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Performance assessment of L and J shaped rotary blade for measuring the mean weight diameter of black soil under laboratory condition

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Abstract

A research investigation aimed to identify the optimal combination of commercially available L and J-shaped blades for soil cultivation in black cotton soil (Vertisol). The study maintained a constant cone index (600±30 KPa) and soil moisture content (14-16%) throughout all experimental runs. The Response Surface Methodology (RSM) employing Box Behnken Design (BBD) was utilized to optimize the impact of operational factors, including forward speed (1, 1.5, 2 km/h), blade speed (75, 100, 125 rpm), and operating depth (3, 6, 9 cm), on the dependent variable, mean weight diameter (MWD), within an indoor soil bin setting. The findings revealed that J-shaped blades resulted in a lower mean weight diameter compared to L-shaped blades, specifically at a rotary speed of 110 rpm, forward speed of 1.5 km/h, and an operating depth of 8.25 cm for the J-shaped blade. The average MWD for J-shaped blades was 2.32 cm, indicating higher pulverization and effectiveness compared to L-shaped blades. Conversely, L-shaped blades yielded a higher MWD than their J-shaped counterparts.

Keywords: L and J-shape blade, soil-bin, mean weight diameter (MWD), box Behnken design, and black soil

1. Introduction

The conventional method of weeding involves manual labor using traditional hand tools like the Khurpi, often resulting in an upright bending posture that leads to back pain for a significant portion of the workforce (De *et al*. 1974, Gupta and Pandey. 1991, and Kumar *et al*. 2018) [2, 3, 8]. This process is time-consuming, expensive, and faces challenges in securing an adequate labor force during peak seasons. Hand weeding, besides being inefficient, tends to leave weed roots in the ground, causing regrowth within a few days and rendering previous removal efforts futile, thereby increasing cultivation costs. Studies indicate that weed-related yield reduction ranges from 30-60%, varying with the crop and location, with about one-third of cultivation costs allocated solely to weeding (Rangasamy *et al*. 1993, Kulaya and Singh. 2019, and Mandal *et al*. 2014) [13, 5, 9]. Farmers and researchers collaborate to address this weed removal challenge (Zareiforoush *et al*. 2010) [17]. In the absence of proper mechanical weeders in the past, manual labor was the only recourse, leading to the need for effective mechanical solutions to enhance productivity and alleviate poverty among subsistent farmers (Matin *et al*. 2021, and Sakai 1978) [10, 14]. To harness the benefits of mechanized weeding and address the limitations of existing machines, an advanced remote-operated weeding machine has been developed. This innovative machine employs a rotary blade for weeding, and this paper delves into the optimization of L and J-shaped rotary blades within an indoor soil bin filled with Vertisol (Chen *et al*. 1993, and Kumar *et al*. 2023a) [1, 6].

2. Methodology

To enhance the kinematic performance of the L and J-shaped soil cutting blades, the chosen response variable was the Mean Weight Diameter (MWD) of soil particles. Following soil tilling, performance parameters were assessed at three levels of forward speeds (1, 1.5, 2 km/h), three levels of blade rotational speeds (75, 100, 125 rpm), and three depth levels (3, 6, 9 cm). These measurements were conducted in a controlled soil bin at the Department of

Farm Machinery and Power Engineering, College of Agricultural Engineering, JNKVV, Jabalpur. The soil bin was filled with black cotton soil (Vertisol), maintaining a constant cone index (600±30 KPa) and soil moisture content (14-16%) throughout all experimental runs. Response Surface Methodology (RSM) utilizing Box Behnken Design (BBD) was employed to optimize the effects of forward speed (km/h), blade speed (rpm), and operation depth (cm) on the dependent variable (MWD) within the indoor soil bin conditions (Nandini *et al*. 2023, Namdeo at al. 2022, and Kumar *et al*. 2018) [12, 11, 8]. Both L and J-shaped blades featured two flanges on the rotor, each with six mounted blades. The specifics of the different blades used are detailed in Plate 1. For the assessment of pulverization index and bulk density, soil samples were collected following the pass of the test trolley equipped with rotary blades (Shiva *et al*. 2017) [15].

