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Automated Prototype Intra Row Weeding System

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Over the course of several decades, considerable efforts have been dedicated to weed control, exploring various methods and technologies such as manual, chemical, biological, and mechanical approaches. Commercial tools are available for mechanical weed control in the inter-row region; however, the weed control in intra-row zone is still a challenge. Therefore, an intra-row weeding unit concept has been developed and evaluated under laboratory condition. The system is based on ultrasonic sensor, fuzzy logic, four bar linkage mechanism and microcontroller circuit. The results of ANOVA indicate that variation in four bar linkage crank speed (S_{rpm}) was found to be highly significantly dependent on forward speed of operation ($P < 0.001$). The system was tested at different depths (20, 40, 60 mm), speed of operations (0.96, 1.71, 2.58 km/h) and cone index of 300 kPa, 400 kPa and 500 kPa. The draft and lateral force was found to in the range of 5.88 N to 22.77 N and 0.97 to 8.01 N respectively for entire range of test plan. It was observed that average plant damage of intra row weeding system was varying from 0.66% to 8.66% for all test range of independent parameters. The newly developed intra-row weeding system can be seamlessly connected to the existing tractor-operated inter-row weeder. This integration enables the performance of weeding operations both within and between rows in a single pass of the tractor.

Keywords: Automation, Dynamic force, Fuzzy logic, Intra-row prototype, Plant damage

Introduction

India is the world's fastest developing economic country with agriculture being the major contributing sector. About 65 to 70% of the Indian population resides in villages and about 80% of those dependent on agriculture for their livelihood.[1,2] The rapidly growing population per year has been increasing the concerns for food demand. These demands claim high requirements for efficient agricultural operations to obtain maximum yield. However, climate changes, severe shortfall of water resources and arable land, weeds, pests and insect infestations have imposed significant challenges for efficient agriculture.[3] In the context of Indian agriculture, weeds are the highest production loss causing agents (33%) followed by pathogens (26%), insects (20%), storage pests (7%), rodents (6%) and others (8%).[4,5] Therefore, fine and timely agricultural practices are required for significant enhancement of food production and demand management. The widespread presence of weeds poses a significant challenge in global agriculture. Weeds, referring to non-native plant species, proliferate haphazardly throughout crop fields. Furthermore, they vie with primary crops for essential resources such as water, nutrients, and sunlight, leading to a notable decline in both the quality and quantity of agricultural production.[6,7] Enormous efforts has been put for several decades for weed control. They observed that weed management takes an account of about one-third of the total cultivation costs, single-handedly and about 25% of the labor (900–1200 man-hours/hectare).[8,9] Recent studies have indicated that an average expense of INR 6000/ha for Kharif crops and INR 4000/ha for Rabi crops is incurred due to weed management, constituting 33% and 22% of the total production costs, respectively.[10,11] A strong impact on crop yield loss has been demonstrated by several studies in relation to weed infestations.[7] Additionally, traditional methods of weed control have been reported to result in an average yield loss of 15–20%. Thus, the critical importance of

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weed management for effective crop loss management and quality production is underscored.

Various methods and technologies have been investigated for the proper management of weeds, including manual, chemical, biological, and mechanical approaches. Manual methods of weed removal by hand or simple hand tools are the oldest and are significantly employed in small scale fields.[12] Typical labor requirements for hand hoe (Khurpi) varies from 300–500 man-h/ha while animal-drawn weeding tools (blade hoe and blade harrow) varies from 6–20 man-h/ha and for push-pull type weeder from 100–125 man-h/ha.[13] Although, manual methods are smoothest of all but demand excess labor and costs. Additionally, it demands continuous human bending and at times leads exposure to infectious weeds species. Manual weeding has been therefore abandoned in many parts of the world.[14–18] Moreover, the labour availability reduces to minimum and costs per labour rises to the maximum during peak seasons.

Chemical application is another method of weed control that has been extensively explored. Nevertheless, the exploration of alternative approaches has been necessitated by researchers due to rising health hazards, environmental concerns, the emergence of herbicide-resistant weed species, and the demand for low-cost and chemical-free production. Biological methods for weed control have also been attempted, but their efficacy is hindered by limitations such as target distraction and uncontrolled insects.[19–24] Mechanical methods are worldwide adopted measures for weed management. Traditionally, mechanical weeding tools were pulled by the draft animals but are now majorly self-propelled or tractor operated. Tools such as power weeder, wheel hoe and tractor operated weeders (sweep cultivator, rotary tiller, etc.) are now been extensively used in Indian agriculture. Tractor operated weeders are now widely used to remove weeds from inter-row zone in wider spaced crops. Wide-row crops are generally grown at a row spacing of 0.3–0.7 m, to allow the tractor and weeding tools to pass between the rows.[25] These tools uproot, cut and bury the weeds using the mechanical input power. Mechanical weeding tools are intended to control weeds in two regions around the crop plant: first, the “inter-row”, the area between rows; second, the “intra-row”, the area between plants in a row.[26] Commercial tools are available for mechanical weed control in the inter-row region, however, the weed control in intra-row zone is still a challenge. Additionally, mechanical weeding is rated better over the manual, chemical and biological methods for its non-risky nature towards humans and environment.[27–29] Field row crops are generally invaded by inter and intra-row weeds. Several commercial tools are available for weed control in the inter-row zone, whereas, weed control in the intra-row zone is a persistent challenge and performed manually after inter row weeding. One of the biggest challenges during intra-row weeding is main crop damage. Weeds in the intra-row zone have been reported to reduce cop yield up to 33%.[30–35] Therefore, an intra-row weeding unit concept has been developed to efficient weed control in the intra-row zone while not disturbing the main crop plants. The intra-row system actuation is based on crop physiology and position sensing using a Fuzzy Logic (FL) algorithm, four bar linkage mechanism, microcontroller derived mechatronics system for an effective technique for intra-row weeding.

