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RESEARCH PAPER

Development of precision pneumatic hill drop planter and fertilizer drill for direct seeded rice: a response surface modelling approach

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Abstract
Hill direct seeded rice endorses the time and labour economy, offers effective aeration, minimizing the chances of pest occurrences, and fostering favorable and sustained long-term development. In this context, the study was intended to develop a tractor-drawn eight-row precision pneumatic hill drop planter cum fertilizer drill for planting 2 ± 1 rice seeds per hill at 250×250 mm spacing. It had rotating drum type metering device which worked as suction chamber from inside. The outer surface of drum possessed ten pairs of orifices for each row of planter. The planter comprised of seed agitating devices, cut-off plates, spill out chamber and seed scraping devices for enhanced performance. Laboratory evaluation was conducted at three orifice diameters (1.0, 1.5 and 2.0 mm) and four suction pressures (1, 2, 3 and 4 kPa) at 0.83 m/s forward speed of sticky belt for response surface optimization. The criterion was to maximize quality seeding and seeding efficiency with minimum over seeding. The orifice diameter of 1.5 mm and suction pressure of 4 kPa was found suitable with 80% quality seeding and 93% seeding efficiency. The recommended dose of fertilizer was achieved at 75% opening of fertilizer hopper sliding gate. The seed rate, field capacity and field efficiency was recorded as 14.20 kg/ha, 0.42 ha/h and 70.36%, respectively during the field evaluation. The cost of operation was ₹ 983.74/ha. Hence, the developed planter was found suitable for rice hill dropping with fertilizer placement at the optimized levels of selected parameters.

Keywords Hill dropping · Direct seeded rice · Pneumatic metering drum · Tractor drawn planter

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Introduction

India's rice production has increased at a compound annual growth rate of 1.54% during 2008–2018 irrespective of any substantial increase in cultivated area (nearly 44.5 mha) and presently contributes about 22% of global rice production (FAOSTAT 2021). The credit is bagged by hybrid cultivars, fertilizers, pesticides, irrigation etc. However, their excess use not only put unnecessary economic burden on farmers but deteriorates the soil, environment and human health as well. Mechanized precision agriculture implies need-based systematic application of these inputs and has the potential to increase productivity and maintain sustainability to meet the demands of the increasing population (Tiwari 2016; Mehta et al. 2020).

Direct seeded rice (DSR) is presently practiced over 28 and 23% of rice cultivated area in country and across the globe, respectively; and getting popular due to ease of operation as compared to transplanting, less water requirement andits less labour requirement of during peak season of plant establishment (Mohapatra et al. 2012; Mahender et al. 2015;

Sandhu et al. 2021). DSR eliminates the need of puddling (Dry-DSR), nursery preparation, seedling uprooting and transplanting operation. Higher labour use for weed management has been reported by several studies, however effective weed control by herbicides substantially reduced the labour requirement (Kumar and Ladha 2011). The mechanization of DSR mainly includes mechanical drilling and hill planting. It is difficult to maintain the precision in former method, resulting in uneven seed distribution and causes difficulty in post emergence field operations. Hill planting has overcome these disadvantages and possesses the benefit of time, water and labour saving, with proper root zone aeration, mitigating the diseases and pests attack and promoting healthy growth. Also, seed input reduction from 80–120 kg/ha to 20–25 kg/ha can be achieved (Kumar and Ladha 2011).

Modern rice cultivation uses hybrid and super hybrid seeds, which are costly but highly viable. Super hybrid rice, a kind of hybrid rice, has stronger tillering ability than ordinary hybrid. In ideal agronomic conditions, single plant per hill is capable of high output with these varieties. However, practically 2 ± 1 seeds per hill are recommended for satisfactory crop establishment (Rao et al. 2013).

