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Development of a Mechanically Assisted Pneumatic Metering Mechanism for High-Speed Planting of Soybean

Manoj Kumar[1], Ramesh K Sahni[1,2]* & Kamal N Agarwal[1]

[1]Agricultural Mechanization Division, ICAR-Central Institute of Agricultural Engineering, Bhopal 462 038, Madhya Pradesh, India
[2]Center for Precision and Automated Agricultural Systems, Washington State University, Prosser, WA, USA, 99350

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A planter for planting soybean seeds up to 1.94 $m \cdot s^{-1}$ (7 $km \cdot h^{-1}$) was designed. In this machine, a hybrid metering mechanism was developed in which singulation was done with the help of vacuum pressure and conveying of seeds was done by cellular ring. The metering mechanism was evaluated for seed plates with three different numbers of holes (64, 74 and 84); three vacuum pressures (2, 3 and 4 kPa) and at three forward speeds (0.83, 1.39 and 1.94 $m \cdot s^{-1}$). The effects of forward speeds on different indices were found insignificant at 5% confidence level. The optimum value of different indices i.e., miss index, multiple index, quality of feed index and precision index were observed for 84 number of seed holes at 3 kPa vacuum pressure for 0.83, 1.39 and 1.94 $m \cdot s^{-1}$. In field evaluation of the machine, the average width of operation, plant to plant spacing, depth of operation, field capacity, and field efficiency were 2.1 m, 9.7×10^{-2} m, 5.2×10^{-2} m and 0.9 $ha \cdot h^{-1}$, 72% at 1.94 $m \cdot s^{-1}$ speed of operation and 0.1 m plant to plant spacing setting. The metering mechanism was found suitable for planting soybean up to 1.94 $m \cdot s^{-1}$ (7 $km \cdot h^{-1}$).

Keywords: Hybrid metering mechanism, Mechanization, Miss index, Precision index, Soybean planting

Introduction

Soybean occupies an important place in world's oilseed cultivation, due to its high productivity, profitability and vital contribution towards maintaining fertility in the soil. Also, it is one of the important sources of nutrition in human and animal food. Soybean contains high quality protein and does not contain cholesterol and saturated fatty acids. It is used in food industry for fat products (refined soybean oil, glycerol), complete soybean products and soybean protein products (soybean flour or soybean crust).[1] The major soybean producing nations are the Brazil, United States and Argentina, which accounts for more than 80% of the total world's soybean production. Other major soybean producing nations are China, India, Paraguay, Canada and Mexico.

Global production of Soybean has increased at a Compound Annual Growth Rate (CAGR) of 3.32% from 260.49 million metric tons in 2009−10 to 385.52 million metric tons in 2021−22. India ranks 5th in soybean production producing about 2.91% of global production. Soybean production in India has increased at a CAGR of 1.21% from 9.70 million tonnes in 2009−10 to 11.20 million tonnes in 2021−22.[(2)] Soybean contributes 43% to the total oilseeds and 25% to the total oil production in the country. In India, production of soybean is dominated by Madhya Pradesh and Maharashtra which contributed 84.6% of the total production in 2021−22. Rajasthan, Karnataka, Telangana, Gujarat and Chhattisgarh contributed 14.4% production of India.[2]

Traditionally agriculture was done by farmers for feeding their own family but in modern times, it became an occupation which requires precise and efficient application of inputs to increase yield and profitability. Among all the operations required for cultivating crops, sowing/planting is one of the most important operations in which proper placement of seed in the soil for optimum growth and high productivity is desired.[3] This is achieved by using seed drill/planter powered by tractor, power tiller, animal or human being. With the increase in mechanization level in India and non-availability of animal power, tractor and power tillers are gaining popularity as power sources for carrying out different agriculture operations.[4] Hence, use of tractor drawn seed drills with fluted roller metering mechanism is gaining popularity for raising different crops. In recent years, severe shortage of agricultural labour is

*Author for Correspondence
E-mail: ramesh.sahni@wsu.edu

observed during sowing season due to increased employment opportunities in urban areas.[5,6] Due to non-availability of agricultural labour and draught animals during sowing seasons, in many places the seed is sown even when the soil is not at optimum moisture content which affects the germination, plant stand and ultimately production. Whereas planters are maintaining plant to plant as well row to row spacing. Therefore, in order to meet timeliness and mechanize crop sowing operation, a suitable seed drill/planter is vital as it places the seed in the zone of adequate moisture and at desired depth. In Indian farming, the maximum speed of sowing and planting is around 3–5 km·h^{-1} and 3–4 km·h^{-1}, respectively.[7] For increasing coverage area per unit time, either width of seed drill/planter should be increased, or speed of sowing/planting should be increased. By increasing width, it requires more headlands for turning. So in Indian condition only option is to increase the speed of sowing/planting.