Plate 1: L and J-shaped rotary blade during test under soil bin

2.1 Mean weight diameter of the soil particles

The soil's particle size post-blade operation serves as a measure of soil quality. Finer grain size indicates improved soil quality after passing through rotary tillage tools (Nandini *et al*. 2023 and Namdeo *et al*. 2022) [12, 11]. The Mean Weight Diameter (MWD) of the tilled soil was determined using a mechanical sieve analyzer. L and J-type rotary blades were employed under simulated soil bed conditions with various combinations of forward speed, rotary RPM, and operation depth. Soil samples were extracted from a 15×15 cm^2 area at the operating depth. These collected soil samples underwent a 24-hour drying process at 105 °C in a hot air oven dryer. A set of sieves arranged in descending order of size (4.75 mm, 2.36 mm, 1.18 mm, 600, 300, 150, 75, and pan, detailed in Plate 2) was utilized in a sieve shaker. Around 800g of dried soil sample was placed on the top sieve. The shaker's motor was activated for 10 minutes, allowing soil particles to pass through the oversized sieve and be retained on the undersized sieve. The soil retained on each sieve was collected and weighed (Shrivastava and Dutta 2006, Kumar *et al*. 2023b and Kumar *et al*. 2018) [16, 7, 8]. The Mean Weight Diameter (MWD) was computed using equation 1 as described by Kemper and Rosenau in 1986.

$$MWD = \sum_{i=1}^{n} \bar{X}_i W_i \qquad \text{Eq. (1)}$$

Where, $\underline{X_i}$ = The mean dia. of the sieves at which soil retained on the preceding sieve, mm;

W_i = Fraction of the weight of soil collected from the retained sieve to the total weight of the sample, g

Plate 2: Measuring the mean weight diameter of the soil sample

3. Results and Discussion

3.1 Impact of operational parameters on mean weight diameter (MWD) of rotary blades (L and J-blade)

Following soil bin tests, it was observed that the L-shaped rotary blade achieved its lowest mean weight diameter (MWD) of 2.43 mm under specific conditions: a forward speed of 1.5 km/h, a rotary speed of 125 rpm for the blade, and an operating depth of 9cm. In contrast, the highest MWD, measuring 4.33 mm, was recorded when the forward speed was set at 2 km/h, the rotary blade operated at 75 rpm, and the depth of operation was 6 cm. For the J-shaped blades, the minimum MWD was observed at 1.94 mm under identical conditions: a forward speed of 1.5 km/h, a rotary speed of 125 rpm for the blade, and an operating depth of 9 cm. Conversely, the maximum MWD, measuring 3.46 mm, was obtained when the forward speed was set at 2 km/h, the rotary blade operated at 75 rpm, and the depth of operation was 6 cm. The study systematically examined the influence of independent parameters, including forward speed of operation, rotary speed of the blade, depth of operation, and their interactions, on the mean weight diameter of the soil. Detailed results are provided below.

3.2 Impact of forward speed and rotary speed on mean weight diameter (MWD)

In the context of a consistent operating depth, Figures 1a and 1b illustrate the impact of rotary speed, forward speed, and their interaction on the MWD for L-shaped and J-shaped blades. Maintaining a constant depth of 6 cm, the highest MWD for soil particles, measuring 4.33 mm and 3.46 mm, was achieved for L-shaped and J-shaped blades at a forward speed of 2 km/h and a rotary speed of 75 rpm. In contrast, the lowest values were recorded at 2.45 mm and 1.96 mm for L-shaped and J-shaped blades, respectively, occurring at a forward speed of 1 km/h and a rotary speed of 125 rpm.

Regardless of the rotary speed, a noteworthy and statistically significant increase ($p<0.05$) in MWD was observed as the forward speed of operation increased from 1 to 2 km/h. For example, at 125 rpm, elevating the forward speed from 1 to 2 km/h resulted in an increase in MWD from 2.45 to 3.25 mm and from 1.96 to 2.6 mm for L-shaped and J-shaped blades, respectively. This increase was attributed to a reduction in the u/v ratio, leading to an augmentation of MWD. An increase in the u/v ratio, associated with a longer bite length, was consistent with findings from previous studies (Gill and Berg, 1968; H. Bernacki, J. Haman *et al.*, 1986; Kulaya and Singh, 2019). However, it is noteworthy that, for various forward speeds of operation, a significant decrease in MWD ($p<0.05$) was observed as the rotary speed of the blades increased. For instance, at a forward speed of 2 km/h, increasing the rotary speed from 75 to 125 rpm resulted in a decrease in the MWD of the rotary blades (L and J) from 4.33 to 3.25 mm and from 3.46 to 2.6 mm. This reduction was attributed to an increase in the u/v ratio, yielding a shorter bite length and consequently reducing MWD. Furthermore, the interaction between forward speed and rotary speed was found to have a significant impact on the MWD of rotary blades (p-value <0.05).

