



Development, optimization and modelling of performance parameters for remote-controlled mechatronic precision planter using RSM and Hybrid PSO-ANN model

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ABSTRACT

Precision planting plays a crucial role in optimizing crop production by ensuring accurate seed placement at the correct depth, uniform spacing, and adequate soil coverage. Inclined plate metering systems are particularly favored for their precision and cost-effectiveness, especially in scenarios involving multiple crops. Researchers are exploring advanced methods such as ANN and PSO to optimize seed metering. Mechatronics-based systems show promise by integrating IoT and robotics to enhance precision and efficiency in planting operations. A recent study focused on designing a seed metering system tailored for cotton (*Gossypium hirsutum* L.) based on prevalent seed characteristics in the Saurashtra region of Gujarat, India. The study involved designing a planter equipped with a ground wheel, optical rotary encoder, microprocessor, stepper motor, and seed metering box. Experimental evaluations were conducted to optimize seed sowing uniformity and operational parameters using laboratory tests and hybrid techniques combining ANN with PSO algorithms. This approach effectively optimized the precision and operational efficiency of the mechatronic precision planter for cotton crop planting. The investigation further delved into the impact of inclination angle (A), seed hole geometry (P), and forward speed (S) on various cotton seed planting parameters using a mechatronic precision planter. Results indicated that with a maximum deviation of just 2.67 percent between the experimental and model-predicted average seed spacing values, the ANN-PSO model accurately approximates the ideal input parameter values for maximizing average seed spacing. The forward speed (S), inclination angle (A), and geometry of the seed hole (P) to maximize average seed spacing are found to be 0.43 m/s, 52 degrees, and 100 percent, respectively. Under the optimized conditions, the predicted values for average seed spacing, miss index, multiple index, quality of feed index, and cell fill percentage were 44.92 cm, 2.72 %, 7.05 %, 90.03 %, and 104.67 %, respectively. The integration of PSO with prediction models offered insights into enhancing precision planting efficiency and overall crop yield in mechatronic precision planters.

1. Introduction

Precision planting is essential for optimal crop production; ensuring seeds are placed at the correct depth with consistent spacing, proper soil cover, and adequate compaction. This practice not only enhances crop quality but also minimizes seed wastage, prevents seed scattering, and

reduces the need for excessive seeding. Moreover, it facilitates uniform germination and plant growth, simplifying subsequent farming operations like weeding and harvesting, resulting in cost savings [1–3]. Various seed metering devices are employed in precision planters, including pneumatic, inclined plate, belt, vertical rotor, and roller types. Roller meters are the most widely used due to their effectiveness in

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mechanized seeding. Even with advancements, enduring challenges such as seed damage, missing seeds, and multiple seed drops persist [4]. Inclined and vertical plate planters have been developed to tackle these issues across different seed types, but they face hurdles like ground wheel skidding and mechanical transmission issues, leading to irregular seed spacing. Despite offering superior seed singulation accuracy, pneumatic planters are less viable for small-scale farming operations due to their high energy consumption and cost. Among these options, inclined plate metering systems are often preferred for their cost-effectiveness and precision in seed singulation, adaptable for multi-crop use [1]. Successful planting with inclined plate seed metering devices relies on a careful sequence of steps. It starts with selecting the right metering plate, based on factors like seed type and size. Adjusting the plate's rotation speed is crucial to ensure optimal seed loading without damage. Fine-tuning the equipment's forward speed aligns with seed rate and spacing recommendations, varying by crop and conditions. Precise mathematical models play a key role, considering seed size, equipment speed, plate rotation, and cell size. These models guide equipment settings, minimize trial and error, and ensure accurate seeding. Optimization techniques, like mathematical algorithms and simulations, help find exact parameters for complete cell fill and desired spacing.

Many researchers have explored the use of ANNs to forecast the performance metrics of inclined plate seed metering devices. ANNs demonstrate exceptional proficiency in capturing complex nonlinear relationships between input and output data, making them indispensable for modeling various agricultural equipment, as evidenced by previous studies [5–7]. However, in recent times, there has been a growing interest in metaheuristic search algorithms, particularly evolutionary algorithms (EAs) such as genetic algorithms and differential evolution, due to their faster convergence and cost-effectiveness in optimization endeavors. While various statistical techniques have been effectively employed for optimizing precision planters [3,5], there has been no reported utilization of more advanced optimization methods like Introduced by Eberhart and Kennedy in 1995 [5], PSO has demonstrated its effectiveness in optimizing a wide range of real-world problems. This efficacy is underscored by studies conducted by Eberhart and Shi in 2000, Shi and Eberhart [8,9], and further supported by the research of Bensingh et al. in 2019 [10]. One notable advantage of PSO is its ability to navigate away from local optima, even in scenarios featuring multiple local minima/maxima within objective functions. This characteristic distinguishes it from other optimization methods, as it necessitates less computational effort and fewer parameter adjustments. Previous investigations have highlighted PSO's effectiveness in modeling the operations of various agricultural machinery, as exemplified by the work of Pareek et al. in 2023. Notably, PSO has demonstrated superior modeling capabilities compared to statistical techniques, as evidenced by studies conducted [5]. It excels in universal function approximation, generalization, and less sensitivity to noise or missing data, making it ideal for complex non-linear modeling without prior knowledge of input-output relationships [10–12]. This modeling technique has been successfully applied in agricultural machine process studies [7–9,13–15]. To enhance the precision of agricultural machinery operations, researchers have employed a variety of optimization techniques to ascertain optimal operating parameter configurations.

Mechatronics-based seed metering systems have emerged as a promising solution to address the limitations of mechanically driven devices. These systems utilize electronically controlled actuators to meter seeds, offering greater precision [16–18]. Unlike traditional designs, mechatronics-based meters not only control seed population but also manage seed timing and placement relative to neighbouring rows. This improved control enhances productivity and yields by reducing inefficiencies seen in mechanical systems. A novel approach aims to make the metering system smaller and closer to the furrow opener for higher precision sowing. Hence, mechatronics-based seed metering systems offer a promising solution to overcome the limitations of

mechanically driven devices. With the integration of IoT and robotics, agriculture is poised for increased efficiency and accuracy in crop sowing and production. Overall, mechatronics-based seed metering systems are progressively supplanting human intervention in continuous crop monitoring and production activities.

Furthermore, despite significant progress in the development of advanced mechatronic planters, many of the current models are cumbersome, energy-intensive, and primarily intended for large-scale commercial agriculture. Research on creating small, remotely operated precision planters that utilize AI-driven optimization tools and are suited to the requirements and limitations of smallholder farmers is obviously lacking.

This study aims to address important limitations by developing a small, remotely operated mechatronic precision planter with a mechanism for measuring seeds using an inclined plate. An Artificial Neural Network (ANN) will be utilized to comprehend the complex factors that influence how well seeds fill the cells, while Particle Swarm Optimization (PSO) will assist in improving the accuracy and dependability of the seed measurement settings. By overcoming the mechanical constraints of traditional methods, these modern technologies aim to provide a scalable and cost-effective precision agriculture solution. This strategy encourages technological development and environmentally friendly farming practices, especially in resource-constrained farming environments.

Based on the literature reviews presented above, Mechatronic systems can automate the planting operation and combining ANNs with the PSO algorithm can be a promising approach for modelling and optimizing the seed-cell filling performance of an inclined plate seed metering device.

Therefore, a study was conducted with the following objectives as given below:

- 1) Development and performance evaluation of remotely-controlled mechatronics precision planter.
- 2) An integration of ANN modeling with PSO algorithms for modeling and optimizing the performance parameters of inclined plate seed metering devices.

2. Material and methods

The study was conducted at the laboratory of the Department of Farm Machinery and Power Engineering, College of Agricultural Engineering and Technology, Junagadh Agricultural University, situated in Junagadh, India, positioned at latitude of 21.5063° N and a longitude of 70.4502° E, at an elevation of 130 m above mean sea level.

2.1. Seed parameters for metering plate design

The components of the planter were designed according to the physical characteristics of cotton seeds. The cotton (*Gossypium hirsutum L*) crop was considered, which is a predominant crop of the Saurashtra region of Gujarat state. The major reason for selecting this crop was to check the compatibility of the planter for seeds having a wide variation in their shape and size. The size, bulk density, shape, angle of repose and thousand-grain weight of the samples were all measured using a standardized process for designing the seed metering plate which can be calculated by following equation [19–21].

$$L = \frac{\sum_{k=1}^n l}{n} \quad (1)$$

$$w = \frac{\sum_{k=1}^n w}{n} \quad (2)$$

$$t = \frac{\sum_{k=1}^n t}{n} \quad (3)$$

$$\varphi = \frac{\sqrt[3]{LBt}}{L} \tag{4}$$

$$\theta = \tan^{-1} \frac{h}{r} \tag{5}$$

$$\rho = \frac{w}{v} \tag{6}$$

Where,

- L =The individual seed's length, mm
- w =The individual seed width, mm
- t =Individual seed thickness, mm
- φ =Sphericity
- θ =Angle of repose, ° h =Heap height, cm
- r =Circular plate radius, cm
- ρ =Bulk density, kg/m³ w =Weight, kg
- v =Volume of seeds, m³

2.2. Design values for seed metering system

The metering system primarily consisted of a ground wheel, an incremental optical rotary encoder (360PPR), a microprocessor (AT mega16UU2), a stepper motor driver (A3967), a stepper motor, and a seed metering box with a hopper. The seed metering plate had a diameter of 120 mm and a thickness of 4 mm. The groove size ranged between 5 and 6 mm, which was 1 to 1.2 times the maximum seed dimension. The rotary encoder detected the rotating speed of the ground wheel. Produces pulses as well and sends them to the microcontroller. Stepper motor speed is managed by a microcontroller via the shaft of the seed measuring plate. The diameter of the sensing wheel measured 143.24 mm, with the rotary encoder mounted on the outer shaft of the sensing wheel. For this study, an incremental rotary encoder (optical) with 360 pulses per revolution was chosen. The study focused on an inclined plate type metering mechanism. Design values for cell diameter, number of seeds per cell, and the number of cells per plate were determined based on the required seed rate and seed spacing, consid-

ering the size and shape of the seeds. The number of cells in metering plate were calculated as per given below equation

$$C = \frac{\pi \times S_n \times D \times R_s}{T_r} \tag{7}$$

Where,

- C = No of cell on seed plate
- D = Diameter of ground wheel, m
- S_n = Number of seed/m² R_s = Row spacing, 1.2 m
- T_r = Transmission ratio.