The conventional pneumatic planter can work efficiently up to 2.6 km·h^{-1} for soybean planting at 100 mm spacing.[8] Using existing pneumatic planter at higher speed will require bigger suction blower as suction pressure is used for picking soybean seed from hopper and conveying seed to near ground level in seed plate. Also, seed may fall on the ground from the seed plate due to higher vibration at higher speed. For planting soybean at higher speed using pneumatic planter will require mechanical assistance for conveyance of seed after seed was picked using suction pressure to near ground on seed plate. Also, the size of the suction chamber needs to reduce to meet the desired suction pressure at the seed pick-up point in the metering mechanism.

Keeping these points in view, a high-speed planter for soybean (1.39−1.94 m·s^{-1}) with a mechanically assisted pneumatic metering mechanism was designed and developed for Indian condition. The design details and evaluation of the developed equipment in laboratory as well as in field are reported.

Machine Design

The equipment consisted of frame, modular unit metering device with hopper and furrow opener, PTO driven blower, ground wheel-based power transmission mechanism and accessories (Fig. 1).

Frame

The frame (1 in Fig. 1) consists of a hitching system and base for mounting different components of machine i.e., blower, high speed planting devices and ground wheel-based power transmission system.

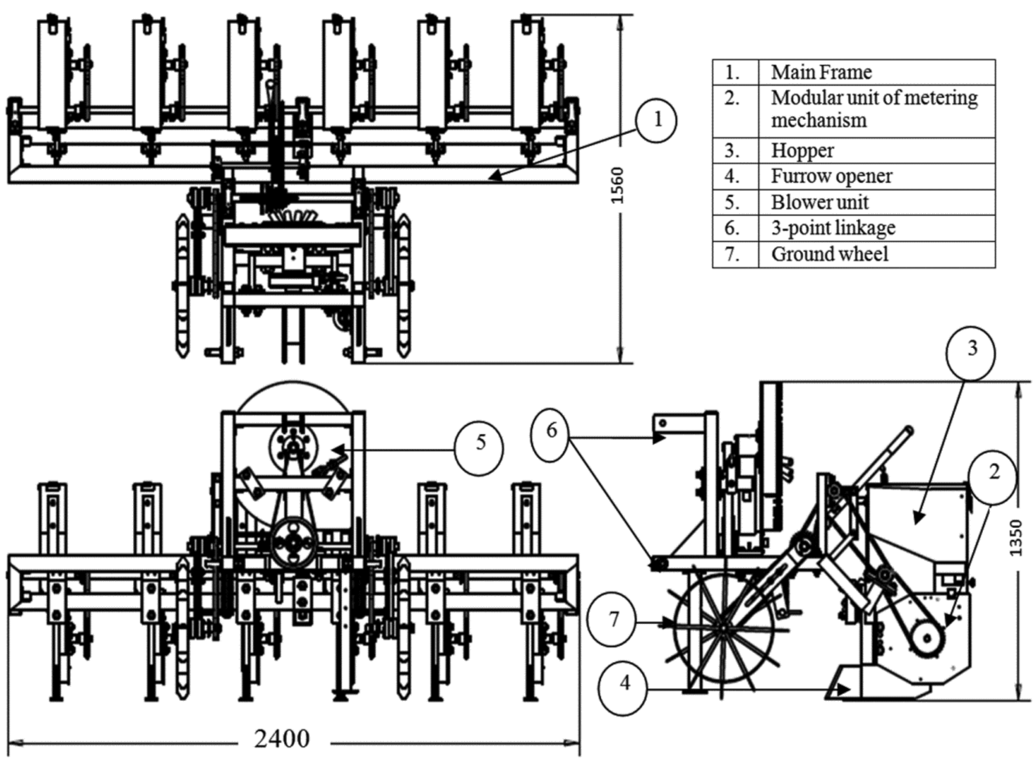

Fig. 1 — Schematics of developed mechanically assisted pneumatic planter

The front part of frame is used for mounting on tractor; middle part used for mounting of blower and ground wheel assembly; and rear part of the frame was used for mounting of tines and power transmission system for metering mechanism. The main frame fabricated from two square hollow beams of 50 × 50 × 5 mm cross-section having 2400 mm length and welded together with same MS box its two sides. The middle of the frame was joined by MS flats of 350 × 70 × 15 mm. The main frame extended in front by use of same MS box for providing base for 3-point hitch system (category–II).

Metering Mechanism

