Research article

Study on Trajectory Motion of Intra Row Weeder

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Curr. Appl. Sci. Technol. 2024, Vol. 24 (No. 5), e0258685; https://doi.org/10.55003/cast.2024.258685

Received: 18 August 2023, Revised: 6 December 2023, Accepted: 12 March 2024, Published: 1 May 2024

Keywords

cycloid;

motion analysis;

trace path;

weeder;

weeding

Abstract

Weeding is a critical and labor-intensive process. A mechanical hydraulic actuated weeder was developed by adopting a rotary mechanism that consisted of a rotating blade with the diameter and width of the weeding blade. Instead of lab and field evaluation, the weeding tool's path was traced using the SolidWorks software to reduce cost and time and improve performance and accuracy. A 3D model of the intra-row weeder complex with relative handling modules was analyzed for motion using the SolidWorks Motion system. The blade center moved parallel to the crop row, with the swept area passing between the plant's forming a acycloidal path in rows. Controlled laboratory experiments were conducted to analyze the effects of the weeding blade geometry, forward speed (1, 1.2 and 1.4 km/h), and weeding tool speed (30, 40, 50 and 60 rpm). The results showed that plant damage was much less at a speed of 1.2 km/h and a weeding tool speed of 50 rpm was found to be optimum for effective weeding operation with plant-to-plant spacing of 45 cm in the experimental test rig.

1. Introduction

Weeding in crop production is a resource-intensive task, but mechanical weeding has emerged as an efficient approach, reducing labor and time while enhancing productivity [1, 2]. Over time, various mechanical weeders have been developed to improve weeding efficiency with minimal plant damage [3]. Inter-row weeding targets the space between crop rows, while intra-row weeding focuses on eliminating weeds within the rows, often requiring precise equipment or manual labor

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[4, 5]. Both methods are chosen based on factors such as crop type, technology availability, and labor resources to minimize weed competition and optimize crop yields.

According to Peruzzi *et al*. [6], despite the benefits of mechanical weeding, most efforts have been concentrated on inter-row weeding. However, for enhanced weeding efficiency, both inter and intra-row weeding should be considered.

Chandel *et al*. [7] explored innovative approaches to address this challenge and developed an automatic obstacle avoidance system utilizing computer vision and GPS technology to improve weeding precision, although it came at a higher cost.

Kumar *et al*. [8] introduced a tractor-drawn integrated inter- and intra-row weeding (IIIRW) system, combining active rotary tines for intra-row weeding and passive tines for inter-row weeding. Their rigorous soil bin experiments and field evaluations demonstrated significant weed mortality, minimal plant damage, with an overall weed mortality rate of 92.8%.

Jakasania *et al*. [9] designed an autonomous weed eradication system using fuzzy logic, and time-of-flight, and inductive sensing technologies for intra-row weeding. Their comprehensive evaluation included soil conditions, forward speed, depth of operation, and plant spacing, achieving operational efficiencies ranging from 80% to 96%. Dedousis *et al*. [10] assessed an intra-row weeding unit under controlled conditions, highlighting optimal plant spacing and operational speed to minimize plant damage.

The primary purpose of motion analysis in weeding operations, as implemented in software like SolidWorks, is to simulate and optimize the movement and behavior of mechanical systems involved in weeding processes. It facilitates the visualization, fine-tuning, and validation of weeding tool trajectories, enabling engineers to design and analyze efficient patterns for weed eradication while minimizing crop damage. Motion analysis offers a cost-effective, precise, and controlled environment for studying weeding operations, providing advantages over physical experiments in terms of efficiency, safety, accessibility, and the ability to perform iterative design improvements. It accelerates the design iteration process and enhances the understanding of weeding processes, making it an invaluable tool for engineers and researchers seeking to improve weeding efficiency and crop protection [11].

Additionally, motion analysis, such as in SolidWorks, offers a cost-effective and precise tool for weeding research, enabling rapid prototyping, optimization, and visualization while reducing financial and safety risks associated with physical experimentation. In this context, researchers aimed to introduce simplified yet effective mechanical designs for inter and intra-row weeders, supported by rigorous simulation testing and laboratory analysis (Scientific Investigation and Engineering Design).

