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Optimization of Tine Spacing of Seed Drill for Dual Banding of Fertilizer

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Dual banding of fertilizer is one of the most effective techniques for plants, which is achieved with a combination of tines mounted on seed drill. Optimization of spacing between tines is essential for band placement of fertilizer and ease of operation of machine. The experiments were conducted in soil bin to optimize the spacings between tines using response surface methodology (RSM). The lateral, vertical and longitudinal spacings between tines were 50–100, 25–75 and 250–300 mm, respectively. Analysis of variance and Pearson's correlation analysis showed that tines spacings significantly influenced the draft, soil disturbance area, specific draft and seeding depth. The optimum lateral, vertical and longitudinal spacings between dual tines were found to be 50, 53 and 250 mm; 50, 51 and 279 mm; and 50, 45 and 283 mm for soil compaction levels of 400, 600 and 800 kPa, respectively. The RSM successfully optimized the spacing between dual tines and predicted the soil-tool interaction parameters with an error of 0.12 to 5%. Dual banding of fertilizer can be accomplished by mounting this dual tine system to an existing seed drill at optimal spacing. It will aid in the performance of seed drill by reducing soil disturbance and power requirement.

Keywords: Draft, RSM, Soil bin, Soil disturbance, Specific draft

Introduction

The application of fertilizers has played an important role in the agricultural production system. The traditional fertilizer application technique is the broadcasting of granular fertilizer, which is performed manually or by a tractor operated fertilizer broadcaster. The fertilizer is applied evenly across the soil surface at the time of sowing and top dressing is accomplished by this method in the standing crop, but this method has the lowest fertilizer use efficiency of plants.[1,2] Broadcasting of fertilizer is a major source of fertilizer induced N_2O emission which is resulted from the nitrate leaching and NH_3 volatilization.[3] In pop up method, fertilizer is applied in close contact with the seed with the help of the single boot furrow opener of the seed drill. The fertilizer can be delivered precisely to the seeds in small quantities at the early stage of the growing season. It can be phytotoxic if too much fertilizer is applied in direct contact with seeds. There are many methods to apply fertilizer within the crop management system, but the banding method is considered the best.[4] Banding refers to the method in which fertilizer is applied below, above, either one side, or both sides of the seed or seedlings, usually 50 to 200 mm deep, in the concentrated strips along the crop rows.[5] Application of fertilizer in bands increases the concentration of nutrients in the root zone which reduces the risk of fixation and increases their availability to the plants.[6] Banding on one side is carried out by a specially designed boot of furrow opener to provide horizontal and vertical separation of seed and fertilizer.[7] Another technique, referring to the positioning of fertilizers on both sides of the seeds or seedlings, is dual banding or both side banding. Dual banding of fertilizer is an old technique, but its application was limited in the past. A starter fertilizer band is positioned near the seeds and a base fertilizer band is placed in the soil farther down, such that the nutrients in the two bands are available to the crop at various growth stages.[8] The dual banding is performed by the single tine with multiple boots/tubes or combination of tines mounted on a seed drill.[9,10]

Various studies have been conducted for application of seeds and fertilizers in bands using separate sets of tines. The effect of the mid-row banding attachment of fertilizer on the seeding depth was studied.[11] In order to place the fertilizer in a deep field separate furrow openers have been used.[12] A cotton planter has been developed that formed two bands and applied the fertilizer at different depths on

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both sides of the seed at a differential rate.[13] Differential depth furrow opener was developed for the positioning of fertilizer at various depths.[14] A dual-band fertilizer applicator was designed to deliver fertilizers in two distinct bands and studied the effect of machine forward speed, vertical tube spacing and longitudinal tube spacing on fertilizer band separation distance.[8] The furrow opener has been designed for putting fertilizers in a shallow and deep band along with seed in a single pass.[9] These studies mainly focus on the development of the dual band fertilizer application mechanism based on the location of the fertilizer placement.

Attempts have been made to study the effect of multiple tines/furrow openers spacing on performance of implements. The relative position of multiple tines on a tool frame, laterally (spacing between tines) and in the direction of travel, has an effect on implement performance, draft forces, specific draft and soil disturbance pattern.[15–17] In addition, excessive soil disturbance by the fertilizer furrow opener adversely affects the seed furrow opener's performance in terms of seed depth.[11,18] In past research work, the optimization of lateral, vertical and longitudinal spacings between multiple tines for dual band fertilizer placement was not considered. The spacing between tines for band placement need to be optimized in such a way that it requires minimum draft, creates less soil disturbance and ensures the correct depth of placement of seeds and fertilizer. In this study, we have attempted to optimize the lateral, vertical and longitudinal spacings of dual tines and predict the draft, soil disturbance area, specific draft and seed placement depth for dual banding of fertilizer using numerical optimization technique of response surface methodology (RSM).

Materials and Methods

Tests were carried out in the soil tillage laboratory of ICAR- Central Institute of Agricultural Engineering, Bhopal, India. The experiment was conducted in the controlled soil bin condition to study the effects of the varying spacing of tines in three orthogonal planes *i.e.* lateral, vertical and longitudinal on draft, specific draft, soil disturbance area, seed placement depth.

Experimental Setup

The proposed dual banding system was intended to put the required amount of fertilizer along with seed on one side in shallow depth and the remaining of the amount on the other side in depth. The position of seed and fertilizer in dual banding system is shown in Fig. 1. Two furrow openers were used for shallow and deep positioning of fertilizers with seeds in a single pass. The shovel type furrow opener was used to place the seed and fertilizer at one side in shallow depth. It maintains the lateral separation of seed and fertilizer with less deviation as compared to other furrow openers.[19] The shovel was made up of medium carbon steel with a cross section of 35 mm and length of 170 mm. The boot wedge and rake angle were 45° and 40°, respectively. At the rear it has a boot with two small tubes for seed and fertilizer delivery. The furrow opener was mounted on shank of 500 × 40 × 20 mm dimensions. Another furrow opener, Inverted-T type, was used for placement of fertilizer at other side in deep zone. It is suitable for deep placement of fertilizer.[20] The furrow opener was made from flat of 8 mm of mild steel. In order to create a narrow slit without much soil disruption, the rake angle was maintained at 20°. Inverted-T type furrow opener was mounted on the shank of 560 × 60 × 16 mm dimensions in front of the shovel type furrow opener. Lateral spacing is the distance between the centers of two tines perpendicular to the direction of travel in a horizontal plane. Vertical spacing is the distance between the lower tip of shallow tine and deep tine in vertical plane. Longitudinal spacing is the forward distance between two tines in the direction of travel. The arrangement and adjustment of dual tines used for band placement of fertilizer is shown in Fig. 2. The clamps were used for changing the tine spacing in three orthogonal planes. Seed and fertilizer tubes were connected with

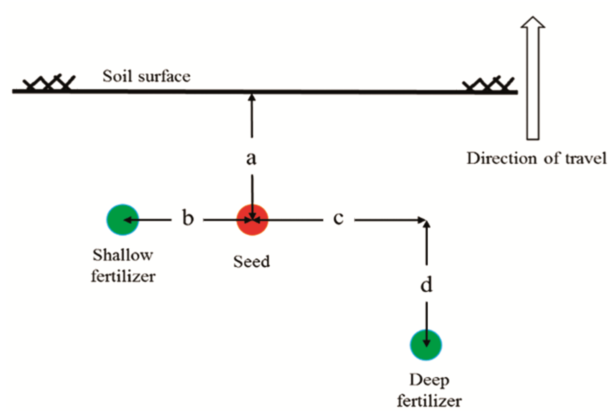

Fig. 1 — Position of seed and fertilizer in dual banding system (a) seed placement depth, (b) lateral placement of shallow fertilizer from seed, (c) lateral placement of deep fertilizer from seed, (d) deep fertilizer placement depth from seed

seed metering unit and fertilizer metering unit, respectively.

