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Response surface modeling of low-cost pneumatic nursery protray seeder parameters for tomato (*Solanum lycopersicum*) seedlings

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ABSTRACT

The performance of pneumatic nursery protray seeder was evaluated in terms of miss seeding, single seeding, multiple seeding, seeding efficiency, and seeder output for different levels of mouthpiece diameter and suction pressure for tomato (*Solanum lycopersicum* L.). With a mouthpiece diameter of 0.84 mm and suction pressure of 6.2 kPa, it was found that 59.25% of single seeding, 97.69% seeding efficiency, and a seeder output of 67 cells/min were suitable for tomato seedlings. The pneumatic protray seeder resulted in a saving of ₹15.04 per 1000 cells sown compared to manual seeding. The payback period was 104.7 hours (3.58% of the expected life of pneumatic protray seeder).

Key Words: Mouthpiece diameter, Nursery protray seeder, Optimization, Suction pressure, Suction unit, Seedlings

Protray seedling production under protected cultivation is a promising technology that fulfills this requirement, providing benefits to both growers and entrepreneurs (Singh, 2013; Saiful-Islam *et al*., 2002). It also enables growers to perform timely planting to maximize the benefits from healthy seedlings (Barik *et al*., 2020). However, manual seeding in protray is a labor-intensive and highly tiresome operation, taking around 8 man-hours for seeding in 100 protrays with a total of 9,800 cells (Nandede *et al*., 2017). The farm power availability in the country has increased from 0.25 kW.ha-1 to 4 kW.ha-1 between 1951 and 2022 (Chandra-Shekara, 2022). Mechanical advancements can enhance the speed and precision of protray seeding operations. However, commercially available seeders are generally designed for large-scale nursery management and are not affordable for small and marginal growers (Rathinakumari *et al*., 2020). Several seeders have been developed for protray seeding, utilizing various principles of operation, such as mechanical (Sriwongras and Dostál, 2014), magnetic (Jianping *et al*., 2003; Yan *et al*., 2013), and pneumatic (Gaikwad *et al*., 2007; Kim *et al*., 2011; Rathinakumari and Kumaran, 2020; Xia *et al*., 2021; Jadhav *et al*., 2023). Due to their desired output, pneumatic devices are preferred for protray seeding. Hence, this study was carried out to optimize a small and cost-effective pneumatic protray seeder.

MATERIALS AND METHODS

The seeder consists of seed picking mouthpieces, a cut-off device, a pressure regulating unit, and a suction unit. Hypodermic needles were used as seed picking mouthpieces, enabling seed picking through the effect of negative pressure controlled by a cut-off device. A flexible pipe was utilized to connect the seeding unit to the pressure regulating assembly, facilitating ease of movement for the seeder. The pressure regulating assembly includes a pressure dial gauge and a control valve connected to the suction unit. The optimization was conducted for DS-21 cultivar of tomato (*Solanum lycopersicum*) seeds in a protray containing 104 circular cells (13×8). The moisture content of the seeds was recorded as 9.71% on a wet basis.

The seeder pipe was constructed using a 12.7 mm diameter and 330 mm long hollow CPVC (Chlorinated Poly Vinyl Chloride) pipe. As the selected protray consisted of 8 cells in a row, the seeder was equipped with 8 seed picking units spaced at a uniform distance of 38 mm, similar to spacing between two consecutive

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cells in protray (Fig. 1). Seed picking mouthpieces were created by trimming nibs of hypodermic needles to a suitable and uniform height. When designing the parts of seeding and planting devices, engineering properties of seeds such as width, geometric mean diameter, thousand seed weight, bulk density, true density, and angle of repose are of utmost importance (Jadhav *et al.*, 2020; Jayan and Kumar, 2004; Singh *et al.*, 2018). The range of mouthpiece diameter selected was based on seed size (Yitao *et al.*, 2017). Needles with gauge sizes (diameters) of 20 (0.60 mm), 18 (0.84 mm), and 16 (1.19 mm) were chosen. The seeder assembly consists of a cut-off device to control the supply and stoppage of suction pressure. To facilitate the handling of seeder assembly without hindrance, it is connected to the pressure regulating assembly by a flexible hose pipe with a thickness of 2 mm, which sustains the suction pressure. The pressure regulating assembly includes a pressure dial gauge (make: Imperial Precision Engineering Pvt. Ltd) and a control valve (CPVC ball valve) connected to the suction unit to maintain the desired pressure in the line. A household vacuum cleaner (make: Eureka Forbes, model: Easy Clean Plus) was used as the suction source. The dimensions of the seed holder were determined based on the engineering properties of the seeds, such as weight and bulk density (Jadhav *et al.*, 2017). To facilitate the flow of seeds towards the bottom center of the seed holder, a half-circle cross-section shape was employed. The length of the seed holder (320 mm) exceeded the distance between the farthest picking units on the seeder pipe