2. Materials and Methods

2.1 Development of intra-row weeder test rig

The test apparatus employed for the intra-row weeder comprised a series of integral components. These components included a sturdy frame, a 3-point hitch system, a hydraulic motor (EPRM-125) capable of delivering a maximum torque of 300 Nm, and an externally geared positive displacement hydraulic pump selected for this specific investigation that was characterized by a displacement rating of 32 cc/rev. Moreover, a hydraulic tank was meticulously designed to align with the pump's capacity. The system also incorporated a flow control valve with a pressure rating of 400 bar (G-LOC), a flow check analyzer (F7160), and a 4/3 directional control valve (DCV). The weeding tool was seamlessly affixed to the hydraulic motor via an intermediary L-frame, which optimized its mechanical functionality. Furthermore, the 3-point hitch system was diligently welded onto the frame assembly, serving as the robust structural underpinning for the secure attachment of the hydraulic motor and weeding tool. This configuration ensured a steadfast and functional setup that was ideal for the execution of rigorous intra-row weeding experiments, as shown in Figure 1.

Figure 1. Test rig of the intra row weeder

2.2 Intra-row weeding rotary mechanism

The weeding apparatus featured a rotary mechanism wherein the weeding tool's movement generates continuous cycloids along its path of travel, as illustrated in Figure 2. This cycloidal path effectively represents the coverage area of the weeding tool. Within this mechanism, each complex cycloid began ahead of the plant and concluded at its rear, ensuring thorough weeding coverage. Concurrently, inter-row weeding was accomplished as the cycloids traversed from their starting to ending points. Then this approach efficiently addressed both inter and intra-row weeding requirements.

The weeding tool possessed the following specific dimensions: an eccentricity of 13 cm, a length of 25 cm, and a thickness of 1.5 cm. It was affixed to the weeding blade, which measured 11x5 cm, and derived its rotary motion from the hydraulic motor positioned above. An 'L'-shaped angular bar was interposed between the weeding tool and the motor to augment the circular path's radius formed by the weeding tool. As the test rig advanced at a constant speed propelled by the hydraulic motor, the circular path's radius underwent modifications contingent upon the speed of movement.

The rotational motion of the weeding unit, coupled with its forward movement, yielded a continuous cycloidal path, a result of the weeding tool's synchronized operation with the test rig's advancement. Figure 2 visually represents the traced path of the weeding tool, which corresponded to to variable forward speeds. This formation of the cycloidal path is further elucidated in relation to the cycloid-to-cycloid distance, with a measured plant-to-plant distance of 45 cm.

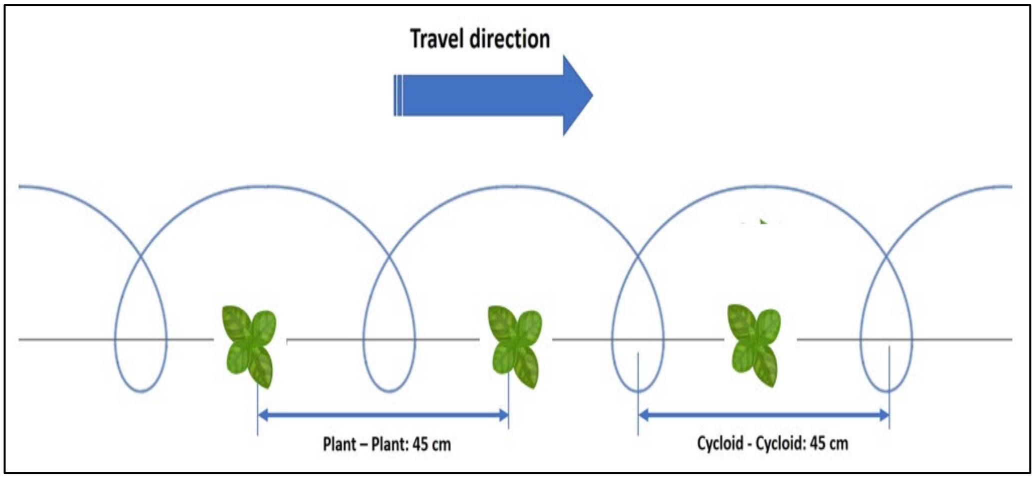

Figure 2. Cycloidal pattern formation in between the plants

2.3 Determining trace path of intra-row weeder

Before laboratory investigation, computer simulation tests were performed. SolidWorks software was used for CAD model development and simulation. The forward speed of the test rig and the speed of the wedding tool attached to the hydraulic motor decided the cycloid-to-cycloid distance. Hence it was essential to optimize the correct combination of both speeds in such a way that plants in between the cycloids were not affected. In this regard, computer simulation helped to reduce the time, cost, and material cost involved in determining the effects of both speeds on cycloid-to-cycloid distance.

