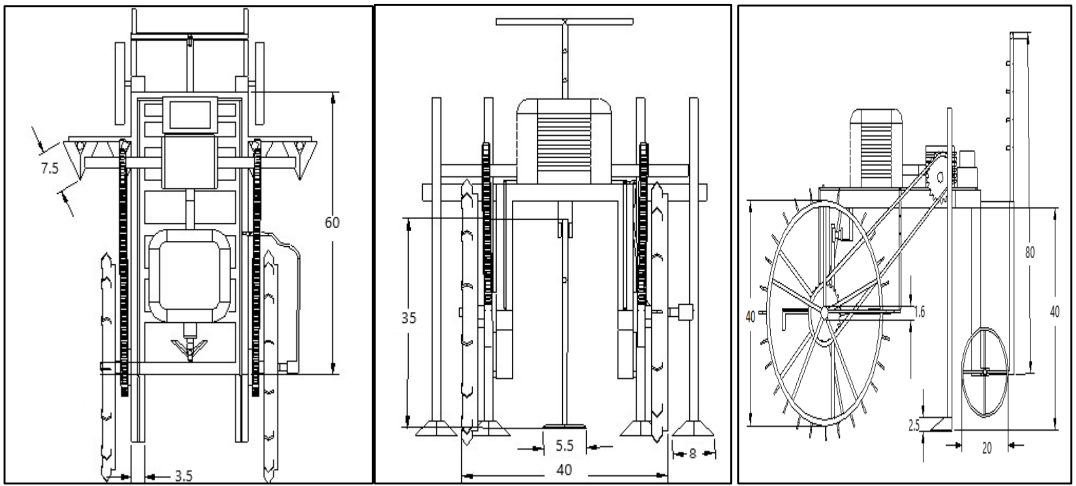


Figure 5. CAD model of the self-propelled intra-row weeder



(a)Top view(b)Front view (c) Side view

Figure 6 Engineering drawings of the developed self-propelled intra row weeder

Selection of fabrication materials

During field operation, self-propelled intra row weeder is subjected to various abrasive, tensile and compressive forces. Therefore, it should be strong, reliable and wear resistant. The details of components and fabrication materials of various components is given in Table 1**.**

Table 1. Specification of self-propelled intra-row weeder components

S.No.	Particulars	Specifications
1.	Type of weeder	Self-propelled
2.	Crop for which suitable	Maize, Chili, Broccoli
3.	Power source	2.5 hp petrol engine
4.	Overall dimension (Length ×Width × Height)	600 mm ×400 mm×900 mm
5.	Weight	65kg
6.	Frame, Dimension	MS angle (35×35×4 mm) 600 mm × 400 mm × 400mm
7.	Ground wheel (Pegged wheel) Diameter: Length of spokes, mm Shaft of drive wheel Length, mm Diameter, mm Width of wheel, mm Length of pegs, mm	MS, High carbon steel flat sheet (35×3 mm) 400 mm 190 Circular mild steel rod 80 16 35 25
8.	Rear wheel Diameter of rear wheel, mm Shaft of drive wheel Length, mm Diameter, mm Width of wheel, mm length of spokes, mm	 200 Circular mild steel rod 80 16 25 90

9.	Shank and weeding blade, mm Type: Detail of inter row weeding Dimension: (Length× Breadth× width) Type: Detail of intra row weeding Dimension:(Length× breadth× width)	Mild steel Vertical shank (sweep blade) 550 mm ×16 mm ×80 mm 350 mm ×14 mm ×55 mm
10.	Chain and sprocket Length:	Heat-treated steel 1.15m
11.	Engine setting	Aluminum alloy
12.	Handle Dimension: (Dia. × Thickness) Height of handle from ground surface Length of handle from frame (mm) Outer diameter of MS conduit pipe(mm)	MS pipe 25×2 mm 90cm 500 250
13.	Ground clearance(From ground surface to main frame)	40 cm

Performance evaluation of the developed self-propelled intra row weeder in field conditions

The evaluation of the weeder was conducted in chilli crop (Dallekhurshani) in experimental plots.

(a) Experimental design for performance evaluation of the weeder

The independent and dependent variables for performance evaluation are given in Table 2. The research was conducted with two main factors: the forward speed of the weeder and the spacing between plants. The ranges for both weeder's forward speed and plant spacing were selected based on results obtained from preliminary field trials andthe previous literature on intra row weeders. The experiments were planned in a full factorial design with 8 (4x2) treatments with 3 replications.