The modular unit of metering unit and seed placement device is shown in Fig. 1. The high-speed planting device consists of hopper, metering mechanism, furrow opener and accessories. The unit is responsible for seed metering and seed placement in soil. The exploded view of metering mechanism is shown in Fig. 2. The metering mechanism is mounted on tine with the help of nuts and bolts. In the metering mechanism, seeds are sucked against a vacuum chamber due to vacuum created by suction blower. The seed in this position carried to the end of vacuum chamber and dropped in corresponding seed cell of circular ring and then carried to the lowest point of metering mechanism with the help of circular ring having multiple cells. In this metering mechanism small vacuum chamber (③ in Fig. 2) is sued, which minimize air leakage losses due to lack of perfect sitting of seed on the seed hole or when one or more seed do not stick. In conventional pneumatic metering mechanism, a full circular vacuum chamber is present and singulation of the seeds as well as movement of seeds to the lowest point of metering mechanism is done by the vacuum.

The developed pneumatic metering mechanism consists of base plate, vacuum chamber plate, seed plate (material: SS plate, diameter: 300 mm and thickness: 1.6 mm), deflectors, ring with multiple cells, cells cover plate, shaft and accessories as shown in Fig 2. This is a hybrid system in which seed stick on seed holes adjacent to vacuum chamber by means of vacuum for seed singulation and circular ring with multiple cells used for conveying of seed until dropping point of seed i.e., end of vacuum chamber to the lowest point of the ring and place into the furrow.

Hopper

Hopper (3 in Fig. 1) was fabricated in two sections i.e., upper and lower seed hopper. The hopper was fabricated using 1.5 mm MS sheet. The seed flow under gravity from upper hopper to lower hopper. The lower hopper consists of two chambers. First chamber of lower hopper is directly connected with upper hopper which received seed under gravity flow, whereas the second chamber is connected to the first chamber by an adjustable open gate. The adjustable gate opening helps in adjusting the seed rate entering in to the second chamber. The seeds in the second chamber come in direct contact of the rotating seed plate adjacent to the vacuum chamber. Seed picked up by the means of vacuum of vacuum chamber. The lower seed hopper with a curved bottom wall helps extra seeds to roll back to the starting point of vacuum chamber for easy picking and simultaneously clearing the upper space of the secondary chamber for

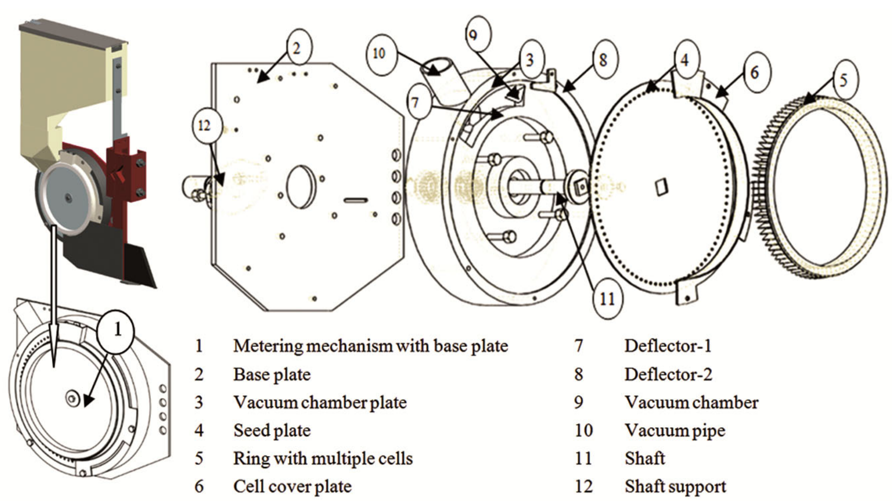

Fig. 2 — Exploded view of designed metering mechanism

hindrance free movement of picked seeds. It also prevents seed entry in cells on circular ring which is rotating below the secondary hopper.