SolidWorks (2018) is a widely employed engineering software tool renowned for its proficiency in conducting an array of analyses encompassing structural, buckling, thermal, fatigue, and more. This comprehensive platform empowers users to delve into intricate examinations of diverse structural properties, thereby facilitating an in-depth exploration of a mechanical system's behavior. The material of choice within the SolidWorks environment is AISI 4130 steel. The results were shown to encompass the scrutiny of critical parameters such as stress, displacement, natural frequency, and other pertinent attributes.

The technique of tracing a path in SolidWorks serves as a valuable tool, facilitating the creation of intricate cam paths essential for motion analysis studies. Tracing a path empowers users to visualize the trajectory of a point or vertex within an assembly or sketch, thereby aiding in the analysis of component motion within an assembly or the development of intricate cam profiles. The path followed by the tool during its motion is aptly termed the "trace path." This trace path can be generated in reference to a fixed component or any moving part within the assembly. The inherent advantage of employing the path-tracing feature in SolidWorks lies in its capacity to provide a clear visualization of part motion within an assembly, as exemplified in Figure 3, which also illustrates the uniform spacing of the trace path, as depicted in Figure 4 [3].

2.4 Selected levels of variables for the intra row weeder

The evaluation was conducted within a designated section of the soil bin, which was filled with sand. This specific soil bin segment featured dimensions of 40 m in length and 2.2 me in width, with sand filling up to a depth of 1 m. On top of the bin, two rails were installed, one on each side which