Materials and Methods

Conceptualization of Intra-Row Weeding System

In this investigation, an advanced sensor-based intra-row weeding system featuring a Vertical Axis Rotor (VAR) design was developed. This weeder boasts a streamlined design, facilitating effortless attachment and detachment when paired with a tractor. The utilization of the VAR has been proposed to be associated with minimal tractor draught requirements and reduced losses attributed to rolling resistance and wheel slips. Moreover, VAR is widely utilized in secondary tillage operations. Importantly, vertical axis rotors, unlike Power Take-Off (PTO)-driven rotary tillers, avoid the formation of tillage hardpans. Additionally, the soil pulverization capacity of VAR can be finely adjusted by manipulating the travel and angular speeds of the rotor.[35] This system has been conceptualized to work on the principle of time of flight sensing and transfer signal received from the sensor (mounted prior to weeding unit) to the Microcontroller (MC). The MC further actuates the driver of Permanente Magnate Direct Control (PMDC) motor after getting a signal from the sensor during the operation. The PMDC motor then shifts the VAR through a Four-Bar Linkage (FBL) cranking mechanism to move the VAR laterally away from the main crop. The whole unit works due to the sensing of main crops in rows prior to the VAR weeding tool and accordingly actuates the PMDC controller to shift the VAR. This way the physical damage of main crops grown in the rows can be avoided. The combination of active components (VAR and PMDC) has been suitably synchronized in such a way that, after the VAR unit passes the main crop, the PMDC motor actuate FBL thereby shifts the VAR unit into the intra-row zone and weeding operation is executed. The mechatronic system was controlled with the help of a customized FL algorithm developed in the microcontroller environment. A PMDC motor was connected to the crank of the FBL mechanism for lateral shifting of the VAR at position P2. As the plant passes by, the VAR retains its original position (P3). The conceptual working outline of the intra-row weeding system is shown in Fig. 1.

Intra Row Vertical Axis Rotor System

Vertical axis rotor dimensions of intra row were designed on the basis of different zones of plants. Different zones of plants are crop spacing zone, soil failure zone and plant protection zones. The dimension and material were selected on the basis of soil specific draft, available power, speed and Depth of Operation (DO). The different zone of plants and CAD model of VAR is shown in Fig. 2 (a) & (b).[35]

Sc = crop spacing, mm
Zf = effective soil failure zone or inter row zone, mm
Zp = protection zone or intra row zone (150 mm to 200 mm)

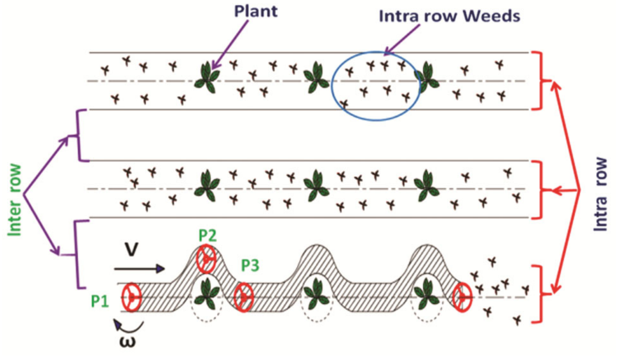

Fig. 1 — The working principle of the intra-row weeding system

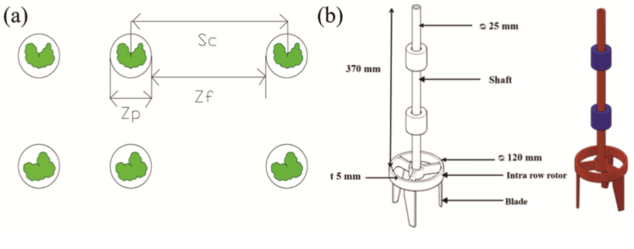

Fig. 2 — (a) Different zones of cops, and (b) Intra row VAR with dimensions

Here plants protection zone has been selected as intra row zone

$Z_{intra} = D + 2d \tan \Phi$

where, Z_{intra} = intra row weeding zone = 160 mm, d = depth of operation = 60 mm, D = diameter of intra row rotor, Φ = soil friction angle = 20°

$D = Z_{intra} - 2d \tan \Phi$

$D = 160 - 2 \times 60 \times \tan 20$

$D_{intra} = 116.32 \text{ mm} \approx 120 \text{ mm}$

MS flat width of 30 mm and thickness of 5 mm was selected to make VAR of 120 mm diameter of intra row and minimum number of tools on VAR was selected as 3 for better tilling pitch of rotor.

Four Bar Linkage Crank Mechanism

Four Bar Linkage (FBL) crank mechanism was fabricated for lateral shifting of VAR. FBL crank mechanism was designed on the basis of path curve analysis of the FBL mechanism for lateral shifting of VAR during weeding operation. The mechanism of working FBL is also described in this section. According to Hrones and Nelson (1951), the value of the ratio of link length to crank for coupler or intermediate (b/a), follower (c/a) and fixed links (d/a) are 3, 2.5 and 3.5 respectively. Motor and rotor pivoted shaft (fixed link) has been mounted on the implement frame and distance between them was maintained 230 mm (d) for facilitating the movement of other relative links. The notation for different lengths of four arms is a, b, c, d for the links of AB, BC, CD and AD, respectively. Considering d = 230 mm, the crank length (a) of 62 mm was determined by d/a ratio of 3.5. The dimension of link lengths for a, b, c, and d was 62 mm, 190 mm, 140 mm and 230 mm, respectively. These lengths were selected to ensure a smooth lateral shift of the VAR and to satisfy the Grashof's Criterion ($a+d<b+c$). The conceptual view of the designed FBL is shown in Fig. 3. The lengths were also simulated in MATLAB software (Mathworks R2016a). It was found that designed links length satisfied the Grashof's Criterion ($a+d<b+c$). The developed mechanism for lateral shifting is shown in Fig. 4.

Mechatronics System and Microcontroller Based Embedded Circuit

The mechatronic unit comprised various electronics components and hardware such as ultrasonic sensor, Microcontroller, motor driver, PMDC motor, proximity sensors, LCD screen, etc. PMDC motor with FBL mechanism has been incorporated to shift the VAR unit so as to avoid crop damage. Once the ultrasonic sensor detects main crop the PMDC operated

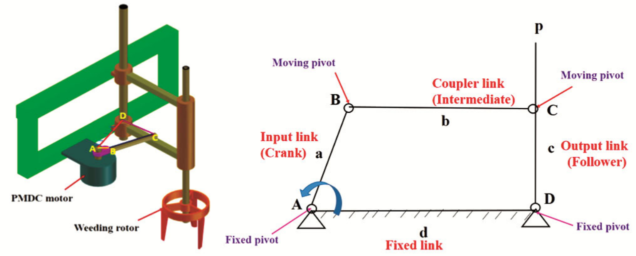

Fig. 3 — Conceptual view of designed FBL mechanism for intra row weeder

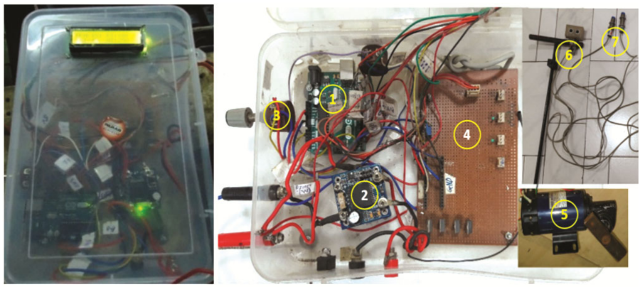

Fig. 4 — Fabricated embedded circuit for intra row weeder [1. Microcontroller, 2. Motor driver, 3. Potentiometer, 4. PCB, 5. PMDC motor, 6. Ultrasonic sensor, 7. Proximity sensor, 8. Circuit box] Cranking mechanism, 5. Proximity sensors, 6. Ultrasonic Sensors, 7. Bevel gear box, 8. Microcontroller Circuit box]

