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DESIGN AND PERFORMANCE EVALUATION OF A FOUR-ROW VACUUM SEEDER POWERED BY A WALKING TRACTOR FOR PRECISION SOYBEAN PLANTING

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ABSTRACT

A previously developed two-row vacuum-type seeder showed promising singulation performance but its operational productivity was limited due to its low row capacity. This study aimed to design, develop, and evaluate a four-row vacuum-type soybean seeder to improve sowing capacity while maintaining high precision. The seeder, mounted on and powered by a walking tractor, used a centrifugal suction blower to generate vacuum pressure for four seed metering devices. Seed disks were driven by a chain-and-sprocket mechanism linked to the tractor's wheel shaft. Bench tests were conducted at two seed disk speeds (12.7 and 26.1 rpm) and six blower speeds (3500, 4000, 4500, 5000, 5500, and 6000 rpm) using two soybean varieties. Singulation efficiency and the percentages of multiple and missing seeds were recorded. Results showed that higher vacuum pressures (>1.70 kPa) at lower disk speeds (12.7 rpm) significantly improved singulation, achieving 99–100% efficiency with minimal missed and multiple seeds (<1.25%) and no seed damage. Higher disk speeds (26.1 rpm) reduced accuracy. Field tests at three blower speeds (5000–6000 rpm) and two tractor speeds (Low-1 and Low-2) confirmed consistent seed spacing (19.2–19.6 cm) and optimal planting depth (4.8–4.9 cm), with minimal variation due to wheel slip. The best field performance (98% singulation) was achieved at Low-1 tractor speed and 6000 rpm blower speed. Increasing tractor speed enhanced field capacity from 0.16 to 0.31 $ha \cdot h^{-1}$. The results validate the prototype's effectiveness for precise and efficient soybean planting.

Introduction

Indonesia's annual soybean consumption reaches 2.2 million tons, while domestic production supplies only about 35%, leaving more than 65% dependent on imports (Ningrum et al., 2018). To reduce this deficit, the government promotes land extensification into tidal swamp areas, with 9.54 million hectares identified as suitable for agriculture (Pusparani et al., 2016). Mechanization is essential to support this program and address labor shortages in land preparation and planting (Hulu and Rahayu, 2024). Developing tractor-powered soybean seeders is therefore crucial, as planting techniques and seeding equipment substantially influence seed distribution, seedling establishment, and yield (Kumar et al., 2013).

Various types of seeders with different metering mechanisms have been developed (Bakhtiari and Loghavi, 2009; Celik et al., 2007; Pedro et al., 2012; Gautam et al., 2019; Verma et al., 2007; Vineet et al., 2013; Sharma et al., 2023). However, the large variability in soybean seed size and weight often causes rotor-type meters to produce skips, doubles, and seed damage (Soza et al., 2004). Vacuum-type systems provide a more accurate alternative, offering superior singulation, reduced seed damage, and improved placement precision (Barut and Özmerzi, 2004; Singh et al., 2005; Bakhtiari and Loghavi, 2009; Fanigliulo and Pochi, 2011; Liu et al., 2015). Pneumatic disk seeders deliver uniform longitudinal distribution (Melo et al., 2013), while mechanical meters show reduced filling performance at higher speeds (Wang et al., 2023). As a result, precision planting technology increasingly adopts vacuum-based mechanisms (Karayel et al., 2004; Ismail, 2008; Karayel, 2009; Zhan et al., 2010; Yasir et al., 2012; Jabraeil and Farjam, 2013; Zhang et al., 2015; Bakhtiari and Ahmad, 2017), which offer advantages such as high accuracy, ease of operation, and low maintenance (Özmerzi et al., 2002; Ebrahim et al., 2009), as well as adaptability to diverse seed types (Xiong et al., 2021) and compatibility with conservation tillage (Karayel, 2009; Wang et al., 2023). Bakhtiari and Ahmad (2017) further demonstrated optimal pickup geometry for kenaf seeds that minimized misses and multiples.

Applications of pneumatic seeders have been widely explored, including soybean planters mounted on four-wheel tractors (Karayel, 2009) and vacuum devices for wheat (Yasir et al., 2012), showing improvements in uniformity, reduced damage, and higher accuracy (Pedro et al., 2012; Zhan et al., 2010). Rezaei Asl et al. (2019) found that lower vacuum pressure and operating speed improved uniformity in a vacuum drum device. Despite these benefits, most vacuum-type seeders are designed for four-wheel tractors (Kumar et al., 2013; Kumar et al., 2015), whereas smallholder systems in Indonesia predominantly rely on walking tractors. Existing walking-tractor seeders (Singh and Vatsa, 2007; Solomon, 2017; Pradhan et al., 2011; Vineet et al., 2013; Hermawan, 2011) still use rotor or mechanical disk mechanisms, which generally lack precision. Integrating seeding devices on walking tractors has shown promise, as demonstrated by a corn seeder–fertilizer applicator achieving 0.35 ha h^{-1} capacity and 84% efficiency (Hermawan, 2011; Sitorus et al., 2015).

A preliminary vacuum-type metering system for soybean seeding on a walking tractor was developed by Hermawan et al. (2016), in which the metering disk was driven by the wheel axle through a chain–sprocket system and the blower was powered by the engine via a V-belt. Although this system achieved 100% single-seed delivery without visible damage, its two-row configuration yielded a low field capacity (0.06 ha h^{-1}). Improving this design requires expanding the system to four rows and resizing the blower to ensure adequate suction for multiple metering units.

Typically, pneumatic seeders use a ground wheel to drive the metering disk, but slippage reduces accuracy. Hermawan et al. (2015) reported 21–36% slippage across five wheel types, with lugged rubber wheels performing best (21–22%). To avoid spacing errors, the metering disk can instead be powered directly from the tractor's wheel axle, which generally experiences minimal slippage during operation.

Designing a four-row vacuum seeder for walking tractors thus requires a reliable vacuum-suction system, a power transmission mechanism to drive the blower from the engine, and a separate axle-driven system for metering-disk rotation. Considering these requirements, this study aimed to design and evaluate a walking-tractor-powered four-row vacuum seeder for precision soybean planting.

Materials and Methods

Seeder Design Considerations and Mode of Operation

The seeder unit was designed as a multi-row planter to be towed by a walking tractor. It was developed to enhance the field working capacity of a previously designed soybean seeder (Hermawan et al., 2016) by doubling the working width through the integration of four seeder units. These units are mounted and supported on a main frame, which is attached to the tractor's hitch point.

The seeder was designed to deposit one seed at each planting point, maintaining an intra-row spacing of 20 cm and an inter-row spacing of 40 cm. A vacuum blower, powered by the tractor's engine through a V-belt and pulley system, generates the vacuum pressure and airflow required to operate all four seed metering units. Each metering device utilizes a vertical seed disk mechanism, driven by the rotation of the tractor's left wheel axle via a chain-and-sprocket transmission system. For greater operational flexibility, a clutch system is incorporated to engage or disengage the rotational power to the metering mechanism as needed during sowing. The seeder is also equipped with furrow openers and covering devices to ensure a consistent planting depth of 3.0–5.0 cm.