Available precision planters with horizontal, vertical, inclined plate and cup type seed metering devices have limitations viz. more seed damage and demand of uniform seed morphology (Ryu and Kim 1998; Singh et al. 2005). Ryu and Kim (1998) designed a roller-type-metering mechanism for hill dropping of rice seeds. In the field testing, it was observed that scattering distance ratio (SDR) was less in case of designed roller as compared to old roller. Four different settings of seed tubes were also evaluated *i.e.* bent, wide, no and narrow. The narrow tube was found most suitable with SDR less than 30. Rajaiah et al. (2016) tested an electronically controlled inclined plate metering device for rice seeding. Laboratory evaluation was resulted in 88% quality feed index and 6% miss index at optimized levels of operational speed, shape of cells in metering device and its inclination with horizontal. Sahu and Verma (2016) also conducted a laboratory evaluation of inclined plate metering system for rice at three different inclination angles and rotational speeds, and found that the values of quality feed index, miss index, seed rate and seed damage were 88.3%, 7.7%, 13.3 kg/ha and 0.19%, respectively at rotational speed of 15 rpm with 45° inclination. Rajaiah et al. (2020) evaluated a nine row precision planter with inclined plate type metering mechanism for direct seeding of rice in field. The results showed that optimum seed rate of 20.15 kg/ha with 90.5% quality feed index was achieved with slanting-cell type inclined plate with 35° inclinations at 0.55 m/s forward speed. Valentin et al. (2023), developed a precision drum type metering device for carrot hill dropping with 2–4 seeds per hill. The seeder was evaluated at seven operating speeds ranging between 0.34 and 0.89 m/s. The seeder performed well at 0.7 m/s with 0.09–0.16 m mean hill center and 0–5.5% missed hills. Pneumatic planters are attracting attention to cope with these limitations. Modifications are also made in modular disc type pneumatic planter to meter multiple seeds per hill (Yasir et al. 2013; Zhang et al. 2014, 2015; He et al. 2017; Ibrahim et al. 2018; Li et al. 2023; Mahapatra et al. 2024). Karayel et al. (2004) evaluated the four different forward speed ranging from 0.5 to 2 m/s and three types of seed plates having two, three and four orifices for melon and watermelon seeds. The scattering distance ratios at 0.5 and 1.0 m/s forward speed were acceptable *i.e.* 20–30%. A vacuum seeder with vacuum plate having 36 sets of double-hole was evaluated by Topakci et al. (2011) for hill dropping of sesame seeds. The study suggested to use modified seed metering mechanism for hill dropping. The longitudinal dispersion of seeds in a hill became a major limitation due to different time of fall in these devices. Hence, the trend is diverting towards drum-type pneumatic devices (Zhang et al. 2015; He et al. 2017; Wang et al. 2018). Therefore, an attempt was made to develop and optimize a tractor drawn eight-row precision pneumatic hill drop planter cum fertilizer drill to meet the planting requirements with reduced design complexity and cost of operation.

Materials and methods

Concept of developed tractor drawn eight-row precision pneumatic hill drop planter cum fertilizer drill (PHDP cum fertilizer drill)

The developed PHDP cum fertilizer drill (Fig. 1) was intended to convey the desired number of seeds from the seed box and plant them in the field at the predefined spacing. The desired number of seeds per hill, hill to hill and row to row spacing were selected as per the agronomic recommendations and reported in Table 1 (Sinha and Talati 2007; Ibrahim and Ismail 2014; Ganapathi and Kumar 2015; He et al. 2017).

The developed tractor drawn eight-row PHDP cum fertilizer drill possessed a drum-type pneumatic seed metering device with ten pairs of orifices for each row on its circumference, a gasoline engine operated blower to create necessary suction pressure, seed boxes, a churning device for seed agitation, cut-off plates and a spill out chamber to manage excess seeds carried on the drum surface, a scrapping plate to mechanically release seeds from the rotating drum to the seed tube, fertilizer boxes with vertical plate type metering unit and shoe type furrow openers.

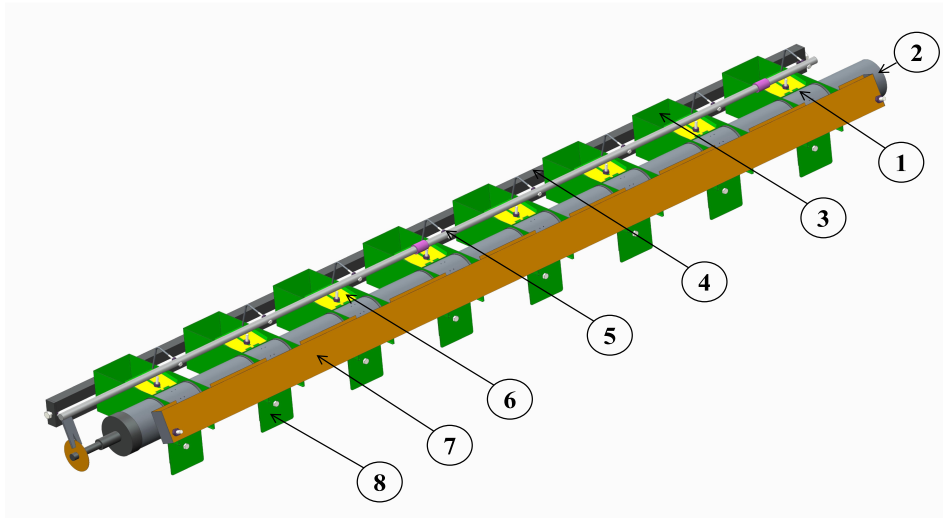


Fig. 1 Conceptual drawing of developed metering device

1. Metering device, 2. Towards suction source, 3. Seed box, 4. Supporting structure, 5. Seed agitating device, 6. Cut-off plate, 7. Spill out chamber, 8. Seed scraping device.