Inverted-T Type Furrow Opener Tines

Six inverted-T type furrow/slit opener tines are clamped on the rear beam of the frame with clamps and bolts (4 in Fig. 1). These tines are consisted of a leg, furrow/slit opener, shin, deflector plates and side cover plates. The legs of the furrow opener tines are made up of MS flats of size 450 × 50 × 20 mm. Two side plates are welded with the lower end of the leg for preventing entrance of soil into the furrow at the time of seed placement. A MS flat of 75 × 50 × 5 mm with its one end kept trapezoidal up to 35 mm length with tip width 0.08 m is welded at the bottom of the front face of the tine. The side of furrow opener machined with 45° cone angle for better cutting and sharing. The delivery/outlet of metering mechanism drops the seed between the soil deflector plates.

Blower

The blower (capacity: 0.21 $m^3 \cdot s^{-1}$ @5333 rpm at 5.7 kPa) is mounted on a fix frame which is fixed on the main frame of the machine (5 in Fig 1). The blower consists of 6 outlets which are used for transfer suction pressure to the metering mechanism by means of flexible PVC hoses.

Power Transmission System

The power transmission system is provided in two parts i.e., for blower and metering mechanism. The different power transmission systems are presented below:

Power Transmission System for Blower

The blower receives power from the tractor's PTO shaft by means of multi-grooved pulley and belt. The speed ratio between pulley shaft and blower shaft is 1:13. The pulley is mounted on the main frame by help of nut and bolts.

Power Transmission System for Metering Mechanism

The metering mechanism shaft receives power from ground wheel. The power transmission take place from ground wheel to the metering mechanism shaft in three stages i.e., ground wheel shaft to intermediate shaft no. 1 (1:1.58), from intermediate shaft no. 1 to intermediate shaft no. 2 (1: 1.67 or 2.25) and from intermediate shaft to the metering mechanism shaft (1:1.21). The gear ratio between ground wheel and metering mechanism shaft is 1:3.19 or 4.30. A gear changing mechanism placed in the intermediate shaft facilitates changing of seed to seed spacing from 100 to 50 mm or vice-versa.

The ground wheel (diameter: 550 mm) is fabricated from MS flat with rim width of 65 mm and thickness of 8 mm (7 in Fig. 1). The wheels had 12 lugs of 70 × 50 × 5 mm MS flats welded on its periphery.

The ground wheel is pined on intermediate shaft no. 1 and a dampening spring is provided with the support of main frame. The ground wheel mounted with the help of adjustable length arm. Floating action is provided to the ground drive wheel by springs connected with the wheel frame so that it can easily ride over the clods or obstructions.

Developed High Speed Planter

The developed prototype of planter with high-speed metering mechanism is shown in Fig. 3. The size of the machine is 2400 × 1560 × 1350 mm and row to row spacing is adjustable between 200 to 900 mm. The weight of machine is about 325 kg.

Material and Methods

Soybean Physical Properties

Soybean physical properties are important to decide the hole diameter of seed plate and other design and operational parameters. Soybean physical properties such as length, width and thickness measurement were done with the help of digital Vernier Caliper. Hundred soybean seeds (variety: JS-9560, National Seed Corporation Ltd., C/S1 class of seeds, moisture content: 9.43%) were used for measurement of seeds physical properties. The moisture content was measured using hot air oven by keeping seed for 24 h at 105°C. The equivalent diameter, arithmetic diameter and sphericity were

Fig. 3 — Prototype of planter for soybean planting at speed upto 1.94 $m \cdot s^{-1}$ (7 $km \cdot h^{-1}$)

Table 1 — Seed properties of soybean seed used in the study

Seed properties	Max	min	Average (mean ± SD)
Length (mm)*	10.51	5.31	6.4 ± 0.6
Width (mm)*	7.80	4.50	6.3 ± 0.5
Thickness (mm)*	6.29	3.27	4.2 ± 0.5
Equivalent diameter (mm)	7.49	4.57	5.3 ± 0.5
Arithmetic diameter (mm)	7.58	4.64	5.4 ± 0.5
Sphericity	0.95	0.67	0.83 ± 0.1
Aspect ratio, Width/Length	0.997	0.69	0.87 ± 0.1
Projected area, mm^2	44.0	16.4	22.3 ± 3.9