The microcontroller can adjust the transmission ratio to achieve the desired seed spacing. Theoretical seed to seed spacing was calculated as per equation

$$S = \frac{\pi \times D}{T_r \times N} \tag{8}$$

Where,

- S = Theoretical Seed to seed spacing, cm
- D = diameter of the ground wheel, cm

The plate's number of cells (N) was calculated as 1. The metering plate was constructed using a 4 mm thick acrylic sheet. The seed metering system comprises the metering plate, stepper motor, metering box, hopper, and seed delivery pipe. Both the seed hopper and metering box were constructed from 2 mm thick galvanized sheet metal. A 3 kg capacity seed hopper was affixed to the seed metering box. This box was designed to house the seed metering plate for delivering the required seed quantity, as depicted in Fig. 1. The Nema 17 stepper motor, with a current rating of 1.7 A, was directly connected to the metering plate, which was mounted on the seed metering box. The speed and rotational direction of the stepper motor were controlled by a micro-stepping motor driver.

2.3. Mechatronic seed metering system

The incremental rotary encoder utilized for measuring the rotational speed of the ground wheel generated an analog signal, which was

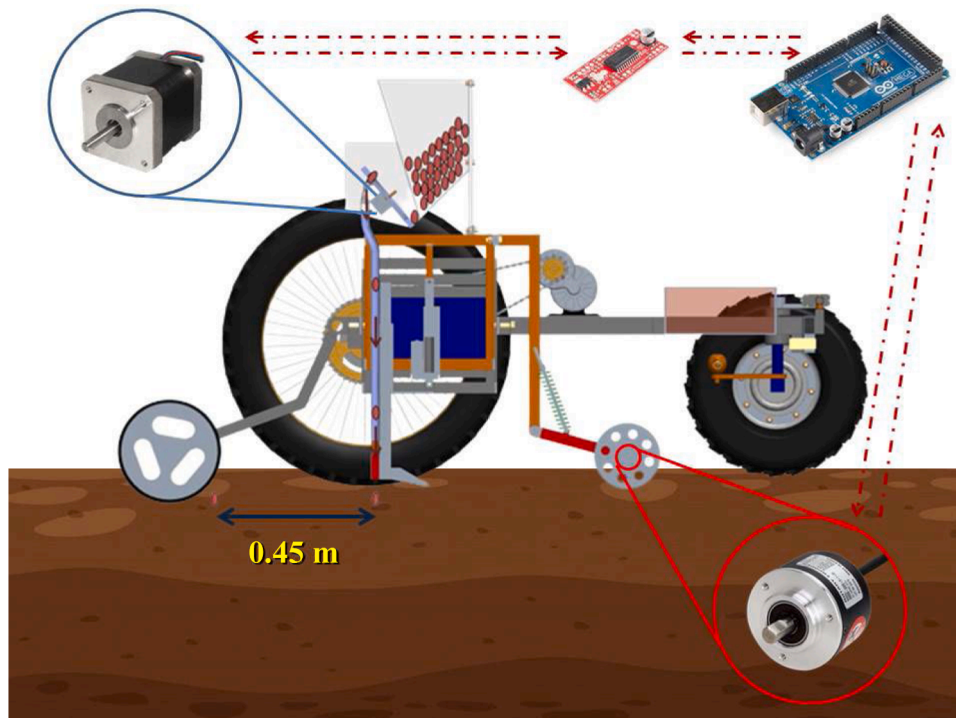


Fig. 1. Working principle of mechatronic precision planter.

directed to the microcontroller’s external interrupt pin. These signals underwent processing and were then transmitted to the stepper motor by the microcontroller (ATmega328P, 8-bit). The encoder generated pulses, which were received by the microcontroller, and subsequently, calibrated signals for the PWM (pulse width modulation) micro steps were dispatched to the micro-step driver. Ultimately, the micro-step driver transmitted the required signal for the desired speed of the metering plate to the stepper motor. The selection of the number of cells on the seed plate and the desired spacing was based on the seed size and crop geometry (seed spacing). These inputs were converted into pulses emitted by the microcontroller. Eq. (9) could be used to determine the pulses’ frequency conveyed to the motor driver module.

$$f_s = \frac{\left(\frac{V}{S}\right)}{C} \times \frac{360}{\gamma} \tag{9}$$

Where,

f_s = frequency of pulse to motor driver module, pulse/sec γ = step angle of stepper motor, degree

C= No of cell on seed plate,

V = Forward speed of planter, m/s

S = Seed spacing, m

2.4. The electronic system’s circuitry

The Arduino Mega 2560 was powered by a 12 V DC supply from a 12 V, 26 Amp battery. The two signal input wires of the rotary encoder were connected to pins 2 and 3 of the microcontroller’s external interrupt pins. The driver module (A3967) was connected to successive output pins 4 and 5 of the microcontroller, providing pulse signals to control the speed and direction of the stepper motor (NEMA 17). The forward speed value was determined by an incremental rotary encoder, which produced output pulses corresponding to the rotation of the sensing wheel (Fig. 2). The controller determined the forward speed by counting the received pulses. All components were integrated into the circuit to regulate the rotational speed (rpm) of the attached seed metering plate.

2.5. The remotely controlled vehicle

Remote control vehicle and mechatronic metering system both are

independent system. For the remotely operation, Flysky Fi6 6-channel transmitter and receiver was used. From that 6 channel, two of them is connected with MDDS30 Cytron smart drive and another 2-channel is connected with MDDSRC-10 Cytron smart drive. MDDS30 Cytron smart drive and MDDSRC-10 Cytron smart drive were used for controlling MY1016Z3 geared dc motors and 24 V DC actuators respectively. Two DC geared motor gave rotation power to individually drive wheel with chain and sprocket mechanism. From the two DC actuator one is used for steering actuating process and another one is connected in planting system. Planting system is connected telescopically to main frame of vehicle and for telescoping motion DC actuator was used.

Transmitter is two joy stick (Left stick and right stick). Left side joy stick is assign for both DC motor controlling. As shown in Fig. 6, Forward and reverse motion of vehicle is done by vertical movement of joystick and if trigger the left stick to horizontally, DC motor rotate oppositely to each other, which help to vehicle for zero turning radius. Right joy stick is assign for DC actuator. Up and down motion of planting system is activated by help of vertically movement of left stick and Steering actuating is activated by moving joystick horizontally (Figs. 3 and 4).

Working flow chart of mechatronics precision planter as depicted in Fig. 9. Electronic connection of electronic vehicle is shown in Fig. 5 Major components of mechatronic precision planter is shown in Figs. 7 and 8.

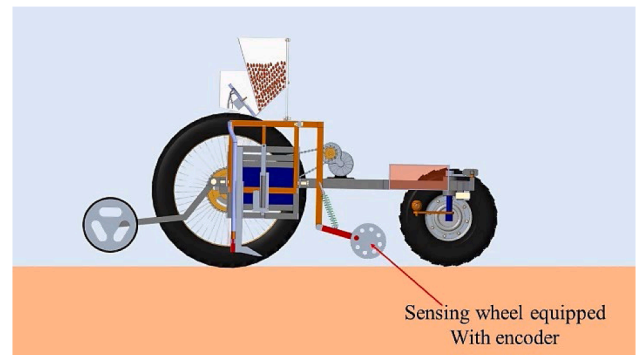
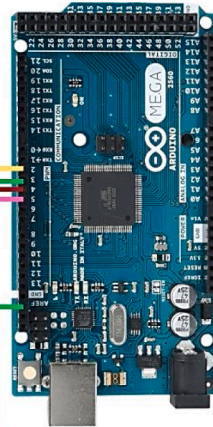


Fig. 3. Mechatronic system at activated condition.

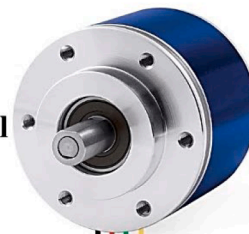
NEMA 17 Stepper motor



Arduino Mega 2560



Incremental Encoder



A3967 driver

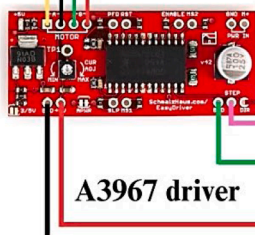


Fig. 2. Wiring diagram of mechatronic system for seed planting.

