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Design and Performance Testing of a Tractor-Integrated Corn Seed Planter on Performance Parameters and Planting Accuracy

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Abstract

Planting corn seeds with uniform hole formation and spacing between holes is an important agronomic requirement for direct sowing of corn seeds into the correct holes. This paper designs a type of corn seed planting tool integrated with a four-wheel tractor. Tests were conducted in dry fields with varying tractor forward speeds. Performance parameters measured included effective work capacity (AWC), theoretical work capacity (TWC), and field efficiency. Meanwhile, accuracy parameters were assessed based on the distance accuracy index, double index, and empty index. The results showed that the tractor forward speed significantly affected the work capacity and planting precision. The most optimal operating speed was achieved at a tractor forward speed of 4.5 km/h with an AWC of 0.45 ha/h and a field efficiency of 78.5%. At this speed, planting accuracy was in the very good category with a distance accuracy index reaching 92.4%, a double index of 4.1%, and an empty index of only

3.5%. The actual planting distance averaged 20.3 cm, very close to the theoretical target of 20.0 cm. On the other hand, increasing the speed to 6.0 km/h significantly increases the working capacity but drastically reduces the accuracy due to wheel slippage.

Keywords: Corn planting tools, empty index, tractor, work capacity, planting accuracy, agricultural mechanization.

Nomenclature	Greek symbols
d seed diameter (m)	ϕ outlet position angle ($^{\circ}$)
F_N force to corn seeds (N)	ω angular speed of rotation (rad/s)
F_C centrifugal inertia force (N)	σ acceleration (m/s^2)
F_f friction force (N)	θ angle of rotation ($^{\circ}$)
E_f Field efficiency	α angle the centre line ($^{\circ}$)
G gravity corn seeds (N)	μ friction coefficient
g acceleration of gravity (m/s^2)	β angle blade ($^{\circ}$)
I_q Quality of Feed Index	γ sliding friction angle ($^{\circ}$)
I_d Multiple Index	$\alpha_{\max}$ maximum diameter (m)
I_m Miss Index	
k number of seed	Acronyms
l distance (m)	TWC theoretical work capacity
n rotational speed (r/min)	AWC effective work capacity
R radius (m)	ANOVA Analysis of Variance
t time (s)	DMRT Duncan's Multiple Range Test
x coordinate values (m)	SPSS Statistical Package Social Science
V volume (m^3)	
v mass velocity (m/s)	

Introduction

Corn (*Zea mays* L.) is the second strategic food commodity after corn in Indonesia which has a vital role in supporting national food security and the animal feed industry (Fitriati et al., 2021). The increase in domestic corn production continues to be driven by the government

through a program to expand planting areas and increase the planting index in various regions (Ansar et al., 2025). However, one of the main obstacles faced in the upstream sector is the limited and significant decrease in the number of agricultural workers from year to year (Ansar et al., 2023). Therefore, the application of agricultural mechanization technology is a necessity to accelerate the cultivation process, reduce production costs, and overcome the phenomenon of labour scarcity.

The planting stage is one of the most critical phases that greatly determines the plant population per hectare and the success of the final productivity of corn crops (Stewart et al., 2021). Traditionally, the majority of farmers in Indonesia still rely on manual methods that not only require a long time and massive labour, but also require high operational costs (Sitorus et al., 2015). In addition to being inefficient in terms of time management, this manual method often results in uneven planting depths and distances between holes due to physical fatigue of human operators (Asshidiq et al., 2025). This geometric unevenness has a direct impact on the emergence of competition between plants in absorbing soil nutrients, water, and sunlight, which ultimately reduces the overall potential yield (Ding et al., 2021).

The use of mechanical planting tools (planters) integrated with four-wheel tractors offers a cutting-edge solution to overcome the latent weaknesses of traditional planting methods (Ansar et al., 2021). This mechanical integration is able to combine several process stages at once, starting from opening the soil furrow, precise seed placement, to closing and compacting the furrow again in one operational pass (Ansar et al., 2024). This integrated planting technology is specifically designed to operate on large expanses of land at a much higher working speed compared to human or livestock power (Ansar, et al., 2020). However, the successful adoption of this technology at the farmer level is highly dependent on the level of compatibility between the mechanical specifications of the tool with the topographic conditions and the physical characteristics of the local soil (Chen et al., 2022, Liu et al., 2017).

To measure the functional effectiveness of this integrated planting tool, a comprehensive evaluation of field performance parameters is absolutely necessary. Key quantitative parameters such as effective work capacity (AWC), theoretical work capacity (TWC), and field efficiency are the main determining indicators in assessing the economic and technical feasibility of machine operations in the field (Coronel et al., 2020). Low field efficiency in mechanical tools is usually influenced by the large amount of wasted non-productive time, such as time to turn at the end of the field, refilling seeds in the compartment (hopper), and technical problems in the form of tractor wheel slip (Shahbazi et al., 2023). A deep understanding of the dynamics of these performance parameters is crucial to minimize fuel consumption and operational costs per hectare of land (Wang et al., 2022).