mechanical units come into functional. A PMDC motor is connected to the crank of FBL mechanism for lateral shifting of the weeding unit. The PMDC motor has been controlled on the basis of FL membership function to perform intra-row weeding tasks. The embedded circuit for intra row VAR position controlling was designed and interface with different sensors. A microcontroller (Arduino Uno) and sensors like ultrasonic sensor for main crop detection; a proximity sensor for measurement of actual ground wheel speed, potentiometer for input parameter and two additional proximity sensors to restrict the position of VAR were interfaced to develop the microcontroller based embedded system. A motor driver (HB-25, Parallax Inc., Rocklin, CA, USA) was used to control the speed of lateral shifting, which was interfaced with microcontroller for signal processing, support decision, data recording and display of output on LCD screen. The circuit diagram for developed embedded system is shown in Fig. 4.

Fuzzy Logic Algorithm for Actuating PMDC Motor

Detection of the crop in the real field condition and actuation of the units for intra row weeding needs some complex decisions during the field operation. Looking at the complexity of controlling mechanism, FL algorithm was developed using Arduino Uno (version 1.8.9) library, verified and uploaded into the micro-controller. The FBL cranking speed ($_{\mathrm{Srpm}}$) of lateral shift of VAR was synchronized with the actual ground wheel speed through a sensors network. Frequently real-time sensing of the main crop within a little time span with respect to the speed of field operation requires on-the-go decision support for the functioning of the VAR weeder in the intra row zone. Henceforth, controlling minimizes main crop damage with effective intra row weeding. This phenomenon of operation requires some high end soft computing methods to perform all the intended functions and take the decision. In this regard, FL has been evolved significantly for more than the last four decades then and has become one of the most popular tools to develop sophisticated control systems. Fuzzy logic works in a way similar to human decision making and gives an incredibly precise solution with either certain or approximate information. The working mechatronics system is function of sensor and controller Actuation Time (AT) and soil tool interactions parameter such as soil Cone Index (CI). The input parameters of the FL model were CI of soil and AT of sensing system and PMDC motor speed (S_{rpm}) was the output parameter of the model. The FL code was written in microcontroller environment and uploaded in microcontroller to control the path of VAR from plant detection to lateral shifting zone and effective intra row weeding zone with help of all interfaced sensors. The S_{rpm} was formulated through FL algorithm as a function of AT and CI. Triangular membership functions were used for CI and AT fuzzifications. The weightage matrix was then formulated by using minima of CI and AT at their corresponding low, medium and high values. The S_{rpm} defuzzification used maxima of CI and AT to calculate S_{rpm}. Complex systems were also simulated using the Adaptive Neuro-Fuzzy inference system (ANFIS) which is an advanced fuzzy based technique. It has been employed here for predicting the S_{rpm} (Fig. 5). The input parameters of the FL model were cone index (CI) of soil and actuation time (AT) of sensing system and PMDC motor speed (S_{rpm}) was the output parameter of the model. The fuzzy model of MATLAB (Mathworks Inc., 2016a) was used to validate the S_{rpm} using the proposed FL model.

Automated Prototype of Intra Row Weeding System

A prototype for an intra-row weeder was created by combining a mechanical linkage actuator system with various electrical sensing and control systems. The prototype included an intra-row VAR, FBL cranking mechanism, sensor, PMDC motor, microcontroller

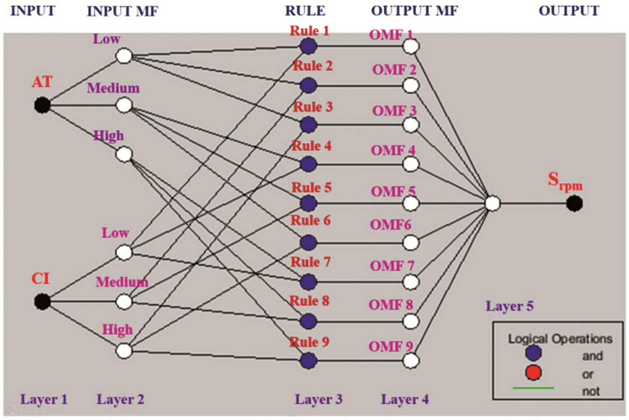

Fig. 5 — ANFIS model with two inputs and one output

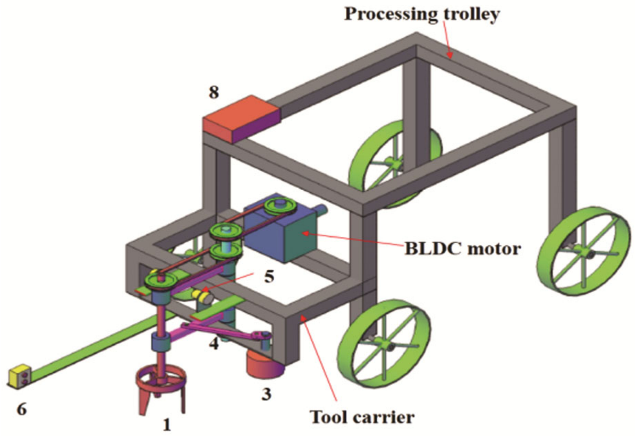

Fig. 6 — CAD view of laboratory set up of intra row weeder [1. VAR for intra row, 2. VAR for inter row, 3. PMDC motor, 4. FBL Cranking mechanism, 5. Proximity sensors, 6. Ultrasonic Sensors, 7. Bevel gear box, 8. Microcontroller Circuit box]