3.3 Impact of forward speed and depth of operation on the MWD: Figure 2a and Figure 2b present the impact of depth of operation, forward speed of operation, and their interaction on the MWD of soil particles with a constant rotary speed for the L-shape and J-shape blades. At a fixed rotary speed of 100 rpm, the highest recorded MWD of soil particles were 3.93 mm and 3.14 mm for L-shape and J shape blades, achieved at a forward speed of 2 km/h and a depth of operation of 3 cm. In contrast, the lowest MWD, measuring 2.59 mm and 2.07 mm, were observed at 1 km/h forward speed and a depth of operation of 9 cm. Regardless of the depth of operation, a note-worthy and statistically significant increase ($p<0.05$) in MWD was evident with an increase in the forward speed of operation from 1 to 2 km/h. For instance, at a 9 cm depth, elevating the forward speed from 1 to 2 km/h resulted in an increase in MWD from 2.59 to 3.43 mm and 2.07 to 2.74 mm for L and J shape blades. This phenomenon can be attributed to a reduction in the u/v ratio. However, it's important to note that for different forward speeds of operation, a significant decrease in MWD ($p<0.05$) was observed when the depth of operation increased. For instance, at 2 km/h forward speed, increasing the depth from 3 to 9 cm at various rotor rpm levels led to a decrease in the MWD of the soil for L and J shape blades from 3.93 to 3.43 mm and 3.14 to 2.74 mm. This decrease was due to higher moisture content at shallower depths. Interestingly, the interaction between forward speed and depth of operation was found to be not significant (p-value >0.05).