Several previous studies have explored the use of mechanical planting tools for various types of seed commodities (Deng et al., 2025a). However, most of this research is still limited to testing on laboratory test rigs or using artificial soil tanks with very homogeneous conditions (Chen et al., 2023). Direct testing on actual dry land with uneven, rocky topography and varying soil textures is still very limited, especially those that examine variations in tractor forward speed above 4.0 km/h. In fact, the dynamic interaction between the tractor wheels, soil moisture conditions, and the internal mechanisms of the seed meter significantly affect the level of wheel slip and seed release precision in real field conditions (Ansar et al., 2024).

Based on these research gaps, this research was conducted to directly test the operational performance of a four-wheeled tractor integrated corn planting equipment in dry land conditions. The main focus of this research is to analyse and map the effect of variations in tractor forward speed on field performance parameters and the accuracy index for planting seeds in the soil. It is hoped that the results of this research can provide scientific recommendations regarding optimum operational speed limit standards to produce high work capacity without sacrificing the geometric quality of planting, as well as becoming a technical

reference in implementing standardization of large-scale maize planting mechanization in Indonesia.

Materials and methods

Corn seed

The planting material used in this research was corn seeds (*Zea mays* L.) of the BISI variety obtained from local markets in Mataram City, West Nusa Tenggara Province, Indonesia. This commercial variety was chosen because it is one of the cultivars most widely cultivated by farmers in Indonesia, so it is relevant to real conditions in the field.

Experimental Design

This experimental study was conducted in a farmer's rice field with post-primary tillage soil. A single-factor randomized block design (RBD) was used, with tractor forward speed (v) as the primary factor. This factor consisted of three treatment levels: 3.0 km/h (P1), 4.5 km/h (P2), and 6.0 km/h (P3). Each treatment was replicated three times, resulting in nine experimental plots. Each plot measured 40×10 m, with a 2 m spacing between plots, which served as a buffer zone to facilitate the tractor's acceleration and deceleration phases.

Structure and operating principle of a corn seed planter

This planter consists of several main components, as shown in Figure 1. The corn seed planter and mechanical fertilizer application are designed to operate synchronously, utilizing the tractor's traction force. As the tractor moves forward, the rear wheel coupler rotates, transferring mechanical power to drive the corn seed sowing hopper and fertilizer dispensing hopper. This wheel rotation activates the automatic and periodic seed and fertilizer distribution process into different holes. The specific design of the wheel rim, equipped with a tapered soil

puncher, utilizes mechanical pressure as the wheel rotates to penetrate the soil and form planting holes. This wheel geometry ensures uniform seed and fertilizer distribution, which is directly proportional to the tool's translational speed.

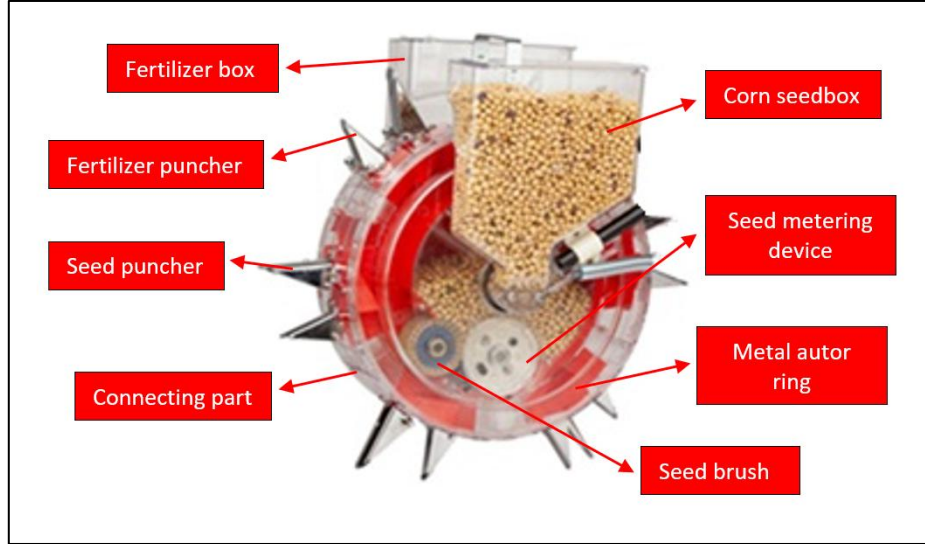


Fig. 1 Corn seed planting and fertilization tools

The equation for the path of motion of corn seeds in the hopper can be written in equation (Shang et al., 2024).

$$\begin{cases} x = vt \\ 2y = gt^2 \end{cases} \quad (1)$$

where,

$$v = 2\pi nl \quad (2)$$

In equations (1) and (2): v is the mass velocity of corn seeds, m/s, and its direction is the same as the forward direction of the planter; l is the distance between the centre of mass of corn seeds and the axis of the seed dispensing funnel, m , n is the rotational speed of the corn seed sowing device, r/min, t is the time for the corn seeds to move into the soil hole, s; x , y are the coordinate values of the mass centre of corn seeds after the vertical launch movement time, m ; g is the acceleration of gravity, $g = 9.8 \text{ m/s}^2$.