* Average of 100 seeds

calculated using Eq. (1), (2) and (3) respectively[9] and results are presented in Table 1.

$$\text{Equivalent diameter} = (\text{Length} \times \text{width} \times \text{thickness})^{1/3} \quad \ldots (1)$$

$$\text{Arithmetic diameter} = (\text{Length} + \text{width} + \text{thickness})/3 \quad \ldots (2)$$

$$\text{Sphericity} = \text{Equivalent diameter}/\text{length} \quad \ldots (3)$$

Based on Barut & Özmerzi results, the shape of openings (holes) for the seed plate was recommended as a circular hole.[10] To prevent the seed from entering the seed opening, angle of openings on the seed (metering) plate should be conical in shape to be completely closed by a seed to avoid multiple seeds being picked up by the seed plate.[11] Finding of Bakhtiari and Singh *et al*. showed that the most suitable conical angle of the seed plate is 120°.[(11,12)] The diameter of opening on the seed metering plate for soybean seeds, considered the opening diameter (d_o) as ≤ 50% of the geometric mean diameter ($d_o \leq 0.50 \times Dg$).[11] So, selected hole diameter was 3 mm ($do \leq 0.50 \times 5.92$ mm ≈3 mm).

Laboratory Evaluation of Metering Mechanism

The developed metering mechanism was evaluated in the laboratory on a sticky belt setup. The experimental setup consists of metering mechanism, air flow meter, manometer, rpm meter, vacuum cleaner (model: trendy steel, capacity: 1400 lpm, suction pressure: 21 kPa, Eureka Forbes, India) and sticky belt unit (Fig. 4). The metering mechanism was tested for three seed plates with 64, 74 and 84 holes: three forward speeds i.e., 3, 5 and 7 $km{\cdot}h^{-1}$ and at three vacuum pressures of 2, 3 and 4 kPa with 3 replicates. The vacuum pressure was varied by rotating the knob on the vacuum cleaner used in the study. The number of holes on the seed plate was decided so that the speed of seed plate should remain in lower side and lesser interaction will be there at seed plate and seeds in the hopper. The distance between the seeds on sticky belt setup was measured manually and performance parameters of the mechanism such as miss index, multiple index, Quality of Feed Index (QFI) and precision index were calculated using Eq. (4), (5), (6) and (7) respectively.[13]

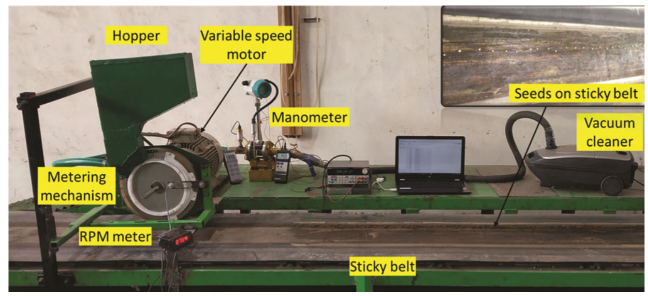

Fig. 4 — Sticky belt setup for evaluation of pneumatic metering mechanism

$$\text{Miss index} = \frac{n_1}{N} \times 100 \quad \ldots (4)$$

$$\text{Multiple index} = \frac{n_2}{N} \times 100 \quad \ldots (5)$$

$$\text{QFI} = 100 - (\text{Miss index} + \text{Multiple index}) \quad \ldots (6)$$

$$\text{Precision index} = \frac{S_d}{S} \times 100 \quad \ldots (7)$$

where, n_1 = number of spacing greater than 1.5 × S; S = set planting distance; n_2 = number of spacing less than equal to 0.5 × S; N is total number of measured spacing and S_d = standard deviation of the spacing more than 0.5 × S but not more than 1.5 × S.