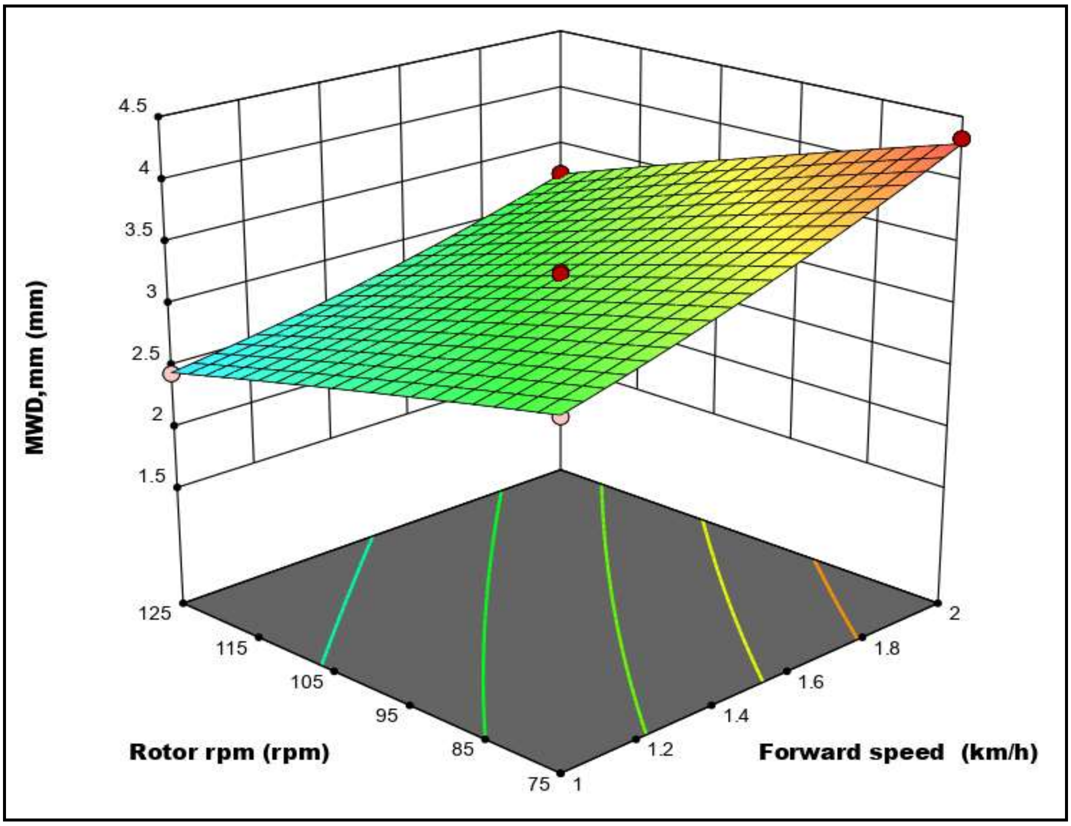

Fig 1a: Effect of forward speed and rotary speed on MWD for L-shape blade

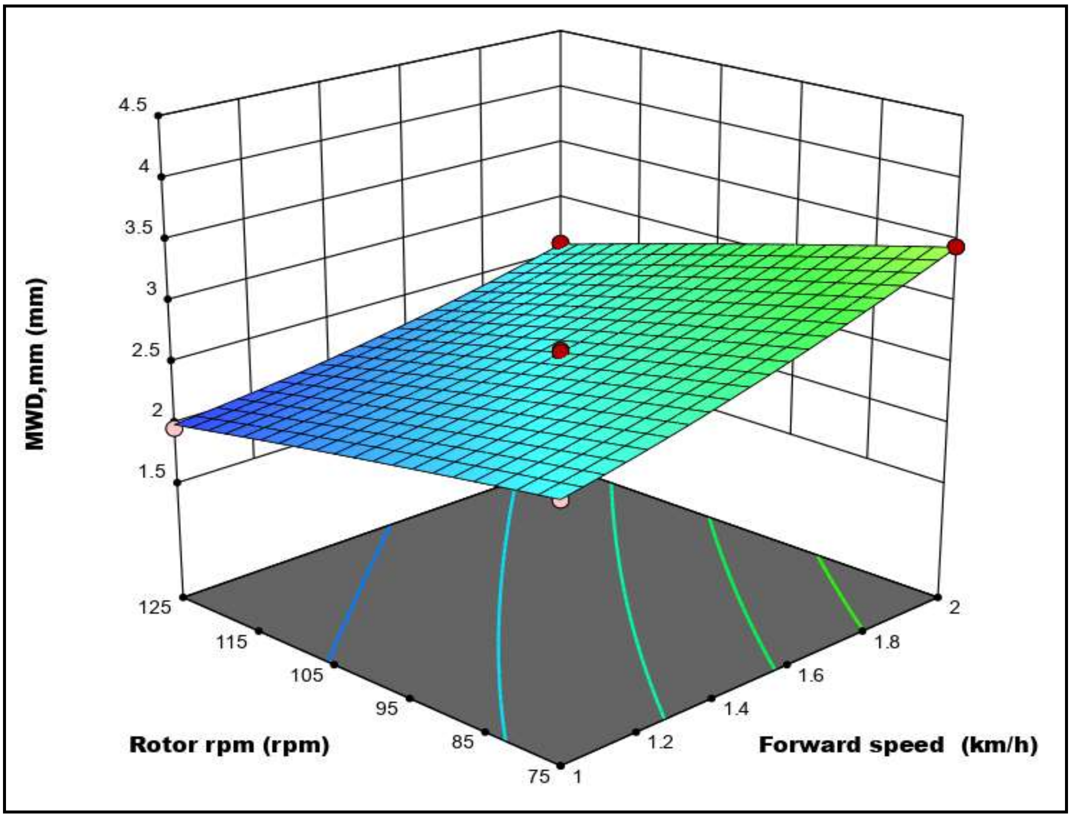

Fig 1b: Effect of forward speed and rotary speed on MWD for J-shape blade

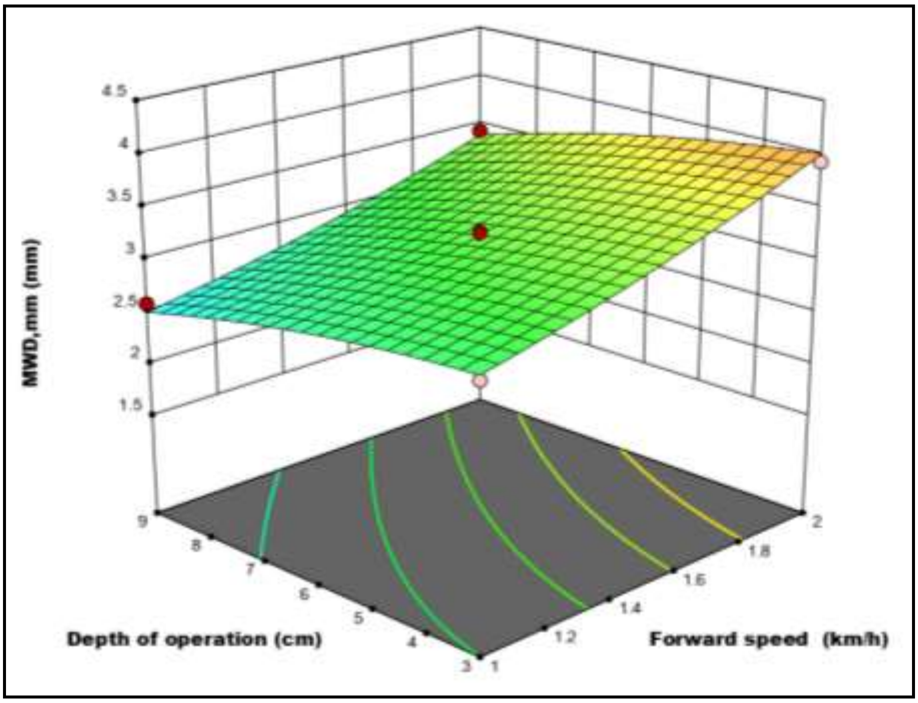

Fig 2a: Effect of forward speed and depth of operation on MWD for L-shape blade

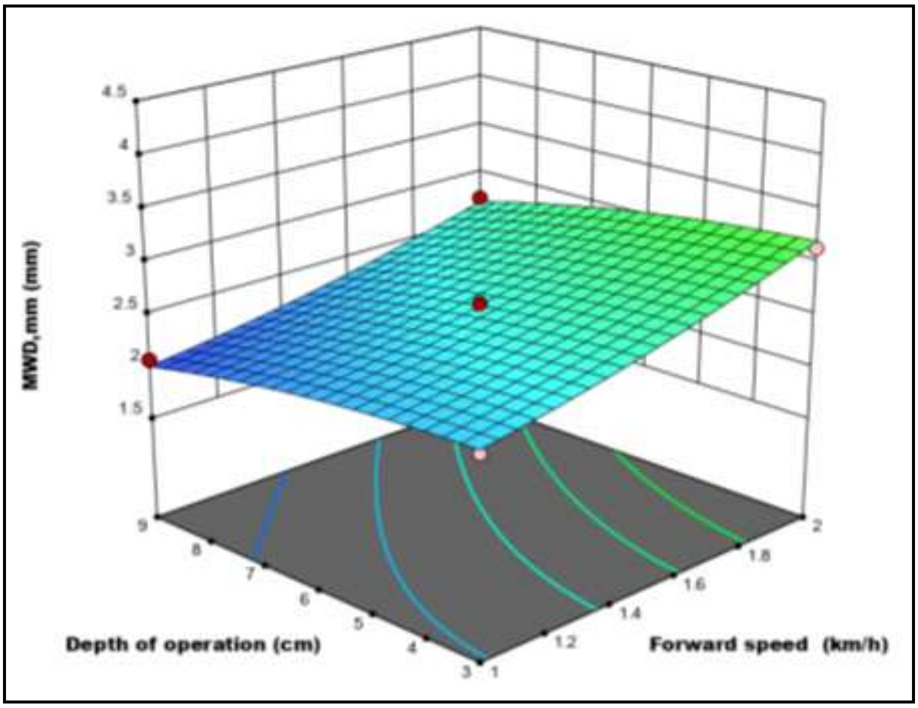

Fig 2b: Effect of forward speed and depth of operation on MWD for J-shape blade

3.4 Effect of depth of operation and rotary speed on the MWD

Figures 3a and 3b elucidate the influence of depth of operation, rotary speed of blades, and their interplay on the MWD of soil particles when the L and J-shape blade maintains a constant forward speed of 1.5 km/h. At this fixed forward speed, the maximum MWD of soil particles, 3.99 mm 3.19 mm, was achieved at a rotary speed of 75 rpm and a depth of operation of 3 cm, while the minimum MWD, measuring 2.43 mm and 1.94 mm for L shape and J shape blade, were recorded at 125 rpm rotary speed and a depth of operation of 9 cm. Consistently at the fixed forward speed with various depths of operation, the MWD demonstrated a significant ($p<0.05$) decrease with an increase in rotary speed from 75 to 125 rpm. For example, at a depth of 9 cm, elevating the rotary speed from 75 to 125 rpm resulted in a notable decrease in MWD, from 3.16 to 2.43 mm and 2.52 to 1.94 mm (significant at $p<0.05$). This reduction in MWD is attributable to an increase in the u/v ratio, leading to a reduction in bite length. Furthermore, a significant ($p<0.05$) decrease in the MWD was observed for different depths of operation when rotary speed increased. For instance, at 125 rpm, increasing the depth from 3 to 9 cm led to a decrease in MWD from 2.97 mm to 2.43 mm and 2.52 to 1.94 mm (L shape and J shape blades). Notably, the interaction between rotary speed and depth of operation was also deemed significant (p-value <0.05).