Single seeds are picked up by the seed metering disk and delivered into the seed chute. As the furrow opener continuously opens the soil, the seeds drop into the furrow, which is then immediately closed by the furrow covering device. As the planter is towed along the row, it continuously deposits seeds at 20 cm intra-row spacing until the seed level in the hopper drops to refilling level.

A design analysis was conducted to determine the optimal shape, size, and elements of the seeder mechanism. The design and material selection were carefully considered to ensure ease of manufacturing and affordability for end users. The seeder was designed using locally available materials and spare parts and can be manufactured using technologies accessible to local workshops.

Soybean Seed Characteristics

Two local soybean varieties, *Anjasmoro* and *Argomulyo*, were used as references for the design and testing of the seeder. The physical characteristics of both varieties were measured and analyzed. Seed dimensions were measured using a 0.01 mm digital caliper on a sample of 100 seeds. Seed sphericity was calculated using the formulas proposed by Soyoye et al.

(2018) and Karababa and Coskuner (2007). The measured dimensions and physical characteristics of the soybean seeds are summarized in Table 1.

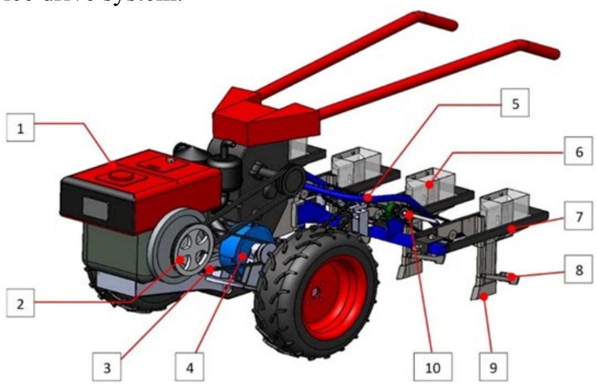
Table 1.
Dimensions and physical characteristics of soybean seeds.

Parameters	Seed Variety	
	Anjasmoro	***Argomulyo***
Length (mm)	7.02 ± 0.46	7.38 ± 0.45
Width (mm)	5.95 ± 0.32	6.15 ± 0.29
Thickness (mm)	4.63 ± 0.55	4.77 ± 0.25
Sphericity	0.82 ± 0.06	0.81 ± 0.02
Bulk density ($kg \cdot m^{-3}$)	0.72 ± 0.01	0.73 ± 0.01
Moisture content (% DM)	10.27 ± 0.35	8.33 ± 0.29
Angle of repose (^{o})	28.19 ± 0.56	30.81 ± 0.74
Mass of one seed (g)	0.142 ± 0.018	0.145 ± 0.021

The terminal velocity of soybean seeds was measured using the vertical air tunnel method, as described by Khoshtaghaza and Mehdizadeh (2006). Measurements were repeated ten times for each seed variety. The results showed that the terminal velocity of *Anjasmoro* and *Argomulyo* soybean seeds was 10.22 ± 0.54 $m \cdot s^{-1}$ and 9.84 ± 0.34 $m \cdot s^{-1}$, respectively. These values are consistent with the findings reported by Polat et al. (2006) and Tunde-Akintunde et al. (2005).

Structure and Components of the Seeder

Figure 1 illustrates the structure and main components of the soybean seeder. The key components include: (1) the suction blower drive system, (2) the suction blower, (3) suction hoses (comprising one primary hose and four secondary hoses), (4) seed hoppers, (5) seed metering devices, (6) the seeder frame, (7) furrow openers, (8) furrow covering devices, and (9) the metering device drive system.



(1) tractor engine; (2) drive pulley; (3) V-belt; (4) suction blower; (5) suction hose; (6) seed box and metering device; (7) seeder frame; (8) furrow covering device; (9) furrow opener; (10) metering device driver shaft

Figure 1. Pictorial drawing of the walking tractor-driven seeder

Design of the Seed Metering Device and Vacuum System

Designing a vacuum system requires data on the required vacuum pressure and suction air velocity. Singh et al. (2005) developed a formula to calculate the vacuum pressure at the seed hole for a horizontal seed plate with seeds positioned below. However, this formula is not suitable for the current design, which uses a vertical seed metering disk. A mathematical model developed by Karayel et al. (2004) estimates the optimal vacuum pressure for vacuum seeders based on seed physical properties, including thousand-seed mass, projected area, sphericity, and kernel density. For soybeans, the model predicts an optimal vacuum pressure of approximately 3.0 kPa (Karayel et al., 2004; Karayel et al., 2022). In contrast, measurements and calculations by Hermawan et al. (2016) determined that the minimum vacuum pressure required to hold an *Anjasmoro* variety soybean seed on the cell of a vertical seed disk is 0.41 kPa. More recently, Xu et al. (2022) proposed a formula for calculating the maximum vacuum pressure required for vertical seed disk systems, as shown in Equation (1).

$$P_{0max} = \frac{8K_1K_2Hmg}{\pi D_i^3}\left(1 + \lambda + \frac{\omega^2}{g}R_a\right) \tag{1}$$

where:

P_{0max} – is the maximum critical vacuum pressure, (Pa)
K_1 – is the reliability coefficient of seed absorption, (typically 1.8–2.0)
K_2 – is the working reliability coefficient,, (typically 1.6–2.0)
H – is the distance between the seed centroid and the seed-metering disk, (m)
m – is one seed mass, (kg)
g – is gravity, ($m \cdot s^{-2}$)
D_i – is the diameter of the suction hole, (m)
λ – is the comprehensive friction coefficient of the seed,
ω – is the angular velocity of the seed-metering disk, ($rad \cdot s^{-1}$)
R_a – is the radius of the hole distribution circle, (m)

The friction coefficient λ is given by: $\lambda = (6\text{–}10) \times \tan(\xi)$, where ξ is the natural angle of repose of the seed.

According to Murray et al. (2006), the thickness of the seed disk should range between 3 and 6 mm to ensure effective seed pickup and to prevent seed damage. In this design, the seed metering disk was constructed from a 6 mm thick nylon plate with a diameter of 160 mm. It was mounted vertically on the horizontal shaft of the metering device. The seed cells (or holes) were specifically designed to pick up individual soybean seeds and are custom-made to match the shape and size of the seeds used.

Both the diameter of the seed hole and the vacuum pressure within the vacuum chamber are critical factors influencing the suction performance of the seed metering disk (Liu et al., 2023). Vacuum pressure is applied to one side of the disk by the suction blower. As the disk rotates, seeds are drawn into the holes and held in place until they reach the discharge zone (seed chute), where they are released.

To prevent seeds from being pulled into the vacuum chamber, the maximum seed hole diameter (D_i) is generally limited to 70% of the seed's geometric diameter (D_g) (Bagherpour, 2019). Other researchers suggest stricter limits: Bakhtiari (2012) recommends D_i be 50% of the average D_g, while Singh et al. (2005) advise that $D_i \leq 50\%\ D_g$. The geometric diameter

(D_g) was calculated using Equation (2), as proposed by Singh et al. (2005). The seed hole cross-section design by Bakhtiari (2012) is illustrated in Figure 2. In line with recommendations by both Singh et al. (2005) and Bakhtiari (2012), the opening angle (2β) was set to 120°.

