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Radish (*Raphanus raphanistrum subsp. sativus*) Seed Planter Parameters Optimization using Response Surface Methodology

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Precision sowing of a seed by a planter requires seed singulation by metering device and placement of that in soil. Pneumatic planters are more popular among precision planters due to their obvious advantages. Design and operating parameters of pneumatic planter needs to be optimized for getting the desired performance from the planter. A picking type pneumatic metering mechanism was developed at CAET, AAU, Godhra, Gujarat, India. Response Surface Methodology (RSM), a useful optimization technique, was used to optimized the operational parameters viz. forward speed & vacuum pressure and design parameter-nozzle hole diameter of developed planter for radish. Experiments were planned using Central Composite Design (CCD) and conducted in laboratory conditions for radish seeds. The independent parameters chosen for the study were forward speed (0.14, 0.22, 0.33, 0.44 and 0.51 m/s), vacuum pressure (19.33, 29.32, 43.98, 58.64 and 68.63 kN/m^2) and nozzle hole diameter (0.50, 0.75, 1.00, 1.25 and 1.50 mm) each with 5 levels. The effect of independent parameters was observed by assessing the miss index, multiple index, quality of feed index, and precision. The parameters under study were optimized based on values of miss index, multi index, quality feed index and precision in spacing. It was found that among different variables nozzle hole diameter was most dominating. The optimum values obtained for developed pneumatic planter were 0.23 m/s, 54.15 kN/m^2 and 1.00 mm for forward speed, vacuum pressure, and nozzle hole diameter, respectively for radish seeds. The study can be utilized for getting the optimum performance of planter for different crops, which will not only help in precisely sowing of seeds, but also result in seed saving.

Keywords: Central composite design, Picking type mechanism, Pneumatic planter, Precision machine, Singulation of seed

Introduction

Sowing of seed is one of the most important activities among different operations in crop production practices. Among different sowing methods, precision sowing is one of the most demanding methods due to uniform seed spacing and accurate placement of seed.[1,2] Precision planting by planter requires seed singulation and placement into the land. Machinery for picking of single seed for different crops has been investigated by researchers and many different types of precision machines have been developed.[3] Among these, seeders working on the principles of pneumatic metering are more prevalent for sowing different crop seeds. To use the pneumatic planters, farmers have to kept sets of metering plates matching to the size of different seeds to be planted.[4] Precision planter's accuracy in seed metering is influenced by numbers of factors. It is expected during the design phase that seeds will fall at equal distance; however, this uniformity may affected by many factors, the most significant of which are the features of seeds themselves, as well as soil conditions, machine-related characteristics, and operating factors. The physical properties of seeds are helpful in determining amount of vacuum pressure needed, diameter of holes required and peripheral speed of the vacuum plate to be maintained. Hence, vacuum pressure, diameter of hole and speed of operation along with peripheral speed of vacuum plate are among most important factors for seed singulation.

Some researchers have tried to optimize planter performance with respect to peripheral speed of plate, nozzle hole diameter and vacuum pressure. They also tried to generate generalized models for predicting optimum value of vacuum pressure for manufacturing as well as research purpose.[5–7] Very few techniques and information are available in the literature for

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predicting the design values for development of new precision planters for different seeds. This study will provide the selection criteria of parameters i.e. design as well as operational parameters during development of pneumatic planter. During a study, comparison was made among[2,3] factorial designs and models were tried to fit using Central Composite Design (CCD) for the identification of significant coefficients and required optimum operating conditions for sprayer. It was found that CCD was more efficient when a second-order surface was used to represent the data and locating optimum conditions.[8–10] Thus, CCD for optimization related studies was recommended. In order to plant radish seeds, a study was conducted on a planter based on single seed picking approach, and physical system was subjected to response methodological principles.[11] This study's goal was to use CCD techniques and Response Surface Methodology (RSM) to optimize the planter's design and operating parameters.