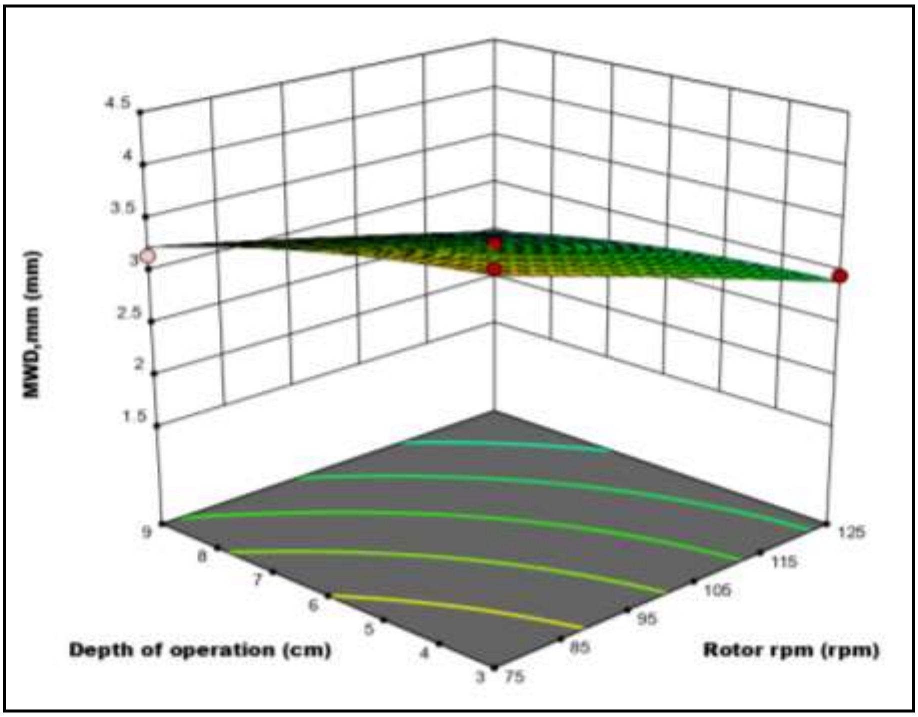

Fig 3a: Effect of depth of operation and rotary speed on MWD for L-shape blade

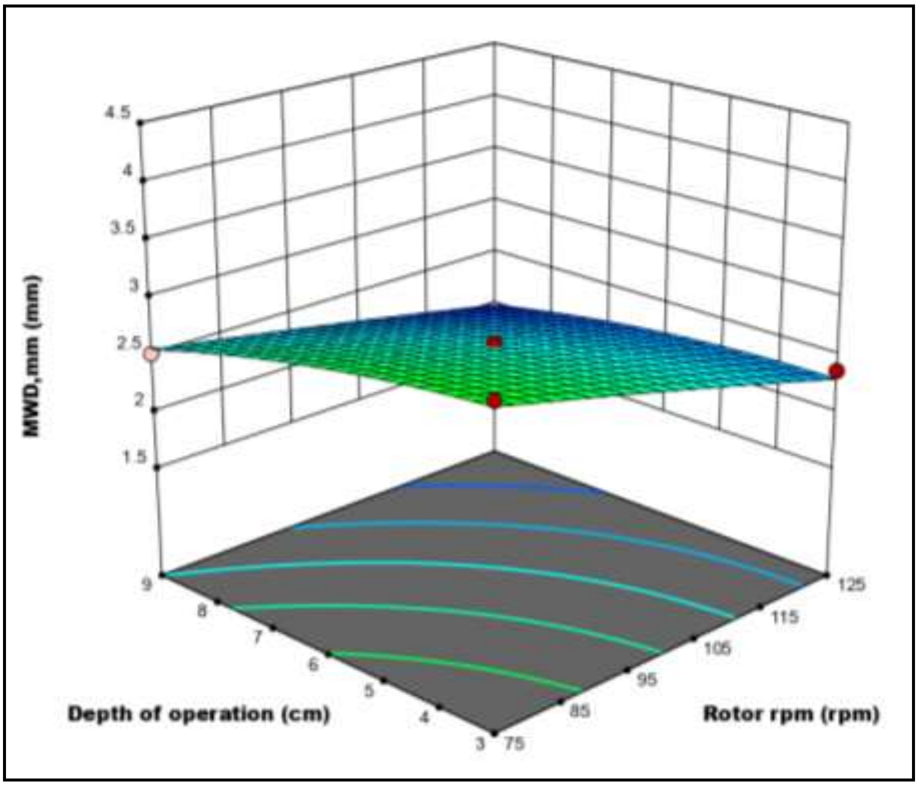

Fig 3b: Effect of depth of operation and rotary speed on MWD for J-shape blade

3.5 ANOVA for response surface quadratic model of MWD

Table 1 of the analysis of variance (ANOVA) indicates the model's significance, with a Model F-value of 113.88, suggesting a mere 0.01% probability that such a substantial F-value could arise from random noise. P-values less than 0.0500 indicate the significance of model terms, and in this instance, terms A, B, C, D, AB, AD, BC, BD, A^2, and C^2 are all considered significant. Values greater than 0.05 suggest the lack of significance for model terms. The Lack of Fit F-value of 1.50 implies that the Lack of Fit is not statistically significant compared to pure error, which is advantageous for fitting the model. The Predicted R^2 of 0.9605 indicates reasonable agreement with the Adjusted R^2 of 0.9780, with a difference of less than 0.2. Adeq Precision, measuring the signal-to-noise ratio, exceeds 4 at a desirable ratio of 43.152, indicating an adequate signal. The model, represented by Equation 2, is deemed suitable for predicting Mean Weight Diameter (MWD). The final equation is presented in terms of coded factors.