circuit box, and virtual plants. The main objective of the laboratory test was to evaluate the FBL crank mechanism, sensors and controller performance of weeding system with virtual plants and model the relationship with sensor performance with weeding tools at various parameters affecting under controlled conditions. The proximity sensor with the ground wheel was also used to measure the speed of the weeding operation. All the mechanical and electronic systems were assembled to a rectangular tool carrier. Tool carrier had the provision to slide up and down to maintain the DOs. Developed weeding tools (VAR) and mechatronics components were attached with tool carriers for soil bin laboratory test of prototype of intra row weeder. Weeding VAR was driven by BLDC motor with the help of belt and pulley drive system. The rotational speed of the rotor was controlled by BLDC motor controller. A ground wheel consisted proximity sensor was used for measurement of actual speed. Microcontroller circuit interfaced with ultrasonic sensor (28015 PING, Parallax Inc., Rocklin, CA, USA) was also used to process the plant sensing signal to actuate the PMDC motor to FBL mechanism. A FL algorithm was uploaded in micro controller to control the S_{rpm}. One of the critical functions of the intra-row weeding system is to avoid damage to the main crop during weeding. The developed intra-row weeder avoids damage to the main crop by lateral shifting of the VAR in real-time, with respect to the Forward Speed (FS) of operation of intra-row crop spacing and spread of the crop plant. Since these dependent parameters change from plant to plant within a field, the accurate control of lateral shift is critical in order to conduct efficient weeding with minimum crop damage. Therefore, a FL-based, low cost and efficient electrical control drive of Suitable load-carrying capacity was developed for instantaneous lateral shift control of the intra row VAR. The developed control system depends on the sensor and control time to real-time plant sensing and lateral shift of intra row VAR position. All the designed components of the weeder have been assembled on the mainframe at appropriate place. The soil bin helps to test the developed prototype under controlled soil and operating parameters. The complete CAD view of the laboratory model of intra row weeder is shown in Fig. 6.

Lateral Shift Force, Draft and Torque

The lateral force is the force required to shift the VAR unit from travel line (OA) to lateral direction (OA’). When the plant is detected, the VAR start to shift from position OA to OA’. The lateral shift force F is required by PMDC motor to shift the rotor from OA to OA’. For measurement of lateral shift force, load cell (F 214, Novatech Measurements Limited, East Sussex, England) has been used. In the soil bin laboratory test, draft of the single unit VAR was also measured by load cell with bush-type linkage arrangement.[36–38] The torque of weeding unit VAR was also measured by a torque transducer.

A torque transducer of 200 Nm capacity (T20WN, Hottinger Baldwin Measurements, Darmstadt, Germany) was used to measure the torque required to pulverise the soil. The real time data of load cells and torque transducer were recorded in the data acquisition system ((1-MX840-PAKEASY, Hottinger Baldwin Mesurements, Darmstadt, Germany). The isometric and top views of lateral shift concept are shown in Fig. 7(a) and (b) respectively.

Working of Major Components of Embedded System

The ultrasonic sensor is used for main crop identification, which serves as the important unit in the intra row weeding system. It consists of a transmitter and a receiver unit. The transmitter transmits the sound continuously and the receiver receives the echo pulses after reflection from the targeted objects. This works in a predecided range of 300 mm within the main crop rows. A short burst of 40 kHz ultrasonic wave is emitted by the sensor whenever it detects any object and this process is controlled by a host micro-controller (trigger pulse). To calculate the targeted distance, the echo pulse width is measured and the signal is processed by the microcontroller. The microcontroller was also interfaced with the LCD for displaying the sensing times. According to signal of ultrasonic sensor position of VAR was found to be intra row zone as well as lateral shift zone. The working principle of the ultrasonic sensor and PMDC motor actuation is presented in Fig. 8.

Evaluation of VAR System

Draft

Draft is the summation of horizontal components of pulling force. It is measured by load cell dynamimetre or strain gauge bridge.

$$\text{Draft} = \Sigma F_p$$

where, F_p = Pulling force, N

Drawbar Power

Power required to pull the implement. It is product of draft and travel speed.

$$\text{Drawbar power} = \text{Draft} \times \text{speed} \qquad \text{... (1)}$$

Plant Damage

Plant damage is the ratio of the number of plants damaged in a row during weeding to the number of plants present in that row before weeding, expressed in percentage as given in Eq. 2

$$q\ (\%) = \frac{n1}{n2} \times 100 \qquad \text{... (2)}$$

where, q = plant damage (%), n_1 = number of plants damaged in a row length after weeding and n_2= number of plants in a row length before weeding.

Superficial Plant Damage

It is similar to plant damage but it only considers plants whose only leaves are damaged during weeding operation. Superficial plant damage is the ratio of the number of plants whose only leaves parts were damaged in a row during weeding to the number of plants present in that row before weeding, expressed in percentage as per Eq. 3.

$$\text{SFD}\ (\%) = \frac{n1}{n2} \times 100 \qquad \text{... (3)}$$

where, SFD = superficial plant damage (%), n_1 = number of plants whose only leaves were damaged in a row length after weeding and n_2 = number of plants in a row length before weeding.

Yield Critical Damage

It is similar to plant damage but it only considers plants that are completely uprooted during weeding operation. Yield critical damage is the ratio of the number of plants completely uprooted in a row during weeding to the number of plants present in that row before weeding, expressed in percentage as Eq. 4.

$$\text{YCD}\ (\%) = \frac{n1}{n2} \times 100 \qquad \text{...(4)}$$

where, Q = yield critical damage (%),n_1 = number of plants completely uprooted in a row length after

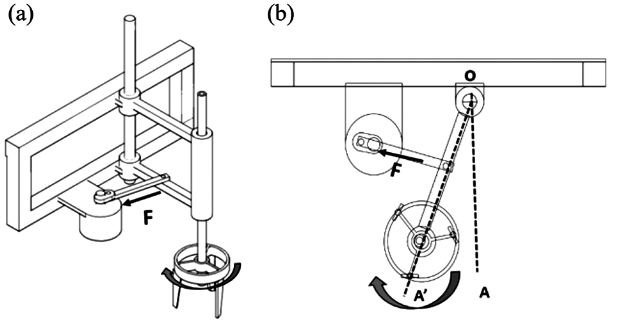

Fig. 7 — Diagramatic representation of LSF of VAR: (a) Isometric view, and (b) top view

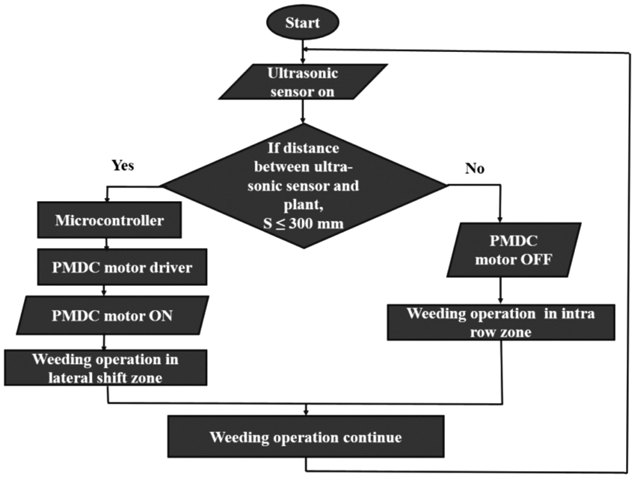

Fig. 8 — Process flow diagram of the ultrasonic plant signal to VAR position control

weeding and n_2 = number of plants in a row length before weeding.