1, Mouthpiece; 2, seeder pipe; 3, pressure cut-off device; 4, flexible hose pipe; 5, pressure dial gauge; 6, pressure control valve; 7, suction unit; 8, protray

Fig. 1. Components of pneumatic protray seeder

The seed holder containing seeds was placed above the tray filled with soil media. Adequate line pressure was maintained as the pneumatic tray seeder drew in the seeds through suction. When the cut-off unit was in the pressed position, suction pressure was supplied to the seeder pipe, enabling seeds to be drawn from the seed holder using the mouthpiece. The cut-off unit was then released as seeder pipe moved over the cells to be sown. Once the pressure supply ceased, the seeds held by the mouthpiece were deposited into the cells of the tray.

The parameters that significantly influence the performance of pneumatic seeding devices are the mouthpiece diameter and suction pressure (Ismail, 2008). Therefore, impact of varying mouthpiece diameters from 0.60 to 1.19 mm and suction pressures ranging from 4 to 6.2 kPa was investigated to assess their effect on seeder performance. To facilitate easy detection of yellow-colored seeds, white-colored paper pieces were affixed to the bottom of the tray cells. The following mathematical expressions (Abdulkadir *et al.*, 2019; Jadhav *et al.*, 2023) were utilized to calculate the dependent parameters, namely miss seeding (MS), single seeding (SS), multiple seeding (MUS), seeding efficiency (SE), and seeder output (SO), in the laboratory.

$$\text{Miss seeding, \%} = \frac{\text{Number of cells without any seed after sowing}}{\text{Total number of cells}} \times 100 \qquad (1)$$

$$\text{Single seeding, \%} = \frac{\text{Number of cells with single seed after sowing}}{\text{Total number of cells}} \times 100 \qquad (2)$$

$$\text{Multiple seeding, \%} = \frac{\text{Number of cells with more than one seeds after sowing}}{\text{Total number of cells}} \times 100 \qquad (3)$$

$$\text{Seeding efficiency, \%} = \frac{\text{Number of cells with atleast one seed after sowing}}{\text{Total number of cells}} \times 100 \qquad (4)$$

$$\text{Seeder output, cells.min}^{-1} = \frac{\text{Total number of cells sown}}{\text{Time required for sowing}} \qquad (5)$$

Miss seeding refers to the absence of seeds and is considered an undesirable parameter, thus its value should be minimized. Conversely, single seeding is desirable as it signifies the proper utilization of inputs. Higher values of multiple seeding indicate greater seed wastage. Seeding efficiency is an important parameter as it reflects the actual population of cells in the tray that contain seeds. Seeder output is a necessary parameter for determining the operational cost of the seeder.

A full factorial experiment was conducted using a completely randomized design to examine the effects of the independent parameters. The experiment comprised 12 treatment combinations, including three mouthpiece diameters (0.60 mm, 0.84 mm, and 1.19 mm) and four suction pressures (4.1 kPa, 4.8 kPa, 5.5 kPa, and 6.2 kPa). Each treatment was replicated three times to enhance error estimation. The experiments were carried out for duration of ten minutes, and the dependent parameters were manually observed and recorded for calculation.

To optimize the parameters of the pneumatic protray seeder, Response Surface Methodology (RSM) was employed using the Stat-ease Design Expert-10 software. Second-order polynomial equations were fitted to analyze the behavior of the dependent parameters. Numerical optimization was performed to suggest the best treatment combination for tomato seeding in the portray.