Materials and Methods

A picking type seed metering mechanism for a planter was evaluated in specially designed lab setup at College of Agricultural Engineering & Technology, Anand Agricultural University, Godhra, Gujarat, India (Fig. 1). The vacuum pump used to exhaust air from a reservoir that maintained below atmospheric pressure. A distributor connects the reservoir with a designed vacuum pick-up device. The pick-up devices are provided with interchangeable size nozzle (hole) for variety of seeds. The vacuum gets blocked as the nozzle reaches above the seed, sticks it and pick-up device transport it towards port knocking system. A set of 4 picking nozzles drop 1 seed each in port knocking system simultaneously. Subsequently, the port knocking then delivers the seeds to seed tube according to predefined timing to maintain desired seeding distance. The vacuum pick-up mechanism is shown in Fig. 1.

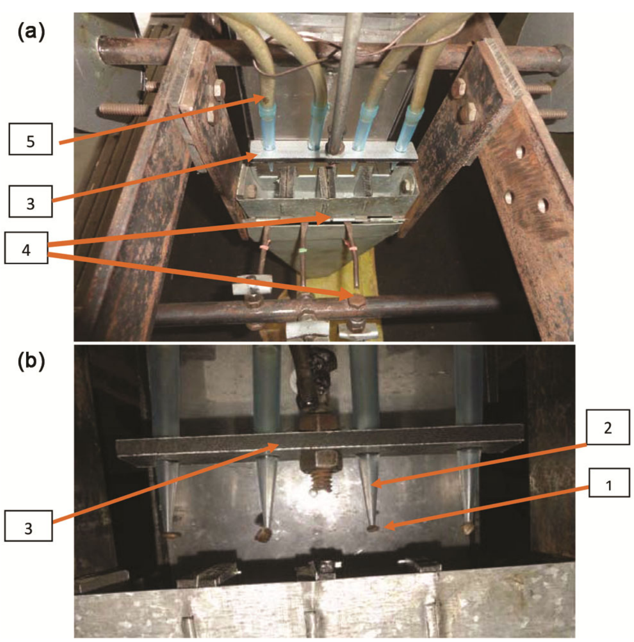

Fig. 1 — Vacuum pick-up device and port knocking system: (a) top view, (b) front view [1= Sticked seed, 2 = Vacuum nozzle, 3 = Pick-up assembly, 4 = Port knocking system, 5 = Vacuum pipe, 6 = Seed hopper]

The physical characteristics of the radish vegetable seed (variety Jaykishan early long white) used in the experiment and results are listed in Table 1.

The independent parameters chosen for the study were forward speed (0.14, 0.22, 0.33, 0.44 and 0.51 m/s), vacuum pressure (19.33, 29.32, 43.98, 58.64 and 68.63 kN/m^{2}) and nozzle hole diameter (0.50, 0.75, 1.00, 1.25 and 1.50 mm) each with 5 levels. The parameters under study were optimized based on values of miss index, multi index, quality feed index and precision in spacing, which were determined from lab test data using standard method.[5,15] Steps for optimization procedures are given in Fig. 2. Further, compared to a standard factorial technique, box-Behnken designs require fewer runs in order to obtain higher order response surfaces[18].

Experimental Procedure

The tests were carried out on a horizontal belt (0.60 m wide and 3.3 m long) with picking type seed metering mechanism set-up (Fig. 3). To create vacuum pressure of different levels, an electric motor attached to a fan was used. The greased belt was driven independently, and extra attention was taken to ensure that the belt speed and the metering mechanism's movement synchronized. The ground-driven wheel of the metering mechanism was utilized

Table 1 — Physical properties of radish seed

Sr. No.	Parameters	Mean value
1	Length (m)	3.91×10^{-3}
2	Width (m)	2.83×10^{-3}
3	Thickness (m)	2.14×10^{-3}
4	Equivalent diameter (m)	2.86×10^{-3}
5	Sphericity	0.73
6	Thousand seed weight (kg)	13.24×10^{-3}
7	Bulk Density (kg/m^3)	714
8	Porosity (%)	32.47
9	Moisture content (%)	8.30
10	Angle of repose (deg)	27°

to transfer motion to a shaft through variety of possible gears. To prevent seed bouncing, metering mechanism was installed as closely as feasible to the greased belt. To stick the falling seed, grease was spread on horizontal belt and the uniformity of seeds was determined at different parameters under study. The metering mechanism was operated at 0.14, 0.22, 0.33, 0.44 and 0.51 m/s speeds. The belt as operated at 0.33 m/s speed, which was close to mean value of speeds undertaken. The planter's travelling speed was taken into account when choosing the belt speed. The theoretical seed to seed distance of radish seed was considered as 10 cm. The setup was functioned as per first run of CCD and each run was repeated 3 times.