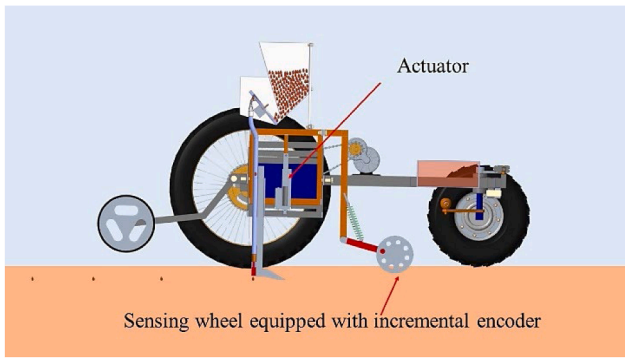


Fig. 4. Mechatronic system at inactivated condition.

2.6. Laboratory test

The primary goal of planting is to ensure seeds are placed precisely at recommended spacing and depth, without any damage or missing seeds, maintaining their uniqueness. Seed metering performance in planters relies on factors such as peripheral velocity, seed metering disc inclination, cell size, cell count, and seed dropping height [22,23]. For precision seeding, key testing parameters include forward speed (S), seed metering plate inclination angle (A), and seed hole geometry on the metering plate (P), as they significantly influence seed placement efficiency.

The experimental setup involved a 9750 mm long and 240 mm wide wooden board with an adhesive strip affixed to it. The wooden board was securely fixed, and the planter was maneuvered over it. This setup, also known as the mobile test, required the planting unit to be attached to a mobile trolley, ensuring it moved at a constant speed without any

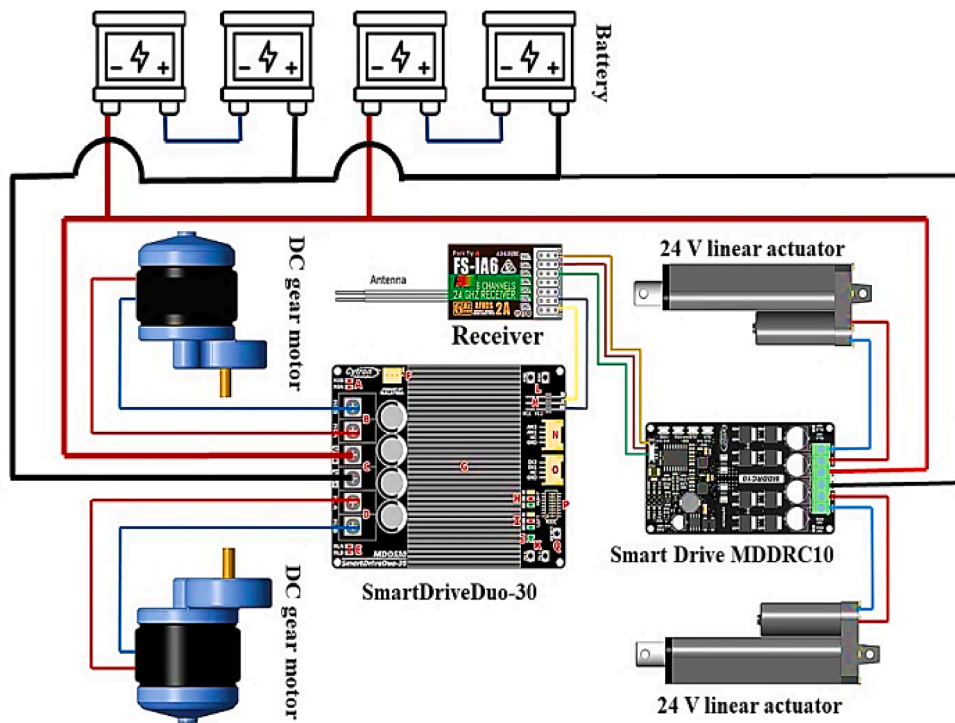


Fig. 5. Wiring diagram for remotely operated vehicle.

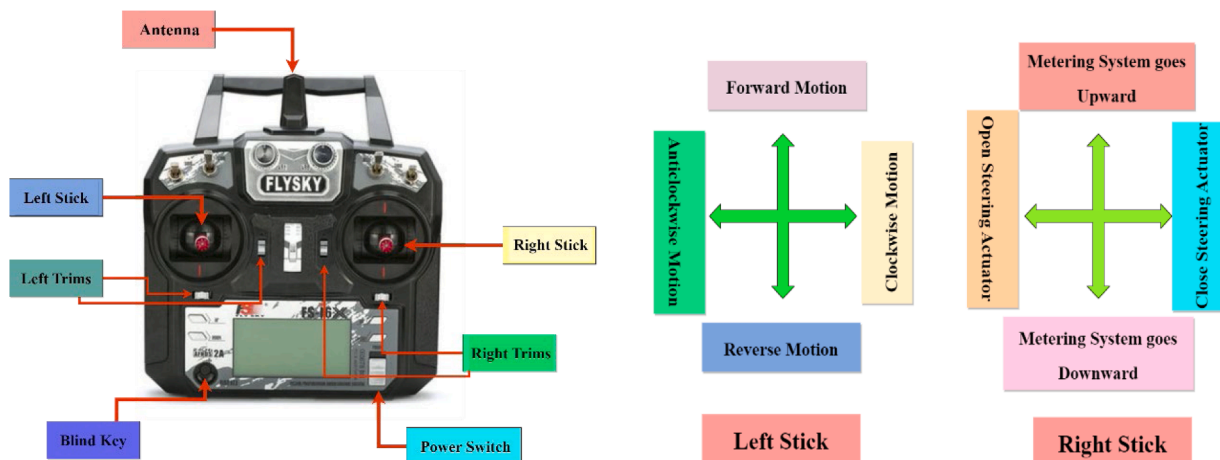


Fig. 6. Representation of functions assigned to transmitter.

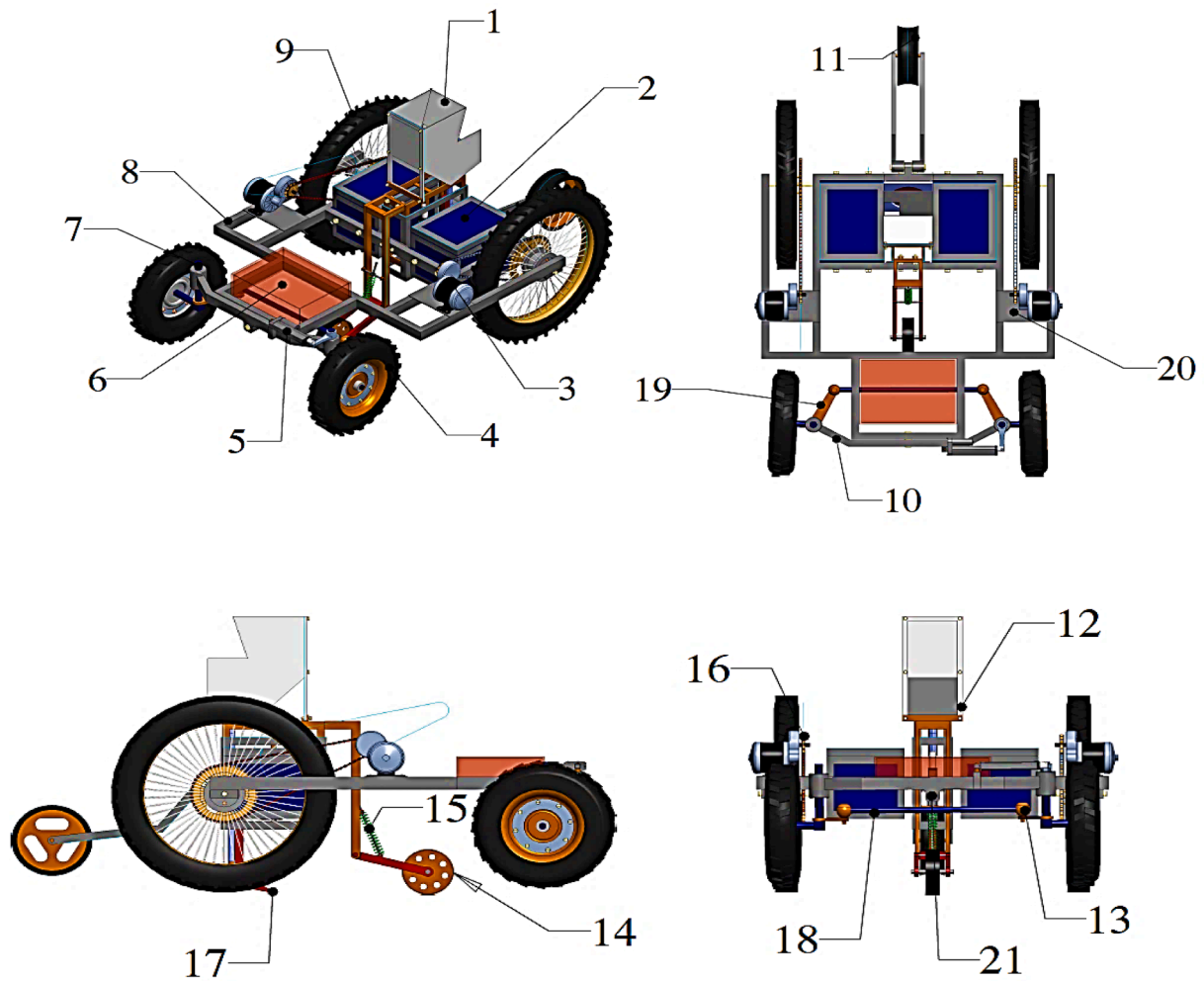


Fig. 7. Major components of Developed planter: (1) Hopper, (2) Battery box, (3) DC geared motor, (4) Front wheel, (5) DC actuator, (6) Control box, (7) King pin, (8) Rear frame, (9) Rear wheel, (10) Front frame, (11) Press wheel, (12) Hopper mounting frame, (13) Ball joint, (14) Sensing wheel, (15) Compressing spring, (16) Chain and sprocket, (17) Furrow opener, (18) Connection rod, (19) Knuckle arm, (20) DC motor Mounting platform, (21) Centre pin.

sudden movements over a stationary adhesive strip, following the guidelines outlined in ISO 7256/1 –1984.