The soil bin comprised of a stationary bin, carriage, soil processing trolley, load cell fixture and power transmission system. The soil bin was 16 m long, 2.5 m wide and 1.0 m deep and filled with vertisol soil up to a depth of 0.8 m. The experimental setup consisted of seed and fertilizer box, seed and fertilizer tubes, metering unit, ground wheel, power transmission unit, seed furrow opener and fertilizer furrow opener as shown in Fig. 3. This setup was mounted on the main frame of carriage of soil bin. Drive to the metering mechanism of drill was given by ground wheel through chain and sprocket mechanism. The metering unit consisted of fluted rollers to meter the amount of the seed and fertilizer. A force transducer for measuring draft of the dual tines arrangement was fixed on the load cell fixture. The dual tines unit was mounted separately on the tool bar provided below the load cell fixture.

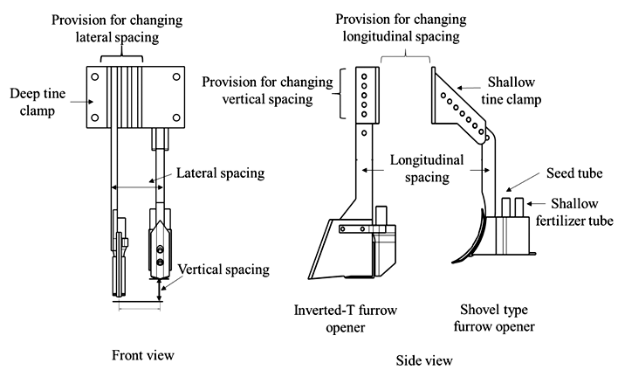

Fig. 2 — Arrangement of dual tines used for band placement of fertilizer

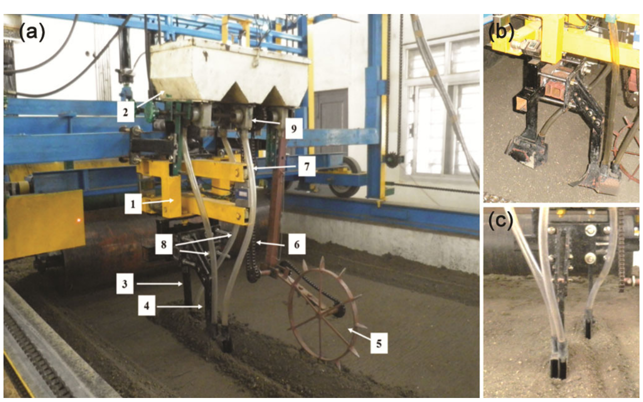

Fig. 3 — (a) Laboratory experimental setup for dual banding fertilizer application, (b) side view of dual tine, (c) back view of dual tine. (1) Force measuring unit, (2) Seed and fertilizer box, (3) fertilizer tine, (4) Shallow tine, (5) Ground wheel, (6) Chain drive, (7) Seed tube, (8) Fertilizer tubes, (9) Metering unit

Experimental Design

Various independent and dependent parameters selected for the study to evaluate the performance of the dual tines in the laboratory are given in Table 1. An experimental design based on the response surface methodology was followed to study the effect of lateral, vertical and longitudinal spacing of dual tines on draft, soil disturbance area, specific draft, seed placement depth. The design used in this study was a face centered central composite design (FCCCD) and it required three levels for each independent variable. These levels were coded as −1, 0 and 1. Total twenty experimental runs were carried out and replicated three times for each compaction level to select the best combination of tines. Forward speed kept 5 km/h and depth of operation of seed tine was 50 mm. The experiments were conducted at soil compaction levels of 400, 600 and 800 kPa. Lateral, vertical and longitudinal spacing between dual tines ranged from 50–100 mm, 25–75 mm and 250–300 mm, respectively. The experimental runs conducted based on their design of experiments are given in Table 1.

Table 1 — Independent and dependent parameters and soil condition for the optimization of dual tines spacing in soil bin

Variables	Levels
Independent parameters	
Lateral spacing, X_1 (mm)	50 (−1), 75 (0) and 100 (+1)
Vertical spacing, X_2 (mm)	25 (−1), 50 (0) and 75 (+1)
Longitudinal spacing, X_3 (mm)	250 (−1), 300 (0) and 350 (+1)
Dependent parameters	
Draft (N)	
Soil disturbance area (m^2)	
Specific draft (kN/m^2)	
Seed placement depth (mm)	
Other parameters	
Moisture content (%, dry basis)	10–12
Speed of operation (km/h)	5
Depth of operation (mm)	50 for seed tine (depth of fertilizer tine varies according to the level of vertical spacing of dual tines)
Soil condition	Low compaction level (CI: 400 kPa, bulk density: 1165 ± 22 kg m^{-3}, moisture content: 11.9 ± 0.88%), Medium compaction level (CI: 600 kPa, bulk density: 1217 ± 55 kg m^{-3}, moisture content: 11.2 ± 0.52%), High compaction level (CI: 800 kPa, bulk density: 1217 ± 55 kg m^{-3}, moisture content: 10.9 ± 0.78%)