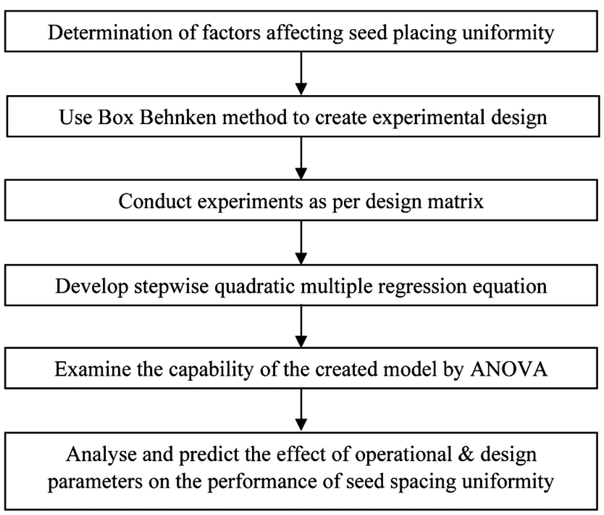

Fig. 2 — Steps for optimization of parameters

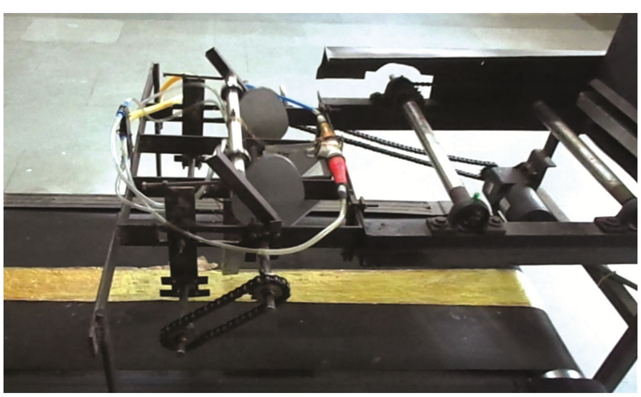

Fig. 3 — Laboratory experimental setup

After each run the spacing between seeds stuck on greased belt were measured. Standard method[11–13] was used to measure the seeding consistency performance of said precision planter. The performance was measured with respect to miss, multi and quality feed index along with precision. The same procedure was repeated for other runs for different independent parameters (Table 2). The experimental data was analyzed and inferences were drawn regarding independent parameters and their interactions along with responses.

Model Development and Optimization Procedure

A mathematical and statistical technique named Response Surface Methodology (RSM) is used to optimize operational variables (forward speed and vacuum pressure) and design values (nozzle hole diameter). This approach is comparatively takes lesser time and effort than other approaches[6,7,12,13] as number of experiments to be carried out are reduced considerably. Even than it is an effective way to optimize complex processes. The actual variables in their natural units (un-coded) of measurement are used in the experiment. The experiment in RSM uses coded variables, x_1 and x_2 centered on 0, and extend −1.682 and +1.682 from the center of the region of experimentation. Therefore, we will take our natural units and then center and rescale them to the range from −1.682 to + 1.682

The response y is a function of k independent variables $x_1, x_2, ..., x_k$, usually centers on an interest in the response surface problem. The response may be defined as $y = f(x_1, x_2, x_3, \ldots\ldots, x_k)$. The form of response surface depends upon type of response function. The response function is given below, which is generally in quadratic polynomial form:

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X_i^2 + \sum_{i=1,j=2}^{3} \beta_{ij} X_i X_j + e \quad \ldots (1)$$

where, Y- response; β_0- intercept; β_i, β_{ii}, β_{ij}- regression coefficients; X_iX_j- coded variables; e- error;

The following equation is used to express the coding of independent parameters into coded variables:

Table 2 — Coded levels of independent parameters in response surface functions

Variable Name	Code	Coded level				
		−1.682 (−α)	−1	0	+1	+1.682 (+α)
Forward speed, m/s	x_1	0.14	0.22	0.33	0.44	0.51
Vacuum pressure, kN/m^2	x_2	19.33	29.32	43.98	58.64	68.63
Nozzle hole diameter, mm	x_3	0.50	0.75	1.00	1.25	1.50

$$X_i = \frac{x_i - x_*}{d_s} \quad \ldots (2)$$

where, x_i- actual value; x_*- mean value (centre point); d_s- step value;