Based on measurements, the average dimensions of the *Argomulyo* soybean variety were length (l_s) 7.38 mm, width (w_s) 6.15 mm, and thickness (t_s) 4.77 mm. For this design, the seed hole specifications are diameter (D_i) of 3 mm, mouth diameter (D_o) of 10 mm, and an opening angle of 120°. The holes were chamfered to minimize air turbulence at the edges–reducing both air loss and suction force, as recommended by Guozhong et al. (2015) and Li et al. (2021).

$$D_g = (l_s \times w_s \times t_s)^{1/3} \quad (2)$$

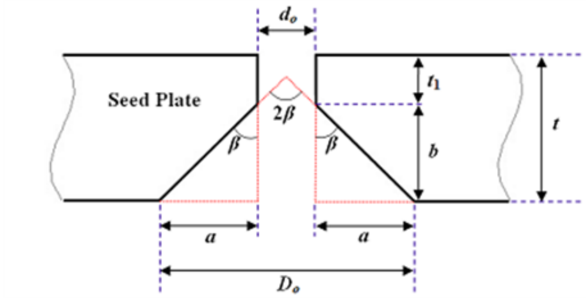


Figure 2. Design of seed hole on vacuum metering device (Bakhtiari, 2012)

Furthermore, using the suction hole design data, seed characteristic data (Table 1), and other known parameters, the required vacuum pressure was calculated using Equation (1) to be 1.05 kPa.

The vacuum system comprises a suction blower, a primary suction hose, four secondary suction hoses, a hose branching unit, and a vacuum chamber. The centrifugal-type suction blower was designed to meet the vacuum pressure requirement for soybean seeds (1.05 kPa), considering the total pressure loss along the suction lines. Its two main components, the impeller and the blower housing (volute) were specifically designed to achieve the required performance.

The impeller design includes key parameters such as the inner and outer diameters, thickness, blade width, blade angle, blade thickness, and the number of blades. The design process followed the methodologies proposed by Dietzel (1990) and Church (1986). The impeller was fabricated from steel plates, with a thickness of 5 mm for the disk and 2 mm for the blades. The inlet and outlet blade angles were both set at 45°. Detailed impeller specifications are provided in Table 2.

Table 2.
The vacuum system impeller specification.

No.	Parameters	Value
1	Inner diameter of impeller (D_{in})	60 mm
2	Outer diameter of impeller (D_{out})	200 mm
3	Blade width of the inlet (b_{in})	33 mm
4	Blade width of the outlet (b_{out})	60 mm
5	Blade thickness (t_s)	2 mm
6	Impeller thickness (t_{ds})	4 mm
7	Blade number (z)	8

The volute design was based on the method developed by Church (1986), which involves calculating key parameters such as the volute width (b_3), volute tongue radius (R_t), and volute tongue angle (ϕ_t). The volute width was determined using the impeller width of 60 mm and an impeller thickness of 4 mm. Allowing a clearance of 5 mm on both the front and rear sides of the impeller, the total volute width was set at 74 mm. According to Church (1986), the volute tongue radius (R_t) is 1.05 times the impeller's outer radius (R_{out}), resulting in a value of 105 mm. The outlet angle (α_2) is recommended to fall within the range of 0°–10°; for this design, a value of 6° was chosen. Based on this assumption, the volute tongue angle (ϕ_t) was calculated using Equation (3), yielding a value of 27°. The impeller and blower housing (volute) are illustrated in Figure 3.

$$\varphi_t = \frac{132\, log \frac{R_t}{R_{out}}}{tan\, \alpha_2} \tag{3}$$

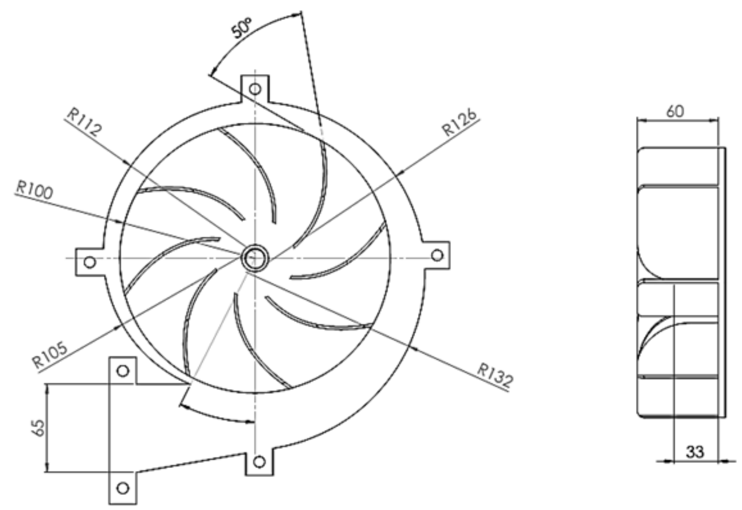


Figure 3. Design of the suction blower (dimensions in mm)

The suction blower unit was mounted on the left side of the engine frame using a custom-designed bracket, ensuring that the pulley on the blower shaft aligns precisely with the rotating pulley attached to the engine flywheel (see Figure 4). Suction from the blower is directed to the seed metering devices via flexible spiral hoses. The system includes a primary suction hose that runs from the blower to a hose branching unit, which then splits the airflow into four secondary hoses, each connected to a metering device.

In this design, the primary hose was branched directly into four secondary hoses, unlike the sub-pipeline system employed by Xing et al. (2021). The diameter of the primary hose is 50 mm, while each secondary hose has a diameter of 25 mm.

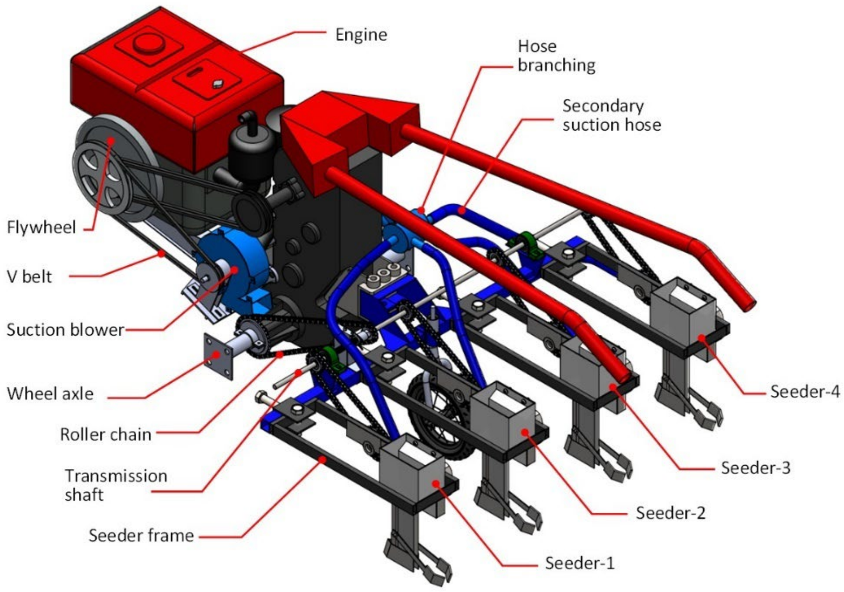


Figure 4. Vacuum system and power transmission of the metering devices.