Table 1 Specifications of the developed tractor drawn eight-row PHDP cum fertilizer drill

Parameter	Details
Prime mover	Tractor (30 kW and above)
Suction source	Gasoline-powered engine (2.83 kW)
Overall dimensions	3254 × 1247 × 1162 mm
Total weight	238 kg
Seed metering device	Pneumatic drum type (Ø90 mm)
Desired seed numbers/hill	2 ± 1
Row to row spacing	250 mm
Plant to plant spacing	250 mm
Fertilizer metering device	Vertical plate type

Engineering properties of selected rice cultivar

The engineering properties of selected rice cultivar (Paddy Kranti) having 9.44 ± 0.57% dry basis moisture content were determined in the engineering properties laboratory, ICAR-Central Institute of Agricultural Engineering, Bhopal, India. The three major dimensions and geometric mean diameter were 8.05 ± 0.39 mm, 3.33 ± 0.15 mm, 2.21 ± 0.11 mm and 3.89 ± 0.14 mm, respectively. The thousand seed weight and bulk density of selected seeds were 27.80 ± 0.23 g and 626.49 ± 9.39 kg/m^3, respectively. The static angle of repose, coefficient of friction on metal and plastic were found as 30.33 ± 1.56°, 0.37 ± 0.02 and 0.34 ± 0.01, respectively.

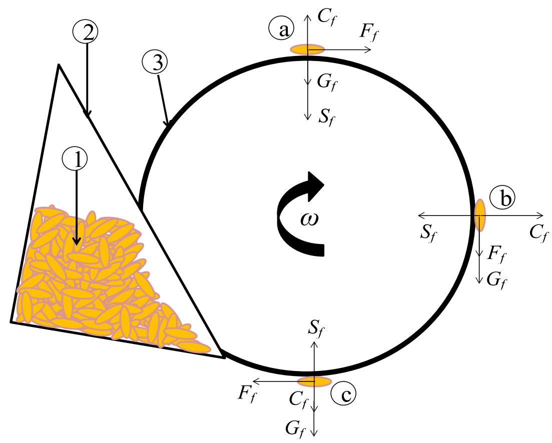
Theoretical considerations

Forces acting on the seed during pneumatic metering operation

The sucked seed is carried to the points a, b, and c by the rotational motion of the drum (Fig. 2). The seed at point ‘a’ has downward acting suction force (S_f) and gravitational force (G_f), the frictional force (F_f) between the seed and the drum surface acts in the direction of drum rotation and the centrifugal force (C_f) is pointed outward. The region between seed box and point ‘a’ was found suitable for cut-off plate; as here it only needs to overcome the F_f for dropping excess seeds back into the seed box. While after point ‘a’, G_f will not allow the same and may result in seed clogging. The portion between points ‘b’ and ‘c’ was proved suitable for seed scraping device, as here it only has to nil out S_f and weak force F_f. Point ‘c’ was selected to maintain a minimum height of fall.

Design considerations

An eight-row unit of two meter nominal width was developed to avoid tractor (1.5 to 1.8 m track width) operation on the planted land with good maneuverability. The diameter of the pneumatic hill drop metering drum (D_d) was selected by considering several parameters viz. drum rotational speed (N_r), planter forward speed (S_p), selected orifice diameter (D), arc length between two successive orifices (ΔL) and hill spacing (H_s). Larger the diameter, more the opportunity time available for seed suction but require more airflow rate, resulting in increased cost and leakage possibilities and vice-versa. Hence, the uPVC pipe of 90 mm in diameter was



1. Rice seeds; 2. Seed box; 3. Precision pneumatic hill drop metering drum; S_f = Suction force; C_f = Centrifugal force; F_f = Coefficient of friction between seed and drum surface; G_f = Gravitational force.

Fig. 2 Forces acting on seeds during operation of precision pneumatic hill drop metering device

selected as per Eq. 1, where N_r in rpm, S_p in m/s and all other dimensions in mm (He et al. 2017).

$$D_d = \frac{0.06S_p(D + \Delta L)}{\pi N_r H_s} \quad (1)$$

Ten pairs of circular-shaped orifices were made along the periphery of the metering drum for effective seed suction performance (Barut and Özmerzi 2004; Ismail 2008). The distance between the two orifices of a pair was kept as 0.01 m considering the maximum seed length (Jadhav et al. 2020). The orifices on metering drum with and without sucked seeds are shown in Fig. 3.

In the laboratory at 4 kPa pressure, it was found that minimum 45 m/s air velocity was required for satisfactory seed suction. A petrol engine operated centrifugal blower (Make: Makita, Model: EB7660TH) having maximum flow rate of 0.33 m^3/s and maximum air velocity of 92 m/s was selected for the study. The fuel consumption of engine operated blower varied between 0.667 and 1.107 l/h at 2 to 4 kPa suction pressure, when operated with gasoline (petrol) fuel of 0.745 specific gravity and 91 octane number.