RESULTS AND DISCUSSION

The ANOVA results demonstrate that the models for miss seeding (MS), single seeding (SS), multiple seeding (MUS), seeding efficiency (SE), and seeder output (SO) were highly significant at a significance level of 0.01% (Table 1). Additionally, the coefficient of determination values for all models exceeded 85%. Consequently, models were deemed capable of accurately representing the variability of the responses.

The linear and quadratic terms of regression equation shows the individual effects of independent parameters. The linear effect of MD was most significant at 0.01% significance level for all the five responses. The negative linear coefficient for *MS* and *SS* indicates that increase in MD decreased both the parameters. On the other hand MUS, SE and SO had positive linear component of *MD*. The quadratic term of MD affected the MS, MUS and SE significantly at 0.01% significance level and the *SS* at 1% level of significance but had no effect on SO. Positive sign of quadratic component of MD explained that the values of MS and SS were increased after central level of MD. Similar to the MD, the linear component of SP also showed a statistically significant ($p<0.0001$) effect on all the responses under study. The linear component of SP had inverse relation with MS and direct relation with remaining parameters, as denoted by the signs of their respective coefficients. Quadratic term of SP possessed no effect on any of the response, except MUS. The negative coefficient showed that after central level, MUS decreased with increasing SP^2.

The interaction between MD and SP was found highly significant at 0.01% level of significance for MS, SS and QS. Also, the term had most significant effect at 1% level of significance on MUS. However, there was no effect of interaction was recorded on *SO*. Fig. 2 (a) shows that at all levels of SP, the MS reduced with increase in MD for the selected experimental range. Similarly for any MD, increase in SP also decreased the MS. The reason may be that with the increased MD and *SP*, suction force was easily able to overcome seeds inertia. Fig. 2 (b) shows that initially increasing in MD at given *SP*, reduced SS. However, after certain value further increase in MD stabilized the *SS*. However, when *SP* was increased at any MD in experimental range, *SS* was improved. The behavior is obvious as in lower range *MS* was more and in higher range *MUS* was more Fig. 2(c). It can also be observed that increasing *SP* at any given level of MD did not increased MUS significantly. The behavior was also reflected by the F values of MD and SP in ANOVA. Fig. 2(d) showed that initially increasing MD and SP resulted in increased *SE* and saturated after certain value.

The quadratic regression equations for the dependent parameters *viz*. MS, SS, MUS, SE and SO

Table 1. ANOVA of response surface regression experiment for tomato protray seedings

	Miss seeding (%)		Single seeding (%)		Multiple seeding (%)		Seeding efficiency (%)		Seeder output (cells.min^{-1})	
SOV	F value	Coeff.	F value	Coeff.	F value	Coeff.	F value	Coeff.	F value	Coeff.
Model	175.64***	9.86	256.58***	48.05	1531.07***	42.09	175.64***	90.14	40.49***	62.63
MD	385.43***	-8.57	1120.98***	-18.27	7496.93***	26.84	385.43***	8.57	38.22***	1.91
SP	420.57***	-9.84	106.08***	6.17	115.80***	3.66	420.57***	9.84	162.39***	4.32
MD×SP	33.39***	3.37	44.11***	-4.83	12.60**	1.47	33.39***	-3.37	0.13^{NS}	-
MD^2	37.25***	4.81	10.54**	3.20	204.81***	-8.01	37.25***	-4.81	078 ^{NS}	-
SP^2	2.03^{NS}	-	23.76^{NS}	-	9.36***	-1.74	2.03^{NS*}	-	1.14E-003^{NS}	-
Mean	14.29		51.69		34.02		85.71		62.16	
R^2	0.97		0.98		0.99		0.97		0.87	

MD, Mouthpiece diameter, mm; SP, Suction pressure, kPa; R^2, Coefficient of determination; Coeff., Coded coefficients of regression equations; ***significant at $p<0.0001$; **significant at $p<0.05$; *significant at $p<0.01$.

of developed pneumatic protray seeder with their R^2 are represented by equation 6 to 10, respectively.