MWD, mm = 2.990.4231*A-0.4000*B-0.2519* C0.3038* D0.0787*AB-0.0300*AC-0.0469*AD + 0.0663*BC + 0.0450*BD + 0.0281*CD+0.0328A^2-0.0485 B^2-0.1172 C^2 Eq. (2)

Table 1: ANOVA for response surface quadratic model: MWD

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9.90	13	0.7612	113.88	< 0.0001	significant
A-Forward speed km/h	2.86	1	2.86	428.54	< 0.0001	*
B-Rotor rpm, rpm	2.56	1	2.56	382.98	< 0.0001	*
C-Depth of operation, cm	1.02	1	1.02	151.85	< 0.0001	*
D-Type of blade	3.14	1	3.14	469.53	< 0.0001	*
AB	0.0496	1	0.0496	7.42	0.0131	*
AC	0.0072	1	0.0072	1.08	0.3117	ns
AD	0.0352	1	0.0352	5.26	0.0328	*
BC	0.0351	1	0.0351	5.25	0.0329	*
BD	0.0324	1	0.0324	4.85	0.0396	*
CD	0.0127	1	0.0127	1.89	0.1840	ns
A^2	0.0090	1	0.0090	1.35	0.2587	ns
B^2	0.0198	1	0.0198	2.96	0.1006	ns
C^2	0.1158	1	0.1158	17.32	0.0005	*
Residual	0.1337	20	0.0067			
Lack of Fit	0.0925	12	0.0077	1.50	0.2886	not significant
Pure Error	0.0412	8	0.0051			
Cor Total	10.03	33				
Std. Dev.		0.0818	R^2		0.9867	
Mean		2.92	Adjusted R^2		0.9780	
C.V.%		2.80	Predicted R^2		0.9605	
			Adeq Precision		43.1520	

*significant, ns-not significant

The coded equation allows predictions for responses based on factor levels. High levels are coded as +1 and low levels as-1 by default. This coded form helps compare the relative impact of factors through their coefficients.

3.6 Optimizing L and J-shaped rotary blade performance through numerical methods

We set constraints for the L-shaped and J-shaped rotary blades based on their intended functionality, as detailed in Table 2. Using Design Expert software, we determined goals and their relative importance through data input. Subsequently, the software pinpointed an optimized solution showcased in Table 3. The Design Expert software generated optimized independent variables: for the J-shaped rotary blade, this resulted in a rotary speed of 110 rpm, a forward speed of 1.5 km/h, and an operating depth of 8.25 cm, corresponding to a predicted response of MWD at 2.320 mm. Visual representation of the individual desirability of these parameters can be found in figures 4 and 5.

Table 2: Constraints decided for numerical optimization

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Forward speed km/h	is in range	1	2	1	1	3
B: Rotary speed, rpm	Is in range	75	125	1	1	3
C: Depth of operation, cm	Is in range	3	9	1	1	3
D: Type of blade	is equal to	L shape blades	J shape blades	1	1	3
MWD, mm	none	1.94	4.33	1	1	3

Table 3: Optimized Solutions provided through analysis by software

No	Forward Speed km/h	Rotary speed rpm	Depth of operation cm	Type of blade	MWD mm	Desirability	
1.	**1.500**	**110.00**	**8.250**	**J-shape**	**2.320**	**1.000**	**Selected**
2.	1.500	107.18	8.147	J-shape	2.302	1.000	
3.	1.500	105.77	8.435	J-shape	2.287	1.000	
4.	1.500	106.24	8.041	J-shape	2.325	1.000	
5.	1.500	109.54	8.453	J-shape	2.239	1.000	
6.	1.500	109.43	8.250	J-shape	2.262	0.995	