Seed sowing uniformity along rows was assessed following Kachman and Smith’s methods. Average seed spacing, Miss index (MI), Multiple index (DI), and Quality of feeding index (QFI) were analyzed. MI reflects skipped seed locations (>1.5x nominal spacing), DI indicates multiple seeds within desired spacing, and QFI signifies single seed drops within half to 1.5x nominal spacing. Calculation formulas are as follows:

$$S = \frac{\sum S_a}{N} \tag{10}$$

$$MI = \frac{N_M}{N} \tag{11}$$

$$DI = \frac{N_D}{N} \tag{12}$$

$$QFI = \frac{N_Q}{N} \tag{13}$$

$$SR = \frac{N_C \times W}{l \times b} \times 10 \tag{14}$$

Where,

S_a =Spacing between consecutive seeds

N =Total observations

N_M =Frequency of spacing exceeding 1.5 times the theoretical spacing.

N_D =Frequency of spacing in the area being equal to or less than half the theoretical spacing.

N_Q =Number of times spacing between 0.5 times and 1.5 times the theoretical spacing.

SR =Seed rate, (kg/ha)

N_c =Number of seeds collected during l , length of run

W =Thousand seed weight, kg

L =Length of run, m

b =Nominal row to row spacing of the crop, m

For evaluation of remote control mechatronic precision planter, speed of operation ($S_1 = 0.42$ m/s, $S_2 = 0.55$ m/s and $S_3 = 0.69$ m/s), inclination angle ($A_1 = 50^\circ$, $A_2 = 55^\circ$ and $A_3 = 60^\circ$) and geometry of seed hole on metering plate ($P_1 = 100\%$ maximum size seed, $P_2 = 110\%$ maximum size seed, and $P_3 = 120\%$ maximum size seed) were decided on three level. Working and navigation of remote controlled mechatronic precision planter shown in Fig. 10.

2.7. Optimization of operational parameters for a mechatronic precision planter

Response Surface Methodology (RSM) was employed to optimize the operational parameters of a mechatronic precision planter’s. Utilizing Design Expert software (version 7.1.6., Stat-Ease, Inc., MN, USA), data

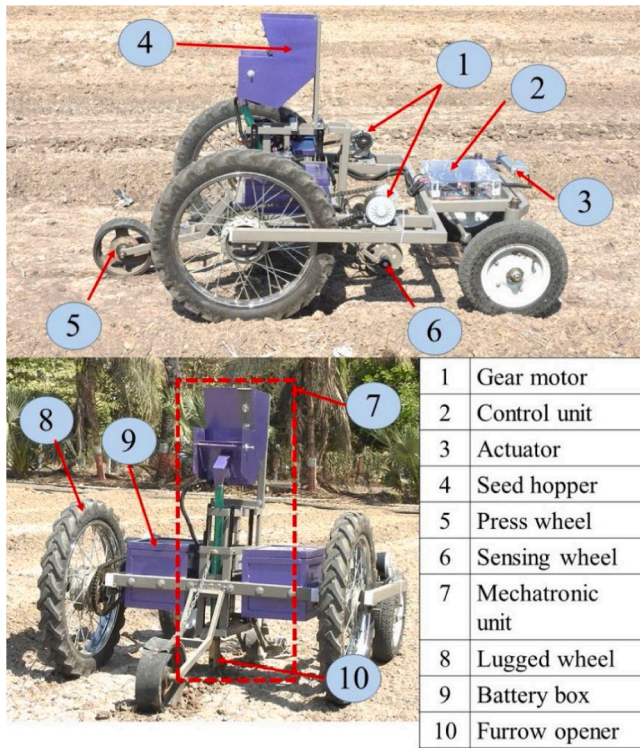


Fig. 8. Remote controlled mechatronic precision planter.

were organized following the Factorial Completely Randomized Design (FCRD). Factors such as Forward speed (S), Inclination angle (A), and Seed hole geometry (P) were optimized, considering their impact on parameters like Average Spacing, Miss Index (MI), multiple index, and Quality of Feed Index. Analysis of variance (ANOVA) evaluated model adequacy using F-value, P-value, and coefficient of determination (R^2).

2.8. Prediction model using Hybrid PSO- ANN approach

For the development of the mechatronic precision planter model, an ANNs with multilayer feedforward backpropagation architecture was selected. The architecture consisted of input, hidden, and output layers. MATLAB [24], equipped with the ANN toolbox, was utilized for constructing the network. The activation function tan-sigmoid was applied to the neurons in the hidden layer, whereas the output layer neurons utilized linear functions. The network had seven input layer neurons corresponding to the independent variables and six output layer neurons representing the dependent variables. Following the principle of having fewer than double the input neurons, the hidden layer was designed with 13 neurons. Thus, the resulting architecture in MATLAB 2019b was a 7–13–6 configuration, as illustrated in the accompanying Fig. 11. The artificial neural network (ANN) was trained using the Levenberg–Marquardt backpropagation algorithm (trainlm) as the training function, with the mean squared error (MSE) serving as the performance metric. The hidden layer utilized the hyperbolic tangent sigmoid (tansig) activation function to introduce nonlinearity, while the output layer employed a linear (purelin) activation function to accommodate continuous-valued outputs. The training process was configured with a maximum of 1000 epochs and a target performance goal of 1×10^{-5} . A fixed learning rate of 0.01 was applied to ensure stable and efficient convergence during training.

The ANNs was trained using 27 experimental data sets. Of these, 24 sets, accounting for 90 % of the total dataset, were used for training, while the remaining 3 sets, constituting 10 % of the total dataset, were reserved for testing purposes. A regression plot illustrating the performance of the trained multilayer feedforward backpropagation ANNs in

mapping the mechatronic precision planter process is shown in the Fig. 11. The plot reveals an impressive R^2 value of 0.966, underscoring the successful training and effectiveness of the neural network.

The evaluation of the constructed ANN's performance included assessing the coefficients of determination (R^2), root mean squared error (RMSE), and relative percent deviation (RPD) as described subsequently.

$$R^2 = 1 - \frac{\sum_{i=1}^N (y_{ai} - y_{pi})^2}{\sum_{i=1}^N (y_{ai} - \bar{y}_{ai})^2} \quad (15)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (y_{ai} - y_{pi})^2}{N}} \quad (16)$$

$$RPD = \frac{100}{N} \sum_{i=1}^N \frac{|(y_{ai} - y_{pi})|}{|y_{ai}|} \quad (17)$$

Where, N represent the number of datasets, y_{ai} and y_{pi} denote the actual and predicted output values of the i^{th} set respectively, and \bar{y}_{ai} represents the mean of actual output values.

2.9. Remote-controlled mechatronic precision planter optimization using hybrid ANN and PSO

In MATLAB 2019b software, a hybrid ANN combined with a PSO algorithm was developed to optimize the operational parameters of the mechatronic precision planter, as illustrated in Fig. 9. Initially, the multilayer feed-forward back propagation ANN (7–13–6) was trained using experimental data. Its performance was then tested, and it was employed to map the operational parameters of the mechatronic precision planter, as detailed in Section 3. Subsequently, the optimization process was conducted.

In the second stage, operational parameters were fine-tuned using the enhanced PSO algorithm. Two types of algorithms were utilized: the standard PSO and the Improved PSO. The standard PSO algorithm employs a constant inertia weight factor, denoted as ω . In contrast, the Improved PSO incorporates enhancements such as a linearly decreasing inertia weight and a confined search space. For this study, the variations in cognitive parameters were not taken into account, focusing the PSO parameter selection solely on the inertia weight. A hybrid ANN-PSO technique, which combines an Improved PSO algorithm (as described by [25]) with an ANN, was developed to optimize the operational parameters of the mechatronic precision planter. This hybrid technique was implemented using MATLAB [24].