Laboratory evaluation of developed pneumatic seed metering device

The laboratory evaluation was carried out on a hydraulic powered three-point linkage type sticky belt setup, having same width as of planter (Fig. 4). The rubber-lined ground wheel was powered by the belt itself to match ground to metering unit speed ratio. Suction pressure was measured using vacuum meter (Make: Lutron; Model: VC9200; Least

Fig. 3 Orifices on metering drum

a. Orifices without seeds

b. Orifices with seeds

Fig. 4 Laboratory setup for evaluation of developed pneumatic seed metering device

count: 0.1 kPa). The forward speed of belt was set as 3 km/h (0.83 m/s) (Singh et al. 2005; Pareek et al. 2021).

Independent parameters

The orifice diameter and suction pressure were taken as independent parameters for the study. Previous literature and Eqs. 2, 3 and 4 were used to decide the range of orifice diameter and suction pressure as 1.0–2.0 mm and 1–4 kPa, respectively (Karayel et al. 2004; Singh et al. 2005; Srivastava et al. 2012; Yasir et al. 2012, 2013; He et al. 2017; Yitao et al. 2017).

$$D = (0.64 to 0.66)b \tag{2}$$

$$D \leq (0.5)D_G \tag{3}$$

$$P_v = a + bm_{1000}^{0.27} + cP^{-0.02} - d\varnothing + e\rho_k \tag{4}$$

where, D = Orifice diameter, mm; b = Minimum width of seed, mm; D_G = Geometric mean diameter of seed, mm; P_v = Suction pressure, kPa; m_{1000} = Thousand seed weight, g; P = Seed projected area, mm^2; $\varnothing$ = Seed sphericity, %; ρ_k = Seed true density, kg/m^3.

Dependent parameters

The developed metering device was intended to meter 2 ± 1 seeds per hill. Hence, the seeding parameters *i.e.* no, quality, over seeding and seeding efficiency (Eqs. 5–8) were studied (Zhang et al. 2015; He et al. 2017; Wang et al. 2018). As depicted by equations, no seeding and over seeding are undesirable parameters and quality seeding and seeding efficiency are desirable parameters.

I. No seeding (*NS*)

$$\text{NS} = \frac{\text{Number of hills metered no seeds}}{\text{Total number of hills}} \tag{5}$$

II. Quality seeding (*QS*)

$$\text{QS} = \frac{\text{Number of hills metered } 1-3 \text{ seeds}}{\text{Total number of hills}} \times 100 \tag{6}$$

III. Over seeding (*OS*)

$$\text{OS} = \frac{\text{Number of hills metered more than 3 seeds}}{\text{Total number of hills}} \times 100 \tag{7}$$

IV. Seeding efficiency (*SE*)

$$\text{SE} = \frac{\text{Number of hills having atleast 1 seed}}{\text{Total number of hills}} \times 100 \tag{8}$$

Response surface optimization

Most of previous seeding-planting device parameters studies have used the traditional approach with single factor, which does not consider interaction effects, resulting in poor optimization. Recent study effectively used the response surface methodology for selecting optimum seeding parameters for pneumatic planting devices (Beerge 2015; Jadhav et al. 2023a, 2023b). Limited literature is available for optimization of rice hill drop planting parameters. Hence, full factorial Completely Randomized Design was incorporated to obtain mathematical models in terms of orifice diameter and suction pressure for achieving higher quality seeding and seeding efficiency with lower no seeding and over seeding, and optimize the other operation conditions in a cost-effective way. The mathematical sum of no seeding, over seeding and quality seeding is 100 at any level. Hence, optimizing two of these three will ultimately optimize the remaining one. Hence, only no seeding, over seeding and seeding efficiency were optimized.

The experiment was conducted at three levels of orifice size (1.0, 1.5 and 2.0 mm) and four levels of suction pressure (1, 2, 3 and 4 kPa). The dependent parameters were worked out by taking 100 observations per replication. As shown in Eq. 9, second-order polynomial regression equations were generated to predict the dependent parameters.

$$R_v = \beta_0 + \beta_1 D + \beta_2 P + \beta_{11} D^2 + \beta_{22} P^2 + \beta_{12} DP \tag{9}$$

where, R_v is the response variable whose equation is to be determined. β_0, β_1, β_2, β_{11}, β_{22} and β_{12} are regression coefficients. D and P are the coded or non-coded linear terms for orifice diameter and suction pressure, respectively; while, D^2 and P^2 are the respective quadratic terms. DP is the interaction term.