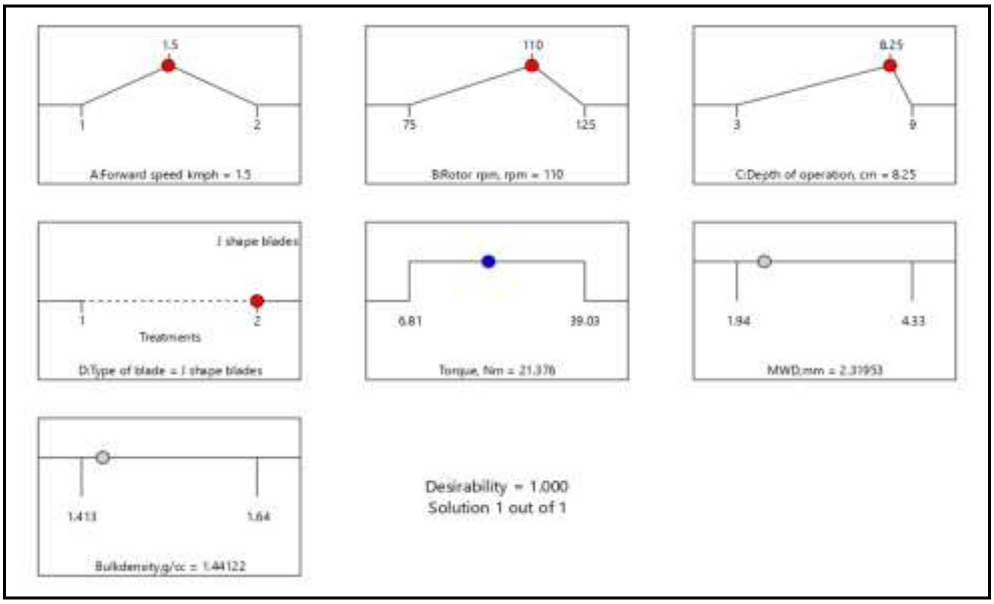

Fig 4: Ramp bar for optimizing the performance parameters

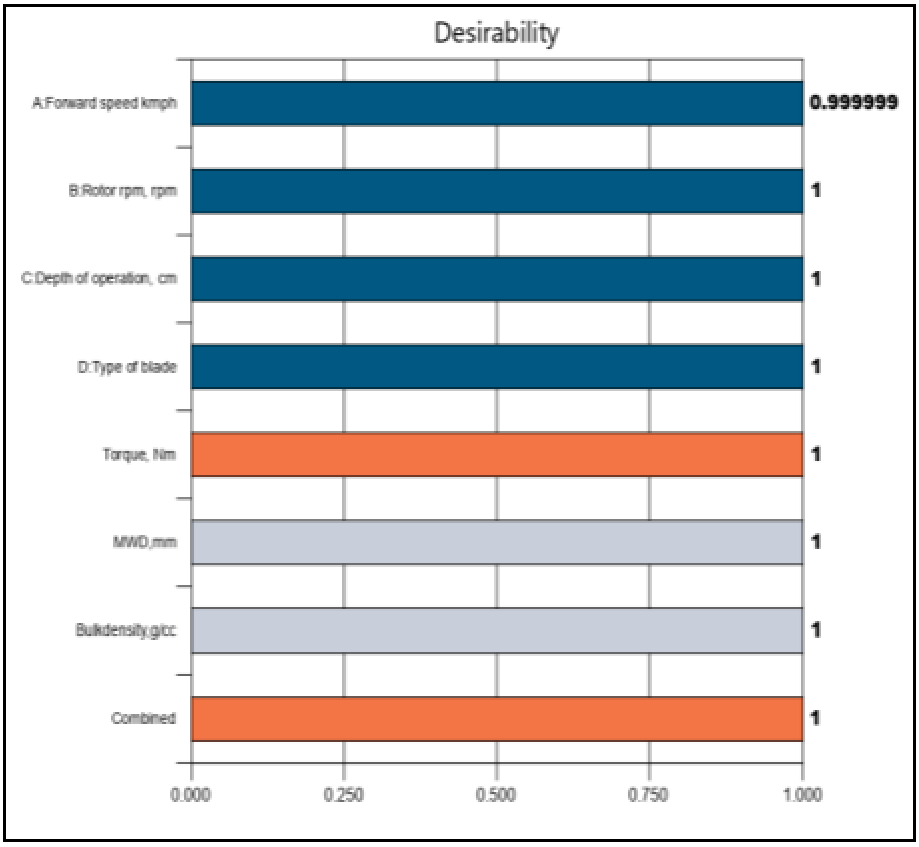

Fig 5: Desirability graph for different parameters after analysis

3.7 Analysis following optimization

Using the software, we obtained point predictions by inputting desired operational conditions and calculated predicted responses with a 95% confidence interval. The model offered predictions based on optimized independent parameters. An experiment was then conducted to validate these predicted response values under optimal operational conditions. The obtained mean value for the observed mean weight diameter of the J-shaped blade was 2.31 mm, falling within the range defined by the 95% confidence interval, detailed in Table 4.

Table 4: Validating point predictions from the model's optimized results

Response	Predicted Mean	Predicted Median	StdDev	SE Mean	95% CI low for Mean	95% CI high for Mean
MWD, mm	2.31953	2.31953	0.082	0.036	2.243	2.395

4. Conclusion
The study concludes that mean weight diameter decreases with increased depth of operation and rotor speed, while it rises with higher forward speed. The interaction between L-shaped and J-shaped blades under soil bin conditions for Vertisol soil was observed. Optimal weeding and tillage were noted at 110 rotor rpm, 1.5 km/h forward speed, and a depth of operation of 8.25 cm, particularly with the J-shaped blade. The predicted MWD, post-analysis, was 2.32mm. Comparatively, the L-shaped blade yielded a higher MWD than the J-shaped one. Notably, the J-shaped blade exhibited superior pulverization and effectiveness compared to the L-shaped blade.

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