Table 2 Experimental parameters for evaluation of weeder

Independent variables	Levels	Dependent variables
Speed of operation, km·h^{-1}	4 (1, 1.5, 2, 2.5)	1) Plant damage (%) 2) Weeding efficiency (%) 3) Performance index 4) Field efficiency (%)
Plant spacing, cm	2 (50, 60)	

(b) Performance parameters for field evaluation of the intra row weeder

Weeding efficiency

The count of weeds in a 1 m² area was taken both before and after the weeding operation. Weeding efficiency was determined using the formula provided by Yadav and Pund (2007). It was be calculated by using equation 22.

$$\eta = \frac{W_1-W_2}{W_1} \times 100. \qquad ...(22)$$

Where, $W1$: Total count of weeds before weeding; $W2$: count of weeds after weeding andη: Weeding efficiency

Plant Damage

Plant damage was determined by counting the number of injured plants in a sample plot and dividing it by the total number of plants in that plot. This provides a percentage representing the extent of plant damage and calculation was done by following equation (Yadav and Pund 2007).

$$P_D = \left[1 - \frac{A}{B}\right] \times 100 \qquad ...(23)$$

Where, P_D: Plant damage, %; A: No. of undamaged plants in sample plot and B: Total No. of plants in sample plot

Field efficiency

Field efficiency is expressed as a percentage and is derived by dividing the effective field capacity by the theoretical field capacity. This computation was undertaken using the formula presented by Dubey (2001).

$$FE = \frac{EFC}{TFC} \times 100 \qquad ...(24)$$

Where FE: Field efficiency, %; EFC: Effective field capacity, $ha.h^{-1}$ and TFC: Theoretical field capacity, $ha.h^{-1}$

Theoretical field capacity

The theoretical field capacity represents the rate at which an agricultural machine would cover a field if it operated at its maximum efficiency, working at the rated forward speed and fully covering its entire width. This calculation assumes 100% operational time and coverage. Theoretical field capacity was calculated by following Dubey (2001).

$$TFC = \frac{S \times W}{10} ...(25)$$

Where, TFC: Theoretical field capacity ($ha.h^{-1}$); S: Speed of operation ($km \cdot h^{-1}$) and W: Theoretical operating width (m)

Effective field capacity

The effective field capacity of a machine indicates the practical average rate at which a field is covered within a specific time frame. This value was calculated using a standard formula derived from equation (Dubey, 2001).

$$EFC = \frac{A}{T} ...(26)$$

Where, EFC: Effective field capacity ($ha.h^{-1}$); A: Actual area covered by weeder (ha) and T: Actual time of operation in the field (h)

Performance index

Performance index is indicator of the performance of the machine and useful for comparing the weeder's. It was calculated by Eq. 27 (Srinivas et al., 2010).

$$PI = \frac{FC \times (100 - PD) \times WE}{P} ...(27)$$

Where PI: Performance index; FC: field capacity, $ha.h^{-1}$, PD: plant damage, %; WE: weeding efficiency, % and P: Total required power, hp

(c) Statistical analysis: The obtained data was analysed with R open access software.

Results and Discussion

Performance evaluation of developed intra row weeder under field conditions

A full factorial design model was used to study the impact of two variables: the weeder's forward speed (A) and the spacing between plants (B). These variables were analysed in relation to four responses: performance index (PI), weeding efficiency (WE), plant damage (PD), and field efficiency (FE). The results showed that plant damage ranged from 0.00% to 3.92%. The highest damage (3.92%) was noted at weeder's speed of 2.50 $km.h^{-1}$ and the plants were spaced 50 cm apart. Conversely, the least damage was observed at a speed of 1.00 $km \cdot h^{-1}$ with a plant spacing of 60 cm. Weeding efficiency fluctuated between 66.66% and 86.66%. The maximum efficiency (89.49%) was achieved at a speed of 1.00 $km \cdot h^{-1}$ and plant spacing of 60 cm, while the minimum efficiency (80.11%) was recorded at a speed of 2.50 $km \cdot h^{-1}$ and plant spacing of 50 cm. The performance index varied from 185.41 to 202.20. The highest index (202.20) was noted at a speed of 1.00 $km \cdot h^{-1}$ and plant spacing of 60 cm, while the lowest index (185.41) was observed at a speed of 2.50 $km \cdot h^{-1}$ and plant spacing of 50 cm. Field efficiency ranged from 81.25% to 86.25%. The highest efficiency (86.25%) was achieved at a speed of 1.00 km·h^{-1} and plant spacing of 60 cm. The lowest efficiency (83.33%) was noted at a speed of 2.50 km·h^{-1} and plant spacing of 50 cm.This can lead to significant cost savings in agricultural operations. Furthermore, the reduction in plant damage at certain speeds and spacings can lead to higher crop yields, enhancing the profitability of farming ventures.