Laboratory calibration of fertilizer metering unit

Diammonium Phosphate (DAP), Urea and Muriate of Potash (KCl) were selected as these are most common inorganic fertilizers for fulfilling the requirements of Nitrogen (N), Phosphorus (P) and Potassium (K) macro-nutrients. As per agronomic recommendations, the rice crop needs split doses of N and K nutrients of 37.5 kg and 12.5 kg, respectively with full dose of 50 kg P nutrient per hectare at the time of sowing. Accordingly, the suitable proportion of these three fertilizers was made for laboratory calibration of the fertilizer metering unit at 25, 50, 75 and 100% sliding gates opening of the seed hopper at 0.83 m/s ground wheel speed.

Field evaluation

The prototype of PHDP cum fertilizer drill was developed and evaluated at the institute farm of the Central Institute of Agricultural Engineering, Bhopal (India) located at 23°18′49″N, 77°24′15.9″E (Fig. 5). The soil, tractor and machine parameters were recorded during field evaluation. Performance indices were also recorded during field evaluation by keeping furrow openers up. The percent hill emergence was also observed 17 days after seeding (Klaij and Hoogmoed 1993). Hills having at least one seedling were considered as emerged hills.

Techno-economics of the developed PHDP cum fertilizer drill

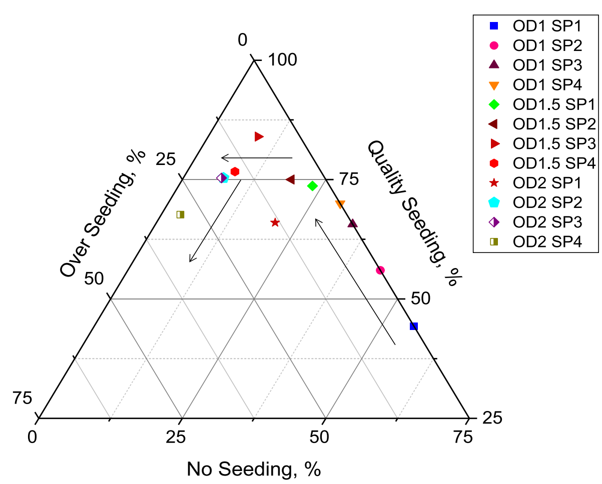
The cost of operation of the planter was calculated using the IS standard (Anonymous 1979). The payback period and break-even point were also determined (Rajaiah 2016).

Results and discussion

Laboratory experiment for optimization of orifice diameter and suction pressure

The values of performance parameters, viz., no, quality and over seeding at different levels of orifice diameter and suction pressure are shown in Fig. 6. The legend notations OD ‘X’ SP ‘Y’ means orifice diameter of X mm and suction pressure of Y kPa, *e.g.* OD1 SP1 means orifice diameter of 1 mm and suction pressure of 1 kPa and so on. The values of no seeding, quality seeding and over seeding varied between 0 and 75%, 25 and 100%, 0 and 75%, respectively. The maximum quality seeding was found at 1.5 mm orifice diameter (OD1.5) and 2 kPa suction pressure (SP2) with minimum value at OD1 SP1. The maximum values of no seeding and over seeding were observed at OD1 SP1 and OD2 SP4, respectively. The arrows in the ternary plot show that at lower orifice diameter and suction pressure combination, quality seeding was less. After increasing up to certain combination, it was again decreased. No seeding was lower and over seeding was more at higher orifice diameter and suction pressure combination. While, no seeding was more and over seeding was less at lower values of independent parameters.

Fig. 5 Field evaluation of developed PHDP cum fertilizer drill



OD‘X’=Orifice diameter ‘X’ mm; SP‘Y’= Suction pressure ‘Y’ kPa

Fig. 6 Ternary plot for no, quality and over seeding

The results of regression analysis are summarized in Table 2. It can be seen that selected model was highly significant for all the responses. All the models were fit as the calculated 'F' value of lack of fit for all responses was less than the table 'F' value. The coefficient of determination also indicated that models represented the most of variability of the responses. The predicted and adjusted R^2 were in close harmony for every response as their arithmetic difference was less than 0.07. The signal-to-noise ratio of selected models was found advisable as the value of adequate precision was more than 12 in all cases.