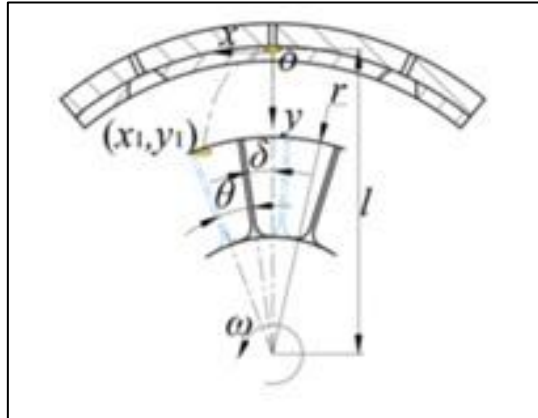
After time t_1 , the trajectory of the corn seed and the surface of the seed sowing funnel intersect at point a (x_1, y_1) . as shown in Figure 2a. The critical conditions for corn seeds to enter the planting hole are:

$$r \sin(\delta + \theta) \geq x_1 + \frac{\alpha_{max}}{2} \quad (3)$$

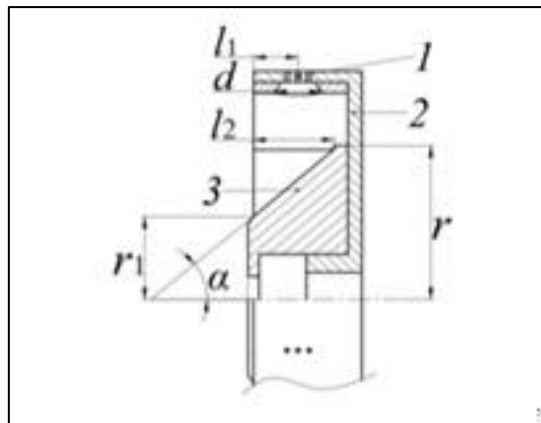
where $\theta = 360 nt_1$. r is the seed sowing radius, m; d is the offset angle of the seed rationed installation, °; θ is the angle of rotation of the seed rationing blade at time t_1 , the forces above are arranged as follows:

$$r \geq x_1 + \frac{2x_1 + \alpha_{max}}{2 \sin(\delta + \theta)} \quad (4)$$

In equation (4), x_1 and θ are related to the rotation speed of the planter, α_{max} is the diameter of the corn seed. Therefore, the diameter of the seed sowing funnel must match the diameter of the corn seed and the offset angle at the rotational speed of the seed sower.



(a)



(b)

Fig. 2 The trajectory of corn seeds and the surface of the seed sowing funnel.

Note: 1. Connecting part, 2. Seed auto ting, and 3. Seed metering device.

To guide the corn seeds to slide from the sower to the planting hole, the funnel is arranged as an inclined surface, as shown in Figure 2b.

$$\begin{cases} \frac{r-r_1}{l_2} \\ l_1 + \frac{d}{2} \leq l_2 \end{cases} \quad (5)$$

In equation (5): r_1 is the radius of the seed sowing funnel circle, m; l_2 is the axial width of the seed sowing funnel, m; α is the angle between the inclination and the centre line of rotation of the meter device seed; l_1 is the distance between the centre axis of the seed funnel hole and the outer end surface of the seed funnel, m; d is the diameter of the seed sowing funnel entrance, m; dimensions l_1 and d are 5 mm and 8 mm respectively.

To ensure that the corn seeds can smoothly enter the seed spreading funnel, the angle α should not be less than the sliding friction angle γ between the corn seeds and the seed brush. When corn seeds move from the sowing funnel to the planting hole, the minimum distance between the funnels must be able to be passed by one corn seed, namely:

$$\frac{2\pi r_1}{k} - b \geq \alpha_{max} \quad (6)$$

In equation (6): α_{max} is the maximum diameter of corn seeds, m, k is the number of seed sowing funnels, b is the seed sowing funnel, m. In this manuscript, take $b = 7.5$ mm. The combination of comprehensive equation (5) and equation (6) is:

$$r - \left(l_1 + \frac{d}{2}\right) \tan \gamma \geq r_1 \geq \frac{k(b+\alpha_{max})}{2\pi} \quad (7)$$

To shorten the movement time of corn seeds in the seed sowing funnel, the seed ratio radius (r_1) adjacent to the end of the sowing funnel must match the size of the corn seed.