Level of variables in central composite design depends upon number of experimental runs in factorial portion. Rotatable CCD design was used in the study. This design requires five levels *viz.* −1.682, −1, 0, 1 and 1.682 (coded) for each independent variable under study.[9,14]

The data obtained from the experiments were analysed using a statistical package programme called Design Expert. The software used full quadratic polynomials functions and variables were entered in linear, interaction and quadratic form to select the model.

Results and Discussion

Design of Experiments

The Central Composite Design (CCD) was used to get the levels of independent variables for conducting laboratory as given in Table 3. It planter gave satisfactorily performance in relations to miss, multi and quality of feed index along with precision for run No. 8 and 13. The quadratic model were tested to find adequacy or describing the response surface.

Effect of Nozzle Hole Diameter and Vacuum Pressure on Miss Index

The miss index models both in terms of coded and un-coded values are given by Eqs. 1 & 2. Table 4 shows the results of stepwise regression values of each independent parameter. The model was found significant by observing the analysis of variance. The chances are very less (0.01%) for occurrence of this model F value. It was observed that X_2X_3, X_3^2, X_2^2, X_2, X_1^2 and X_1X_2 significantly contributed in miss index model factor. From the function it was observed that the most important factors for miss index were interaction of nozzle hole diameter and vacuum pressure and followed by nozzle hole diameter and vacuum pressure. The model terms are significance as shown by values greater than 0.100. The model lack of fit was found to be non-significant (Table 4).

The "R-squared" values obtained were 0.99, 0.81, 0.76 and 0.63 for miss index, multi index, quality feed index and precision, respectively. These values showed effectiveness of overall mean in predicting response over current model. Also, these values are in agreement with the "Adj R-squared" values of 0.98, 0.79, 0.73 and 0.53, respectively (Table 5). This model will be useful in deciding the design

Table 3 — Independent variables with coded and un-coded values

Run No.	Independent variables			Run no.	Independent variables		
	X_1 [x_1, m/s]	X_2 [x_2, kN/m^2]	X_3 [x_3, mm]		X_1 [x_1, m/s]	X_2 [x_2, kN/m^2]	X_3 [x_3, mm]
1	0 [0.33]	0 [43.98]	0 [1]	11	0 [0.33]	0 [43.98]	0 [1]
2	1.682 [0.51]	0 [43.98]	0 [1]	12	−1 [0.22]	−1 [29.32]	1 [1.25]
3	0 [0.33]	0 [43.98]	−1.682 [0.5]	13	1 [0.44]	−1 [29.32]	−1 [0.75]
4	−1 [0.22]	1 [58.64]	−1 [0.75]	14	0 [0.33]	0 [43.98]	0 [1]
5	0 [0.33]	0 [43.98]	0 [1]	15	0 [0.33]	−1.682 [19.33]	0 [1]
6	0 [0.33]	0 [43.98]	0 [1]	16	0 [0.33]	0 [43.98]	0 [1]
7	0 [0.33]	1.682 [68.63]	0 [1]	17	−1.682 [0.14]	0 [43.98]	0 [1]
8	−1 [0.22]	−1 [29.32]	−1 [0.75]	18	1 [0.44]	1 [58.64]	1 [1.25]
9	0 [0.33]	0 [43.98]	1.682 [1.5]	19	1 [0.44]	1 [58.64]	−1 [0.75]
10	1 [0.44]	−1 [29.32]	1 [1.25]	20	−1 [0.22]	1 [58.64]	1 [1.25]

Table 4 — Values of variables obtained by stepwise regression analysis for miss index model

Variable	Coefficient	Standard error	Probability, (P)	Coefficient of determination (R^2), %
Constant	13.18		—	—
X_2X_3	0.08	3.24	<0.0001	61.04
X_3^2	0.14	3.361×10^{-3}	<0.0001	91.53
X_2^2	0.077	8.514×10^{-3}	0.0016	95.53
X_2	9.85	0.48	0.0080	97.25
X_1^2	0.023	2.49	0.0291	98.06
X_1X_2	-7.366×10^{-3}	3.365×10^{-3}	0.0474	98.59

Table 5 — Precision adequacy and coefficient of determination and of different output model

Parameter	Adeq precision	R-square	Adj R-square	Pred R-square
Miss index	35.77	0.99	0.98	0.93
Multi index	19.12	0.81	0.79	0.71
Quality feed index	14.67	0.76	0.73	0.59
Precision in spacing	8.71	0.63	0.53	0.39

parameters for seed metering mechanism based on pneumatic principle.