The fitness function for the enhanced PSO algorithm is based on the error sum-of-squares between the required parameters and those predicted by the ANN, as presented below.

$$F = \sum_{i=1}^O (y_{ri} - y_{pi})^2 \quad (18)$$

Where, F is fitness function, y_{ri} and y_{pi} are required and predicted i^{th} output parameter respectively, and there is O number of output parameters; in the present study O is 6, i.e. R1, W1, Ra1, R2, W2 and Ra2

In the Improved PSO algorithm, the swarm comprises 50 particles, and the iteration count remains set at 1000. Both cognizant parameters, $c1$ and $c2$, are equated to 2. Throughout the 1000 iterations, the inertia weight factor ω in the Improved PSO linearly decreases from 0.9 to 0.4. Additionally, the swarm particles are constrained within specified bounds during each iteration of the algorithm. The selection of the inertia weight and acceleration coefficients in the Particle Swarm Optimization (PSO) algorithm is critical for balancing exploration and exploitation during the search process. In this study, an inertia weight of 0.9 was chosen to promote global exploration in the initial stages of

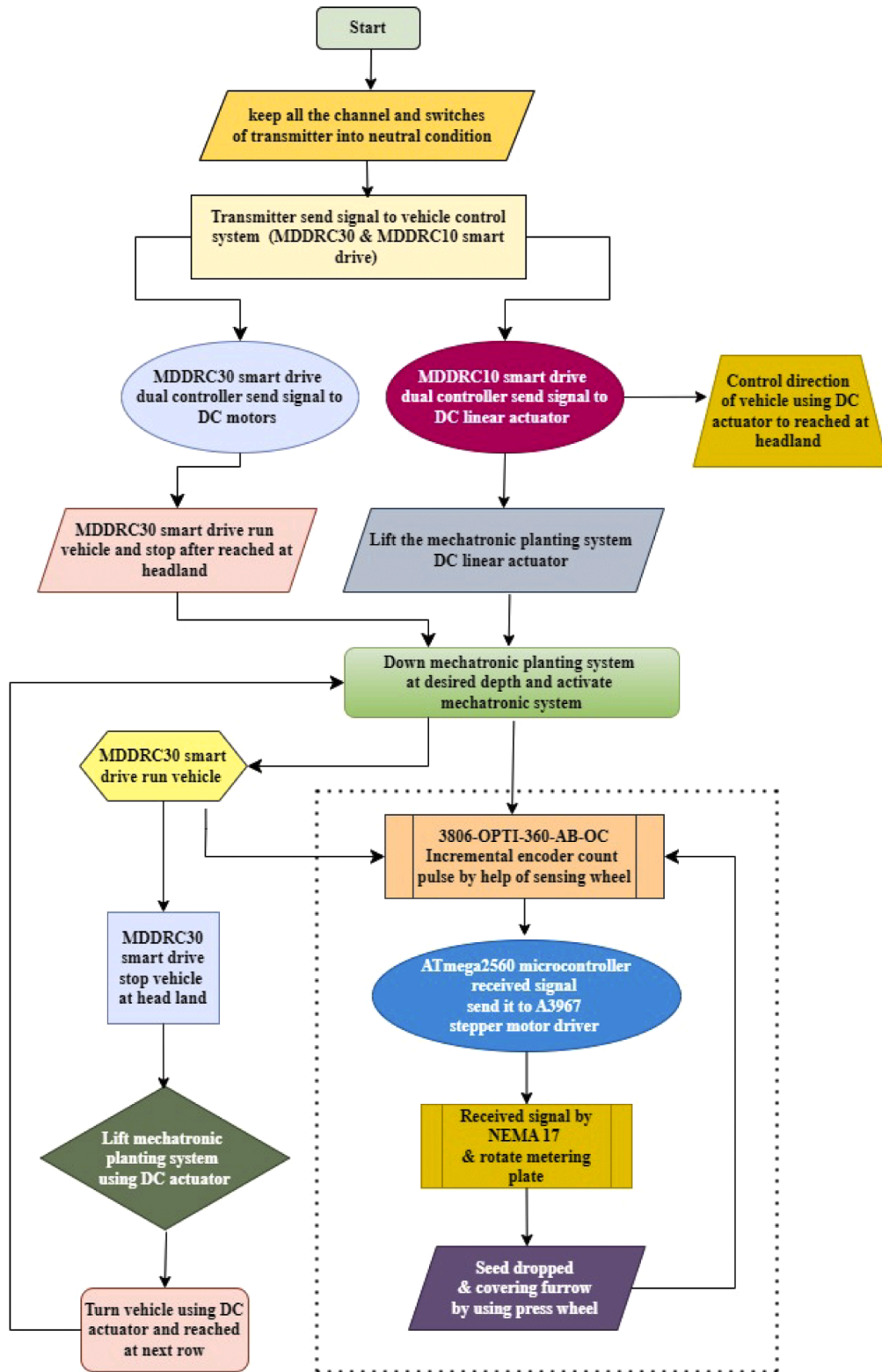


Fig. 9. Flowchart of working of a mechatronic precision planter.

optimization, thereby reducing the likelihood of premature convergence to local optima. The acceleration coefficients c_1 (cognitive component) and c_2 (social component) were both set to 2, aligning with standard PSO practice, to ensure a balanced influence between individual particle experience and swarm-wide knowledge. This configuration has been widely adopted in the literature due to its effectiveness in maintaining convergence stability and enhancing search efficiency across various

engineering optimization problems.

2.10. Optimization of operating parameters of mechatronic precision planter

The efficiency of the Mechatronic precision planter was enhanced by optimizing its operating parameters through Response Surface

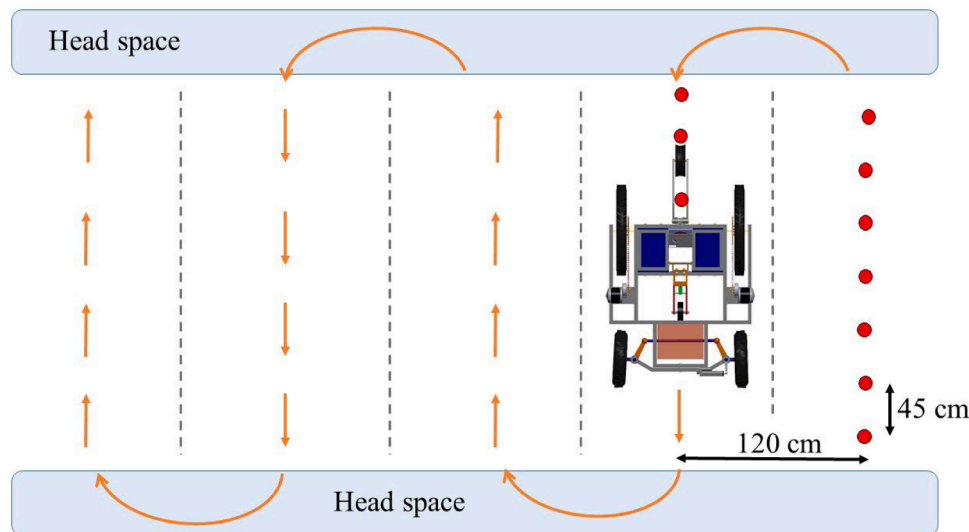


Fig. 10. Navigation of remote controlled mechatronic precision planter.

Methodology (RSM). The Design Expert software (version 7.1.6., Stat-Ease, Inc., MN, USA) was utilized for this optimization, with data structured based on the face centered central composite design (FCCD) as detailed in Table 1. The application of response surface methodology entails several stages. Initially, an experiment was devised using the Factorial Completely Randomized Design (CRD). Subsequently, the experiment was executed according to this design, with responses recorded accordingly. Following this, a mathematical model was developed to depict the correlation between the variables and responses. This model facilitated the determination of optimal conditions that either maximize or minimize the response. The accuracy of the model was validated through experimental verification of the optimal conditions, leading to iterative refinement for improved precision. The factors considered for optimization, namely working height, working speed, and discharge rate, were evaluated based on their influence on Average Spacing, Miss Index (MI), multiple index, and Quality of Feed Index. An analysis of variance (ANOVA) test was conducted, and the model's adequacy was assessed using F-value, P-value, and the coefficient of determination (R²).

3. Results and discussion

3.1. Effect of inclination angle (A), geometry of seed hole (P) and forward speed (S) on average spacing

It was observed that the average spacing between two seeds tended to rise with an increase in both forward speed and inclination angle. The suggested distance between cotton seeds, seed-to-seed, was 45 cm. However, the mean value of the average spacing was determined to be 45.33 cm, which closely aligns with the recommended spacing. The highest (S3A1P1) and lowest (S1A3P3) values for average seed spacing were recorded at 47.15 cm and 43.80 cm, respectively. Proximity to the nominal spacing of cotton seeds was evident in values such as 44.90 cm and 45.95 cm for average spacing. The forward speed exhibited a highly significant ($p < 0.01$) impact on average seed spacing (Table 2), while the geometry of the seed hole on the metering plate had a noteworthy effect. Elevated speeds of the metering plate resulted in a lack of sufficient time to accurately collect seeds in cells, leading to increased instances of missing seeds and consequently higher average seed spacing. Conversely, lower speeds had the opposite effect. The analysis revealed that the inclination angle did not have a statistically significant effect. The coefficient of variance was determined to be 2.22 %, a value within an acceptable range. These findings align with Kachman and Smith's

work from 1995.