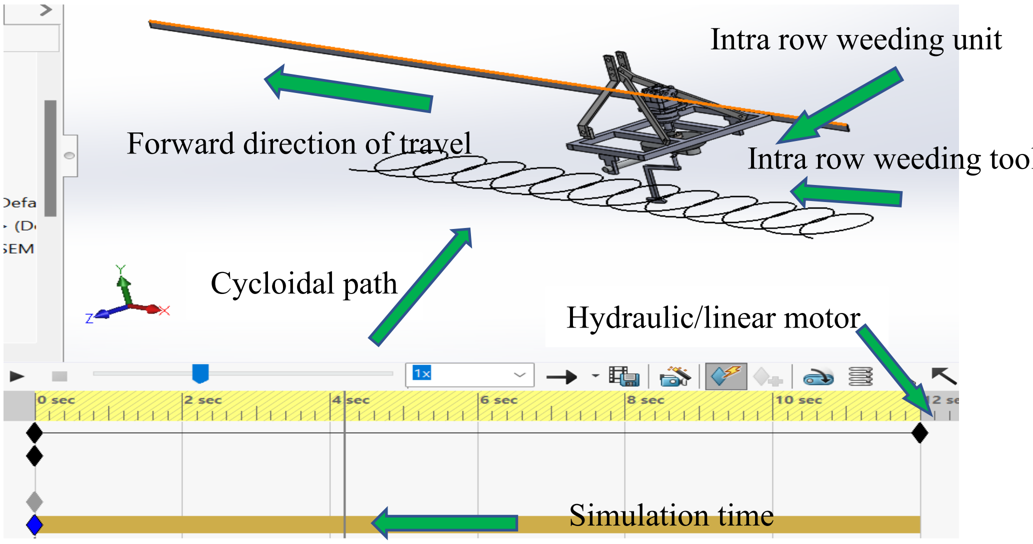

Figure 3. Cycloidal path formation without any uniformity of spacing

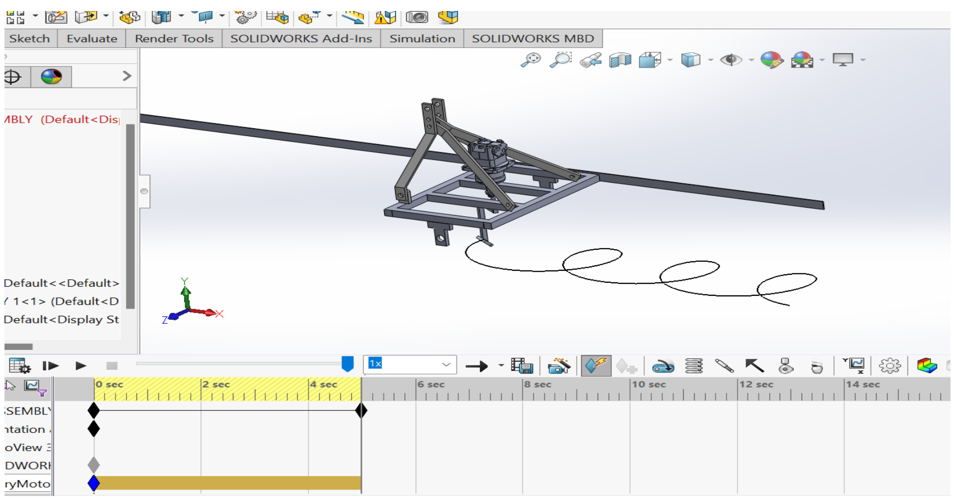

Figure 4. Trajectory motion of cycloidal pattern with uniformity of spacing

served as tracks for a common carriage. The common carriage was engineered to accommodate either the tool carriage or the soil processing carriage, and was thus suitable for various operations. To facilitate movement, the common carriage and any carriages placed upon it were pulled in either direction by a steel rope, operated by a mechanical power system. Throughout all treatments, consistent soil moisture content (12%) and compaction level (2200 kPa) were meticulously maintained. The forward speed and duration were systematically recorded using a digital stopwatch to cover a 20-m length within the soil bin. A cone penetrometer was used to measure the cone index, which was 1.9 when operated at a 3 cm depth of the weeder.

For analysis, the path of the blade in the developed intra-row weeder, the forward speed, and the hydraulic motor speed were taken as the variables in the study of the behavior of the blade [12-14]. The blade behavior was tested at three levels of forward speeds viz., 1, 1.2, and 1.4 (km/h), which were the minimum to the maximum speeds of travel. After this, three levels of oscillation speeds viz., 30, 40, 50, and 60 (rpm) were taken in this study. Three operational speeds of 0.96, 1.71, and 2.58 (km/h) were selected, which were within the recommended ranges.

2.5 Evaluation of trajectory motion in experimental test rig

The study involved an examination of the soil to facilitate a comparative analysis of motion dynamics. The soil, characterized by its length and width in meters, served as the substrate upon which an experimental test rig was positioned. This test rig was affixed to a rail system capable of forward and reverse motion [15]. Rope mechanism was achieved through the utilization of an iron that was securely fastened to it.

Moreover, a separate end of the rope was connected to a pulley mechanism, driven by an electric motor. By manipulating the speed of this pulley, the velocity of the test rig mounted on the rail system could be adjusted [16]. The primary objective of this experiment was to replicate and correlate the motion analysis outcomes with those generated by SolidWorks software.

3. Results and Discussion

Figure 5 presents the outcomes of the weeding tool's trajectory analysis at a test rig forward speed of 1 km/h. Notably, the analysis reveals that at 60 rpm of the weeding tool, a maximum overlap of 2.5 cm was observed. In contrast, at 30 rpm, no overlap occurred, but a cycloid-to-cycloid clearance of 5.4 cm was evident. At 40 rpm, this clearance decreased to 3.1 cm, and was further reduced to 2 cm at 50 rpm. These findings underscore a noteworthy trend: at low speeds (1 km/h), an increase in the weeding tool's rotational speed resulted in an augmented overlap as opposed to increased clearance [17]. Consequently, lower speeds were deemed less effective for weeding purposes, potentially leading to heightened plant damage [18]. This analysis provides valuable insights into the intricate dynamics of weeding operations at varying tool speeds and their implications for plant protection.

Figure 6 elucidates the outcomes of the weeding tool's trajectory at a test rig forward speed of 1.2 km/h. At this increased speed, a notable observation was the absence of overlap, which distinguished the results from the results obtained at 1 km/h. However, when the weeding tool was operated at 60 rpm, clearances were evident at 30, 40, and 50 rpm. The augmentation in the weeding tool's speed correspondingly led to a reduction in the clearance between cycloids, both at the center-centers and edge-edges [19].