To analyze the performance of the vacuum system, both analytical methods (Srivastava et al., 2006) and computational fluid dynamics (CFD) simulations were employed. The CFD analysis was conducted using the SolidWorks® software package, based on the finite volume method. A 3D model of the pneumatic system was developed, and airflow simulations were performed using the Flow Simulation tool in SolidWorks.

Several previous studies have also used CFD to evaluate blower performance (Jaiswal, 2014; Myaing et al., 2014; Li et al., 2018; Guzman et al., 2020; and Rosa et al., 2021). In this study, simulations were conducted at various blower speeds: 3000, 3500, 4000, 4500, 5000, 5500, and 6000 rpm. Examples of the simulation results for pressure and airflow velocity at a blower speed of 3000 rpm are shown in Figures 5 and 6.

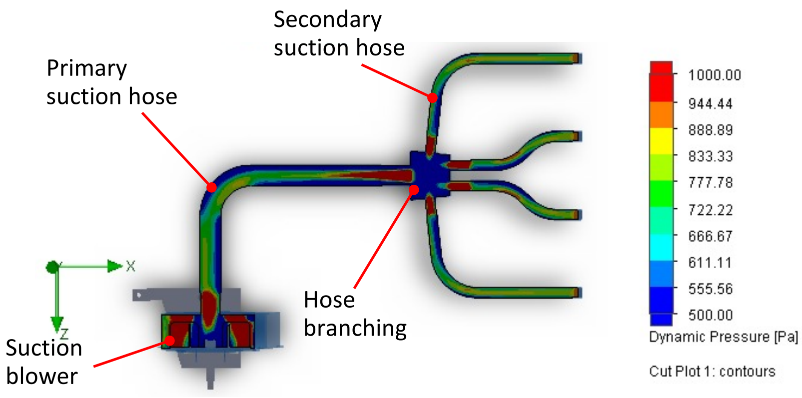


Figure 5. Simulation result of vacuum pressure resulted by the suction blower at 3000 rpm rotational speed.

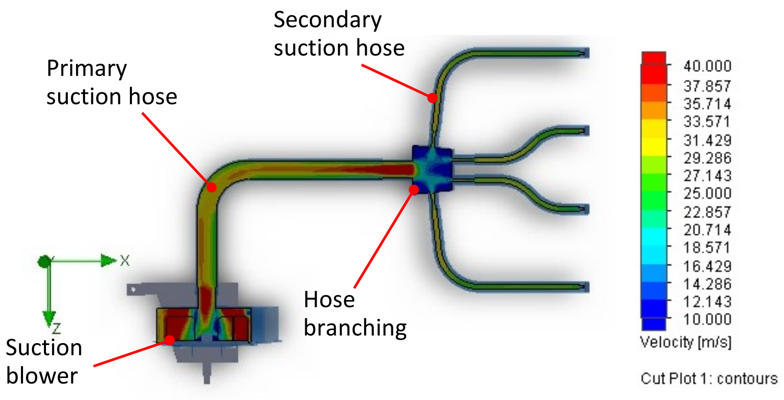


Figure 6. Simulation result of suction velocity resulted by the suction blower at 3000 rpm rotational speed

The simulation results of the pneumatic system, specifically the dynamic pressure values, were used to calculate the vacuum pressure at the end of the secondary suction hose. The resulting vacuum pressure and airflow velocity at the hose outlet for various blower rotational speeds are presented in Figure 7. According to the simulation, a minimum blower speed of 5000 rpm is required to achieve the necessary vacuum pressure of 1.05 kPa. At this speed, the suction velocity reaches 30 $m \cdot s^{-1}$, which exceeds the terminal velocity of soybean seeds (10.22 $m \cdot s^{-1}$), thereby meeting the system’s performance requirements.

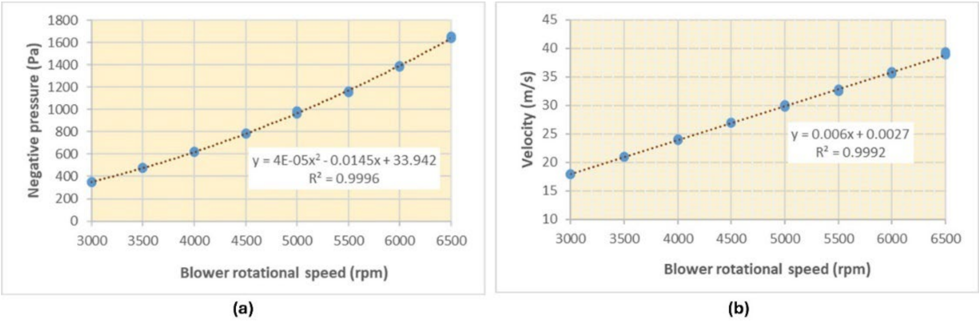


Figure 7. Vacuum pressure (a) and air velocity (b) at the end of secondary hose based on the simulation results of the blower

To drive the blower, rotary power from the engine flywheel was transmitted to the blower shaft via a pulley and V-belt system (Figure 4). Based on simulation results, achieving the required vacuum pressure necessitates a blower speed of over 5000 rpm. Therefore, the engine's rotational speed–approximately 1800–2000 rpm at the flywheel–must be increased by about threefold. For experimental purposes at various blower speeds (3000, 3500, 4000, 4500, 5000, 5500, and 6000 rpm), pulley pairs of different diameters were selected and used to match the desired speed settings for each treatment.

The suction blower prototype is shown in Figure 8, while the prototype and layout of the pneumatic system–including the positions of the primary and secondary suction hoses—are illustrated in Figure 9.

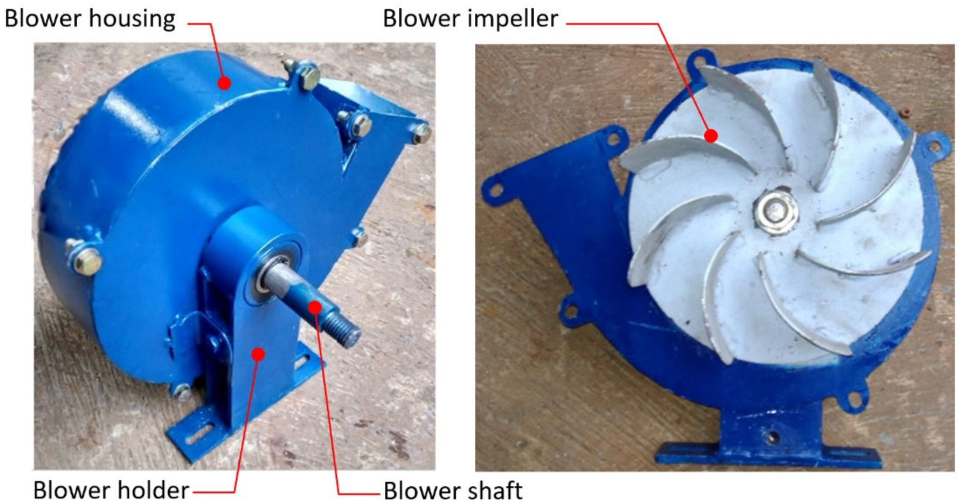


Figure 8. Prototype of the suction blower

Figure 9. The arrangement and position of the primary suction hose and secondary suction hoses

The seeder's metering devices are powered by the rotation of the tractor's left wheel axle. This rotation is transmitted through a sprocket-chain system to a primary shaft, then to a secondary shaft, and finally to the metering device shaft. A chain transmission was selected due to the low rotational speed required for the seed metering disk and the need for precise transmission of motion from the tractor wheels. The dimensions and configuration of the sprockets were calculated based on several factors: the tractor wheel size, an assumed wheel slip rate of 10%, a target seed spacing of 20 cm, and eight seed holes on the metering disk. The resulting gear ratio between the tractor wheel and the seed metering disk is 1:1.05. The power transmission system includes a clutch mechanism that allows the operator to engage or disengage the connection between the wheel axle and the primary shaft. This feature prevents the disk from rotating when sowing is not required, such as during turns at the end of a row.