3.2. Effect of inclination angle (A), geometry of seed hole (P) and forward speed (S) on miss index (MI)

To enhance the efficiency of the metering device, it is advisable to minimize the miss index. Fig. 12 illustrates the impact of various combinations, such as the inclination angle, seed hole geometry on the metering plate, and forward speed, on the miss index of cotton seeds. The results indicate a noticeable upward trend in the miss index as the forward speed increases. Forward speed, inclination angle and geometry of seed hole found highly significant ($p < 0.01$) for miss index shown in Table 2. The miss index exhibited varying values, with the minimum, maximum, and average values identified as 2.10 %, 5.92 %, and 3.76 %, respectively. The minimum miss index occurred when the forward speed (S1) was 0.41 m/s, inclination angle (A3) was 60°, and the seed hole geometry (P1) was at 100 %. Conversely, the maximum miss index (5.92 %) was recorded when the forward speed (S3) was 0.69 m/s, inclination angle (A1) was 50°, and the seed hole geometry (P3) was at 120 %. The trend indicated an increase in miss index with higher forward speeds, aligning with findings from Kachman and Smith [26], and Singh et al. [4].

At increased forward velocity, there was insufficient time to adequately fill the seeds within a cell, leading to the maximum miss index value. Furthermore, the size of the seed hole in the metering plate was noted to significantly influence variations in the miss index. Both of these factors exhibited higher significance in generating variations. The inclination angle was deemed non-significant in affecting the miss index, as the intervals between inclinations were only 5°

3.3. Effect of inclination angle (A), geometry of seed hole (P) and forward speed (S) on multiple index (DI)

Fig. 12 depicts the analysis of variance for the multiple index (DI) concerning inclination angle (A), seed hole geometry (P), and forward speed (S). The results revealed a decreasing trend in the multiple index as the forward speed level increased from 0.42 to 0.69 m/s. The minimum, maximum, and average values for the multiple index were determined to be 5.86 %, 8.86 %, and 7.15 %, respectively. The lowest value was observed at the combination (S3A1P3) corresponding to a forward speed of 0.69 m/s, an inclination angle of 50°, and a seed hole geometry of 120 %. The highest value of the multiple index (DI) was identified when utilizing A3P3 in conjunction with the S1 forward

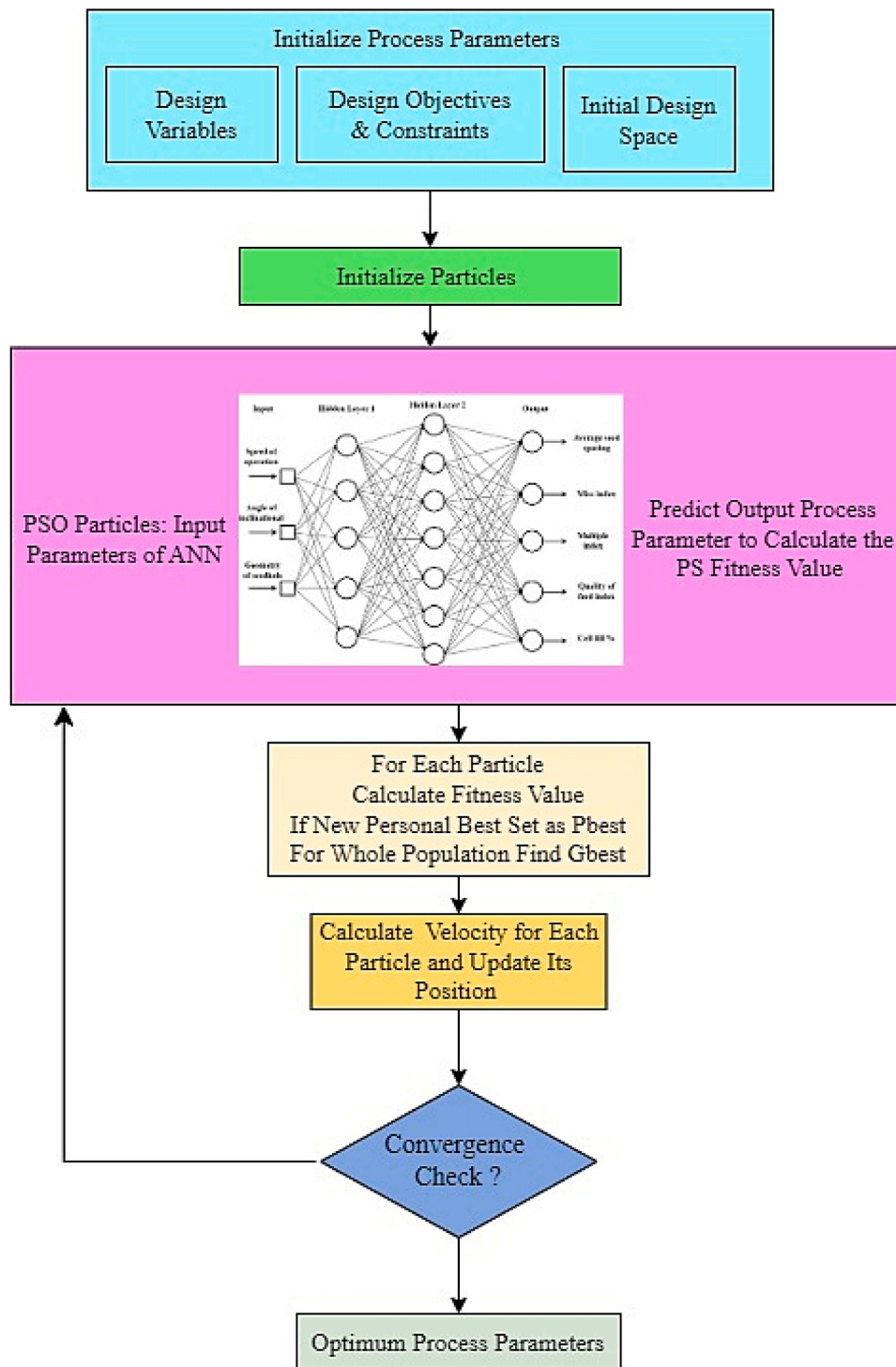


Fig. 11. Flow chart of Hybrid PSO- ANN approach.

speed. Table 2 displays the Anova effects of forward speed (S), inclination angle (A), and seed hole geometry (P) on the multiple index. Forward speed (S) and seed hole geometry (P) were observed to have a highly significant ($p < 0.01$) impact on the multiple index. Additionally, the interaction between inclination angle and forward speed ($A \times S$) exhibited a highly significant effect on the multiple index. The coefficient of variance was determined to be 4.79 %. Most of the seeds could readily be placed in cells on the metering plate at a lower forward speed. However, at a higher forward speed, the seeds struggled to settle in the cells due to variations in the miss index (MI) and multiple index (DI).

The geometry of the seed hole (P) played a crucial role in the multiple index, with an increase in the size of the seed hole leading to higher chances of successfully picking up a seed. The interaction effect of forward speed and inclination angle ($S \times A$) was deemed highly significant because the metering plate took more time to pick up speed at lower forward speeds (S1) compared to higher forward speeds (S3).

Table 1

Experimental design for the performance evaluation of mechatronic precision planter in laboratory.

Code for the values	Operating parameters				
	Forward speed, m/s	Inclination angle, degree	Seed hole geometry, Percentage		
-1	0.42	50	100		
0	0.55	55	110		
+1	0.69	60	120		
No. of experiments	X ₁	X ₂	X ₃	X ₄	X ₅
18	±1	±1	±1	±1	±1
9	0	0	0	0	0

27 = Total number of experiments

Code '0' is for the central point of the parameter range investigated, ±1 for factorial points,

X₁: Average Spacing, X₂: Miss Index (MI), X₃: multiple index, X₄: Quality of Feed Index, and X₅: Cell fill percentage.

3.4. Effect of inclination angle (A), geometry of seed hole (P) and forward speed (S) on quality of feed index

Fig. 12 illustrates the real impact of various combinations of inclination angle geometry in the seed hole on the metering plate and the forward speed on the feed index quality. It is noted that a higher quality of feed index (QFI) resulted in better precision. The average value of the feed quality index (QFI) was determined to be 89.08 %. The highest quality feed index (90.45 %) was observed when utilizing a combination of 0.41 m/s forward speed (S1), 60° inclination angle (A3), and 120 % seed hole geometry (P3). Conversely, the lowest quality feed index (87.38 %) was recorded with a combination of 0.69 m/s forward speed (S3), 50° inclination angle (A1), and 110 % seed hole geometry (P2). It is noteworthy that the obtained values for the quality of feed index were generally close to the average. The evaluation results indicated that fluctuations in the quality of feed index for each combination of inclination angle, forward speed, and seed hole geometry on the metering plate were influenced by the combined impact of respective misses and multiple indices. The acceptable threshold for the quality of feed index was set at 85 %, as suggested by Kachman and Smith [26] for a precision planter. Similar trends in results were observed for this combination in studies by Kachman and Smith [26] and Singh et al. [4]. An examination of variance (as depicted in Table 2) elucidated the variability in the feed quality index of cotton seeds attributed to factors such as inclination angle, the seed hole's geometry on the metering plate, and the forward

Table 2

ANOVA for the planter characteristic of Mechatronic precision planter at different operating parameters.