Specifically, the maximum center-center clearance, amounting to 9.6 cm, was observed when the weeding tool was operated at 30 rpm. This clearance progressively decreased to 7.3 cm at 40 rpm, further to 6.4 cm at 50 rpm, and finally to 4 cm at 60 rpm. A similar increasing trend in edge-edge clearance was also observed, signifying the intricate relationship between weeding tool speed and cycloid clearance dynamics. These findings underscore the importance of considering weeding tool speed in optimizing weeding operations, as it directly influences the spacing between cycloids, impacting the effectiveness of the weeding process [20].

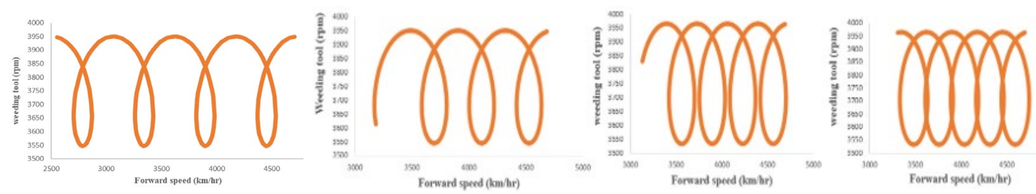

Figure 5. Cycloidal pattern for 1 km/h of the test rig at 30, 40, 50 and 60 rpm of weeding tool

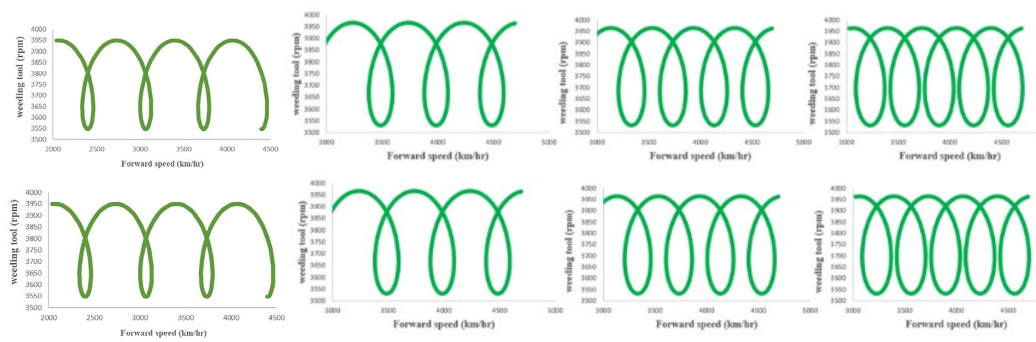

Figure 6. Cycloidal pattern for 1.2 kmph of the test rig at 40, 50 and 60 rpm of weeding tool design of experiments

Two independent variables were selected: forward speed (1, 1.2, 1.4) and rotational speed (30, 40, 50 and 60 rpm), and three dependent variables were selected: clearance between cycloids centers (cm), clearance between cycloids edges (cm) and clearance between cycloids. These were based on the optimal parameters that had been custom designed for the analysis.

Figure 7 provides a comprehensive illustration of the weeding tool's trajectory at a test rig forward speed of 1.4 km/h. Remarkably, the results exhibited a consistent pattern in alignment with the observations made at 1.2 km/h. Specifically, there was a discernible increase in the clearance between the center-center and edge-edge positions for all weeding tool rotational speeds.

The detailed findings regarding clearance measurements are systematically summarized and tabulated in Table 1. These outcomes underscored the persistence of the observed trends, emphasizing the notable impact of weeding tool speed on the spacing dynamics between the cycloids, which held critical implications for the efficiency and efficacy of the weeding process.

The formation and spacing of cycloids are profoundly influenced by both the speed of the test rig and the rotational speed of the weeding tool. Notably, the presence of overlap in the tool path is indicative of a low travel speed and high weeding tool rpm, while substantial clearance signals a high test rig speed, generally exceeding 1 km/h. The occurrence of overlap, characterized by reduced clearance, can be attributed to the increased frequency of cycloid formation. At lower speeds (<1 km/h), the weeding tool must traverse the area in less than 40 cm to prevent overlap and attain the requisite clearance. However, reducing the weeding tool speed (<40 rpm) has the undesirable consequence of removing weeds or improving weeding quality [21].