Linear, quadratic and interaction effect of independent parameters

From Table 2, the linear and quadratic terms of orifice diameter (*D*) and linear term of suction pressure (*P*) had a highly significant effect ($p<0.0001$) on the no seeding (*NS*) parameter. The interaction term ($D\times P$) did not influenced the *NS* significantly, while the quadratic term of *P* had less significant effect on *NS* ($p<0.05$). The negative signs of quadratic terms indicate their inverse relationship with the *NS*. Similar to *NS, D* affected the over seeding (*OS*) and seeding efficiency (*SE*) most significantly ($p<0.0001$). Effect of *P* was more significant ($p<0.01$) on *OS* and most significant ($p<0.0001$) on *SE*. The interaction term had more significant effect on *OS*; however, it had no effect on *SE*. Similarly, quadratic terms of individual effects had no effect on *OS*, but they had significant effect on *SE*. The likely reason for the non-significant effect of interaction term on *NS* is that, regardless of the level of one independent parameter, the *NS* consistently decreased with an increase in the level of the other independent parameter. Similarly, the *SE* was continuously improved with increasing the levels of independent parameters. In addition, as the quadratic terms were found significant, there may be a weak curvilinear effect of *D* and *P* on *NS* and *SE*. While on the other hand, in case of *OS* at quadratic terms found non-significant due to dominance of linear effects.

Response surface regression models

The second order polynomial regression equations developed for prediction of *NS*, *OS* and *SE* are as given by Eqs. 10, 11 and 12, respectively with corresponding coefficient of determination values.

$$\begin{aligned}\mathrm{NS} =& 193.68 - 164.67D - 20.66P + 3.43DP \\ &+ 41.5D^2 + 1.81P^2 \ldots (R^2 = 0.92)\end{aligned} \tag{10}$$

$$\begin{aligned}\mathrm{OS} =& 11.25 - 15.33D - 9P - 4.73DP \\ &+ 7.67D^2 + 0.94P^2 \ldots (R^2 = 0.82)\end{aligned} \tag{11}$$

$$\begin{aligned}\mathrm{SE} =& -93.68 + 164.67D + 20.66P - 3.43DP \\ &- 41.5D^2 - 1.81P^2 \ldots \left(R^2 = 0.92\right)\end{aligned} \tag{12}$$

The plot of normal (%) probability verses externally studentized residuals is a very useful diagnostic technique to verify the systematic deviation of normally distributed errors and not dependent on one another. The points in the plots aligned in vicinity of a straight line, which points towards normal error distribution (Fig. 7 (a, d, g)). The plots of predicted verses actual observations show the behaviour of linear regression without any ambiguous dispersion (Fig. 7b,

Table 2. ANOVA of second-order polynomial regression models with coded coefficients of the responses

Source	No seeding, % ANOVA	Over seeding, %	Seeding efficiency, %
Model F-value	70.53***	26.56***	70.53***
Lack of fit	NS	NS	NS
R^2	0.92	0.82	0.92
Adjusted R^2	0.91	0.79	0.91
Predicted R^2	0.89	0.72	0.89
Adequate precision	14.04	15.49	24.82
Coded values of regression coefficients			
Intercept	12.58	6.65	87.42
Orifice diameter (*D*)	− 15.79***	9.75***	15.79***
Suction pressure (*P*)	− 9.72***	4.23**	9.72***
$D\times P$	2.58^{NS}	3.55**	-2.58^{NS}
D^2	10.37***	1.92^{NS}	− 10.37***
P^2	4.06*	2.13^{NS}	− 4.06*

R^2 = Coefficient of determination, ***Highly significant at < 0.01% level of significance; **Significant at 1% level of significance, *Significant at 5% level of significance; *NS* Non-significant.