$$MS = 205.97 - 183.98\,MD - 29.76\,SP + 10.87\,MD \times SP + 55.28\,MD^2 \ldots \left(R^2 = 0.97\right) \quad (6)$$

$$SS = 45.14 - 47.31\,MD + 14.23\,SP - 15.61\,MD \times SP + 36.73\,MD^2 \ldots \left(R^2 = 0.98\right) \quad (7)$$

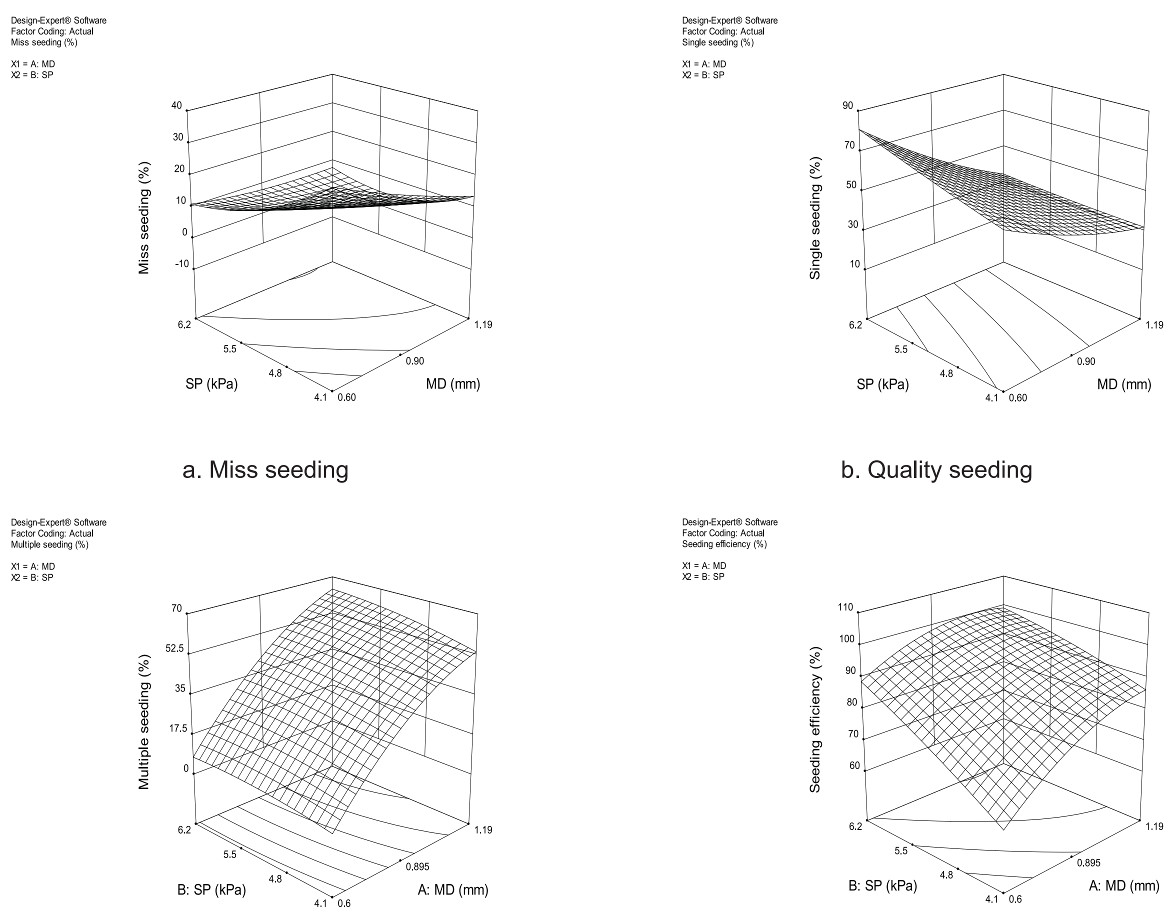
$$MUS = -151.11 + 231.29\,MD + 15.53\,SP + 4.74\,MD \times SP - 92.01\,MD^2 - 1.58\,SP^2 \ldots \left(R^2 = 0.99\right) \quad (8)$$