The arrangement of the hopper and metering device, along with the prototype of the seed metering unit, is shown in Figure 10. In this design, seeds are initially picked up by suction at the lowest point of the seed disk, held in place as the disk rotates through an angle of 270°, and then released when the suction stops.

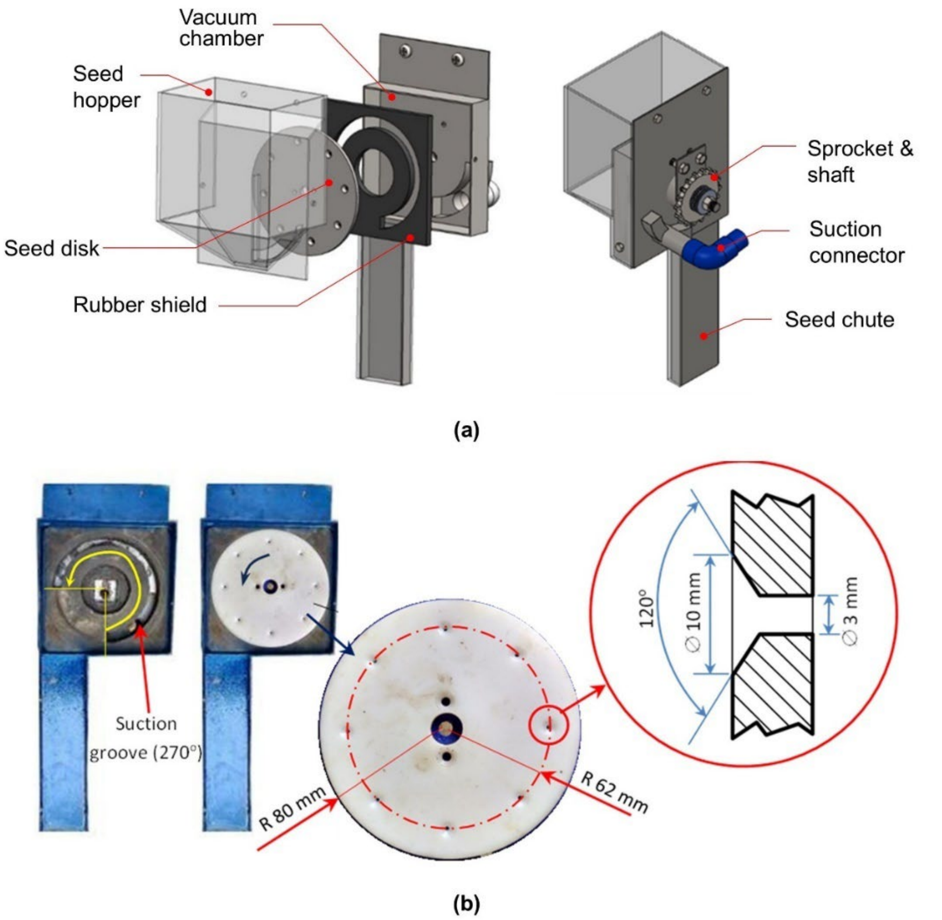


Figure 10. (a) The arrangement of the hopper and metering device, and (b) the prototype of the seed metering device and seed disk

Design of the Frame and Furrow Opener

The primary frame was built from 40 × 40 × 3.0 mm mild steel box sections and 5.0 mm plate, attached to the tractor hitch using a 19 mm locking bar and bolts. Its geometry was designed to avoid interference with tractor controls. Static load analysis using SolidWorks applied 1500 N to the primary frame and 400 N to the secondary frame, using AISI 1018 steel and a standard mesh. The maximum stress was about 55 MPa – far below the 220 MPa yield strength–indicating the frame design is structurally safe (Figure 11).

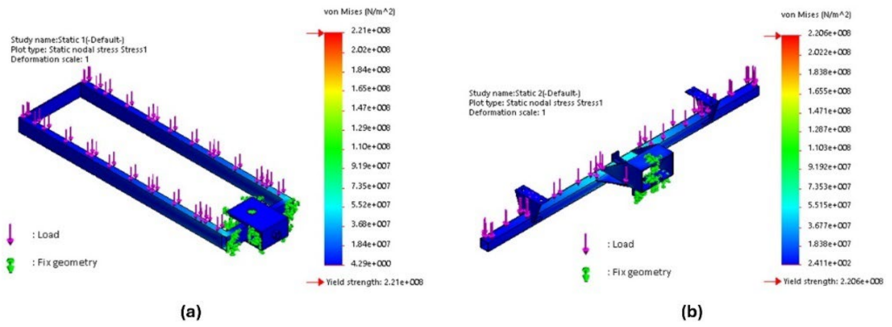


Figure 11. Static loading simulation result of primary frame (a) and secondary frame (b)

The adjustable shoe-type furrow opener, fabricated from 2.0 mm mild steel plate, forms a V-shaped furrow suitable for soybean planting and allows precise depth control. A gauge wheel was added to maintain a planting depth of 3.0–5.0 cm, and a pair of curved mild steel plates trailing behind the opener were used to cover the furrow after seed placement.

Pneumatic System Performance Test Method

To test the pneumatic system, all components were properly installed on the tractor in their designated positions. The blower was driven by the tractor engine through a pulley and V-belt transmission system, with the tractor kept in a stationary position. For the blower performance tests, various pulley size combinations were used to achieve six blower speed levels: 3000, 3500, 4000, 4500, 5000, 5500, and 6000 rpm, while maintaining the engine speed between 1800 and 2000 rpm. The actual blower speeds were verified using a digital tachometer. Vacuum pressure was measured at two points–at the end of the primary hose and at the inlet of the seed metering device vacuum chamber–using a digital vacuum pressure gauge. Each measurement was repeated three times to ensure accuracy.

Bench Test Method for Evaluating Seed Metering Performance

To evaluate the performance of the seed metering system, the prototype was tested on a bench test. During testing, the tractor was securely lifted and supported to allow the wheels to rotate freely above the ground, ensuring stability and minimal vibration (Figure 12). For experimental purposes, the rotational speed of the tractor wheel axle was set at two levels, resulting in seed metering disk speeds of 12.7 rpm and 26.1 rpm. Soybean seeds dropped by the metering disk were recorded using a video camera. This was made possible using transparent materials for the seed hopper walls and seeding tubes, allowing clear observation of seed movement.