Total Plant Damage

It is the sum of yield critical damage (YCD) and superficial damage (SFD).

$$TPD = SFD + YCD \quad \ldots (5)$$

Test Procedure for Soil Bin Evaluation of Intra Row Weeding Unit

Test beds were prepared using soil processing trolley, keeping different compaction levels at different soil conditions in the soil bin. A separate drive system was used to enable to and fro movement of the trolley. The complete system was controlled from a control chamber that housed electrical control panel and various recording units. The recording unit included a DAS and a computer. Torque transducer was used to measure the torque required to pulverize the soil using VAR weeder and the data was recorded in the DAS. The torque transducer was mounted horizontally between the DC controller motor and a gearbox (5:1) and two sets of flexible couplings to ensure continuous measurement of the dynamic torque. The sandy clay loam soil collected from the research farm of the institute was filled in the soil bin. The soil bin was prepared up to a depth of 0.5 m and moisture content of 10–12% db was maintained. A soil processing trolley comprised of a rotary tiller, a leveler and a roller for soil tilling, leveling, compacting respectively was used to prepare the soil bed. The draft of the weeding system was measured by load cell mounted in a horizontal position between implement trolley and prime mover of soil processing trolley. The speed of the system was measured by a peg type ground wheel with the proximity sensor and magnetic strip of eight units. The tests were performed in lateritic sandy clay loam soil. Important soil parameters like soil CI, bulk density, and moisture content were measured prior to the experiments to check the uniformity of the bed. Soil strength (consistency) was measured in terms of CI of the soil. Bulk density of the soil was measured using a core sampler with 30-degree bevel edge at the cutting end for smooth penetration into the soil. Standard oven-dry method was adapted to measure the moisture content of the soil. Virtual plants were placed at different plant spacing (300 mm, 400mm and 500 mm). The system was tested at different depths of 20 mm, 40 mm, 60 mm, and CI values of 300, 400 and 500 kPa at moisture content of 10–12% (db). Experiments were conducted at different CIs, DO and FS. The data of soil pulverization, plant damage, draft, torque and LS forces were recorded in data logger. Actually soil bin is ideal conditions and there were no weeds so soil pulverization can predict the soil failure and weeding ability of VAR system in field condition. The different sensor responses were observed in LCD display unit with help of microcontroller. The soil bin laboratory evaluation of intra row prototype is shown in Fig. 9.

Results and Discussion

These sections deals with the analysis and interpretation of data obtained from laboratory evaluation of intra row weeding system. Prior to the evaluation of the Intra-Row Weeding (IRW) system in the soil bin, calibration was performed on essential sensors, including the depth sensor, ring transducer, torque transducer, load cells, proximity sensor, and ultrasonic sensors for studying different forces as well as actuation of different mechanisms and plant damage avoidance.

Physical Plants and Weed Dimensions

Weeding in the field crops is typically carried out in the 21 Days After Transplanting (DAT) to ensure good crop growth. The field should be kept weed free for a period of 3–4 weeks after planting which requires two to three weeding operations in a cropping season. Physical dimensions of the plant and weed have been determined and taken into consideration for determining the position of ultrasonic sensor for intra row weeding. Twenty samples of plants and weeds were randomly selected for measuring their physical dimensions. Height of

Fig. 9 — Soil bin laboratory evaluation of intra row prototype

the plants and weeds transplanted at farm were measured using a ruler. It was observed that weeds height is less than crops height in wider row transplanted crops at the time of weeding (Fig. 10). The height of weeds and plant was measured in transplanted chili crops at fixed interval of days. The comparison of the height of plant and weeds at chili, tomato, cabbage, cauliflower, beans, marigold, brinjal and maize crops is shown in Fig. 10(a) and (b). The average height of plants and weeds after 21 DAT were found to be 240 mm and 70 mm for chili transplanted crops. The same trend was also observed by some researchers.[39,40]

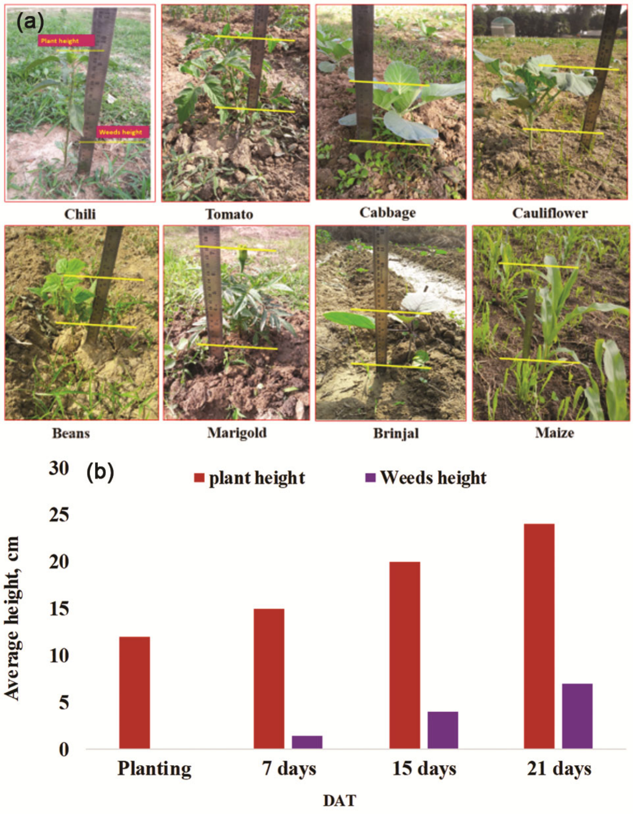

Fig. 10 — Comparison of plant and weed height: (a) in field after three weeks of DAT, and (b) graphical representation.

Calibration of Load Cells

The load cells of each load sensing unit of dynamometer were calibrated under laboratory to know its sensitivity at different loads. The predefined force was applied on load cells of 1.2-tonne capacity and corresponding voltage output in mV was recorded. This procedure was followed for all three load cells one after another. The graphs of the input load versus output in millivolts of three load cells are shown in Fig. 11. It was observed that the voltage output linearly increased with an increase with the applied load having R^2 of 0.99.