Seed metering device

The purpose of installing an internal partition between the seed chamber and the dosing mechanism is to prevent the seeds from sliding freely into the sowing funnel. When the metering device component operates, the corn seeds released into the planting hole have a certain initial speed which is in the same direction as the wheel rotation vector. This measuring component is designed to regulate the fall of seeds so that they remain precise in the target zone. When the wheel rotates backwards and causes excess seed accumulation in the same measuring hole, some of the seeds will be stuck on the inclined plane of the measuring component so that they do not enter the sowing funnel. Furthermore, when the measuring component moves downwards, the remaining seed in the measuring compartment will flow back to the feeding zone through the guide bar. This self-cleaning mechanism ensures that each dosing compartment re-enters the next seed cell retention phase in an empty state without any seeds left behind.

The seed metering component is equipped with a seed outing ring, where the positioning of this channel directly influences the consistency of corn seed flow within the dosing compartment. The outlet position angle (ϕ) is defined as the angle formed between the plane of the outlet and the sowing shaft. When the angle between the seed measuring blade and the horizontal plane is no less than the kinetic friction angle (γ) of the corn seed, the seed will start to slide down along the blade. In this configuration, the angle between the blade and the measuring surface is set to β , as illustrated in Figure 3.

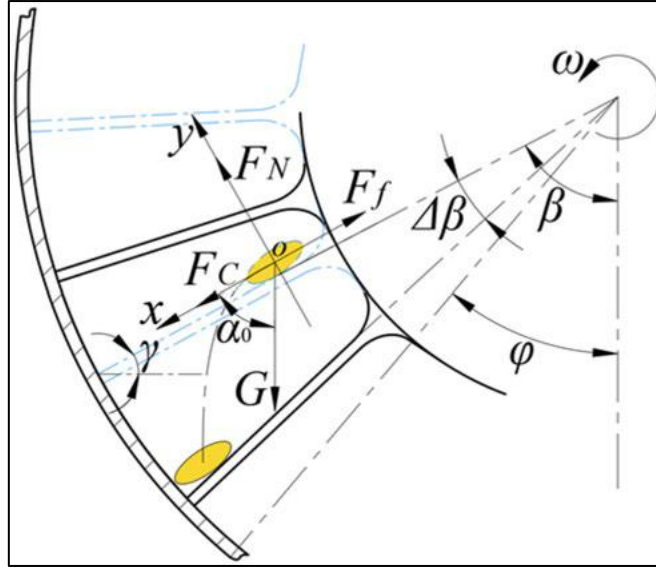


Fig. 3 Schematic diagram of seed metering device. Note: G is the gravity of corn seeds, F_C is the centrifugal inertia force of corn seeds, F_N is the support force to corn seeds, and F_f is the friction force.

Based on initial observations of the performance of the seed measuring components, the movement characteristics of multi-grain corn seeds in one separator compartment are dominated by the sliding phenomenon. Therefore, this research constructs a simplified mechanical model to model the behaviour of a single corn seed, as presented in Figure 3. In order to simplify the kinematic analysis, collision interactions between corn seeds are ignored. When the duration of the seed shift is expressed as t_2 and the rotation angle of the seed measuring component is $\Delta\beta$, then the following equation applies:

$$\Delta\beta = \omega t_2 \quad (8)$$

where, ω is the angular speed of rotation of the seed metering component, rad/s.

The equation for the force load of corn seeds is:

$$\begin{cases} G = mg \\ F_C = m\omega^2 l_4 \\ F_f = \mu F_N \\ F_N = G \sin \alpha_0 \end{cases} \quad (9)$$

where, m is the mass of corn seeds, g ; μ is the friction coefficient between the corn seeds and the seed dispenser, $\mu = \tan \gamma$; α_0 is the angle between gravity and the blade; l_4 is the distance between the centre of mass of the corn seed and the sowing axis, m ; σ is the acceleration of the movement of corn seeds, m/s^2 .

Combining equations (8) and (9), we can obtain the equation:

$$\sigma = g\sqrt{\mu^2 + \sin^2 \omega t_2} + \omega^2 l_4 \quad (10)$$

Corn seeds have various positions after being collected between the components of the seed dispenser. To simplify the analysis, this paper refers to the equivalent radius R of a sphere of equal volume V , and the calculation formula is:

$$2R = \sqrt[3]{\frac{6V}{\pi}} \quad (11)$$

The movement distance of the seed metering component L on corn seeds meets the equation:

$$L = l_4 - r_2 - R \quad (12)$$

According to the analysis of equation (11), when the seed measuring component rotates at a constant speed, the movement of the corn seeds is a variable acceleration. The integration of the corn seed movement process is:

$$L = \int \sigma dt^2 (t \in (0, t_2)) \quad (13)$$

The equation for the relative movement distance of corn seeds L can be obtained by combining equations (10), (12), and (13) into the equation:

$$L = \frac{2g\omega t_2 \sqrt{\mu^2 + 1} + \omega^2 t_2^2 (R + r_2) - 2g\sqrt{\mu^2 + \sin^2 \omega t_2}}{(2 - \omega^2 t_2^2)\omega^2} \quad (14)$$

Based on equation (14), it can be identified that if the seed diameter and measuring component material have been determined, the distance that the corn seeds move in the measuring mechanism is only influenced by the angular speed and duration of rotation. When the measuring angle is too large, the seed collection (multi-grain) does not have enough time

to exit the measuring compartment, so the seeds tend to accumulate before the sowing phase. On the other hand, when the measuring angle is too small, some of the corn seeds in the same compartment will be stuck on the outer cover plate, resulting in a decrease in the effectiveness of seed grouping (singulation/batching) before the dropping process. Therefore, determining the optimal measuring angle value is crucial for improving the quality of seed grouping in one planting hole, maintaining consistent seed release, and optimizing the uniformity of spatial distribution and distance between planting holes in the field.