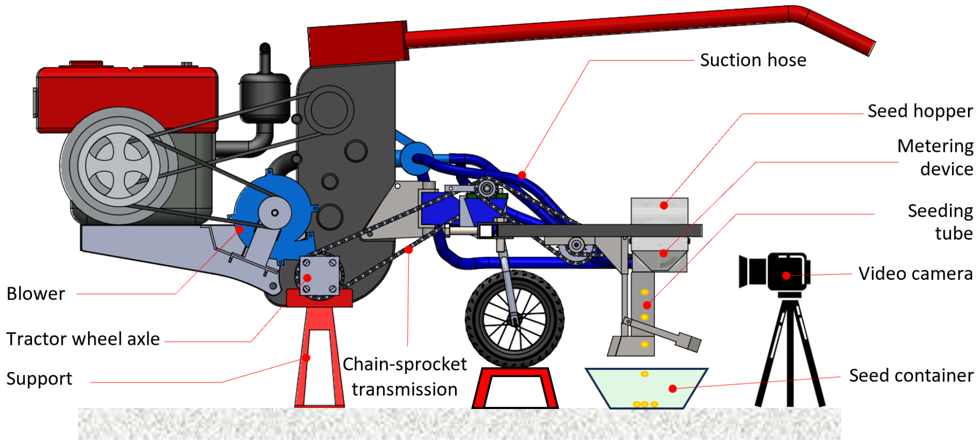


Figure 12. *Experimental setup for seed metering performance test*

The test was conducted at two levels of seed disk rotational speed (12.7 and 26.1 rpm) and six levels of blower rotational speed (3500, 4000, 4500, 5000, 5500, and 6000 rpm). Vacuum pressure at the vacuum chamber was measured for each metering unit during the experiment. Two soybean varieties, *Argomulyo* and *Anjasmoro*, were used in the tests. During each trial, the number of seeds dropped from each metering unit was recorded to calculate the percentages of single seeds, multiples, and misses. To support these measurements, the seed metering process was captured on video through the transparent seed hopper wall. Additionally, the number of mechanically damaged seeds was counted, and the seed damage percentage was calculated. For each test condition, measurements were taken over 12.5 rotations of the metering disk (equivalent to 100 seed pickup opportunities) and repeated four times. Performance was evaluated in terms of singulation efficiency, percentage of multiples, and missing percentage. These parameters–singulation efficiency (S_s), percentage of multiples (D_s), and missing percentage (M_s) – were calculated using Equations (4), (5), and (6), respectively.

$$S_s = \frac{N_{ss}}{N_{pu}} \times 100 \tag{4}$$

$$D_s = \frac{N_{ds}}{N_{pu}} \times 100 \tag{5}$$

$$M_s = \frac{N_{ms}}{N_{pu}} \times 100 \tag{6}$$

where:

S_s – singulation efficiency, (%)
N_{ss} – number of one seed pick up,
N_{pu} – total number of pick up,
D_s – percentage of multiples, (%)
N_{ds} – number of two or more seeds picked up,

M_s – missing percentage, (%)
N_{ms} – number of seed cells fail to pick up.

An ANOVA statistical analysis was conducted to determine whether there were significant differences among the test treatments for singulation efficiency (S_s), percentage of multiples (D_s), and missing percentage (M_s). When significant differences were found, a Duncan's Multiple Range Test (DMRT) was performed for further comparison.

Field Performance Test Method

Seeder performance testing was conducted on land that had been previously prepared using a rotary tiller to a depth of 15 cm. The soil was classified as silty clay loam, with an average bulk density of 1.04 g·cm^{-3}, penetration resistance of 400 kPa, and water content of 28%. Four modular seed-metering units were mounted on the secondary frame at a row spacing of 40 cm (Figure 13).

Field tests were performed using a Yanmar YZD two-wheel tractor equipped with an 8.5 hp (6.34 kW) engine, rubber wheels with a diameter of 60 cm, and a wheel spacing of 70 cm. *Anjasmoro* soybean seeds, with a viability of 93%, were used for planting. Based on the pneumatic system performance tests, blower rotational speeds of 5000, 5500, and 6000 rpm were selected for field evaluation. Two tractor speed levels, corresponding to Low-1 and Low-2 gears, were tested while maintaining an engine speed of 2000 rpm.

Each treatment was conducted over four passes along a 50-meter plot, resulting in a plot area of 320 m^2 per treatment, with a working width of 1.6 m. The actual forward speed of the tractor was determined by recording the time required to cover a 20-meter distance using a digital stopwatch. Tractor wheel slip was measured using the distance-traveled method, by measuring the distance covered in five-wheel revolutions with a measuring tape (resolution: 1 mm). Each measurement was repeated three times per treatment. Seeder working time in each plot was recorded to calculate the effective field capacity.

Figure 13. Prototype of the vacuum-type soybean seeder mounted on a walking tractor, prepared for field testing

The parameters measured during the field test included seed spacing, seed placement depth, the number of seeds deposited, and the number of mechanically damaged seeds. To facilitate direct observation, the furrow covering devices were intentionally omitted during the test, allowing the seeds released by the metering units to be examined immediately after placement. Seed spacing and planting depth were measured using a steel ruler with a resolution of 1 mm (Figure 14). Measurements were conducted on 25 randomly selected samples within each planting row corresponding to each metering unit. Following measurement, the seeds were manually covered with soil. Seed germination was assessed seven days after planting. Germination percentage was calculated as the ratio of the number of emerged seedlings to the expected number of seeds in the sampled area. Observations were carried out on two randomly selected planting rows, each 10 meters in length, for each treatment.

Figure 14. Method for measuring inter-row seed spacing and planting depth using a steel ruler

The forward speed of the tractor was determined by recording the time required to travel 20 meters using a digital stopwatch. Total operation time for each plot was also recorded. Based on these measurements, the theoretical field capacity and effective field capacity were calculated. Field efficiency was subsequently determined as the ratio of effective field capacity to theoretical field capacity.

Data collected on seed spacing, planting depth, singulation efficiency, and germination rate for each treatment were analyzed to determine the mean and standard deviation. Analysis of variance (ANOVA) was performed to assess the significance of differences among treatments. When significant differences were detected, Duncan's Multiple Range Test (DMRT) was applied to identify specific differences between treatment means.

Results and Discussion

Pneumatic System Performance

The measured vacuum pressures for both the primary and secondary hoses are presented in Figure 15. The results show that blower vacuum pressure increases linearly with increasing blower rotational speed. This trend is expected, as higher blower speeds result in faster impeller rotation, leading to greater air intake and expulsion rates, thereby creating a larger pressure differential across the blower. The vacuum pressure measured at the end of the primary hose was consistently higher than that at the secondary hose. The primary reason for this difference is the pressure drop that occurs after the flow is divided into four branches. When the suction flow passes from the primary hose into the smaller secondary hoses, several pressure-loss mechanisms are introduced along the flow path. The vacuum reduction is mainly caused by: (i) junction (minor) losses at the branching point, (ii) frictional losses along the smaller-diameter secondary hoses with a higher L/D ratio, and (iii) additional losses generated by bends and fittings. These cumulative losses substantially reduce the effective vacuum level.

When compared to the simulation results (Figure 7), the measured vacuum pressure at the end of the secondary hose was approximately 30–40% higher than predicted. This discrepancy is likely due to differences in boundary conditions between the simulation and actual measurements. In the simulation, the end of the secondary hose was modeled with an open inner diameter of 20 mm, whereas in the actual measurements, the hose was connected to the vacuum chamber of the metering device, complete with a seed disk containing eight seed holes of 3 mm diameter each.