Source	Average seed spacing		Miss index		Multiple index		Quality feed index		Cell fill percentage	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Model	34.51	< 0.0001**	108.12	< 0.0001**	120.54	< 0.0001**	13.69	< 0.0001**	23.75	< 0.0001**
S	236.84	< 0.0001**	891.14	< 0.0001**	690.84	< 0.0001**	79.01	< 0.0001**	209.04	< 0.0001**
A	0.1488	0.7044 ^{NS}	12.55	0.0025**	1.71	0.2083 ^{NS}	0.5188	0.4811 ^{NS}	2.50	0.1325 ^{NS}
P	69.88	< 0.0001**	55.26	< 0.0001**	233.35	< 0.0001**	20.14	0.0003**	0.3548	0.5593 ^{NS}
S × A	0.3645	0.5540 ^{NS}	6.40	0.0216*	67.00	< 0.0001**	5.48	0.0316*	1.47	0.2413 ^{NS}
S × P	0.1351	0.7178 ^{NS}	5.55	0.0308*	14.71	0.0013**	12.25	0.0027**	0.0600	0.8094 ^{NS}
A × P	0.0689	0.7961 ^{NS}	1.65	0.2161 ^{NS}	0.8107	0.3805 ^{NS}	0.4337	0.5190 ^{NS}	0.0613	0.8074 ^{NS}
S ²	3.00	0.1013 ^{NS}	0.4330	0.5194 ^{NS}	75.95	< 0.0001**	0.0160	0.9008 ^{NS}	0.1105	0.7436 ^{NS}
A ²	0.1201	0.7332 ^{NS}	0.0087	0.9266 ^{NS}	0.0615	0.8071 ^{NS}	0.1074	0.7471 ^{NS}	1.610E-06**	0.9990 ^{NS}
P ²	0.0392	0.8454 ^{NS}	0.1342	0.7186 ^{NS}	0.4824	0.4967 ^{NS}	5.29	0.0344*	0.1236	0.7295 ^{NS}
R ²	0.9481	0.9828	0.9846	0.8788	0.9263					

** Significant at 1 % (p < 0.01).

* Significant at 5 % (p < 0.05).

^{NS} Non-significant, R²: Coefficient of determination

S: Forward speed

A: Inclination angle

P: Seed hole geometry.

speed. Notably, both the forward speed (S) and the seed hole's geometry (P) were individually deemed highly significant. Additionally, the interaction between forward speed and seed hole geometry (S × P) demonstrated a noteworthy impact on the feed quality index. The coefficient of variance, at 0.46 %, indicated minimal variation among the combinations in the quality of the feed index.

3.5. Effect of inclination angle (A), geometry of seed hole (P) and forward speed (S) on cell fill percentage (CF)

As depicted in Fig. 12, the percentage of cell fill increased as the inclination angle rose, but it decreased with an increase in the forward speed of the machine. The seed hole geometry significantly influenced cell fill percentage, with both miss and multiple indices impacting it. A higher miss index resulted in a lower cell fill percentage, whereas a higher multiple index led to an increased cell fill percentage. The maximum, minimum, and average values for cell fill percentage were 105.88 %, 99.95 %, and 103.05 %, respectively. The highest cell fill percentage (105.88 %) was achieved with a combination of a forward speed of 0.41 m/s (S1), an inclination angle of 60° (A3), and a seed hole geometry of 120 % (P3). Cell fill percentage represents the ratio of the number of cells passed to the number of seeds collected. If the cell fill percentage exceeded 100 %, it indicated a lower likelihood of miss index compared to multiple index. This observation underscores the metering plate's capability to effectively extract seeds from a metering box. Table 2 presents a statistical examination of the impact of inclination angle, seed hole geometry, and forward speed on cell fill percentage. Forward speed (S) exhibited a highly significant influence on cell fill percentage (CF), and the interaction between forward speed and seed hole geometry (S × P) also yielded a noteworthy effect on CF. The coefficient of variance was determined to be 0.59 %. The evaluation results suggested that variations in cell fill percentage across different combinations of forward speed (S), inclination angle (A), and seed hole geometry (P) were attributed to the cumulative impact of respective miss and multiple indices.

3.6. Optimization of operating parameters of mechatronic precision planter

In order to determine the optimal values for the independent variable, a combination of numerical and graphical optimization techniques of RSM were employed. The primary objective was to minimize the miss index and multiple index and average seed spacing was near to the 45 cm, which are important factors for successful planting applications. An overlay plot was created in Fig. 13 by superimposing the contours of

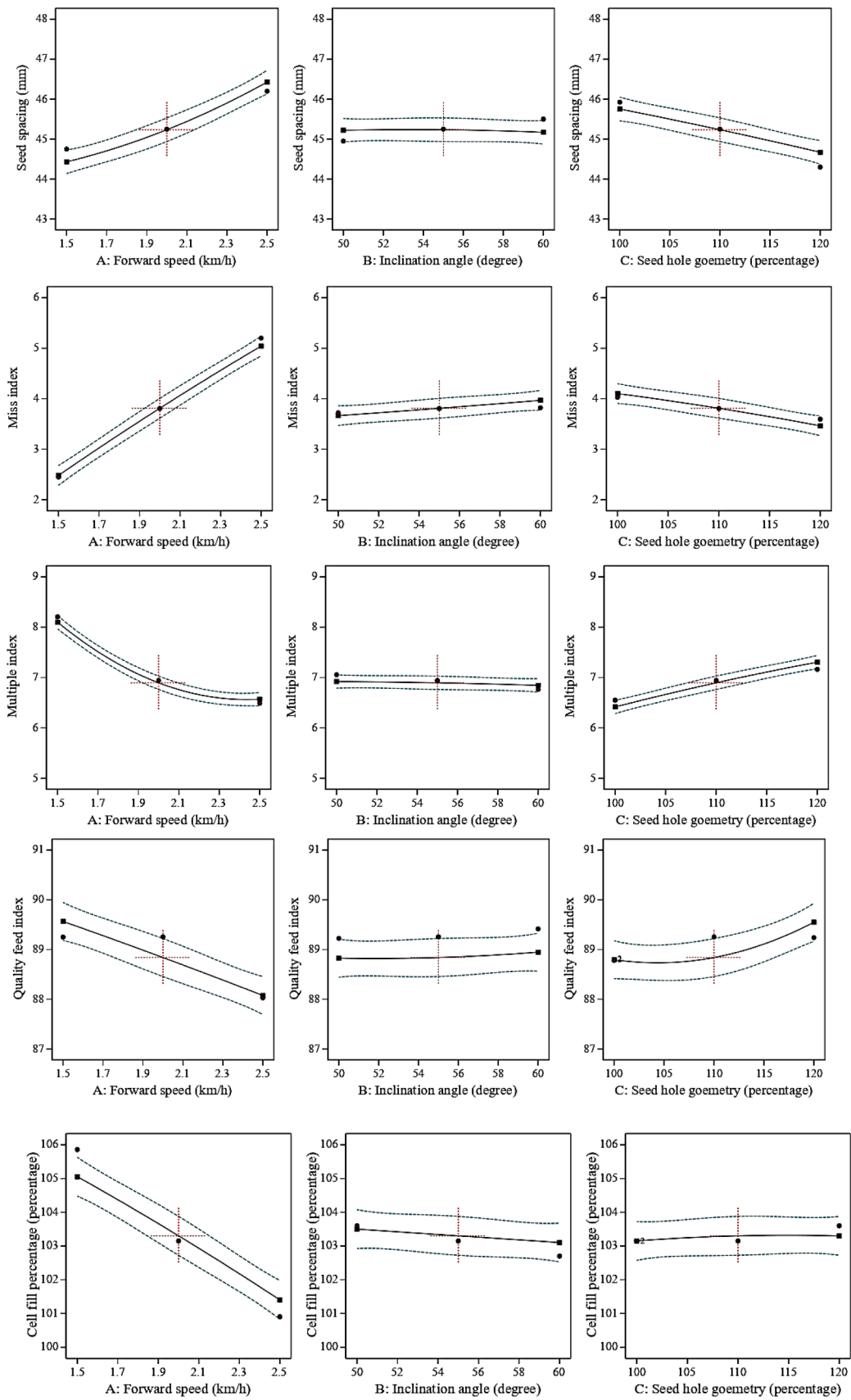


Fig. 12. Effect of different operating parameters of Mechatronic precision planter on average seed spacing, miss index, multiple index, quality feed index and cell fill percentage.

seed hole geometry and forward speed at the inclination angle's centre value. The optimal values for forward speed, inclination angle and seed hole geometry were found to be 0.43 m/s, 50° and 100 % respectively. At these optimal values, the predicted values of average seed spacing, miss index, multiple index, quality of feed index and cell fill percentage were 44.92 cm, 2.72 %, 7.05 %, 90.03 % and 104.67 % respectively. The optimal values obtained through the RSM optimization techniques represent the most favourable outcome for the mechatronic precision planter, taking into consideration the limitations imposed by the independent variables. Achieving these values is expected to enhance the efficiency and effectiveness of the planting, leading to improved performance and productivity of mechatronic precision planter.

3.7. Optimization of performance parameters of mechatronic precision planter using Hybrid PSO-ANN algorithm

The optimization of the mechatronic precision planter's performance parameters was achieved through the integration of the top-performing prediction model with the Particle Swarm Optimizer (PSO). The PSO simulation employed an inertia weight parameter of 0.9, along with acceleration coefficients (c_1 and c_2) set at 2 throughout the process. A swarm size of 100 and a maximum number of iterations capped at 1000 were chosen for the optimization process. The convergence curve of the PSO, illustrated in Fig. 14, depicted the global best and mean best fitness values of all particles across each iteration. Significant observations from the convergence curve revealed that the mean fitness value closely approximated the global best fitness value by specific iterations: 941st for average seed spacing, 944th for miss index, 920th for multiple index, 967th for quality of feed index, and 994th for cell fill percentage. These indications suggested that all particles within the swarm converged towards similar optimal solutions for the performance parameters. Table 3 presents the optimal parameters derived from the ANN-PSO model, alongside their cross-validation outcomes. Notably, the optimal values identified for Forward speed (S), Inclination angle (A), and Geometry of seed hole (P) to maximize average seed spacing were determined as 0.43 m/s, 52 degrees, and 100 percent, respectively.