Test procedure

The observation procedure in the field is divided into three main stages. First, the seeds are put into a compartment (hopper). The planting tool is raised using a three-point hitch system, then the planter's drive wheel is turned manually to ensure the seeds come out smoothly. Soil physical characteristics (moisture and hardness) were measured at 5 random points per plot. Second, the tractor is driven according to the target treatment speed (P1, P2, P3) in a predetermined path. The total travel time from the start to the end of the plot, as well as the turning time at the end of the plot were recorded using a stopwatch. Third, after the track is complete, the planting furrow is carefully opened for 10 meters in the central area of the plot (avoiding edge effects) to reveal the embedded seeds without changing their position. The distance between consecutive seeds was measured manually.

Operational performance parameters of the tool

a. Theoretical Work Capacity (TWC)

The working capacity of the planting tool per unit of time if it runs straight continuously without any technical interference or lost time, can be calculated using the equation:

$$TWC = \frac{W \times v}{10} \quad (15)$$

where, TWC is the theoretical work capacity (ha/hour), W is the total working width of the tool (m), and v is the theoretical forward speed of the tractor (km/h).

b. Actual Work Capacity (AWC)

The actual capacity in the field, which considers lost time (turning, seed refilling, and wheel slippage), is calculated using the equation:

$$AWC = \frac{A}{T_t} \quad (16)$$

where AWC is the effective work capacity (ha/h), A is the actual planted land area (ha), and T_t is the total operating time of the equipment in the field (h).

c. Field Efficiency (E_f)

The ratio between actual work capacity (AWC) and theoretical work capacity (TWC) in percent:

$$E_f = \left(\frac{AWC}{TWC} \right) \times 100\% \quad (17)$$

Planting accuracy parameters

Evaluation of plant spacing accuracy refers to the international standard ISO 7256-1. Based on the planned theoretical plant spacing ($x_{ref} = 20$ cm), the normal plant spacing range (x) is set at the interval of $0.5 x_{ref} \leq x \leq 1.5 x_{ref}$ (10 to 30 cm). The measured inter-seed distance is grouped into the following three indices:

a. Quality of Feed Index (I_q)

Percentage of the number of seeds that fall exactly within the normal (single) distance range:

$$I_q = \frac{N_q}{N} \times 100\% \quad (18)$$

b. Multiple Index (I_d)

Percentage of events where two or more seeds fell too close due to failure of gauge selection,
i.e. inter-seed distance $< 0.5 x_{\text{ref}}$ (< 20 cm):

$$I_d = \frac{n_d}{N} \times 100\% \quad (19)$$

c. Miss Index (I_m)

Percentage of occurrences where seeds failed to be dropped into the furrow, indicated by an
inter-seed distance $> 1.5 x_{\text{ref}}$ (> 20 cm):

$$I_m = \left(\frac{n_m}{N} \right) \times 100\% \quad (20)$$

N is the total number of samples of inter-seed distances measured in the observation area,
while n_q , n_d , and n_m are the number of data that fall into the normal, double, and empty
categories, respectively.

Data Analysis

Quantitative data obtained from field measurements were tabulated and analysed using statistical methods. Analysis of Variance (ANOVA) was carried out at a confidence level of 95% ($\alpha = 0.05$) using statistical software (SPSS) to determine whether variations in tractor speed had a significant effect on performance parameters and accuracy indices. Further tests were carried out if the ANOVA results showed a significant effect ($P < 0.05$), then the analysis was continued with Duncan's Multiple Range Test (DMRT) at the 5% level to determine specific differences between treatment levels (Ansar et al., 2020).

Results and discussion

1. Physical characteristics of the test site

The results of field testing showed that the average soil moisture content in the planting area ranged from 18.4% to 21.2%, with an average soil penetration resistance level (soil penetrometer resistance) of 145 kPa (Fig. 4).



Fig. 4 Land conditions at the planting tool testing location.