−1, 0 and +1 are the coded level of independent variables

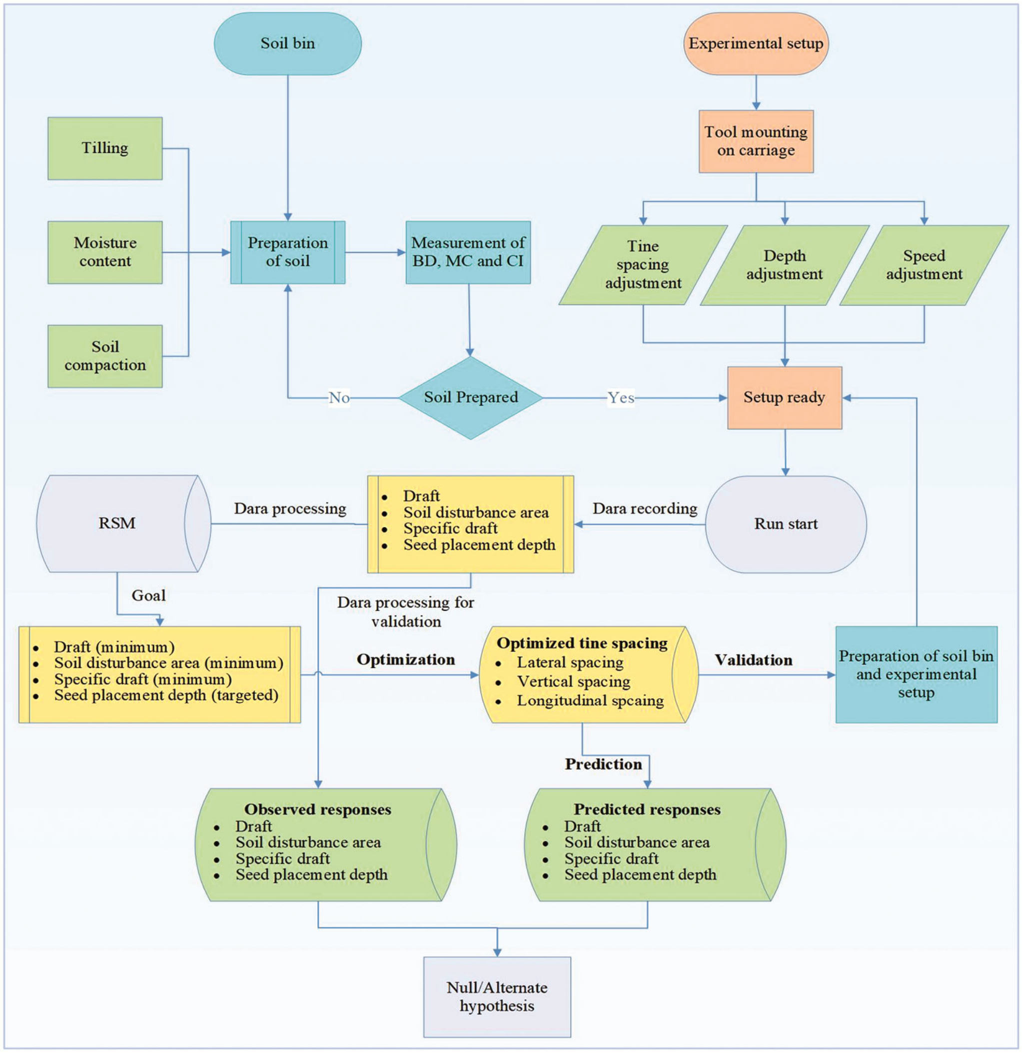

Fig. 4 — Flow chart of complete experimental procedure and optimization of tines spacing using RSM

Experimental Procedure

The soil bin experiments were conducted in vertisol soil. The flow chart of experimental procedure followed for optimization of tines spacing is shown in Fig. 4. Prior to each experiment, the soil was carefully prepared using soil processing unit to achieve the desired compaction levels. Water was sprayed before soil preparation to maintain the desired moisture content of the soil. Tilling of soil was done with the help of roto-tiller of soil processing unit. The cone index readings were recorded to a depth of 150 mm at six designated locations using cone penetrometer. After each run, three soil samples from entrance, middle and end of soil bin were collected with the help of core cutter. The moisture content and bulk density of soil were measured. After the preparation of soil, the seed box was filled with wheat seeds. Seed rate was set to maximum with full exposure length of fluted roller for easy identification of seed after dropping into the soil. The main frame of the carriage was lowered so that the furrow opener tip touched the soil surface. This was gauged through depth adjustment wheel mounted on carriage. The desired depth of fertilizer tine, 125 mm from the soil surface, was obtained by rotating the depth adjustment wheel. At this position of fertilizer tine, the seed tine was at 50 mm from the soil surface. The draft of dual tines was measured with the help of S-type load cell (IPA Weighing and Automation, Bengaluru, India, accuracy ± 0.05%) fixed on the load cell fixture. The data was obtained continuously inthe data logging software (Catman®Easy /AP) and stored through data acquisition system (QuantumX MX840A, Hottinger Baldwin Messtechnik GmbH, Germany). Disturbed soil was then removed by hand at three locations in the furrow and the soil disturbance area was measured using soil profilometer. Specific draft was calculated as a draft divided by the soil disturbance area. The depth of seed placement was measured by carefully removing the disturbed soil at five locations in the row without disturbing the seed.

Optimization of Dual Tines Spacing

After the soil bin experiments the data were analysed for finding optimum condition of responses. The independent parameters were optimized for each compaction level. The tine position was optimized based on three input variables i.e. lateral, vertical and longitudinal spacing, the interactions of which were studied as four major responses viz. draft, soil disturbance area, specific draft and seed placement depth. A second order polynomial model was equipped with the experimental data obtained from the soil bin study. It was used to establish a mathematical relationship between the variables and the responses with general form as following:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum_i \sum_j \beta_{ij} X_i X_j + \varepsilon \quad \text{... (2)}$$

where, Y is predicted response; k is number of variables; β_0 is intercept; β_i, β_{ii} and β_{ij} are regression coefficients; X_i and X_j are independent variables; and ε is error.

The optimum values of the independent variables were obtained using numerical optimization technique with the help of Design-Expert software (V10.0.1, Stat-Ease, Inc., USA). The software necessitates assigning goals to the input variables (lateral, vertical and longitudinal spacing) and the responses (draft, soil disturbance area, specific draft and seed placement depth). All the input variables were kept within range while the responses were either minimized/maximized or kept in range. The draft requirement and soil disturbance were considered to be minimum for field operation. Minimum values of draft, soil disturbance area and specific draft and a targeted value of seed depth of 40 mm were selected for optimization of spacing between dual tines. After assigning the goal to the parameters, various combinations of optimal values of tine spacing with their desirability were obtained. The optimum tine spacing with the highest desirability was selected.

Validation of Dual Tines Spacing

Validation was carried out for the comparison of predicted responses to the observed responses at the optimized dual tine spacing. It was ensured that the developed model was suitable for predicting the responses. The experiment was carried out to measure the responses at optimized dual tine spacings in the soil bin. The tines were arranged according to their optimized spacing for different soil compaction levels. Experiments were performed in accordance with the previous description of the procedure and various dependent parameters were recorded. The difference between the predicted and actual value was used to calculate the prediction error, which was expressed as a percentage.

The dual banding parameters were also recorded during the experiment of validation in soil bin. The measurements were taken for lateral placement of shallow fertilizer, lateral placement of deep fertilizer and deep fertilizer placement depth for selected level of soil compaction, as shown in Fig. 1.

Statistical Analysis

The analysis of variance (ANOVA) was used to check the statistical validity of the models obtained. The adequacy of the model was determined using model analysis, lack-of-fit test and R^2 (coefficient of determination) analysis. To calculate the error sum of squares and the lack of fit of the developed regression equation between the responses and independent variables, six repeated experiments were conducted at the central points of the coded variables. The model is perfect in depicting the response if the lack-of-fit would be insignificant. The Pearson's correlation analysis was carried out to check the statistical correlation between variables. For validation of the results, the null hypothesis of the study assumed that the predicted values for the draft, soil disturbance area, specific draft and seed placement depth were equal to those of the observed values. On the other hand, the alternative hypothesis assumed that the predicted values for the draft, soil disturbance area, specific draft and seed placement depth and observed values were different. The statistical analysis was carried using two-tailed, t-test at 5% level of significance ($p < 0.05$). The mean, standard deviation (SD), and degrees of freedom (df) were used to calculate the t-statistic (t_{cal}) and t-tabulated values (t_{table}), as well as the F-statistic (F-stat) for a number of observations taken.

Results and Discussion

Effect of Tines Spacing on Different Parameters

The regression coefficients of the response surface quadratic models for draft, soil disturbance area, specific draft and seed placement depth are shown in Table 2. The observed values of responses at different combinations of independent variable generated by RSM are given in Table 3.