$$SE = -105.97 + 183.98\,MD + 29.76\,SP - 10.87\,MD \times SP - 55.28\,MD^2 \ldots \left(R^2 = 0.97\right) \quad (9)$$

$$SO = 28.43 + 19.08\,MD + 4.73\,SP \ldots \left(R^2 = 0.87\right) \quad (10)$$

To achieve an acceptable output from the developed seeder, optimization was carried out by applying criteria to SS, MUS, SE, and SO. The desired output aimed for the least MS and MUS while maximizing SS, SE, and SO. Numerical optimization was conducted with the following criteria: MD and SP were kept within the specified range, MS and MUS were set to minimize, and SS, SE, and SO were set to maximize. Table 2 presents some of the solutions suggested by the Design Expert software.

In the first solution, SS was deemed acceptable at 81.13%. However, the higher MS (11.18%) and lower SE (88.82%) could result in a higher likelihood of empty cells, thus making this solution unfavorable. The second solution had a good SE value of 90.04%, but the MUS was considerably high (60.22%), and the MS remained relatively high (6.97%). Due to the potential increase in seeding costs associated with these factors, the second solution was rejected.



a. Miss seeding   b. Quality seeding

c. Multiple seeding   d. Seeding efficiency

Fig. 2. Surface plot for interaction between mouthpiece diameter and suction pressure

Table 2. Solutions suggested by numerical optimization

Mouthpiece diameter, mm	Suction pressure, kPa	Miss seeding, %	Single seeding, %	Multiple seeding, %	Seeding efficiency, %	Seeder output, cells.min^{-1}	Desirability
0.60	6.2	11.18	81.13	7.69	88.82	65	0.79
1.19	5.0	6.97	32.82	60.22	93.04	63	0.29
0.84	6.2	2.30	59.25	38.45	97.69	67	0.71

The third solution exhibited SS and MUS values of 59.25% and 38.45%, respectively. Although the MUS value was higher, the MS value (2.30) was the lowest among all the solutions. The preference for multiples over misses lies in ensuring the presence of seeds in cells. Furthermore, the SE value (97.69%) was found to be the maximum in this solution. Considering these justifications, the third solution was selected as the optimized solution, using a 0.84 mm mouthpiece diameter and 6.2 kPa suction pressure.

The solution of numerical optimization is shown in the form of overlay plot (Fig. 3) by superimposing the significant responses in respect to interaction of MD and SP.

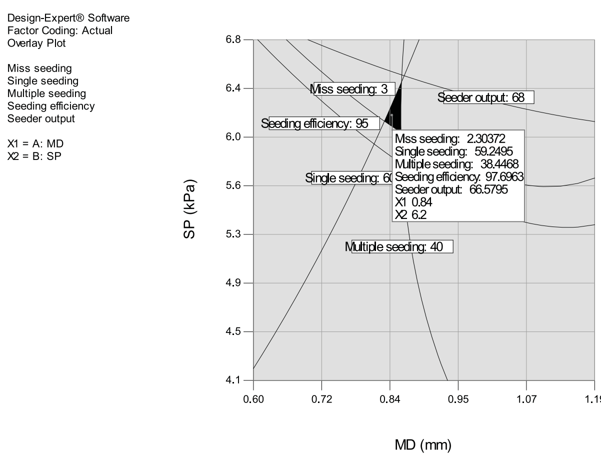


Fig. 3. Overlay plot

The cost of seeding using the developed pneumatic protray seeder was calculated and compared with manual operation. The development cost of the seeder was ₹5,600. The capacity of manual seeding was determined to be 1,225 cells per hour, while the developed seeder had a capacity of 3,350 cells per hour. The cost of seeding 1,000 cells manually was found to be ₹30.61, whereas the cost with the developed seeder was ₹15.04, resulting in a total saving of ₹15.57 using the pneumatic seeder.

The payback period, considering the hours of seeder operation and its total expected life, was determined to be 104.7 hours and 3.58%, respectively.

CONCLUSION

The operational cost of the protray seeder was determined to be ₹15.04 per 1000 cells. The payback period, calculated based on the hours of seeder operation and its total expected life, was found to be 104.7 hours, with a total expected life of 3.58%.

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