Sensing and FL Derived for Crank Speed of Four-Bar Linkage Mechanism

The mechatronics based intra weeding technology was operated as per research plan and different data was recorded. The data were analyzed statistically and presented in Table 1.

The results revealed that the individual effect of CI, DO, FS, PS and their interactions on crank speed (S_{rpm}) had a significant effect at 5% level with Adj. R^2 of 0.97, SD of 3.47 and CV of 2%. It was evident from the ANOVA table, FS ($F_{2,178} = 2009.82, p < 0.0001$) had a highly significant effect on S_{rpm} of FBL crank mechanism compare to the PS, CI and DO. S_{rpm} was also effected by DO ($F_{2,178}= 1054.78, p < 0.0001$). The interaction effect of DO and FS ($F_{2,178}= 62.17, p < 0.0001$) had a significant effect on S_{rpm}, which means at S_{rpm} both parameters had an effect. The effect of DO on S_{rpm} is hopefully due to the soil- tool interaction force and also by FS due to the inertia force of soil tool motion.

Effect of Speed

The results of ANOVA indicate that variation in S_{rpm} was found to be significantly dependent on FS

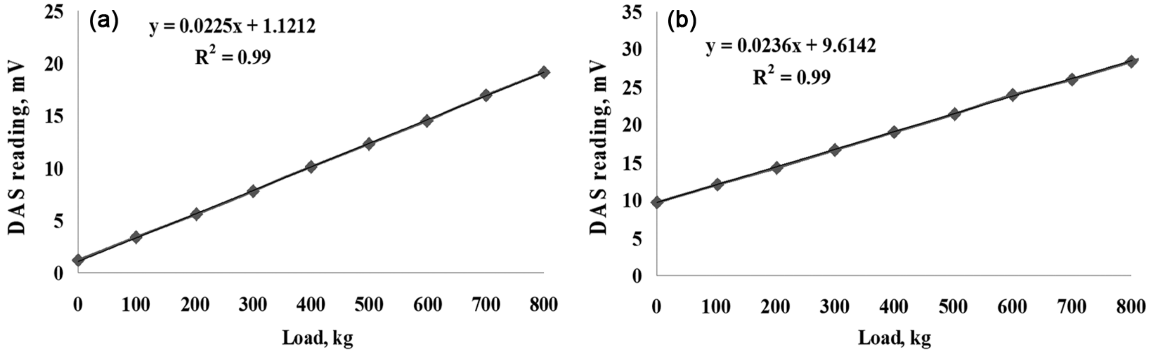

Fig. 11 — Calibration graphs of load cells for measurement of (a) draft, and (b) LSF

Table 1 — ANOVA for the FBL crank speed of intra row VAR

Source	Sum of square	df	Mean Square	F -Value	p-value Prob > F
Model	1.209×10^{5}	64	1888.48	156.43	< 0.0001
Cone index (CI)	11571.39	2	5785.70	479.26	< 0.0001
Depth of operation (DO)	25467.09	2	12733.55	1054.78	< 0.0001
Forward speed (FS)	48526.06	2	24263.03	2009.82	< 0.0001
Plant spacing (PS)	19088.63	2	9544.31	790.60	< 0.0001
CI×DO	1755.37	4	438.84	36.35	< 0.0001
CI× FS	2238.78	4	559.70	46.36	< 0.0001
CI× PS	1351.33	4	337.83	27.98	< 0.0001
DO × FS	3002.04	4	750.51	62.17	< 0.0001
DO × PS	3006.58	4	751.65	62.26	< 0.0001
FS × PS	1488.44	4	372.11	30.82	< 0.0001
CI×DO× FS	952.67	8	119.08	9.86	< 0.0001
CI×DO× PS	1563.69	8	195.46	16.19	< 0.0001
CI× FS × PS	659.02	8	82.38	6.82	< 0.0001
DO× FS × PS	191.91	8	23.99	1.99	0.0505
Residual	619.25	178	5.67		

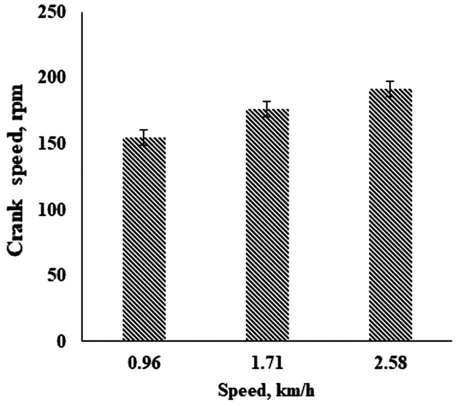

Fig. 12 — Response curves of crank speed with FS

of operation ($F_{2,178} = 2009.82, p < 0.001$). Moreover, the average S_{rpm} (Fig. 12) of 154.85 rpm (SE: ±4.38 rpm), 176.41 rpm (SE: ±3.44 rpm) and 191.60 rpm (SE: ±2.24 rpm) were obtained from the FL algorithm at the operational speeds of 0.96, 1.71 and 2.58 km/h, respectively. The interaction effect of speed with CI, DO and PS had a significant effect on S_{rpm}. The interaction of DO × FS ($F_{4,178} = 62.17, p < 0.001$) had highly significant effect on S_{rpm} compare to CI× FS ($F_{4,178} = 46.36, p < 0.001$) and FS × PS ($F_{4,178} = 30.82, p < 0.001$).

The results of ANOVA indicate that variation in S_{rpm} was found to be significantly dependent on FS of operation ($F_{2,178} = 2009.82, p < 0.001$). Moreover, the average S_{rpm} (Fig. 12) of 154.85 rpm (SE: ±4.38 rpm), 176.41 rpm (SE: ±3.44 rpm) and 191.60 rpm (SE: ±2.24 rpm) were obtained from the FL algorithm at the operational speeds of 0.96, 1.71 and 2.58 km/h, respectively. The interaction effect of speed with CI, DO and PS had a significant effect on S_{rpm}. The interaction of DO × FS ($F_{4,178} = 62.17, p < 0.001$) had highly significant effect on S_{rpm} compare to CI× FS ($F_{4,178} = 46.36, p < 0.001$) and FS × PS ($F_{4,178} = 30.82, p < 0.001$).

Effect of Plant Spacing

The results of N-way ANOVA indicate that variation in S_{rpm} was found to be significantly dependent on plant spacing ($F_{4,178} = 790.60, p < 0.0001$). The average S_{rpm} of FBL mechanism of 186.20 ms (SE: ±5.85 ms) at a PS of 300 mm. Similarly, the average S_{rpm} for the FBL was 172.62 ms (SE: ±3.98 ms) and 163.92 ms (SE: ±7.25 ms) at the PS of 400 mm and 500 mm, respectively. The interaction of PS with CI ($F_{4,178} = 27.98, p <0.001$) and DO ($F_{4,178} = 62.26, p <0.001$) had also a significant effect on S_{rpm}.