Draft

Effect of lateral, vertical and longitudinal spacing of dual tines on draft shows that the spacing in three orthogonal planes were found significant at all the soil compaction levels (Table 2). Interaction effect of lateral and vertical spacing was significant at 600 and 800 kPa soil compaction levels, whereas, the interaction effect of vertical and longitudinal spacing was significant at soil compaction levels of 400 and 600 kPa. The interaction effect of lateral with longitudinal spacing was not found significant. The models of draft at soil compaction levels of 400, 600 and 800 kPa were found significant (p > 0.01). The estimated coefficients of second order polynomials regression model in coded form of independent variables were determined (Table 2). The non-significant coefficients were eliminated based on the

Table 2 — Analysis of variance and estimated coefficients of second order polynomial regression model at different soil compaction levels

Coefficient	Draft			Soil disturbance area			Specific draft			Seed placement depth		
	400	600	800	400	600	800	400	600	800	400	600	800
β_0	234^{**}	294^{**}	330^{**}	80.6^{**}	91.6^{**}	101.8^{**}	28.9^{**}	31.8^{**}	32.3^{**}	39.6^{**}	40.5^{**}	42.7^{**}
β_1	25^{**}	37^{**}	49^{**}	3.4^{**}	4.3^{**}	3.1^{*}	1.6^{*}	1.8^{*}	3.8^{**}	NS	NS	NS
β_2	136^{**}	176^{**}	186^{**}	24.6^{**}	25.0^{**}	25.9^{**}	6.9^{**}	9.1^{**}	8.9^{**}	5.7^{**}	6.2^{**}	5.4^{**}
β_3	14^{**}	36^{**}	33^{**}	2.8^{**}	2.8^{**}	2.2^{*}	0.6*	2.9^{**}	2.6^{**}	NS	NS	NS
β_{12}	NS	25^{**}	18^{*}	NS	-1.2^{*}	NS	NS	2.9^{*}	NS	NS	NS	NS
β_{13}	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
β_{23}	-16^{*}	20^{*}	NS	NS	NS	NS	-3.0^{**}	NS	NS	NS	NS	NS
β_1^2	NS	NS	NS	-10.7^{**}	-10.6^{**}	-10.0^{**}	2.8^{*}	NS	3.5^{*}	NS	NS	NS
β_2^2	44^{**}	59^{**}	31^{*}	-3.9^{*}	-3.3^{**}	NS	5.3^{**}	5.2^{**}	NS	NS	NS	-3.3^{*}
β_3^2	NS	NS	46^{**}	NS	NS	NS	NS	NS	5.1^{**}	NS	NS	NS
R^2	0.98	0.98	0.99	0.99	0.99	0.99	0.95	0.95	0.96	0.89	0.89	0.94

** Significant at 1% ($P < 0.01$), * Significant at 5% ($P < 0.05$), NS = Not significant, R^2 = Coefficient of determination

Table 3 — Results of experiments conducted for dual tines spacing at different soil compaction levels

Run	Factors			Responses at various soil compaction levels											
				400 kPa				600 kPa				800 kPa			
	Lateral spacing (mm)	Vertical spacing (mm)	Longitudinal spacing (mm)	Draft (N)	Soil disturbance area ($\times 10^{-4}$ m^2)	Specific draft (kN/m^2)	Seed placement depth (mm)	Draft (N)	Soil disturbance area ($\times 10^{-4}$ m^2)	Specific draft (kN/m^2)	Seed placement depth (mm)	Draft (N)	Soil disturbance area ($\times 10^{-4}$ m^2)	Specific draft (kN/m^2)	Seed placement depth (mm)
1	75	75	300	426	102.5	41.6	49	557	114.8	48.5	50	569	126.5	45	46
2	75	50	350	284	84.8	33.5	41	337	96.0	35.1	40	399	101.8	39.2	42
3	75	50	300	242	83.5	29.0	41	317	92.5	34.3	39	354	103.3	34.3	42
4	50	50	300	203	68.0	29.8	38	232	77.3	30.1	38	267	88.5	30.2	41
5	100	50	300	248	70.3	35.3	41	327	84.3	38.8	45	398	93.3	42.6	44
6	75	50	300	214	79.5	27.0	38	280	92.8	30.2	41	337	100.5	33.5	40
7	50	75	350	337	89.8	37.5	42	499	102.3	48.8	43	569	112.8	50.5	42
8	100	75	250	425	89.0	47.8	44	497	103.3	48.1	46	601	114.3	52.6	51
9	75	50	300	243	80.8	30.1	42	303	89.0	34.1	41	320	100	32	45
10	75	50	300	230	79.8	28.9	40	292	92.3	31.7	41	297	98.8	30.1	42
11	50	75	250	384	87.8	43.8	46	420	98.0	42.9	46	470	112.8	41.7	43
12	50	25	350	124	39.5	31.3	33	188	50.8	37.0	35	215	63.3	34	36
13	75	50	250	195	77.0	25.4	38	297	89.0	33.4	41	367	99.8	36.8	45
14	50	25	250	99	35.8	27.8	35	148	46.5	31.8	34	165	57.3	28.9	33
15	75	50	300	217	79.3	27.4	37	270	91.8	29.4	39	326	102.8	31.7	44
16	75	50	300	231	83.5	27.7	38	278	92.5	30.1	38	322	109.3	29.4	43
17	75	25	300	141	49.3	28.6	32	161	61.5	26.2	34	167	71	23.5	33
18	100	25	350	176	51.0	34.6	35	207	62.5	33.2	33	277	72.3	38.3	36
19	100	75	350	436	98.3	44.4	45	660	110.5	59.8	46	690	121	57	44
20	100	25	250	110	46.3	23.8	34	166	57.5	28.9	33	213	64.8	32.9	34
Standard deviation				19	2.4	1.9	2.2	22	1.4	2.6	2.21	20.6	3.1	2.3	1.5
Coefficient of variation, **(%)**				7	3.2	6.1	5.6	7	1.7	7.0	5.5	5.6	3.2	6.1	3.7

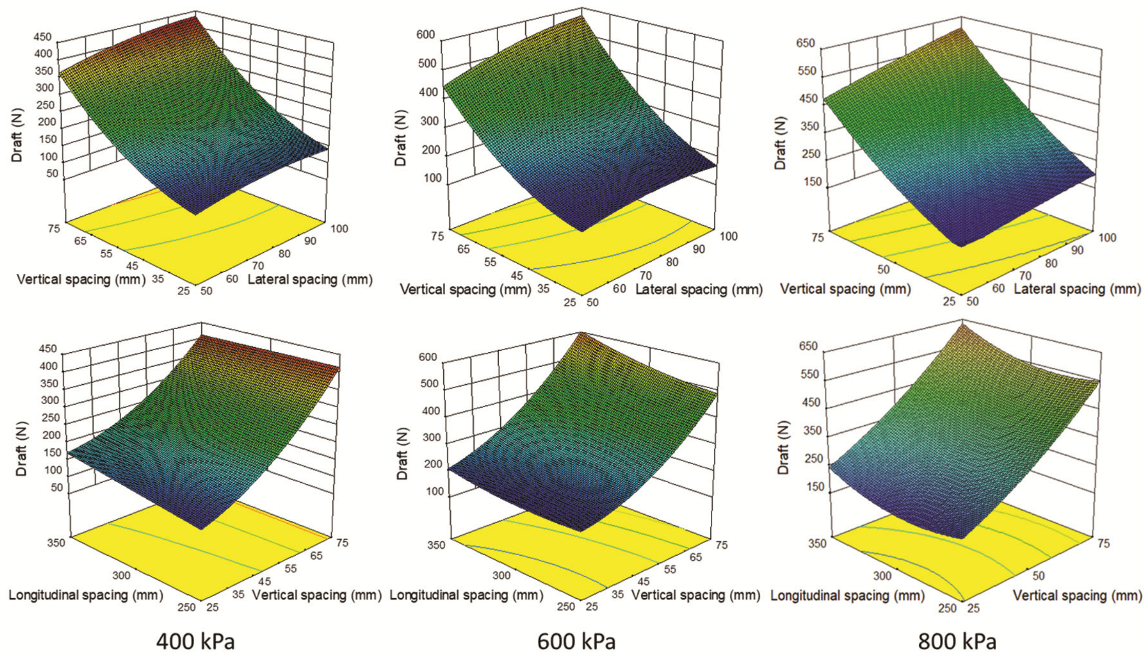

Fig. 5 — Effect of tines spacing on draft at different soil compactions levels

p-value and final models of draft in terms of coded factors were established. Equations 3, 4 and 5 gives the predicted values of draft as a function of lateral, vertical and longitudinal spacing and expressed in coded terms as follows:

$$Y_{1\,(400)} = 234 + 25\,X_1 + 136\,X_2 + 14\,X_3 - 16\,X_2X_3 + 44\,X_2^2 \quad \ldots (3)$$

$$Y_{1\,(600)} = 294 + 37\,X_1 + 176\,X_2 + 36\,X_3 + 25\,X_1X_2 + 20\,X_2X_3 + 59\,X_2^2 \quad \ldots (4)$$

$$Y_{1\,(800)} = 330 + 49\,X_1 + 186\,X_2 + 33\,X_3 + 18\,X_1X_2 + 31\,X_2^2 + X_3^2 \quad \ldots (5)$$

where, $Y_{1\,(400)}$, $Y_{1\,(600)}$ and $Y_{1\,(800)}$ are the draft of dual tines at soil compaction of 400, 600 and 800 kPa, X_1, X_2, and X_3 are coded terms for lateral, vertical and longitudinal spacing, respectively. The coefficient of determination (R^2) of developed models ranged from 0.98 to 0.99.

The draft of dual tines ranged from 99 to 690 N. The draft increased with increase in lateral spacing (Fig. 5) and there was a positive corelation between them (Fig. 6). This may be attributed to the increase in soil disturbance and produced a separate soil failure boundary for each tine. An increase in soil disturbance area increased the inertial force associated with the wedge of furrow openers.[21] The inertial

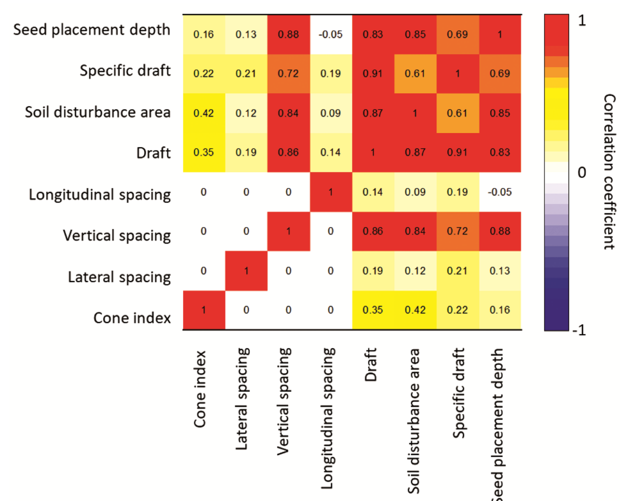

Fig. 6 — Pearson's correlation coefficients among different independent and dependent parameters considered for soil bin study

forces generated were found proportional to the volume and disturbed weight of the soil. In clay soil, shear strength was found to increase substantially with the increase in shear rates. This resistance increased the draft requirement of the tool. At closer lateral spacing, the shallow working tine follows to the soil failure boundary created by the operation of the deep working tine resulting in lower draft. This was in agreement with the studies conducted by the authors.[15] They reported that the closer tine spacing lowered the draft. At a fixed depth of 50 mm of shallow tine operation, increase in depth of deep tine from 75 to 125 mm, increased the draft. Similar results were reported by the researchers in their study.[21,22] The draft increased with increase in longitudinal spacing.[15] As Fig. 5 shows that the draft increased with increase in the lateral and longitudinal spacing at different values of vertical spacing. However, this draft was smaller in magnitude as compared to the draft obtained with increased in vertical spacing. In comparison to lateral and longitudinal spacings, the correlation coefficient (0.86) between vertical spacing and draft was higher (Fig. 6). It is reported that the draft force depends on working depth of furrow opener.[22] Similar trends of increase in draft with increase in lateral, vertical and longitudinal spacing were obtained at soil compaction of 400, 600 and 800 kPa. However, the magnitude of draft at soil compaction of 800 kPa was higher for all combinations of the spacing between dual tines. A positive correlation of daft was also observed with cone index (Fig. 6). In similar, authors reported that the draft of tillage tools increased with increase in soil compaction.[14,23]

Soil Disturbance Area

The result of soil bin study shows that the lateral, vertical and longitudinal spacing had a significant impact on soil disturbance area. The interaction effect of lateral and vertical spacing was found to be significant only at soil compaction level of 600 kPa. The models of soil disturbance area at soil compaction levels of 400, 600 and 800 kPa were found significant ($p>0.01$). The estimated coefficients of second order polynomials regression model for soil disturbance area in coded form of independent variables were determined. After eliminating the non-significant terms, the models for soil disturbance area in coded terms for different soil compaction levels are as follows:

$$Y_{2\,(400)} = 80.6 + 3.4\,X_1 + 24.6\,X_2 + 2.6\,X_3 - 10.7\,X_1^2 - 3.9\,X_2^2 \quad \text{... (6)}$$

$$Y_{2\,(600)} = 91.6 + 4.3\,X_1 + 25\,X_2 + 2.8\,X_3 - 1.2\,X_1X_2 - 10.6\,X_1^2 - 3.3\,X_2^2 \quad \text{... (7)}$$

$$Y_{2\,(800)} = 101.8 + 3.1\,X_1 + 25.9\,X_2 + 2.2\,X_3 - 10\,X_1^2 \quad \text{... (8)}$$

where, $Y_{2\,(400)}$, $Y_{2\,(600)}$ and $Y_{2\,(800)}$ are the soil disturbance area in coded term at soil compaction level of 400, 600 and 800 kPa, respectively. The R^2 of developed models was 0.99. Equations 6, 7 and 8 gives the predicted value of soil disturbance area as a function of lateral, vertical and longitudinal spacing expressed in coded terms.

The soil disturbance area varied from of 35.8×10^{-4} to 126.5×10^{-4} m^2. Minimum soil disturbance area was found at 50, 25 and 250 mm and maximum at 75, 75 and 300 mm for lateral, vertical and longitudinal spacing, respectively for all the soil compaction levels. The soil disturbance area increased with increase in lateral spacing from 50 mm to 75 mm. Further increase from 75 to 100 mm decreased the soil disturbance area (Fig. 7). The soil disturbance caused by dual tine at different lateral spacing is shown in Fig. 8. At the lateral spacing of 75 mm, both the tines worked as a single unit and had more soil disturbance. At 100 mm lateral spacing, both the tines opened separate soil profiles and their overall soil disturbance area was lower compared to 75 mm lateral spacing. The soil disturbance area increased with increase in vertical spacing between the tines also. It was due to increase in depth of deep tine. The overall soil disturbance by the tines was more at greater depth of operation than compared to the operation at lower depth.[24] These results were in confirmation with the studies conducted by the authors.[22,25] The soil disturbance area increased with increase in longitudinal spacing from 250 mm to 350 mm. As the longitudinal spacing increases, the soil extracted by the fertilizer tine falls into the furrow before the seed tine arrive and the soil has to be disturbed again. This results in an additional soil disruption which increases the soil disturbance area during the operation of dual tines at higher longitudinal spacing. It was observed that the soil disturbance area increased in smaller magnitude for lateral and longitudinal spacing as compared to increase in vertical spacing. The trend of changing the soil disturbance area at different combinations of lateral, vertical and longitudinal spacing was similar at soil compaction levels of 400, 600 and 800 kPa. However, the magnitude of soil disturbance area at soil compaction of 800 kPa was higher for different spacing of dual tines. A positive correlation of soil disturbance area was also observed with cone index (Fig. 6). It was reported that the increase in cone index from 200 to 800 kPa increased the soil disturbance.[26]