The physical characteristics of the land used to test corn seed planters play a crucial role in determining the mechanical efficiency and kinematic performance of the equipment in the field. One of the main physical parameters that must be evaluated is soil penetration resistance, or soil hardness. This characteristic is measured using a soil penetrometer. Measurement results have shown an ideal soil hardness condition for testing with an average hardness of 145 kPa. This value represents perfect tillage (OTS). If the penetration resistance value is too high, it can hinder the penetration of the double disk opener component in forming the planting furrow. Conversely, soil that is too loose risks causing slippage on the drive wheels of the seed metering device, which directly disrupts the accuracy of longitudinal plant spacing. The results of this study are consistent with several previously reported studies (Zhang et al., 2025).

In addition to hardness, soil moisture content on a dry basis is a physical property of the soil that significantly influences the dynamic interaction between the soil and the wheels of

agricultural machinery. Testing of corn seed planting equipment is generally required at field capacity, with an optimal moisture content range of 20 to 25% for sandy loam soils (Jun et al., 2022). If the moisture content exceeds its plasticity limit, the soil will become sticky and trigger the accumulation of soil mass on the press wheel and seed tube. This soil adhesion phenomenon not only increases the functional draft requirement of the pulling tractor but also has the potential to mechanically block the seed flow. A similar statement was reported by Wang et al. (2024) that soil adhesion forces not only increase the operational tensile load on the machine but also risk causing mechanical blockages in the seed distribution channel.

Soil texture and particle size distribution in the topography of the test site are also physical variables that influence the operational stability of the planting tool. Test sites dominated by sandy loam fractions provide lower shear strength than heavy clay loam, thus facilitating the adjustment of seed planting depth uniformly. Evaluation of this texture is important because it is directly related to the hydraulic conductivity and porosity of the soil, which determine how the soil will re-cover and compact the area around the seed (seedbed) after the dropping process. According to Li et al. (2025) a uniform distribution of soil aggregates after secondary tillage is necessary to ensure optimum contact between the seed and the soil (seed-to-soil contact) to support the imbibition process.

Equally important physical factors are the slope and micrographic flatness of the test field surface. Evaluating the mechanical performance of corn planting equipment requires relatively flat land conditions with a micro slope of no more than 2% to 3% to minimize lateral gravitational forces that can shift the tool's traction (Deng et al., 2025b). Extreme land surface unevenness (high surface roughness index) will trigger high vertical vibrations in the tool frame structure. This excessive mechanical vibration risks causing double planting or even planting failure in mechanical or pneumatic seed bags (Deng et al., 2025c).

The soil conditions where the seed spreader was tested represent dryland characteristics after secondary tillage, ideal for furrow opener penetration without causing soil build up (clogging) in the seed cover unit. Implementing a seed spreader requires perfect tillage (OTS) and proper soil dynamics. The soil must be loose with a certain level of compaction (penetration resistance) for optimal furrow opener performance, uniform seed depth, and maximum germination.

2. Operational performance of planting equipment

The results of quantitative measurements of Theoretical Work Capacity (TWC), Actual Work Capacity (AWC), and Field Efficiency (Ef) at three levels of tractor forward speed treatment are summarized in Table 1.

Table 1 Operational performance parameters of the planting tool at various tractor forward speeds

Speed Treatment	Actual Velocity (km/h)	TWC (ha/h)	AWC (ha/h)	Field Efficiency (Ef) (%)
P1 (3.0 km/h)	2.95	0.36 ^a	0.30 ^a	83.33 ^c
P2 (4.5 km/h)	4.42	0.54 ^b	0.45 ^b	78.50 ^b
P3 (6.0 km/h)	5.88	0.72 ^c	0.52 ^c	68.20 ^a

Note: Numbers followed by different letters in the same column indicate significant differences based on the DMRT test at the $\alpha = 0.05$ level.

Analysis of variance showed that variations in tractor forward speed had a significant effect ($P < 0.05$) on all operational performance parameters. Increasing tractor speed linearly increased the TWC and AWC values. Treatment P3 produced the highest AWC of 0.52 ha/h due to the high linear speed of the tractor. However, Ef decreased significantly with increasing

speed, from 83.33% in P1 to 68.20% in P3. The decrease in efficiency at high speeds was caused by increased non-productive time, especially the duration of turning manipulation at the edge of the field which requires higher tractor stability and fluctuations in drive wheel slip which increased exponentially at a speed of 6.0 km/h. The decreasing trend in E_f from 83.33% to 68.20% as the tractor forward speed increased from 3.0 km/h to 6.0 km/h showed a pattern consistent with the universal law of agricultural mechanization.

These findings align with research by Woo et al. (2017), who found that the standard E_f range for row-crop planters is between 70 and 85%. The decrease in efficiency below 68.20% in the P3 treatment (6.0 km/h) confirmed a surge in downtime. Bai et al. (2025) also tested mechanical seed in dryland. They reported that at speeds above 5.0 km/h, turning time increased significantly because the operator required greater precision to realign the tractor to the next furrow, resulting in a decrease in E_f .