From Table 4 it is clear that the combination of nozzle hole diameter and vacuum pressure was found to be most important variable accounting 61.04% in governing the seeding phenomenon for radish crop (Table 4). However, 30% contribution was due to vacuum pressure.

Response surfaces drawn in Fig. 4 using polynomial functions shows the behavioral consistency of metering unit in response to parameters under study.

Miss index model having un-coded factors

$$I_{miss} = 4.0622 - 1.0198\,x_1 - 0.0246x_2 - 5.7839\,x_3 - 5.872 \times 10^{-4}\,x_1x_2 + 5.9425 \times 10^{-3}\,x_2x_3 + 1.8481\,x_1^2 + 1.7358 \times 10^{-4}x_2^2 + 2.3479\,x_3^2 \quad \ldots (1)$$

Miss index model having coded factors

$$I_{miss} = 13.18 + 6.785 \times 10^{-4}X_1 + 10.53X_2 + 0.22\,X_3 - 7.105 \times 10^{-3}\,X_1X_2 + 0.16\,X_2X_3 + 0.22\,X_1^2 + 2.10\,X_2^2 + 0.15\,X_3^2 \quad \ldots (2)$$

Effect of Nozzle Hole Diameter and Vacuum Pressure on Multi Index

The significant factors for multi index model were X_3 and X_3^2 as given by Eqs 3 & 4. The chances are very less (0.01%) for occurrence of this model F value. The model developed for multi index was found to be significant 1% level of significance by observing the analysis of variance. Nozzle hole diameter was found to be most important factor for multi index of seed. As the nozzle hole diameter increased multi index increased. The model terms are significance as shown by values greater than 0.100. The model lack of fit was found to be non significant.

The "Pre R-squared" values of the different models were obtained 0.71 in comparison to "Adj R-squared" of 0.79 for the same models (Table 5). The stepwise regression analysis results are given in Table 6 for each function. It was observed that multi index did not depend on operating speed and vacuum pressure.

Optimum levels of different variables were obtained by taking the partial derivatives of Eqs 3 & 4 with respect to each independent variable. Different models gave optimum values for nozzle hole diameter and vacuum pressure, but these values were almost similar. Response surfaces were drawn with the help of polynomial functions, which are given in Fig. 5.

Multi index model having un-coded factors

$$I_{multi} = 1.0186 - 2.6281\,x_3 + 1.6782\,x_3^2 \quad \ldots (3)$$

Multi index model having coded factors

$$I_{multi} = 0.069 + 0.18\,X_3 + 0.10\,X_3^2 \quad \ldots (4)$$

Effect of Nozzle Hole Diameter and Vacuum Pressure on Quality Feed Index

The vacuum pressure, operational speed, and nozzle hole diameter are the governing variables for