(a) (b)

Figure 7. View of the developed self-propelled intra row weeder

Effect of operating parameters on the performance of the weeder under field conditions

Multiple linear regression models were used to examine the effects of the weeder's forward speed (A) and plant spacing (B) on performance indicators such as Plant Damage (PD), Weeding Efficiency (WE), Performance Index (PI), and Field Efficiency (FE). The study found that the weeder's speed significantly impacted all performance indicators, while plant spacing did not have a significant effect on all parameters.

(a) Plant damage

In terms of plant damage, the analysis showed that both the weeder's speed and plant spacing contributed significantly to the model, as indicated by the low p-values of these variables. The model fit the data well, with an R-squared value of 0.79. The derived equation suggested that an increase in speed positively affected PD, while an increase in plant spacing negatively affected it. Specifically, for each unit increase in speed, PD increased by 1.26 units. Conversely, for each unit increase in plant spacing, PD decreased by 0.081 units.

The study observed that plant damage is influenced by both the weeder's speed and plant spacing(Fig.8). At lower speeds and a plant spacing of 50 cm, the PD was relatively low. However, as the speed increased, PD also increased. This suggests that higher speeds result in more plant damage due to the machine's reduced time for effective plant detection.Moreover, when the plant spacing was increased to 60 cm, there was a reduction in PD across all speed levels compared to a plant spacing of 50 cm. This indicates that larger plant spacings can mitigate the effect of increased speeds by reducing PD, possibly because the machine covers a larger area and has more time for effective plant detection.This study aligns with research by Jakasania et al. (2023), which reported that plant damage increased with higher speeds and decreased with larger plant spacings. The research attributed this to the fact that higher speeds reduce the weeding mechanism's response time, while larger plant spacings increase the accuracy of plant detection. Therefore, the optimal combination of speed and plant spacing for minimizing plant damage was found to be 1 km·h^{-1} and 60 cm, respectively.

$$PD = 4.39 + 1.26 \times (A) - 0.081 \times (B) \ldots (28)$$

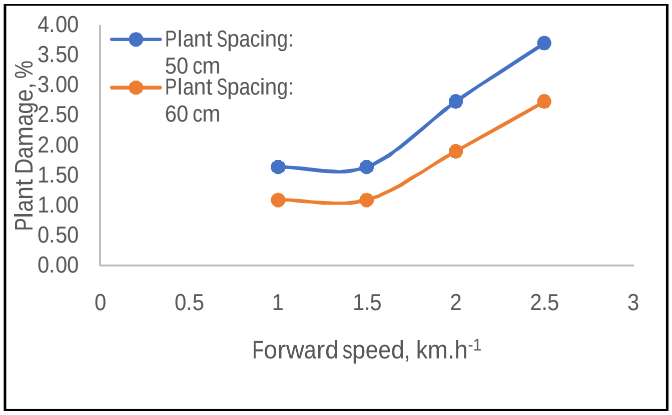


Figure 8. Effect of forward speed and plant spacing on plant damage

(b) Weeding efficiency

The regression analysis was conducted to study the impact of the weeder's forward speed and plant spacing on Weeding Efficiency (WE). The analysis revealed that the weeder's speed negatively affected WE, with an estimate of -5.06. This means that for every unit increase in speed, WE decreased by 5.06 units. On the other hand, plant spacing had a positive impact on WE, with an estimate of 0.2068. This indicates that for every unit increase in plant spacing, WE increased by 0.2068 units.In other words, weeding efficiency decreased with an increase in forward speed and increased with an increase in plant spacing. The model was significant and explained 83.61% of the variation in WE.