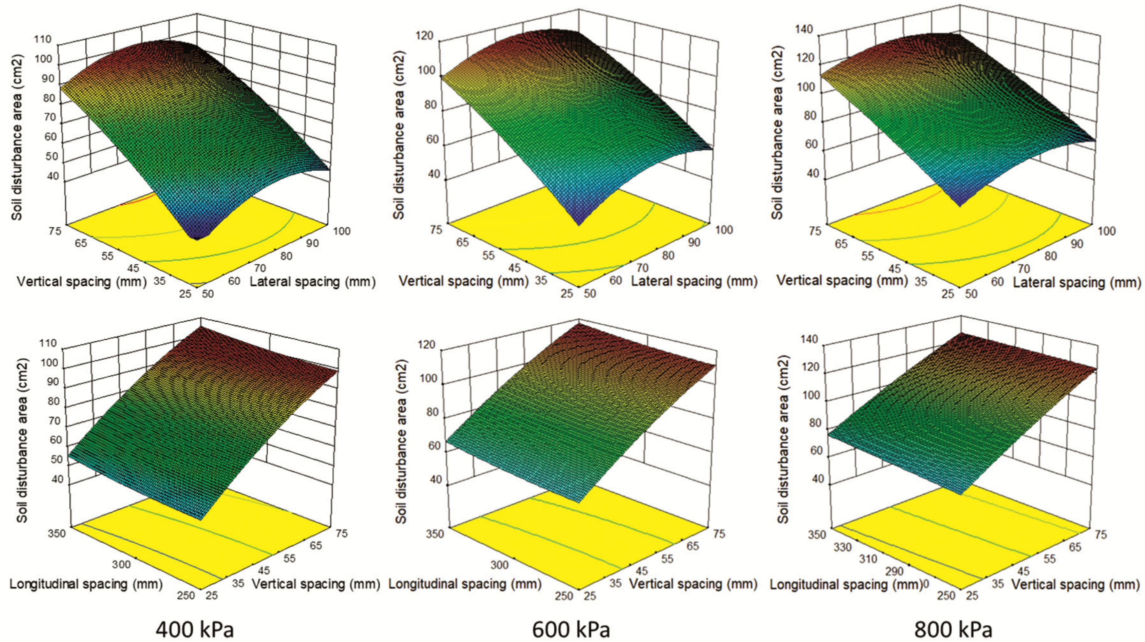

Fig. 7 — Effect of tines spacing on soil disturbance area at different soil compactions levels

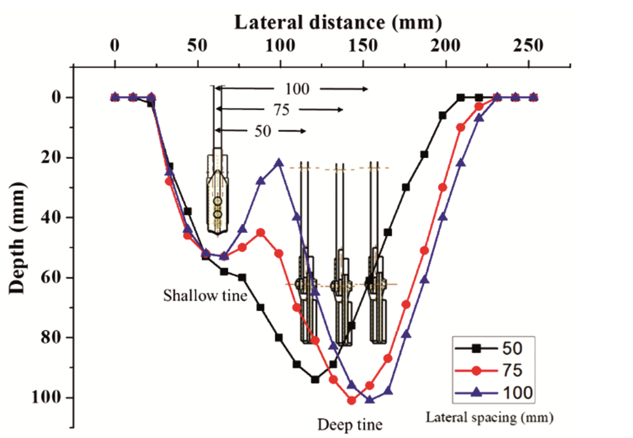

Fig. 8 — Soil disturbance caused by dual tine at different lateral spacing, 50 mm vertical spacing and 300 mm longitudinal

Specific Draft

The lateral, vertical and longitudinal spacing were significantly ($p < 0.01$) influenced the specific draft at different soil compaction level. The interaction effect of lateral and vertical spacing was found significant at soil compaction level of 600 kPa. The interaction effect of vertical and longitudinal spacing was found significant at soil compaction level of 400 kPa. The models of specific draft at soil compaction levels of 400, 600 and 800 kPa were found significant ($p < 0.01$). The models of specific draft in coded terms after eliminating non-significant terms are as follows:

$$Y_{2\ (400)} = 80.6 + 3.4\ X_1 + 24.6\ X_2 + 2.6\ X_3 - 10.7\ X_1^2 - 3.9\ X_2^2 \quad \ldots (9)$$

$$Y_{3\ (600)} = 31.8 + 1.8\ X_1 + 9.1\ X_2 + 2.9\ X_3 + 2.9\ X_1X_2 + 5.2\ X_1^2 \quad \ldots (10)$$

$$Y_{3\ (800)} = 32.3 + 3.8\ X_1 + 8.9\ X_2 + 2.6\ X_3 + 3.5\ X_1^2 + 5.1\ X_3^2 \quad \ldots (11)$$

where, $Y_{3\ (400)}$, $Y_{3\ (600)}$ and $Y_{3\ (800)}$ are the specific draft in coded term at soil compaction level of 400, 600 and 800 kPa, respectively. The R^2 of the model was 0.95 to 0.96, showing the fitted value is close to the experimental results for specific draft.

The minimum specific draft (23.8 kN/m^2) was found at 100 mm lateral spacing, 25 mm vertical spacing and 250 mm longitudinal spacing at soil compaction of 400 kPa. The maximum specific draft (57 kN/m^2) was obtained at maximum lateral spacing (100 mm), maximum vertical spacing (75 mm) and maximum longitudinal spacing (350 mm) at the soil compaction level of 800 kPa. Response surface of effects of dual tines spacing on specific draft is shown in Fig. 9. Specific draft decreased with increase in lateral spacing from 50 to 75 mm. Further increase in lateral spacing from 75 to 100 mm increased specific draft. At 75 mm lateral spacing, dual tines were positioned in such a way that the soil disturbance area of deep tine corresponded with the shallow tine which resulted in increase in the soil disturbance area. This leads to significant reduction in the specific draft at 75 mm lateral spacing.[17] The specific draft increased with increase in vertical spacing at all the

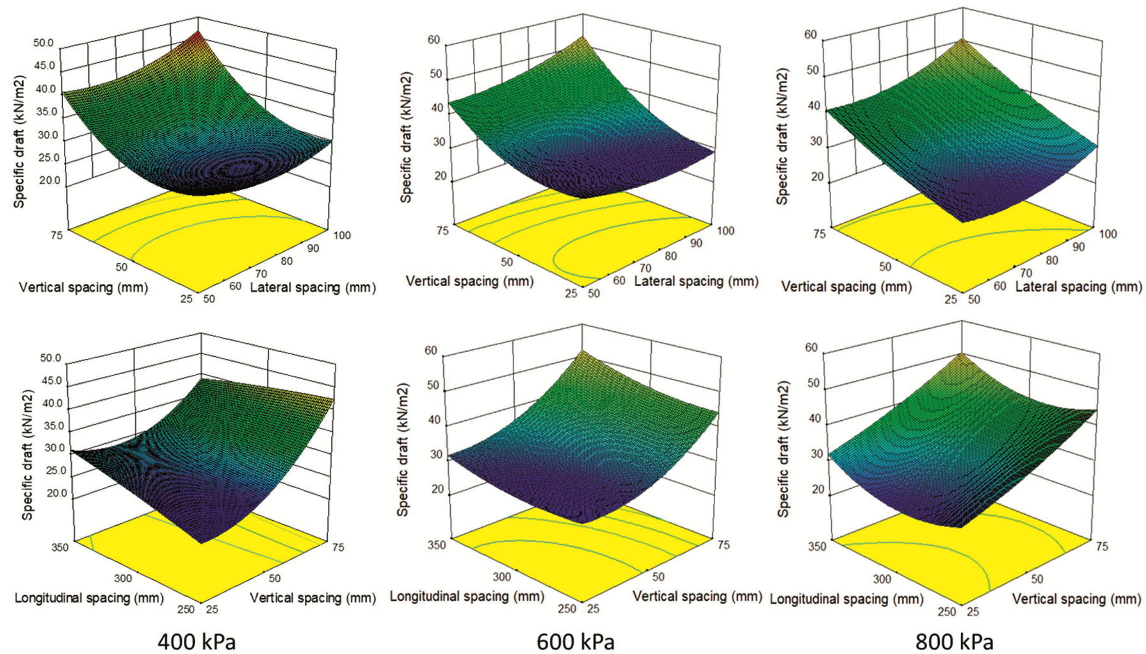

Fig. 9 — Effect of tines spacing on specific draft at different soil compactions levels