Effect of Cone Index

The results indicate that variation in S_{rpm} was found to be significantly dependent on CI ($F_{2,178} = 479.26, p <0.0001$). The lateral shift of FBL is with an average S_{rpm} of 165.43 ms (SE: ±9.81 ms), 173.77 ms (SE: ±10.23 ms) and 183.66 ms (SE: ±5.98 ms) at the CI of 300 kPa, 400 kPa and 500 kPa, respectively. The interaction of CI and DO ($F_{4,178} = 36.35, p <0.001$) had also a significant effect on S_{rpm}.

Effect of Depth

The results of the analysis indicate that variation in S_{rpm} was found to be significantly dependent on DO ($F_{2,178} = 1054.78, p <0.0001$). During soil bin laboratory condition test, S_{rpm} obtained lateral shift of VAR was found to vary from 161.35 ms (SE: ±7.65 ms), 175.42 ms (SE: ±5.68 ms) and 186.15 ms (SE: ±8.32 ms) at the depth of 20 mm, 40 mm and 60 mm, respectively. The combined effect of DO, FS and PS on S_{rpm} is shown in Fig. 13.

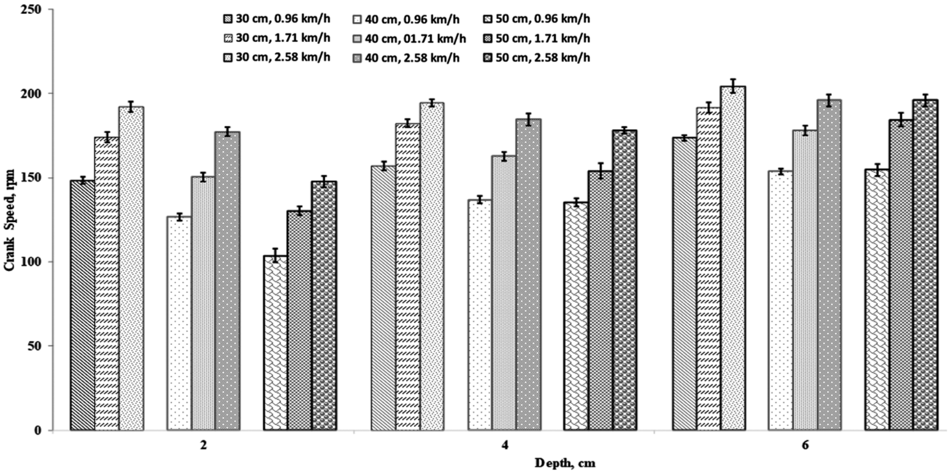

Fig. 13 — Variation of crank speed with depths of operation at different plant spacing and speed of operation

When DO was increased from 20 mm to 60 mm then S_{rpm} increased from 148.33 to 199.33 rpm for 300 mm PS, 126.66 to 195.23 rpm for 400 mm PS and 103.23 to 196 rpm for 500 mm PS of FS range 0.96 km/h to 2.58 km/h at cone index of 300 kPa. The actual S_{rpm} data obtained during soil bin test varied by about 10 to 15% compared to ANFIS fuzzy model data due to variation of compaction level of soil in soil bin bed.

Effects of Operating Parameters on Dynamic Force Requirement and Plant Damage

Intra row VAR (Diameter 120 mm and no. of tools 3) weeding unit was tested in the soil bin laboratory condition at different FS (0.96, 1.71, 2.58 km/h), CI (300 ± 25 kPa and 400 ± 25 kPa and 500 ± 25 kPa), PS (300, 400 and 500 mm) and at DO (20, 40, 60 mm). Analysis of variance (ANOVA) was carried out in full factorial design with design expert software package for the draft, torque and LSF values of VAR to know the effects of FS, DO, CI and PS. It can be seen from ANOVA that the individual effects of FS, DO, CI and PS and their interactions on the draft were significant at 5% level with Adj. R^2 of 0.99, SD of 1.6 and CV of 4.34%. It is also clear from the ANOVA table, the effect of CI of soil (*N-way ANOVA*, $F_{2,178} = 12952.76, P < 0.0001$) on the draft was having the highest influence than the effects of FS and DO. There is an effect of PS on draft ($F_{2,178} = 2.88, P = 0.0691$) and the effect of DO ($F_{2,178} = 642.88, P < 0.0001$) on draft of VAR is higher than the speed of operation ($F_{2,178} = 160.62, P < 0.0001$). This could be due to the greater effect of volume of soil handled associated with increase in DO of VAR than that with increase in FS on the draft. The average Total Response Time (TRTs) observed for the entire lateral shift of the VAR to return intra row weeding zone was 1000.22 ms (SE: ±29.13 ms), 676.23 ms (SE: ±30.80 ms) and 386.89 ms (SE: ±21.19 ms).

Draft

During soil bin laboratory condition test, the mean draft required to pull the VAR was found to vary from 28.24 N, 37.28 N and 48.12 N at the DO of 20, 40 and 60 mm, respectively. When the DO was increased from 20 to 60 mm, the draft was found to be increased from 5.88 N to 16.80 N, 8.49 N to 19.5 N and 11.31 N to 22.77 N at 0.96, 1.71 and 2.58 km/h of FS respectively at the lowest test range of PS of 300 mm and 300 kPa of CI. When the DO was increased from 20 to 60 mm, draft force was found to be increased from 34.9 to 67 N for FS of 0.96 km/h, 43.6 to 80 N for 1.71 km/h and was 64 to 95.5 N for 2.58 km/h for the highest range of PS of 500 mm and CI of 500 kPa. When the speed of operation was increased from 0.96 km/h to 2.58 km/h, the drawbar power was found to be increased from 20.33 to 58.09 W, 57.86 to 127.19 W and 105.06 to 211.55 W at 20, 40 and 60 mm of DO respectively at the lowest test range of PS of 300 mm and 300 kPa of CI. The drawbar power of single unit intra row VAR at different FSs is shown in Fig. 14.