The study observed that weeding efficiency varied from 76% to 84%, indicating that both the weeder's speed and plant spacing significantly influenced the weeding mechanism(Fig.9.). The highest efficiency was noted at a speed of 1.0 km·h^{-1} and a plant spacing of 50 cm, while the lowest efficiency occurred at a speed of 2.5 km·h^{-1} with a plant spacing of 60 cm. This suggests that the weeding mechanism performed optimally at lower speeds.

The study aligns with research by Kumar *et al*. (2020), which reported a weeding efficiency of 87.56% using an intra-row weeder with an ultrasonic sensor and fuzzy logic algorithm for plant detection. Therefore, it can be concluded that both the weeder's forward speed and plant spacing are effective parameters in determining the extent of weeding efficiency.

$$WE = 97.2841 - 0.1990 \times A - 0.2068 \times B \ldots(29)$$

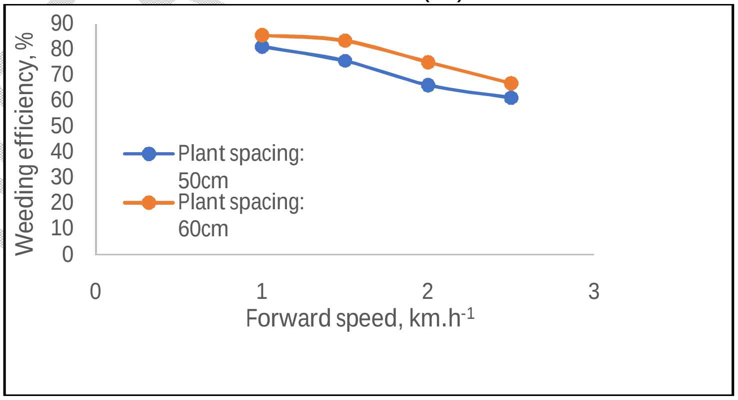


Figure 9. Effect of forward speed and plant spacing on weeding efficiency

(c) Performance index

The regression analysis revealed that the forward speed had a significant impact on the Performance Index (PI), with each unit increase in speed leading to a decrease in PI. However, plant spacing did not significantly affect PI. The model suggested that both forward speed and plant spacing negatively influenced the performance index. Specifically, an increase in forward speed led to a 6.08 unit decrease in the performance index, assuming plant spacing remained constant. Conversely, each unit increase in plant spacing led to a 0.015 unit increase in the performance index, assuming forward speed remained constant.

The model explained 67.87% of the variation in the performance index, as indicated by the multiple R-squared value of 0.6787. After adjusting for the number of predictor variables, the model explained 64.82% of the variation, as indicated by the adjusted R-squared value of 0.6482.

Observations from Fig. 10. showed a positive correlation between the performance index and forward speed levels for both 50 and 60 plant spacings. An increase in forward speed levels correspondingly increased the performance index. This trend was consistent for both plant spacings, although the performance index for a plant spacing of 60 was slightly higher than that for a plant spacing of 50 at every forward speed level. This suggests that a plant spacing of 60 is more effective at higher forward speeds than a plant spacing of 50. Therefore, it was concluded that the weeder's performance improved with both increased forward speed and increased plant spacing. This finding aligns with a study by Balas *et al*. (2023), which found that the performance index of intra-row weeders with sensor detection increased with the forward speed.

$$PI = 204.83 - 6.08 \times A + 0.015 \times B \qquad \text{...(30)}$$

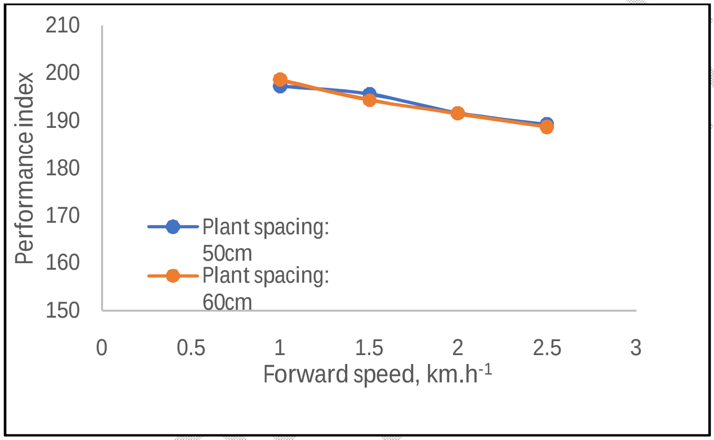


Figure 10. Effect of forward speed and plant spacing on performance index

(d) Field efficiency

The analysis of the model for Field Efficiency (FE) revealed that the forward speed had a significant impact, with each unit increase in speed leading to a 2.06 unit decrease in FE. Plant spacing also had a significant effect on FE. The model accounted for 68.31% of the variation in FE, as indicated by the multiple R-squared value. After adjusting for the number of predictors, the model explained 65.29% of the variation.