Field Evaluation

The developed high-speed planter was evaluated at the research farm of Central Institute of Agricultural Engineering, Bhopal (23.31354°N, 77.40035°E) during the Kharif 2018−19. The soil type was black cotton soil. The moisture content (22.7% dry basis) of the soil was measured using oven dry method. The planter was operated by a tractor (model: 3630, 55 hp, New Hallond, Turin, Italy) at 1.94 $m \cdot s^{-1}$ (7 $km \cdot h^{-1}$) and row spacing, depth and width of operation was measured using scale and measuring tape. The soybean seed used for planting was at 14.2% moisture content. The wheel slippage, field capacity and field efficiency of the developed planter were measured as per BIS code.[14] The operational cost per hour was estimated according using BIS code.[15] The break-even point and payback period[15] was calculated by using following Eqs (7 & 8).

BEP, hour per annum = annual fixed cost/(custom fee, ₹/h − operating cost, ₹/h) …(7)

where, Custom fee (₹/h) = (cost of operation/h + 25% overhead charges) + 10% profit, ₹/h

Payback period, year = initial cost of machine /average net annual profit … (8)

where, Average net annual profit, ₹ = (custom fee, ₹/h – total operating cost, ₹/h) × annual utility (h)

For comparison, time taken by CIAE pneumatic planter was used with time taken by the developed planter.[8]

Results and Discussion

Laboratory Evaluation

The laboratory evaluation result of pneumatic metering mechanism is shown in Fig. 5. The 84-holes seed plate with 3 kPa vacuum pressure was observed best among all the tested combinations based on different indices. The miss index, multiple index, quality of feed index and precision index were observed 3, 3, 94 and 15 respectively, for 84-hole seed plate at 3 kPa vacuum pressure at 100 mm spacing for soybean (Fig. 4). The 84-hole seed plate with 3 kPa suction pressure was selected for metering mechanism for the development of planter. The Results of Tukey's Studentized Range (HSD) test analyses for different levels of testing parameters are shown in Table 2. There was no significant difference in miss index at different levels of NH, SP and FS at 5% level of significance. The multiple index was also same at different levels of NH and FS but it was not significantly same at different levels of SP. The multiple index was found to be same at 2 and 4 kPa. The multiple index was lowest at 3 kPa. There was no significant difference in QFI at different levels of NH, SP and FS. The precision index was statistically same

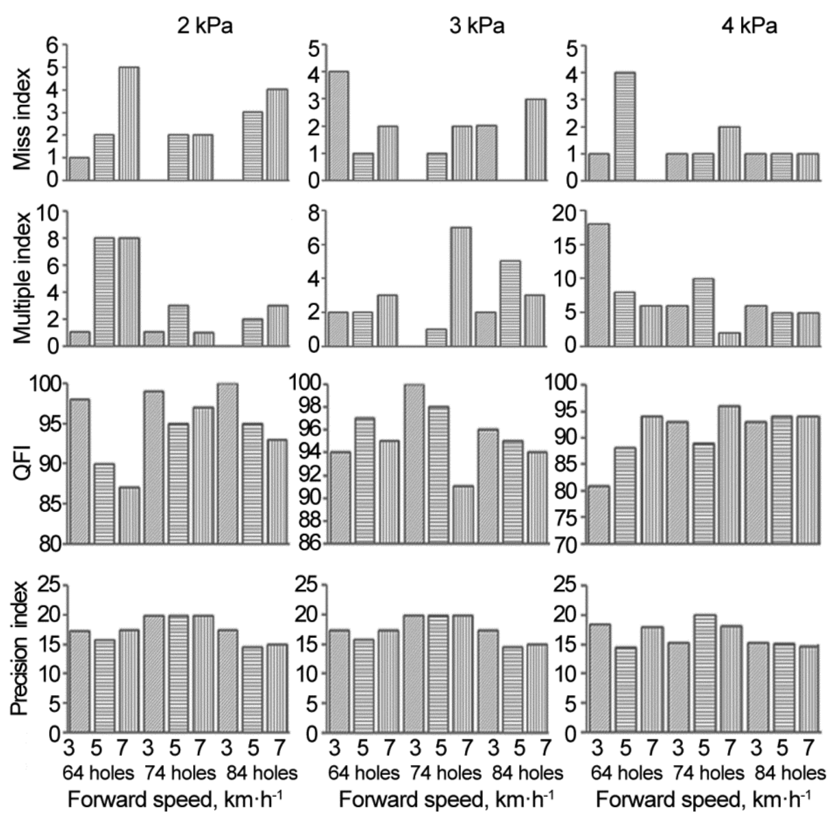

Fig. 5 — The laboratory test result of pneumatic metering mechanism at different holes numbers, suction pressure and forward speed