The degree of clearance between the cycloids significantly impacts both weeding quality and plant damage. A higher clearance corresponds to improved weeding quality and reduced plant damage, whereas a lower clearance signifies lower weeding quality and heightened plant damage.

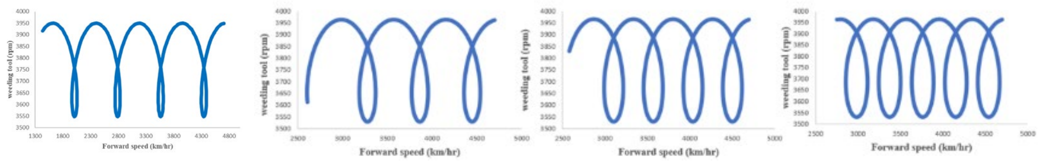

Figure 7. Cycloidal pattern for 1.4 kmph of test rig at 40, 50 and 60 rpm of weeding tool

Table 1. Trajectory motion of intra row weeder

Forward Speed (kmph)	Weeding Tool (rpm)	Clearance between Cycloid Center (cm)	Clearance between Cycloid Edges (cm)	Overlap (cm)
1	30	5.4	6.3	-
	40	3.1	2.4	-
	50	2	0.9	-
	60	-	-	2.5
1.2	30	9.6	10.4	-
	40	7.3	8.7	-
	50	6.4	6.9	-
	60	4	5.5	-
1.4	30	12.3	11.7	-
	40	9.9	9.3	-
	50	7.9	7.1	-
	60	5.6	6.4	-

Importantly, the speeds of the test rig and weeding tool are not mutually independent; thus, determining the optimal combination becomes imperative for achieving enhanced weeding efficiency [22]. This intricate interplay between speed parameters underscores the critical importance of balance and precision in weeding operations, where both tool speed and test rig speed are vital factors in optimizing the overall effectiveness of the process (Figure 8).

The outcome of the cycloidal pattern formation, as simulated within the SolidWorks software, was subjected to a comparative analysis with the results obtained through experimentation in the soil bin, as depicted in Figure 9. Notably, the results derived from the soil bin experimentation exhibited a commendable accuracy level, amounting to 96%. However, it is essential to acknowledge a minor deviation of 4%, which may have been attributed to the presence of frictional factors inherent to the mechanical components and potential slippage within the experimental setup (Figure 10) [23]. This observation underscores the importance of accounting for real-world physical phenomena and frictional effects when comparing virtual simulations with practical experiments, an approach that ensures a comprehensive understanding of the system's behavior.

Figure 8. Distinct cycloidal patterns formed in the soil bin at different forward speeds

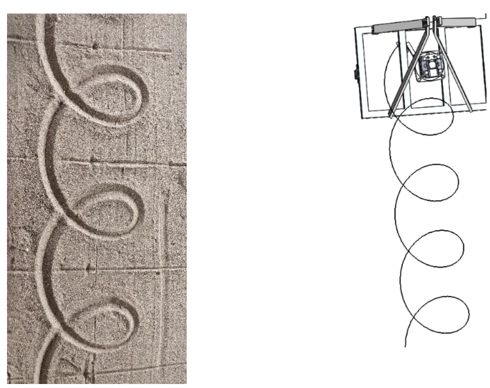

Figure 9. Cycloidal pattern formation in soil bin and software

Figure 10. Measurement of plant damage in the soil bin

The interaction effect of individual parameters was highly significant at three levels of forward speed and four levels of rotational speed, space between centroid center increased by 5.82 cm ($P< 0.01$) [24], while forward speed and rotational speed were highly significant at three levels. When forward speed increased, the clearance between the centroid center increased by 3.13 cm. When the rotational speed of the weeder increased, the clearance between the centroid centers increased by 0.21 cm (Table 2).

The analysis of variance reveals a significant difference between two individual variables, forward speed (F) and rotational speed (R), as well as their interaction effect. When forward speed and rotational speed increase, there is a notable decrease in clearance between centroid centers by 0.21 cm [25].

Furthermore, the interaction effect of all variables, including forward speed and rotational speed, proves to be significant, with an R^2 value of 0.91 indicating that 91% of the variation in clearance between centroid centers is explained by the studied factors [26] (Table 3).