Torque

The results of full factorial ANOVA indicate that variation in torque was found to be significantly dependent on CI of soil ($F_{2,178} = 510.68, p < 0.0001$). It can be observed that the torque of VAR increased with increased in soil CI values. This could be due to higher soil resistance associated with higher CI values. When CI was increased from 300 to 500 kPa, the torque was found to be increased from 0.42 to 2.12 Nm, 1.49 to 2.33 Nm and 2.36 to 2.88 Nm at 20, 40 and 60 mm of

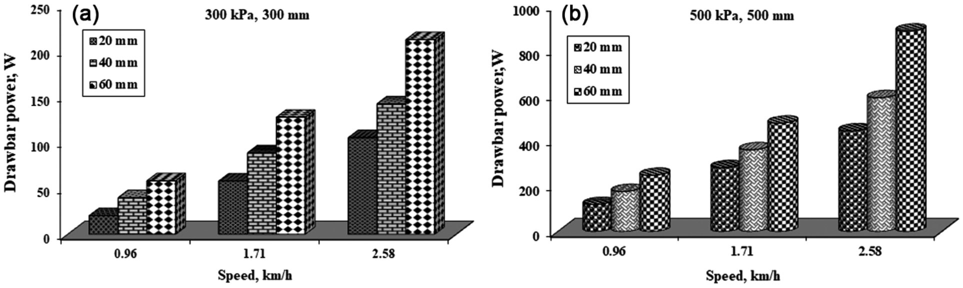

Fig. 14 — Drawbar power of single unit intra row R_{VA} at different FSs: (a) at CI of 300 kPa and PS of 300 mm, and (b) at CI of 500 kPa and PS of 500 mm

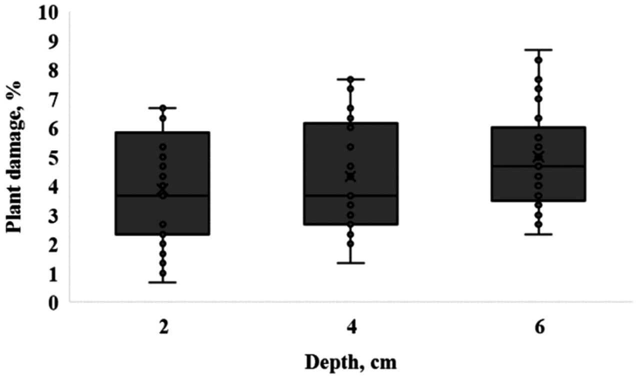

Fig. 15 — Plant damage as a function of operational depth

DO respectively at the lowest test range of PS of 300 mm and 0.96 km/h of FS. When the CI was increased from 300 to 500 kPa, the torque was found to be increased from 4.56 to 8.96 Nm for depth 20 mm, 6.08 to 9.94 Nm for 40 mm and was 7.7 to 11.47 Nm for 60 mm for the highest range of PS of 500 mm and 2.58 km/h of FS. With increase in average CI from 300 to 500 kPa torque was found to be increased from 79.66 to 324.54%, 24.10 to 68.25% and 21.04 to 64.79% for 300 mm, 400 mm and 500 mm plant spacing respectively for all test range of depth and speed. This could be due to higher soil resistance associated with higher cone index values. A similar trend was also reported by others.[41–44]

Lateral Shift Force

The results of full factorial ANOVA indicate that variation in LS force was found to be significantly dependent on FS ($F_{2,178} = 385.93, p <0.0001$). When the speed of operation was increased from 0.96 to 2.58 km/h, the LS force was found to be increased from 0.97 to 3.97 N, 2.87 to 5.89 N and 4.07 to 8.01 N at 20, 40 and 60 mm of FS respectively at the lowest test range of PS of 300 mm and 300 kPa of CI. When the FS was increased from 0.96 to 2.58 km/h, LS force was found to be increased from 5.6 to 13.88 N for 20 mm of DO, 10.50 to 17.6 N for 40 mm and was 13.6 to 23.8 N for 60 mm for the highest range of PS of 500 mm and CI of 500 kPa. The general trend shows that LS force values of VAR increased with increase in the speed of operation.[45,46]

Plant Damage

Analysis of variance (ANOVA) of the effect of operating parameters on plant damage showed that the effect of CI, DO, FS and PS are significant at 1% level of significance with adjusted R^2 of 0.76, Standard Deviation (SD) of 1.17 and Coefficient of Variation (CV) of 31.06%. It was observed that average Plant Damage (PD) of intra row weeding system was varying from 0.66% to 8.66% for all test range of FS, PS, DO and CI. Amongst all the independent variables, the effect of CI was found most significant with F value of 391.15 followed by DO, FS and PS having F-value of 5.64, 4.93 and 3.83, respectively. The results of N-way ANOVA indicate that variation in PD was found to be significantly dependent on DO ($F_{2,178} = 5.64, p < 0.05$). The general trend shows that PD increased with increase in DO. The observed average PD was 3.87% (SE: ±0.38%), 4.32% (SE: ±0.18%) and 5.01% (±0.52%) at the intra-row DO of 20 mm, 40 mm and 60 mm, respectively. Generally weeding is carried out at less than 40 mm depth due to initial stage growth of weed at shallow depth. In this study, the experiment was conducted up to 60 mm for considering the chances of late weeding at the mature stage of weeds. The general trend shows that PD was found to be increased with an increase in FS. The maximum average value of YCD was found to be 2.17% (SE: ±1.12%), respectively for entire range of DO, CI and PS. The maximum average value of SFD at given range of FS was found to 6.49% (SE: ±2.34%), respectively for entire range of DO, CI and PS. The value of soil pulverization and cone index value after the VAR operations depicts that VAR system will able to remove weeds from field also. The variation of plant damage of weeder with DO is shown in Fig. 15.

Conclusions

A Four Bar Linkage (FBL) mechanism actuated by PMDC motor with a signal from an ultrasonic sensor named as sensor-based mechatronic intra-row weeding unit was developed for detecting the intra row region of wider-row crops. Intra-row weeder prototype was initially developed for laboratory evaluation. The crank speed of four bar linkage was predicted by a FL algorithm for smooth operation of lateral shifting during intra row weeding considering the soil Cone Index (CI) and actuation time. The crank speed was found to be 163.4 to 183.7 rpm against CI values of 300 to 500 kPa. The prototype integrated mechanical linkage and actuator system and electronic sensing and control systems. Pertinent to laboratory evaluations, CI, DO, FS, PS and their interactions had a significant on the PD (adjusted $R^2 = 0.76$) that ranged from 0.7–8.7% (SD = 1.17%) for all evaluation configurations. Minimum draft, torque and lateral shift force of intra row weeding unit was found to be 28.24 N, 2.88 N m and 5.6 N respectively. The system performed efficiently under laboratory conditions. The system can also be retrofitted with existing tractor operated inter-row weeder for additionally performing weeding in the intra row region in a single pass of the tractor. The system can also be used for cash crops where intra row weeds deteriorate the quality of product and reduce farmer incomes.

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