combinations of lateral and longitudinal spacing. The increase in specific draft with an increase in vertical spacing was due to increasing depth of fertilizer tine. As the depth of tine increases, the rate of increase of draft is higher than that of soil disturbance area.[27] So that the ratio of draft and soil disturbance area, which is defined as the specific draft increases. Authors reported that the specific draft increased with increase in depth of tine.[25] The longitudinal spacing also influenced the specific draft of dual tine. As the longitudinal spacing increases, the soil removed by the fertilizer tines is filled before coming into contact with the seed tines. Therefore, additional force was required to remove the soil again by the seed tine. Which increased the draft. As a result, the specific draft also increased. The trend of changing the specific draft was similar at all the soil compaction levels. But its magnitude was higher at higher soil compaction level. It was observed that the specific draft increased in smaller magnitude for lateral and longitudinal spacing as compared to increase in vertical spacing. Similar trend of change in specific draft with increased in lateral, vertical and longitudinal spacing was observed at all the soil compaction levels. The specific draft had positive correlation with cone index (Fig. 6).

Seed Placement Depth

ANOVA for response surface quadratic model for seed placement depth shows that the vertical spacing had a significant ($P < 0.01$) effect on the seed placement depth for all the soil compaction levels. Whereas, the lateral spacing had significant effect on seed placement depth only at higher soil compaction. The longitudinal spacing did not significantly affect the seed placement depth. Also, the interaction of lateral with vertical spacing, lateral with longitudinal spacing and vertical with longitudinal spacing had no significant effect. The estimated coefficients of second order polynomials regression model in terms of coded factor for predicting the seed placement depth were established as follows:

$$Y_{4\,(400)} = 39.6 + 5.7\,X_2 \quad \text{... (12)}$$

$$Y_{4\,(600)} = 40.5 + 6.2\,X_2 \quad \text{... (13)}$$

$$Y_{4\,(800)} = 42.7 + 1.4\,X_1 + 5.4\,X_2 - 1.6\,X_2X_3 - 3.3\,X_2^2 \quad \text{... (14)}$$

where, $Y_{4\,(400)}$, $Y_{4\,(600)}$ and $Y_{4\,(800)}$ are the seed placement depth in coded term at soil compaction level of 400, 600 and 800 kPa, respectively. Coefficient of determination R^2 of the models ranged from 0.89 to 0.94. Results of the seed placement depth as affected by different spacing between dual tines are given in Table 3. The minimum and maximum seed placement depths of 32 mm and 51 mm were found at 25 mm and 75 mm vertical spacing, respectively. Soil disturbance caused by the furrow openers affected the seeding depth.[28] The position of deep fertilizer tine operating ahead of shallow tine disturbed the soil and resulted in improper seed placement. The depth of seeding was found less than the depth of operation of shallow tine. The ratio of mean seeding depth to the depth of operation ranged from 0.64 to 1.02. This agreed with the findings reported by researchers.[20,28] The seed placement depth increased with increase in the vertical spacing (Fig. 10). This may be due to the increase in soil disturbance by the deep tine with increase in depth. The soil disturbance by a tine corresponds to the boundary of another tine and resulted in greater seeding depth.[18] The soil compaction level also influenced the seed placement depth with positive correlation coefficient (Fig. 6).

Optimization of Tines Spacing and Validation of the Model

The overlay plot of lateral and vertical spacing at optimized longitudinal spacing for different soil compaction levels is shown in Fig. 11. The values given in the flagged area were grouped together and the optimized values of the lateral, vertical and longitudinal spacing were obtained as 50, 53 and 250 mm, respectively at soil compaction of 400 kPa. At this optimized spacing of tine, the predicted values of draft of 209 N, soil disturbance area of 68.5×10^{-4} m^2 and specific draft of 30.7 kN/m^2 were obtained for soil compaction level of 400 kPa (Table 4). The desirability for various responses ranged from 0.51 to 1. The overall desirability of responses was 0.739. Similarly, the optimized values of lateral, vertical and

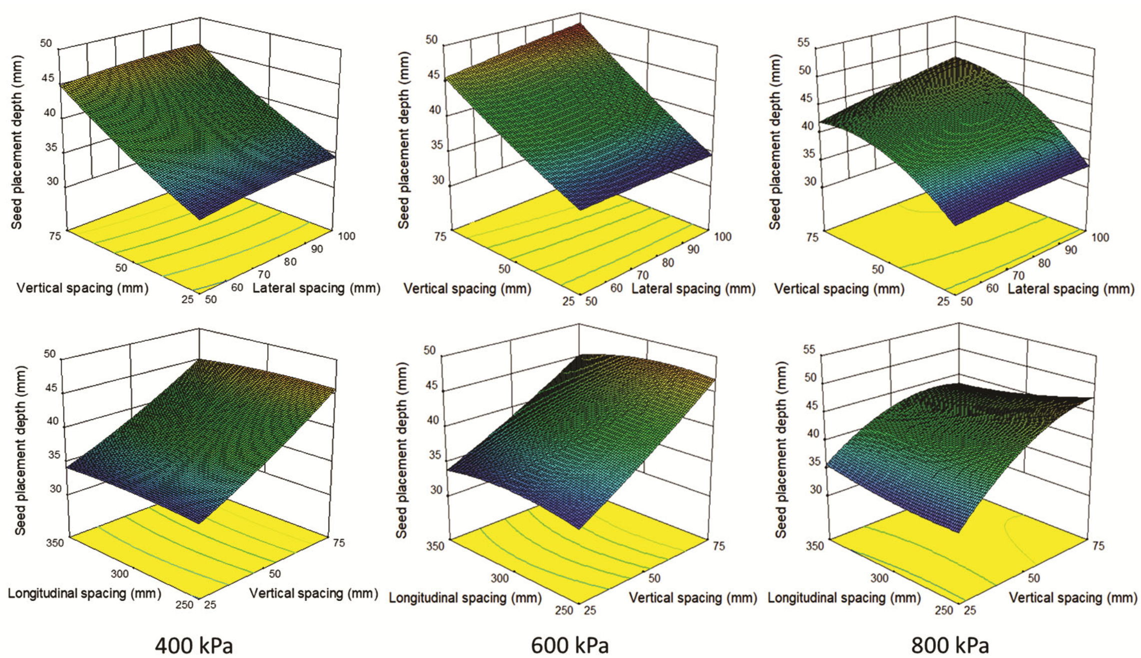

Fig. 10 — Effect of tines spacing on seed placement depth at different soil compactions levels