Importantly, the measured vacuum pressure at blower speeds ≥ 4000 rpm exceeded the target requirement of 1.05 kPa. These findings confirm that the blower design and its operational speed are sufficient to meet the vacuum pressure requirements for the seed metering device.

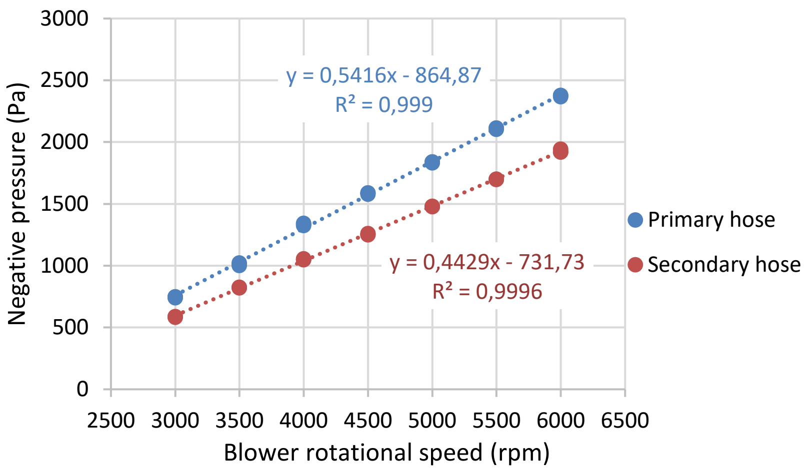


Figure 15. Measured vacuum pressure in the primary and secondary hoses

Seed Metering Performance in Bench Test

In general, changes in vacuum pressure significantly affected the singulation efficiency (Figure 16), the missing percentage (Figure 17), and the percentage of multiple seeds. As shown in Figures 16 and 17, increasing vacuum pressure improved singulation efficiency and reduced the missing percentage. This effect is due to the direct relationship between blower speed and vacuum pressure: higher blower speeds generate greater suction, enhancing the ability of the seed holes to hold seeds and thus increasing the proportion of seeds successfully picked up.

The test results demonstrated that singulation efficiency levels of 99–100% were achieved at vacuum pressures exceeding 1.70 kPa (corresponding to blower speeds of 5500 rpm), at a low seed disk rotational speed of 12.7 rpm for both tested seed varieties. This performance is comparable to that reported for general mechanical-pneumatic seed metering devices, such as those developed by Xiong et al. (2021). At a higher seed disk rotational speed (26.1 rpm), singulation efficiency was generally lower, particularly at vacuum pressures below 1.40 kPa. Even at vacuum pressures exceeding 1.70 kPa, singulation efficiency did not reach 100%, achieving approximately 96–99% for *Argomulyo* seeds and 93–97% for *Anjasmoro* seeds. This reduction in efficiency at higher disk speeds is attributed to the decreased opportunity for seeds to be captured by the suction holes as they move more rapidly – a phenomenon consistent with findings reported by Özmerzi et al. (2002), Barut and Özmerzi (2004), Singh et al. (2005), and Karayel (2009). To address this limitation, improvements such as adding a triangular seed guide strip to the seed disk (Li et al., 2024) or incorporating guiding grooves (Shen et al., 2021) have been suggested.

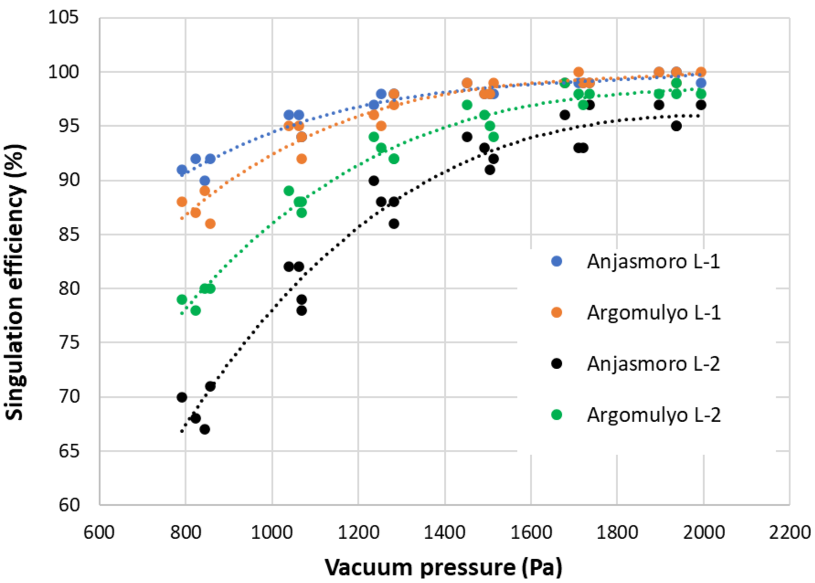


Figure 16. *Singulation efficiency at different vacuum pressure and seed disk rotational speed*

Further statistical analysis revealed no significant differences in singulation efficiency among the four seed metering units. Additionally, no significant differences ($p < 0.05$) were found in singulation efficiency, missing percentage, or percentage of multiples across vacuum pressures of 1490 Pa, 1711 Pa, and 1941 Pa, for both *Anjasmoro* and *Argomulyo* seeds.

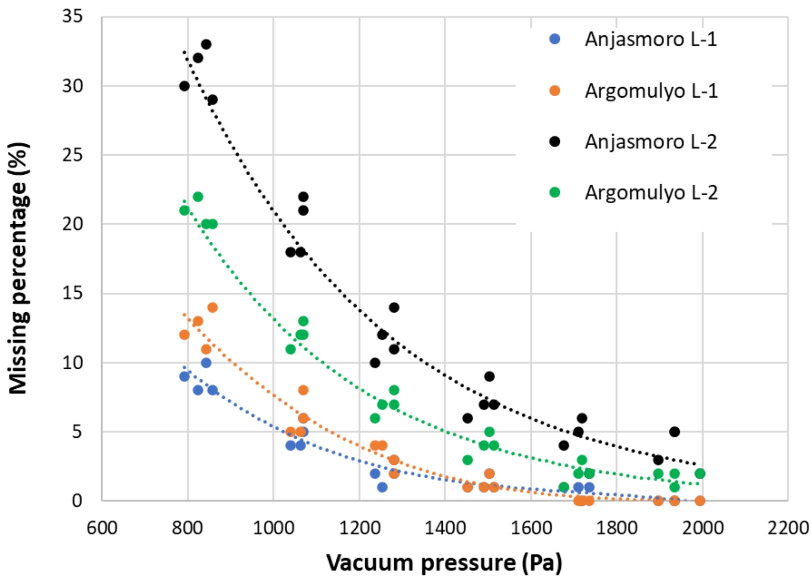


Figure 17. Missing percentage at different vacuum pressure and seed disk rotational speed

Using a seed disk with eight seed holes, a seed spacing of 20 cm, and a seed disk rotational speed of 12.7 rpm, the seeder achieves a forward speed of approximately 0.75 $m \cdot s^{-1}$. In this design, the low seed disk rotational speed (12.7 rpm) corresponds to the tractor operating at Low-1 gear with an engine speed of 2200 rpm. When shifted to Low-2 gear, the seed disk rotational speed increases to 26.1 rpm, resulting in a forward speed and planting capacity that are approximately double those at Low-1. However, to maintain a high singulation efficiency (greater than 98%) at the higher forward speed, it is necessary to achieve a vacuum pressure exceeding 1.70 kPa, corresponding to a blower rotational speed above 5500 rpm. Based on the test results, it is recommended that for operation at Low-1 speed, the blower should be operated at 5500–6000 rpm, whereas for Low-2 speed, a blower rotational speed of 6000 rpm is required.