3. Accuracy of corn seed planting

Quantitative work capacity and planting quality, as reflected in the precision of seed placement in the soil, are also crucial factors. Corn planting accuracy is internationally assessed based on three main indicators: the spacing accuracy index (I_q), the multiple seed index (I_d), and the missing seed index (I_m). Inaccurate seed metering devices can cause overcrowding or even complete seed emptying. This decrease in accuracy is often caused by instability in the rotation of the seed metering system's drive wheels when the tractor is driven at a certain speed.

The level of precision of seed dropping based on actual planting distance parameters referring to the ISO 7256-1 standard is presented in Table 2.

Table 2 Seed planting accuracy index based on speed variation

Speed	Actual	Spacing Accuracy	Multiple Seed	Missing Seed
Treatment	Planting	Index (I_q) (%)	Index (I_d) (%)	Index (I_m) (%)
	Distance (cm)			
P1 (3.0 km/h)	20.1	94.50 ^c	3.00 ^a	2.50 ^a
P2 (4.5 km/h)	20.3	92.40 ^b	4.10 ^a	3.50 ^a
P3 (6.0 km/h)	21.8	71.20 ^a	12.30 ^b	16.50 ^b

Note: Numbers followed by different letters in the same column indicate significant differences based on the DMRT test at the $\alpha = 0.05$ level.

The highest planting accuracy was obtained in treatments P1 ($I_q = 94.50\%$) and P2 ($I_q = 92.40\%$), which were statistically in the very good performance category. The actual planting distance produced by P1 (20.1 cm) and P2 (20.3 cm) showed very minimal deviation from the theoretical target (20.0 cm). In contrast, in treatment P3 (6.0 km/h), there was a drastic degradation in accuracy where the accuracy index (I_q) dropped to 71.20%, accompanied by a spike in the empty miss index of 16.50% and the multiple index of 12.30%.

The most crucial aspect of this study was the drastic decrease in the spacing accuracy index (I_q) to 71.20% at a speed of 6.0 km/h. This pattern reinforces the theory regarding the physical limitations of mechanical seed metering systems. Liu et al. (2025), in their study on precision corn planting, stated that mechanical metering devices experienced a sharp decrease in accuracy index when driven at speeds > 4.8 km/h.

In contrast to pneumatic trans planters (vacuum trans planters) that are capable of maintaining I_q values $> 90\%$ up to speeds of 8.0 km/h (Valentin et al., 2023), the mechanical system of the device tested in this study experienced failure due to external centrifugal forces. The excessively high rotational speed of the measuring disc at 6.0 km/h resulted in insufficient cell filling time for the seeds, a phenomenon also reported by Li et al. (2025).

The spike in miss index ($I_m = 16.50\%$) and multiple index ($I_d = 12.30\%$) at high speeds in this study is closely related to the phenomenon of kinematic slip on the ground wheel. Shang et al. (2024) explained that dry soil after secondary tillage has microaggregates that tend to be unstable. When the tractor moves quickly, ground wheel traction is reduced due to the skidding effect or micro-slip. The findings of Deng et al. (2025c) support this analysis by stating that slip on the drive wheel disrupts the synchronization between the linear speed of the machine and seed release. This triggers seed accumulation at one point (increasing I_d) or emptying the furrow at another point (increasing I_m).

4. Analysis of the filling mechanism of the seed metering device

When the device is pulled at high speed (6.0 km/h), the ground wheel rotates faster to transmit power to the seed metering device. However, this high speed shortens the cell filling time of the metering disc. Seeds do not have enough time to fall by gravity into the metering hole (cell). The interaction of the ground wheel with the uneven micro-topography of dry land at high speeds triggers the excitation of high vertical vibrations in the planter body. These vibrations transfer additional kinetic energy to the seed metering structure, causing seeds already in the metering hole to be thrown back out before they can be dropped into the seed tube. Based on Newton's Second Law ($F = ma$), the increase in speed and vibration causes the acceleration experienced by the seeds in the hopper to increase sharply. This inertial force causes the mass of seeds in the hopper to experience density fluctuations (seeds tend to move randomly and float/bounce), thus breaking the continuity of seed flow to the metering disc.

The phenomenon of decreased accuracy at high speeds (P3) can be explained by the mechanical power transfer mechanism from the ground wheel to the seed metering device. At a speed of 6.0 km/h, high inertial forces occur on the seeds in the hopper and vertical mechanical vibrations occur in the planter body due to uneven micro-topography of dry land.

These vibrations disrupt the stability of the metering cell filling, so the cell is often empty when passing through the discharge channel, which directly increases the miss index value.

In addition to causing a vacuum in the measuring cell, intense mechanical vibrations at a speed of 6.0 km/h also cause seed bouncing immediately after the seeds are released into the seed tube. This unstable seed release dynamic causes the time of flight of each seed to vary and be non-uniform. When seeds hit the bottom of the furrow with high kinetic energy due to the accumulated forward speed of the tool, they tend to roll or bounce far from their ideal drop point. The ripple effect of this unstable final position directly degrades the quality of feed index value and widens the deviation distance between plants within the row.