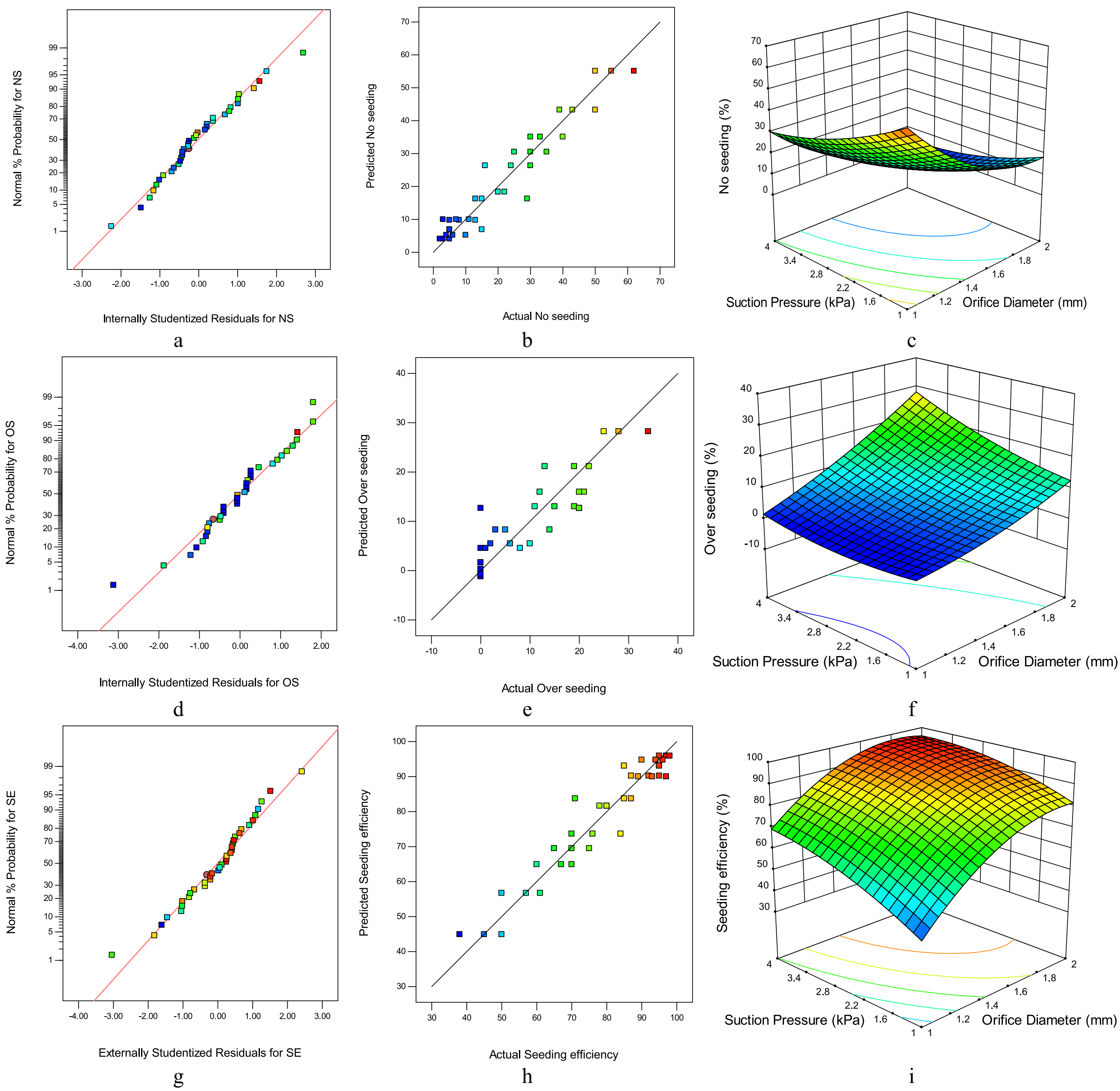


Fig. 7 Normal probability plots, predicted verses actual data and contours of $D \times P$ interaction respectively for No seeding (**a**, **b**, **c**), Over seeding (**d**, **e**, **f**) and Seeding efficiency (**g**, **h**, **i**)

e, h). Hence, the developed models are adequate and explain the behaviour of responses.

The *NS* was maximum at the lower augmented points of the *D* and *P*. It was reduced towards higher augmented levels for the selected range of the *D* and *P* (Fig. 7c). The increase in *P* at constant *D* increased the *OS* gradually (Fig. 7f). A similar trend was observed in case of *OS* when the *D* was increased at constant *P*. As shown in (Fig. 7i), *SE* was less at lower augmented points of both the independent parameters and showed an improving trend towards higher augmented points.

Numerical approach for optimization of metering operation

To draw the optimized solution, constraints were applied to the responses and the independent parameters were kept in range. The lower values of *OS* and *NS* with higher value of *SE* were desirable. In Table 3, first solution with 1.5 mm

Table 3 Numerical solutions for optimization of rice metering

Orifice diameter, mm	Suction pressure, kPa	No seeding, %	Over seeding, %	Seeding efficiency, %	Desirability
1.5	4	6.92	13.01	93.08	0.8
1.5	3	9.79	8.30	90.21	0.8
1.5	2	16.27	5.48	83.73	0.8