The study observed that FE varied between 80% and 90% across different forward speed levels (Fig.11). FE was higher at a plant spacing of 50 cm compared to 60 cm at all speed levels, suggesting that both forward speed and plant spacing significantly influenced FE. This aligns with the research by Jakasania et al. (2023), which found acceptable efficiency levels within the examined range.

$$FE = 82.50 - 2.06 \times A + 0.09 \times B \qquad \text{...(31)}$$

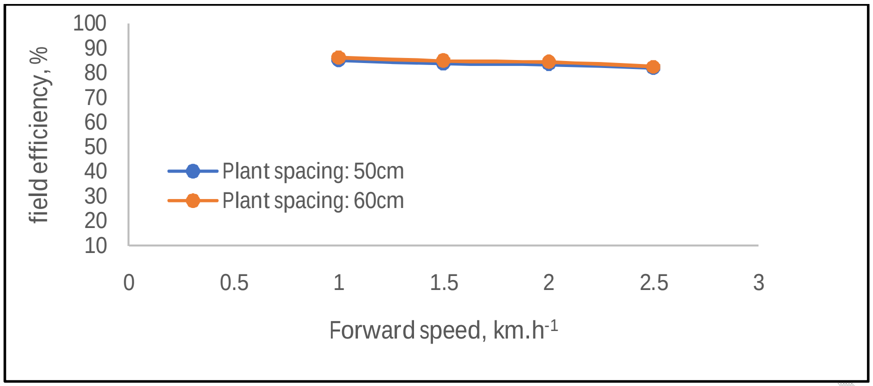


Figure 11. Effect of forward speed and plant spacing on field efficiency

A thorough analysis of performance indicators provided a comprehensive understanding of the weeder's performance in terms of plant damage, weeding efficiency, and performance index. The study found that forward speed significantly affected all performance indicators, indicating its importance in optimizing the weeder's operation.As the weeder's speed increased, it might not have had enough time to accurately identify and remove weeds, leading to increased plant damage. This was reflected in the positive relationship between forward speed and PD. On the other hand, the negative coefficient of forward speed in the weeding efficiency suggested that as the speed increased, the weeder's ability to effectively remove weeds decreased. This was reflected in the negative correlation between forward speed and WE, PI, and FE.

(a) Front view of weeder (b) Back view of weeder

Figure 12. Field view of the developed sensor based intra row weeder

(a) (b) (c)

Figure13. (a):Field evaluation of developed intra row weeder, (b): Field view after weeding operation and (c): Coverage of width of inter and intra row weeder

Moreover, plant spacing had a non-significant effect on the weeder's performance, possibly due to the weeder's design, which might have been able to adapt to different row plant spacings without affecting its performance. The results of this research agreed with Cordill and Grift (2011) and Balas et al. (2023), emphasizing the importance of managing operational forward speed to optimize weeder's performance, particularly in controlling plant damage and enhancing weeding efficiency. The findings suggested that for optimal performance, the system should have been operated at medium forward speeds and wider plant spacing.

Conclusion

The weeding machine consisted with electrical tools (sensor, motor, encoder, Arduino uno and connecting wires) and plant detection algorithm. The sensor detection signal, plant distance and cutting tool position was used for programming of plant detection algorithm. The cutting tool was programmed as that it moves at fixed angular position of 45 degree after detection of crop within the row for avoidance of crop damage after getting signal from sensor and gets repositioned when there is no plant detected by sensor and does continue the weeding operation.The field trials exhibited correlations between the operating parameters like forward speed and plant spacing, and the observed responses, which include plant damage, weeding efficiency, performance index, and field efficiency. The strong correlations suggest that careful control of the operating parameters can optimize the weeder's performance, minimizing plant damage while maximizing weeding and field efficiency. This development marks a significant advancement in agricultural technology, offering potential for improved crop management and productivity. Future work could explore the application of these findings in different soil types and crops to further validate the versatility of this innovative weeding solution.

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