Examining the impact of individual parameters at three levels of forward speed and four levels of rotational speed, a noteworthy finding is that the clearance between cycloid edges increases by 6.61 cm when the interaction effect is highly significant. Additionally, at three levels of forward speed, an increase leads to a 3.75 cm rise in clearance between cycloid edges, while the rotational speed increase results in a 2.73 cm decrease [27] (Table 4).

Table 2. ANOVA for the effect of forward speed x rotational speed on clearance between centriod center

S. No	Source	Sum of Squares	df	Mean Square	F-value	p-value
1.	Model	75.57	3	25.19	10.23	0.0041
2.	Forward Speed	56.47	1	56.47	22.92	0.0014
3.	Rotational Speed	29.59	1	29.59	12.01	0.0085
4.	Forward Speed x Rotational Speed	0.1406	1	0.1406	0.0571	0.8172
5.	R2	0.91				

Table 3. Regression analysis for the effect of forward speed x rotational speed clearance between centriod center

S. No	Source	Coefficient Estimate	df	Standard Error	t-value	p-value
1	Intercept	5.82	1	0.4992	5.89	<0.01
2	Forward Speed	3.13	1	0.6527	4.79	<0.01
3	Rotational Speed	-0.218	1	0.9125	0.23	<0.01
4	Forward Speed x Rotational Speed	-2.45	1	0.7061	3.46	>0.01

Clearance between centriod center = 5.81871 + 3.1251 * F + -2.44686 * R -0.218037 * FR (1)

Table 4. ANOVA for the effect of forward speed x rotational speed clearance between cycloids

S. No	Source	Sum of Squares	df	Mean Square	F-value	p-value
1	Model	105.92	3	35.31	15.05	0.0012
2	Forward Speed	81.44	1	81.44	34.72	0.0004
3	Rotational Speed	36.76	1	36.76	15.67	0.0042
4	Forward Speed x Rotational Speed	0.0209	1	0.0209	0.0089	0.927
5	R2	0.93				

In another investigation, the analysis of variance indicates a significant difference between two individual variables and the interaction effect of forward speed and rotational speed. However, the increase in these variables does not yield a significant change in the clearance between cycloid edges [28]. Nevertheless, the interaction effect of all variables remains significant, with an impressive R^2 value of 0.93 indicating that 93% of the variation in clearance between cycloid edges is explained by forward speed and rotational speed [29] (Table 5). To know the plat spacing, two important factors, i.e. cycloid center to cycloid center and cycloid edges to cycloid edges are needed (statistical analysis separately).

Table 5. Regression analysis for the effect of forward speed x rotational speed clearance between cycloids

S. No	Source	Coefficient Estimate	df	Standard Error	t-value	p-value
1	Intercept	6.61	1	0.4871	6.61	<0.01
2	Forward Speed	3.75	1	0.6369	5.88	<0.01
3	Rotational Speed	-2.73	1	0.689	11.86	<0.01
4	Forward Speed x Rotational Speed	-0.0841	1	0.8904	0.024	>0.01

Clearance between cycloids edges (cm) = 6.60513 + 3.753 * F + -2.72756 * R -0.0841* FR (2)

4. Conclusions

Our results concluded that at a forward speed of 1 $km.h^{-1}$, the maximum overlap of 2.5 cm was observed at 60 rpm of the weeding tool. cycloid-cycloid clearance of 3.1 cm was obtained at 40 rpm followed by 2 cm at 50 rpm. The provided observations highlight the critical interplay between weeding tool speed, rotational speed, and clearance during weeding operations. At low speed like 1 km.h-1, an increase in tool speed leads to increased overlap rather than clearance, diminishing the weeding effectiveness and potentially causing plant damage. At 1.2 $km.h^{-1}$, different center-to-center clearances at varying rotational speeds indicate the potential for fine-tuning weeding parameters based on crop spacing requirements. Through experimentation at a test rig speed of 1.2 kmph and a weeding tool speed of 50 rpm, a clearance of 6.4 cm between cycloid-cycloid interactions and an edge-to-edge clearance of 6.9 cm were achieved. Furthermore, the reduction in clearance from 7.1 cm to 4 cm when increasing the speed to 1.4 $km.h^{-1}$at 50 rpm underscores the speed-dependent nature of clearance, offering valuable insights for optimizing weeding processes. These findings emphasize the importance of balancing weeding tool speed and rotational speed to achieve effective weed removal while minimizing the risk of crop damage in agricultural operations.

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