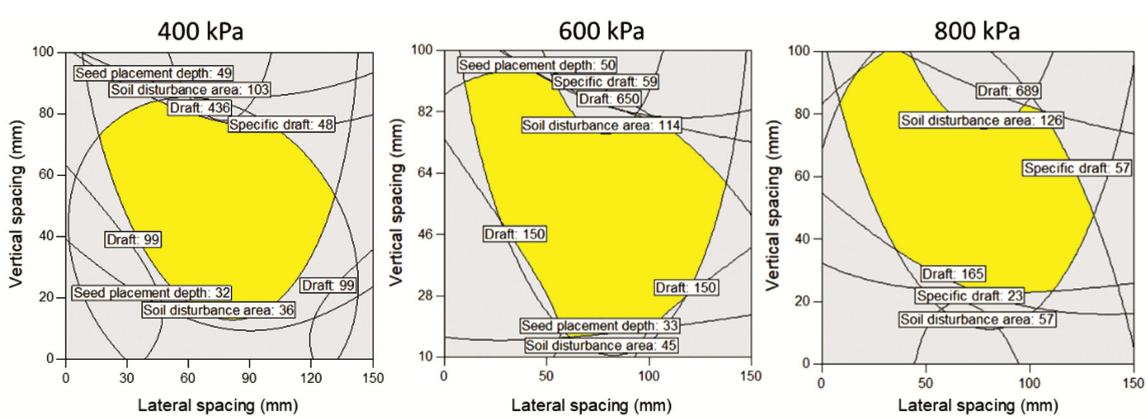

Fig. 11 — Overlay plot of lateral and vertical spacings at optimized longitudinal spacing for different soil compaction levels

Table 4 — Validation of predicted responses at different soil compaction levels

Responses	400 kPa*				600 kPa**				800 kPa***			
	Predicted value	Observed value	Error (%)	t-test	Predicted value	Observed value	Error (%)	t-test	Predicted value	Observed value	Error (%)	t-test
Draft (N)	209	213 ± 6.6	1.91	1.37^{NS}	234	237 ± 4.5	1.28	1.57^{NS}	241	248 ± 7.1	2.90	2.33^{NS}
Soil disturbance area ($\times 10^{-4}$ m^2)	68.5	70.4 ± 1.7	2.77	2.5^{NS}	76.9	76.6 ± 2.4	0.39	0.31^{NS}	83.1	83.2 ± 1.4	0.12	0.16^{NS}
Specific draft (kN/m^2)	30.7	30.3 ± 0.4	1.30	2.71^{NS}	31.9	31 ± 0.8	2.82	2.36^{NS}	30.1	29.9±0.7	0.66	0.79^{NS}
Seed placement depth (mm)	40	39 ± 1.6	2.50	1.41^{NS}	40	39.8 ± 1.9	0.50	0.23^{NS}	40	38±1.3	5.00	2.67^{NS}

Ho: $\mu_o = \mu_1$, $t_{cal} < t_{table}$ at P < 0.05, 'H$_o$' was accepted

^{NS} – Not significant.

*Values are at operating conditions of lateral, vertical and longitudinal spacing of 50, 53 and 250 mm, respectively

**Values are at operating conditions of lateral, vertical and longitudinal spacing of 50, 51 and 279 mm, respectively

***Values are at operating conditions of lateral, vertical and longitudinal spacing of 50, 45 and 283 mm, respectively

longitudinal spacing were 50, 51 and 279 mm, respectively for soil compaction of 600 kPa. The predicted values of draft of 234 N, soil disturbance area of 76.9×10^{-4} m^2 and specific draft of 31.9 kN/m^2 were obtained. Further, the desirability for the various responses ranged from 0.55 to 1.0. The overall desirability of responses was 0.814. For the soil compaction of 800 kPa, the optimized values were 50 mm lateral spacing, 45 mm vertical spacing and 283 longitudinal spacing. The predicted values of draft of 241 N, soil disturbance area of 83.1×10^{-4} m^2 and specific draft of 30.1 kN/m^2 were obtained. The desirability for the various responses ranged from 0.62 to 1 with overall desirability of responses was 0.835.

The confirmation test was carried out to validate the models of draft, soil disturbance area, specific draft and seed placement depth. The experiment was conducted at optimized condition of tine spacing with five replications for each soil compaction level. The results obtained from the confirmation tests are given in Table 4. The two tailed simple t-test showed no significant difference (P < 0.05) between the predicted and observed responses. The observed values of draft were very close to the predicted values with the error of 1.28 to 2.90% at different soil compaction levels. The confirmation of soil disturbance area was investigated with the error in the range of 0.12 to 2.77%. The observed and predicted values were in close ranges. The error of confirmation tests of specific draft was observed between 0.66 to 2.82%. The models of specific draft were overestimated the values in comparison with observed values. The error limits of seed placement depth were between 0.5 to 5%. The error was more at high soil compaction level but the predicted values are within the acceptable range. The result predicted by RSM can be used to optimize tine spacing for dual fertilizer banding with seeds.

Table 5 — Dual banding at optimized tine spacing on selected soil compaction level

Parameters	400 kPa	600 kPa	800 kPa
Lateral placement of shallow fertilizer (mm)	32.6 (1.5)	32.2 (1.9)	32.8 (1.9)
Deep fertilizer placement depth (mm)	51.8 (1.8)	48.8 (0.8)	42.8 (1.5)
Lateral placement of deep fertilizer (mm)	47.6 (1.1)	46.8 (1.5)	47.0 (1.6)

Dual Band Placement at Optimum Tines Spacing

The dual tines were operated in soil bin at optimized lateral, vertical and longitudinal spacing of 50, 51 and 279 mm, respectively. The fertilizer application depth below and side of seeds were measured for dual banding and present in Table 5. The lateral placement of shallow fertilizer from the seed varied from 32.2–32.8 mm. The variation in lateral placement was very less because the placement of seeds and fertilizers at shallow depth was performed with the same furrow opener, which had two boots. The deep fertilizer placement depths were found as 51.8, 48.8 and 42.8 mm for soil compaction of 400, 600 and 800 kPa, respectively. The deep tine was operated at lower depth at higher compaction level, resulting in a decrease in deep fertilizer placement depth. It may be due to the lower value of optimized vertical spacing (45 mm) at higher soil compaction level (800 kPa). The lateral placement of deep fertilizer was found to be 47.6, 46.8 and 47 mm soil compaction of 400, 600 and 800 kPa, respectively. The variation was less due to the same lateral spacing (50 mm) between the tines at all the soil compaction levels. The location of fertilizer placement with optimized dual tine spacing was within the range for maximizing the crop yield and improving fertilizer use efficiency as suggested by authors.[14,29,30]

Conclusions

In the present study, the lateral, vertical and longitudinal spacings of tines were optimized using response surface methodology for dual band placement of fertilizers along with seeds. The experiments were conducted in a controlled soil bin condition. The optimum values were obtained by analyzing the effect of tine spacing on draft, soil disturbance area, specific draft and seed placement depth. The second order polynomial models were developed and validated against observed responses. RSM optimizes the spacing of the tines effectively and predicts the responses with relatively low error, which were within the acceptable limit. The change in lateral, vertical and longitudinal spacings of dual tines influenced the draft, soil disturbance area and specific draft. The seed placement depth was mainly influenced by the vertical spacing between tines. The optimum vertical spacing of the opener was found to decrease and longitudinal spacing was found to increase with increase in soil compaction level. The optimized dual tine spacing for application of fertilizers in dual banding at appropriate depth will help to operate the seed drill with lower power requirement, produce minimum soil disturbance and seeding at the required depth as well as increase the fertilizer use efficiency. The numerical optimization technique and RSM models predicted and optimized the soil and tool parameters effectively. This study will help the researchers and farm machinery manufacturers in accelerating the process of parameter optimization in soil-tool interaction studies.

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