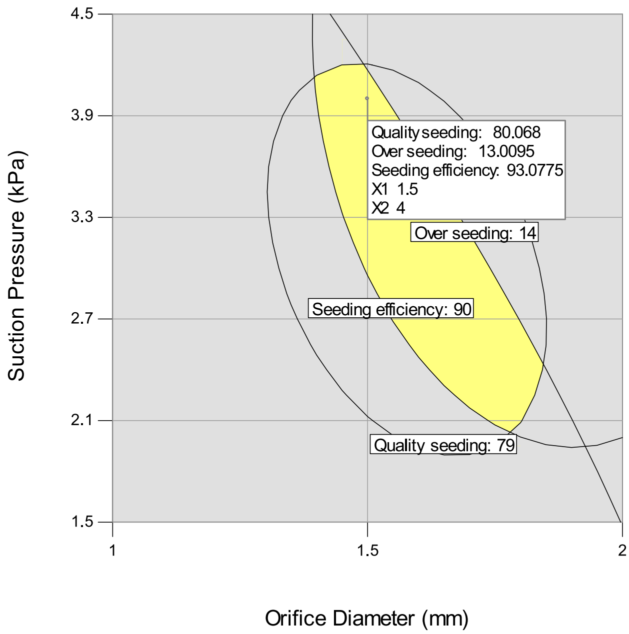


Fig. 8 Overlay plot of optimized solution for rice metering

D and 4 kPa *P* was selected as optimized because of its minimum *NS* (6.92%), optimum *OS* (13.015) with maximum *SE* (93.08%) values. The corresponding value of QS was 80.07%. The selected solution had acceptable desirability of 0.8. The same orifice diameter was suggested in previous studies (Zhang et al. 2013; He et al. 2017) while one suggested a diameter of 1.6 mm for rice metering (Zhang et al. 2015). Nearly equal suction pressure of 3.2 kPa for rice metering suggested in literature (Zhang et al. 2013).

Graphical representation by overlay plot

The overlay plot shown in Fig. 8 was generated as per the solution suggested by the numerical optimization to observe all the responses in one go. The curves of responses were superimposed for the interaction $D \times P$. The desirable area (shown in the yellow colour) is bounded on every side by different responses.

Validation of models for seed metering

To check the suitability of developed models five replications were conducted in the laboratory at optimized solution. The validation results from the confirmation tool of Design expert software are represented in Table 4. The data means of all responses fall within the prediction interval of the confirmation tool at a 5% level of significance. Hence, developed regression models predicted the behaviour of responses with reasonable accuracy.

Table 5 Effect of percent opening of sliding gate on fertilizer rate

Sr. No	Sliding gate opening, %	Fertilizer dropped, kg/ha
1	25	53.07
2	50	125.42
3	75	165.54
4	100	214.12

Table 4 Validation of regression model through confirmation tool for rice metering

Response	Mean	Median	Std. dev	n	Std. Er. predicted	95% PI low	Data mean	95% PI high
No seeding, %	6.9	6.9	5.03	5	3.03	0.74	8.60	13.10
Over seeding, %	13.01	13.01	4.65	5	2.79	7.31	13.00	18.72
Seeding efficiency, %	93.08	93.08	5.04	5	3.03	86.90	91.40	99.26

Std. dev. Standard deviation; *n* number of observations; *Std. Er.* Standard error; *PI* Prediction interval

Fig. 9 Crop condition after 17 days of planting

Laboratory calibration of fertilizer metering unit

The fertilizer drop varied between 53.07 at 25% opening to 214.12 kg/ha at 100% opening (Table 5). Hence, the basal dose requirement of rice of 168.12 kg/ha was fulfilled by keeping the sliding gate 75% open (Fulton and Port 2016).

Field performance of developed precision pneumatic hill drop planter cum fertilizer drill

The evaluation was carried out in black cotton soil having moisture content of 19.58% (*wb*) and a wet bulk density of 1210 kg/m^3. The fuel consumption and wheel slip were 5.12 l/h and 6.73%, respectively, measured at 0.83 m/s forward speed. The observed actual field capacity and field efficiency were 0.42 ha/h and 70.36%, respectively. The average seed rate and depth of planting were recorded as 14.20 kg/ha and 35 mm. Three replications, each of 15 m length, were taken. The observed values were 11.1% *NS*, 12.27% *OS*, 76.29% *QS* and 88.56% *SE*. The percent hill emergence was observed as 91%. The crop condition after 17 days is shown in Fig. 9.

Economics of the developed PHDP cum fertilizer drill

The initial cost of the planter was about ₹ 92,500/- and ₹ 35,000/- with and without the cost of the engine-operated blower, respectively. The life of planter was considered as 10 years as per BIS standard. The calculated fixed and variable costs of planter on per hour basis were ₹ 30.87 and ₹ 10.50, respectively. The calculated operational cost was ₹ 983.74/h and ₹ 2342/ha. The values of break-even point were obtained as 114.03 h/yr, 47.89 ha/yr. On the basis of estimated fixed cost and annual use of 200 h, the payback period was found to be as 7.7 years.

Conclusions

Response surface methodology was effectively used for selection of best pneumatic hill drop metering parameters, viz., orifice diameter and suction pressure as 1.5 mm and 4 kPa, respectively for the optimized response parameters as 80.07% quality seeding, 13.01% over seeding, 6.92% no seeding and 93.08% seeding efficiency. Nearly similar output was obtained in the field within selected range of independent parameters. The actual field capacity and field efficiency were 0.42 ha/h and 70.36%, respectively. The average planting depth of 35 mm was found. The observed seed rate in the field was 14.20 kg/ha. The vertical plate fertilizer metering device met the basal dose requirement for rice at a 75% opening of the hopper sliding gate. The cost of operation of the developed PHDP with a fertilizer drill was ₹ 983.74/ha.

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Data availability The research data will be made available on request.

Declarations

Conflict of interest The authors have declared that no conflict of interest exist.

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