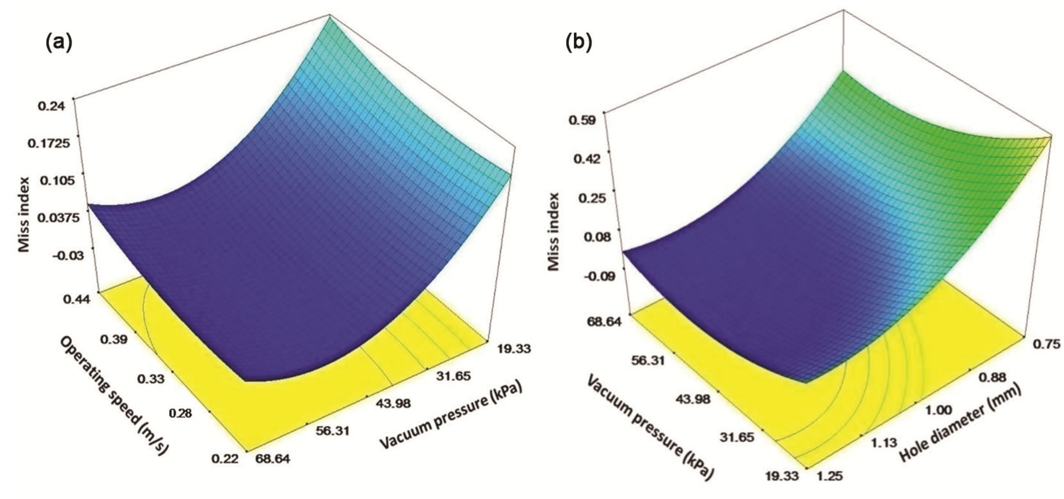

Fig. 4 — Effect of parameters on miss index

Table 6 — Stepwise regression analysis results for multi index model

Parameter	Coefficient	Standard error	Probability, (P)	Coefficient of determination (R^2), %
Constant	0.069	0.026	—	—
X_3	0.180	0.025	<0.0001	59.76
X_3^2	0.100	0.024	0.004	81.07

quality feed index. Out of these 3 parameters nozzle hole diameters contributed maximum (75.10%). The precision models in terms of coded and un-coded factors are stated in Eqs 5 & 6. The results obtained from stepwise regression analysis are given below in Table 7.

The probability level for model is significant. Also, the data shows good lack of fit for the model. The values of "Adj R-squared" and "Pre R-squared" of the different parameters under study are given in Table 5. Response surfaces drawn using polynomial functions are given in Fig. 6. It shows the behavioral consistency of metering unit in response to parameters under study.

Quality feed index model having un-coded factors

$$\mathrm{I_{qf}} = -3.1489 + 7.97541\, x_3 - 3.9385\, x_3^2 \quad \ldots (5)$$

Quality feed index model having coded factors

$$\mathrm{I_{multi}} = 0.89 + 0.025\, X_3 - 0.25\, X_3^2 \quad \ldots (6)$$

Effect of Nozzle Hole Diameter and Vacuum Pressure on Precision

Out of three parameters under study, nozzle hole diameters affects the precision of metering mechanism maximum. The chances are very less (0.01%) for occurrence of this model F value. The operational speed did not affected the quality feed index.

The stepwise quadratic multiple regression developed was found to be highly significant. Similar type of equation was development for site specific grape vineyard fertilizer applicator prototype.[16] The results of stepwise regression analysis are given in Table 8. The coefficient of determination was found maximum for vacuum pressure followed by interaction of nozzle hole diameter and vacuum pressure.

The precision models in terms of coded and un-coded factors are stated in Eqs 7 & 8. Out of three parameters under study, contribution of nozzle hole diameters was maximum (33.88%) followed by interaction of vacuum pressure with nozzle hole diameter (62.65%). Response surfaces drawn using polynomial functions are given in Fig. 7.

Precision model in terms of un-coded factors

$$\mathrm{I_{prec}} = 39.2901 - 0.05356\, x_2 - 69.3989\, x_3 + 0.04717\, x_2 x_3 + 30.0786\, x_3^2 \quad \ldots (7)$$

Precision model in terms of coded factors

$$\mathrm{I_{prec}} = -2.14 - 0.70\, X_2 + 1.58\, X_3 + 1.30\, X_2 X_3 + 1.88\, X_3^2 \quad \ldots (8)$$

Optimum Value of parameters

The results of stepwise quadratic regression analysis found the validity of models for the following conditions:

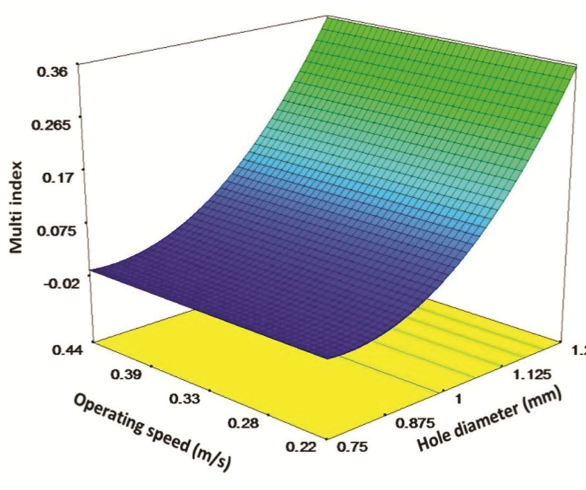

Fig. 5 — Effect of parameters on multi index

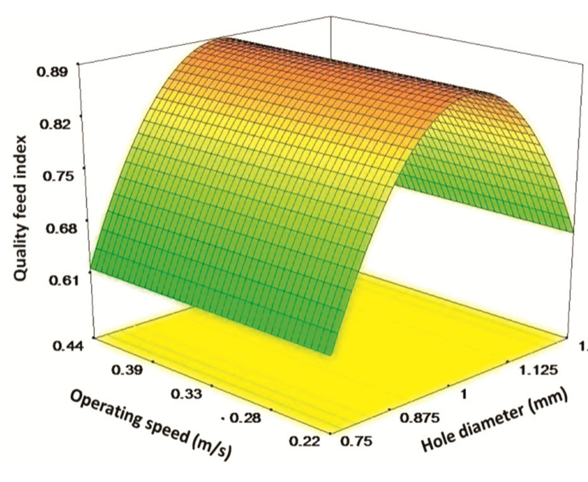

Fig. 6 — Effect of parameters on quality feed index

Table 7 — Stepwise regression analysis results for quality feed index model

Variable	Coefficient	Standard error	Probability, (P)	Coefficient of determination (R^2), %
Constant	0.89	0.037	—	—
X_3^2	−0.25	0.033	<0.0001	75.10

Table 8 — Stepwise regression analysis results for precision model

Variable	Coefficient	Standard error	Probability, (P)	Coefficient of determination (R^2), %
Constant	−0.31	0.52	—	—
X_3^2	1.88	0.19	0.0071	33.88
X_2X_3	0.69	0.48	0.0021	62.65

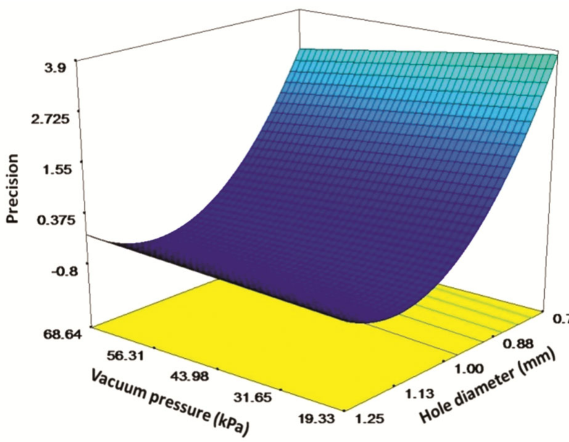

Fig. 7 — Effect of parameters on Precision

$0.22 \text{ m/s} < v > 0.44 \text{ m/s}$

$29.32 \text{ kN/m}^2 < p > 58.64 \text{ kN/m}^2$

$0.75 \text{ mm} < d > 1.25 \text{ mm}$

The optimum design value of operating speed, vacuum pressure and nozzle hole diameter for radish crops were obtained by taking the partial derivatives of Eqs 1 to 8 with respect to each independent variable. The optimum value of 1.00 mm nozzle hole diameter and 54.15 kN/m^2 vacuum pressure and 0.23 m/s operating speed were obtained from different models of performance parameters.

Conclusions

Response Surface Methodology (RSM) is used to optimized the design and operating parameters of picking type pneumatic planter needs for getting the desired performance for radish seeds. The equations developed for miss, multi and quality feed index as well as precision may be used for estimating the performance of similar type planters/pneumatic planters as used under such operating conditions. The coefficient of determination for miss index, multi index, quality feed index and precision in spacing was 0.99, 0.81, 0.76 and 0.63, respectively. Results shows that nozzle hole diameter was most important parameter followed by vacuum pressure for radish seed planting. The optimum values obtained for developed pneumatic planter were 0.23 m/forward speeds, 54.15 kN/m^2 vacuum pressure and 1.00 mm nozzle hole diameter for radish seeds. The similar optimization technique may be carried out for different crops and optimum values of parameters may be find out for getting optimum performance of planter.

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