This integration of prediction models with optimization algorithms signifies a sophisticated approach to enhance the performance of mechatronic systems like precision planters. The Particle Swarm Optimizer, a nature-inspired algorithm, effectively explored the performance parameter, seeking the best configuration for the planter's operation. The selection of an inertia weight of 0.9 and acceleration coefficients of

2 ensured a balance between exploration and exploitation, guiding the swarm towards promising regions of the search space while allowing for local refinement. The convergence curve analysis provided insights into the optimization process, showcasing the gradual improvement in fitness values over iterations and the eventual convergence towards optimal solutions. The close alignment between mean and global best fitness values across different performance parameters indicated the effectiveness of the PSO algorithm in finding consistent and robust solutions.

These optimized parameters not only maximize seed spacing but also contribute to minimizing miss index, multiple index, and improving the quality of feed index and cell fill percentage, thereby enhancing overall planting efficiency and crop yield. This comprehensive approach, combining advanced prediction modeling with optimization techniques, demonstrates a systematic method for fine-tuning mechatronic systems for optimal performance in precision agriculture applications.

4. Conclusion

- 1) The Particle Swarm Optimization (PSO) algorithm was utilized to determine the optimal values of performance parameters for the mechatronic precision planter. The optimal values identified for the Forward speed (S), Inclination angle (A), and Geometry of seed hole (P) to maximize average seed spacing are determined as 0.43 m/s, 52°, and 100 percent, respectively.
- 2) The cross-validation outcomes demonstrate that the ANN-PSO model accurately approximates the optimal input parameter values for maximizing average seed spacing, with a maximum deviation of only 2.67 % between the experimental and model-predicted average seed spacing values.
- 3) The remote-controlled vehicle and mechatronic metering system utilize independent systems, with specific components assigned to control functions and this setup enables precise remote operation and manoeuvrability, enhancing functionality and efficiency in agricultural planting applications.
- 4) The study demonstrated that forward speed and the geometry of seed holes on the metering plate significantly influenced the average spacing between cotton seeds during planting. While the suggested seed-to-seed distance was 45 cm, the mean average spacing closely aligned with this recommendation at 45.33 cm.
- 5) Increasing forward speed led to a rise in the miss index, indicating reduced efficiency in seed placement. The miss index ranged from 2.10 % to 5.92 %, with higher speeds contributing to more missed seed placements. The size of the seed hole on the metering plate also impacted the miss index, with larger holes exhibiting greater variability. The inclination angle showed minimal influence on the miss index.
- 6) The quality of feed index reflected the precision of seed placement, with higher values indicating better accuracy. Forward speed and seed hole geometry significantly affected the feed index, with interactions between these factors also playing a notable role. Achieving a high-quality feed index required optimal combinations of forward speed, inclination angle, and seed hole geometry.

Ethical statement

The authors declare that the work described has not involved experimentation on humans or animals.

CRediT authorship contribution statement

Vimalsinh Vala: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Rajvir Yadav:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Conceptualization. **Bikram Jyoti:** Writing – review & editing, Visualization, Methodology,

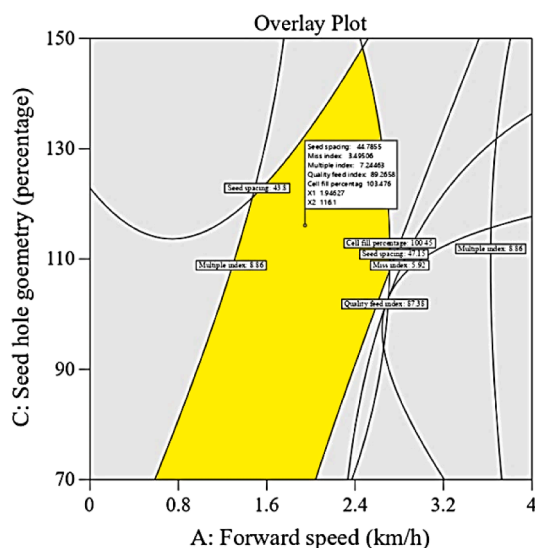


Fig. 13. Overlay plot of optimum values of operating parameters for mechatronic precision planter.

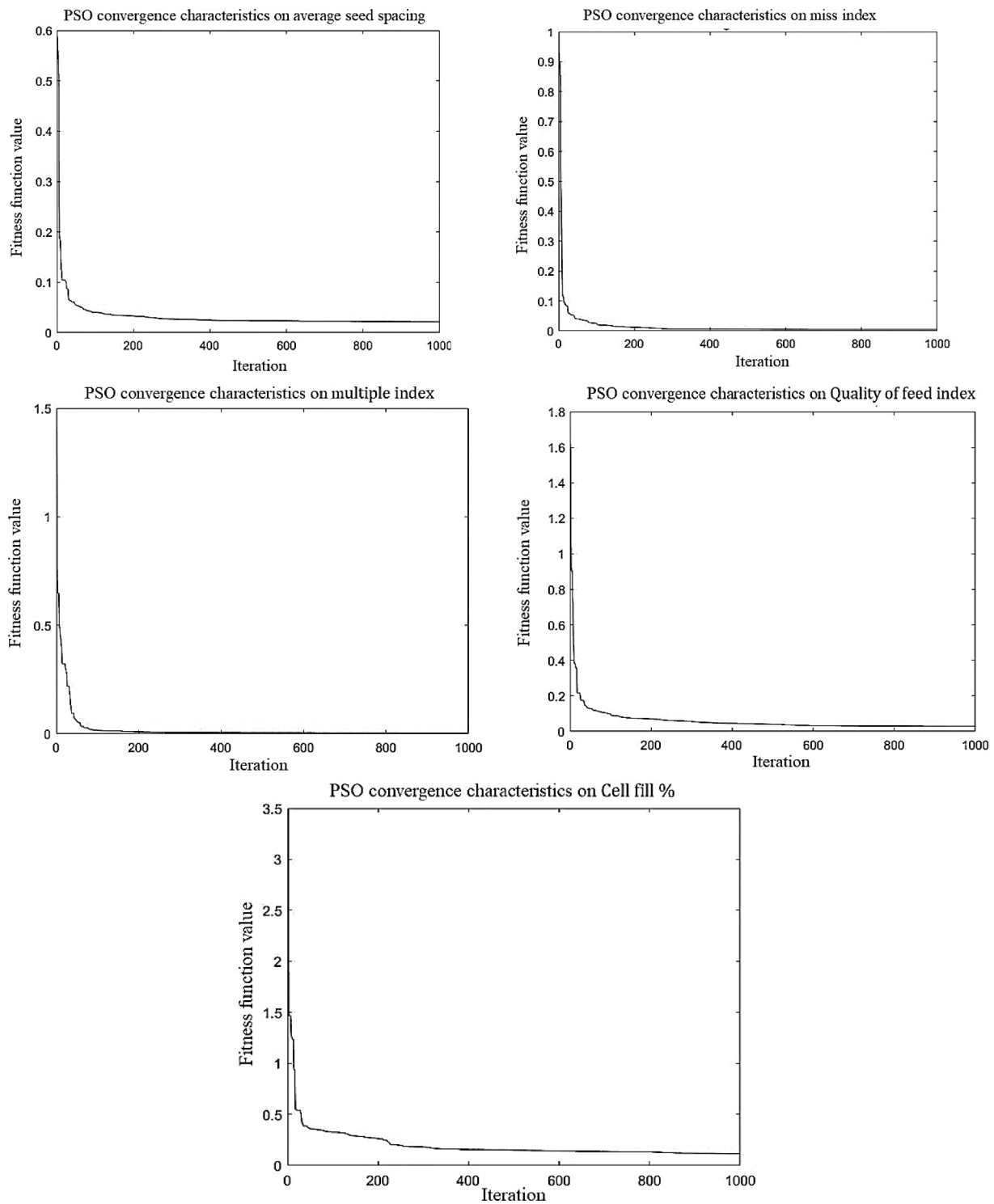


Fig. 14. PSO convergence characteristics on average on average seed spacing, miss index, multiple index, quality of feed index and cell fill percentage.

Table 3
Optimized performance parameters by ANN-PSO.

Forward speed (S)	Inclination angle (A)	Geometry of seed hole (P)	Average seed spacing		
			Predicted	Observed	Deviation (%)
1.54	52	100	46.12	44.92	2.67

Data curation, Conceptualization. **Ali Salem:** Writing – review & editing, Resources, Investigation, Funding acquisition, Data curation, Conceptualization. **Ajay K Roul:** Writing – review & editing, Resources, Investigation, Formal analysis, Conceptualization. **Rahul Potdar:** Writing – review & editing, Resources, Methodology, Formal analysis, Conceptualization. **Ankur Srivastava:** Writing – review & editing, Resources, Investigation, Data curation, Conceptualization. **Ahmed Elbeltagi:** Writing – review & editing, Resources, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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