To minimize the negative impact of dryland micro-topography at high operating speeds, modifications to the planter's suspension system and optimization of the seed delivery channel geometry are required. Implementing an independent suspension system using down-force springs or pneumatic cylinders on each row unit can significantly dampen vertical vibrations, thus maintaining constant contact between the drive wheels and the ground. Furthermore, redesigning the seed tube's curvature to align with the horizontal velocity vector of the plant eliminates the impact force backlash when the seeds hit the ground. This combination of mechanical improvements maintains optimum filling stability of the metering cell, while ensuring accurate spacing accuracy even when the plant is operated at high field capacity efficiency. Previous researchers have also reported that high tractor linear speeds induce kinematic slippage in the ground wheels (Li et al., 2025), (Subandi et al., 2024), (Wang et al., 2024). When slippage occurs, the drive wheels stop rotating momentarily, but the tractor continues to move forward. This results in a wider seed spacing (an average of 21.8 cm) and compromises the uniform plant geometry required for optimal corn growth.

5. Field validation test

Based on the integration of performance and accuracy data, the P2 (4.5 km/h) treatment was identified as the optimum operating condition for this mechanization system. At this point, the machine is capable of achieving a relatively high work capacity (0.45 ha/h) without sacrificing planting precision ($I_q > 90\%$), therefore, this speed limit is recommended as the operational standard for large-scale corn planting in dryland conditions. Establishing a speed of 4.5 km/h (P2) as the optimum condition, with an I_q value of 92.40%, provides an important scientific contribution to the standardization of corn cultivation.

The success of the P2 (4.5 km/h) treatment in maintaining the separation quality index ($I_q = 92.40\%$) demonstrates an ideal kinetic balance between the machine's translational rate and the angular velocity of the seed metering component. At this operating speed, the centrifugal force experienced by the seeds in the hopper remains below the critical threshold, allowing the seeds to fall by gravity into the metering cell consistently and precisely. Furthermore, minimal mechanical slippage on the ground wheel ensures synchronous power distribution to the seed metering device. This condition minimizes variation in seed fall time, ultimately suppressing the miss index and multiple index values to the lowest levels compared to other speed treatments.

From an agronomic perspective, achieving a field capacity of 0.45 ha/hour under optimal conditions offers crucial time efficiency for corn cultivation in dryland areas. The highly dependent nature of dryland rainfall patterns necessitates rapid and simultaneous planting. This capacity allows for optimal soil moisture utilization early in the growing season before evaporation reduces groundwater availability. Appropriate plant spacing, resulting from a high I_q value, also ensures uniform plant density and reduces interplant competition for nutrients (Fig. 5).



Fig. 5 Field validation test on various treatments

As a practical implication for future technological development, performance data from the P2 treatment can serve as baseline data in the design of automatic control systems or smart

planters. The standard 4.5 km/h speed can be integrated with a GPS-based speed sensor or wheel encoder to automatically maintain stable seed meter rotation, despite fluctuations in tractor speed due to slippage in dryland fields. Further development of this automation will not only lock in the highest level of planting accuracy but also expand the planter's flexibility to operate across a wide range of land micro-topographic variability without compromising the quality of the results.

Zhang et al. (2025) confirmed that a spacing accuracy index (I_q) below 80% can significantly reduce corn yield potential by 10-15% due to interspecific nutrient competition and uneven canopy coverage. Therefore, the success of the P2 treatment in maintaining an I_q value above 90% demonstrates that this integrated seed planter is not only technically superior (AWC of 0.45 ha/h), but also safe and meets the agronomic requirements for industrial-scale dryland farming in Indonesia, similar to recommendations issued by several previous researchers.

Conclusion

Increasing tractor forward speed has been shown to quantitatively increase work capacity, but significantly reduce field efficiency. A speed of 6.0 km/h resulted in the highest Actual Work Capacity (AWC) of 0.52 ha/h, but decreased field efficiency to a low of 68.20% due to increased downtime during turning manoeuvres and increased drive wheel slippage.

Increasing tractor forward speed also negatively impacted the geometric quality of seed placement. The performance of the mechanical seed metering system experienced drastic degradation at high speeds (6.0 km/h), marked by a decrease in the quality of feed index to 71.20%, as well as a spike in the miss index (16.50%) and multiple index (12.30%) due to the effects of inertia, mechanical vibration, and ground wheel slippage.

A tractor forward speed of 4.5 km/h represents the optimum operating condition for this integrated corn planter. At these parameters, the tool is capable of producing high working

capacity (0.45 ha/h) with stable field efficiency (78.50%), while maintaining planting accuracy in the very good category (92.40%) with an average actual planting distance of 20.3 cm.

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Competing interests

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

Publication Consent Statement

I hereby agree and give full permission to the publisher to publish this work for academic purposes and the dissemination of knowledge.

Ethics Statement and Consent

I hereby declare that the entire research process has been conducted in accordance with applicable ethical standards and that all participants have provided voluntary written consent.

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Data availability

Data may be shared on request to the authors.

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