Table 2 — Variance analysis of different parameters of pneumatic planter *(Tukey's Studentized Range (HSD) test)*

Parameters[#]	Levels name	Miss index	Multiple index	QFI	Precision index
NH	64	2.22a	5.0	92.78	17.09[ab]
	74	1.22a	2.78	94.89	18.69[a]
	84	1.67a	3.44	**96.11**	**15.53[b]**
SP	2 kPa	2.11	3[ab]	94.89	17.42
	3 kPa	1.67	2.78[a]	**95.56**	**17.33**
	4 kPa	1.33	5.44[b]	93.22	16.56
FS	0.83 $m \cdot s^{-1}$ (3 $km \cdot h^{-1}$)	1.11	2.78	96.11	17.27
	1.39 $m \cdot s^{-1}$ (5 $km \cdot h^{-1}$)	1.67	4.22	94.44	16.91
	1.94 $m \cdot s^{-1}$ (7 $km \cdot h^{-1}$)	2.33	4.22	93.44	17.13
CD		1.59	2.61	3.37	1.64

[#] FS-forward speed of prime mover, SP-suction pressure, and NH-number of holes on seed plate (means with the same letter are not significantly different)

Table 3 — Variance analysis of different parameters observed during laboratory testing

Parameters	DF	Miss index	Multiple index	QFI	Precision index
		p value	p value	p value	p value
NH	2	0.30	0.11	0.07	0.0004***
FS	2	0.18	0.29	0.14	0.86
SP	2	0.48	0.03*	0.22	0.35
Error	20				

[#] FS-forward speed of prime mover, SP-suction pressure and NH – number of holes on seed plate

at different levels of SP and FS but it was not statistically same at different levels of NH. The precision index was highest at 74-holes seed plate and minimum at 84-holes seed plate. There was no significant difference in precision index at 64-holes seed plate with 74- and 84-holes seed plate.

The analysis of variance for different parameters observed during laboratory testing is shown in Table 3. The effect of number of holes on precision index was highly significant ($p < 0.05$) whereas on other indices, the effects of number of holes are found insignificant (Table 3). The significant difference in precision index may be due to smaller seed cell size may lead to less deviation and less variation in seed spacing of seed coming out from the cell at the lowest position of circular ring.

The effect of vacuum pressure is found significant on multiple index whereas effect on other indices are insignificant (Table 3). This significant difference in multiple index may be due to increase of pressure, increased number of seed sucked on the plate which increase the number of multiples.

The effect of forward speed on different indices found insignificant (Table 3), whereas the miss index increases with the increase in forward speed of the planter. It may be due to less pick-up time for seed form the hopper. The increase in multiple index may be due to some seeds also moving/riding in between two seeds.

Fig. 6 — Field evaluation of developed prototype

Field Evaluation

The developed prototype of high-speed planter was evaluated in the field (Fig. 6). The average width of operation, plant to plant spacing, depth of operation, field capacity, slip and field efficiency of the machine were 2.1 m, 0.097 m, 0.052 m, 0.9 $ha \cdot h^{-1}$, 10% and 72% at 1.94 $m \cdot s^{-1}$ speed of operation.

The operation cost of the machine is ₹790/h (for 200 h annual use with 10% profit). The approximate cost of planter is ₹1,20,000. The breakeven point and payback period of the machine are 56 h/year and 1.7 year, respectively. The time reduced in operation in comparison to conventional pneumatic planter is 64.3%.

Conclusions

A mechanically assisted pneumatic metering mechanism was developed for high-speed planting of soybean seed and evaluated in laboratory and field condition. The metering mechanism with 84-hole seed plate at 3 kPa vacuum pressure performed best amongst all the tested combination and selected for development of prototype planter for planting soybean seed upto 1.94 $m \cdot s^{-1}$. A prototype planter was developed with designed metering mechanism and soybean seed was planted in kharif season of 2018−19 in CIAE research field. The developed high-speed planter was found suitable for planting soybean seed up to 1.94 $m \cdot s^{-1}$.

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