The percentage of multiple seeds was not significantly affected by changes in vacuum pressure, and no consistent trend was observed between vacuum pressure variation and the occurrence of multiple seeds. Moreover, the incidence of double seeds remained very low, at less than 1.25%. Instances of double seed pickup were primarily observed at higher blower speeds, specifically at 5500 rpm and 6000 rpm. The issue of multiple seeds being retained in a single seed hole could be addressed through the implementation of a seed-cleaning mechanism (Hu et al., 2022) or a disturbance-assisted seed feeding mechanism (Liu et al., 2022). These results indicate that the seed metering device was properly designed to achieve precise distribution with a high rate of single seed pickup. Additionally, throughout the experiment, no mechanically damaged soybean seeds were observed.

Overall, tests conducted at low seed disk rotational speeds consistently demonstrated superior performance compared to high rotational speeds for both soybean varieties. Statistical analysis revealed a significant difference ($p < 0.05$) between low and high rotational speeds for the *Anjasmoro* variety in terms of single seed percentage and miss rate. In contrast, for the *Argomulyo* variety, no significant difference was detected, although the performance at low rotational speed was consistently higher than at high speed. The generally better performance at low rotational speeds can be attributed to the slower movement of the seed metering device, which allows more time for effective seed pickup, thereby reducing misses and improving singulation.

ANOVA results indicated that there were no significant differences ($p < 0.05$) in the singulation efficiency, missing percentage, or percentage of multiples among the vacuum pressure levels of 1490 Pa, 1711 Pa, and 1941 Pa for both *Anjasmoro* and *Argomulyo* varieties at a seed disk rotational speed of 12.7 rpm. However, the best performance was consistently achieved at the vacuum pressure of 1941 Pa for both seed varieties. Based on these findings, the optimum recommended rotational speed for field operation of the blower is between 5500 rpm and 6000 rpm, corresponding to a vacuum pressure range of 1711 Pa to 1941 Pa.

The seed metering performance for *Anjasmoro* variety seeds at vacuum pressures above 1490 Pa is summarized in Table 3. An increase in singulation efficiency was observed with increasing vacuum pressure. However, Duncan's multiple range test indicated that the increase in vacuum pressure did not significantly ($p < 0.05$) affect singulation efficiency at a seed disk rotational speed of 12.7 rpm. In contrast, a higher seed disk rotational speed (26.1 rpm) significantly reduced ($p < 0.05$) singulation efficiency. At both vacuum pressures of 1711 Pa and 1941 Pa, no significant difference ($p < 0.05$) in singulation efficiency was detected at the lower seed disk rotational speed. Additionally, the missing percentage decreased with increasing vacuum pressure. Notably, at a seed disk rotational speed of 12.7 rpm and a vacuum pressure of 1941 Pa, no missed seeds were observed. Under these conditions, the total seed pickup rate exceeded 98%. However, at the higher seed disk rotational speed (26.1 rpm), the total seed pickup rate decreased, ranging from 92% to 96%.

The seed metering performance for the *Argomulyo* variety at different vacuum pressures is summarized in Table 4. Similar to the *Anjasmoro* variety, singulation efficiency increased with rising vacuum pressure. However, Duncan's multiple range test indicated that the effect of vacuum pressure on singulation efficiency was not statistically significant ($p < 0.05$). Consistent with the results observed for *Anjasmoro* seeds, a higher seed disk rotational speed (26.1 rpm) significantly ($p < 0.05$) reduced singulation efficiency. At a rotational speed of 26.1 rpm, increasing the vacuum pressure from 1711 Pa to 1941 Pa did not lead to a significant improvement in singulation efficiency. The trend of decreasing missed seeds with increasing vacuum pressure was also similar to that observed for the *Anjasmoro* variety. However, when using *Argomulyo* seeds, singulation efficiency and the total seed pickup rates were slightly higher compared to those obtained with *Anjasmoro* seeds.

Table 3.
Summary of seed metering performance at vacuum pressure of 1490, 1711 and 1941 Pa, for Anjasmoro variety seeds.

Seed disk rotational speed (rpm)	Vacuum pressure (Pa)	Singulation efficiency (%)	Miss percentage (%)	Total seed picked up (%)
12.7	1490	98.3±0.5[a]	1.3±0.5[a]	98.8
12.7	1711	99.0±0.0[a]	0.8±0.5[a]	99.3
12.7	1941	99.8±0.5[a]	0.0±0.0[a]	100.0
26.1	1490	92.5±1.3[c]	7.3±1.3[b]	92.8
26.1	1711	94.8±2.1[b]	4.3±1.7[b]	95.8
26.1	1941	96.0±1.2[b]	3.8±1.5[c]	96.3

Note: Values in the same column with the same letter are not significantly different ($p < 0.05$).

Table 4.
Summary of seed metering performance at vacuum pressure of 1490, 1711 and 1941 Pa, for Argomulyo variety seeds.

Seed disk rotational speed (rpm)	Vacuum pressure (Pa)	Singulation efficiency (%)	Miss percentage (%)	Total seed picked up (%)
12.7	1490	98.5±0.6[ab]	1.3±0.5[a]	98.8
12.7	1711	99.3±0.5[a]	0.3±0.5[a]	99.8
12.7	1941	99.8±0.5[a]	0.0±0.0[a]	100.0
26.1	1490	95.5±1.3[c]	4.0±0.8[b]	96.0
26.1	1711	98.0±0.8[b]	2.0±0.8[b]	98.0
26.1	1941	98.3±0.5[b]	1.8±0.5[c]	98.3

Note: Values in the same column with the same letter are not significantly different *($p < 0.05$)*.

Field Performance of the Seeder

Table 5 presents the measured results of average seed spacing and planting depth obtained from each trial. Both parameters closely approached the targeted planting criteria, with the desired seed spacing set at 20 cm and the planting depth at 5 cm. The measured average seed spacing was consistently slightly lower than the target in all trials. This discrepancy can be attributed to the assumption made during the initial design phase, where wheel slip was estimated at 10%. However, during field testing, the actual wheel slip was found to be 12.73%

and 14.65% for tractor speed settings Low-1 and Low-2, respectively. Higher wheel slip results in reduced seed spacing because increased slippage leads to additional wheel rotation without corresponding forward movement, causing seeds to be deposited at shorter intervals. In addition to wheel slip, field slope can also affect the uniformity of intra-row seed spacing (Searle et al., 2008). Improvements in seed spacing uniformity could be achieved using a circular air blower-assisted seed guide (Zhou et al., 2024) or a precision seed delivery mechanism developed by Liu et al. (2018).

The planting depth measurements also conformed closely to the target values. ANOVA analysis indicated that neither tractor forward speed nor blower rotational speed had a significant effect on planting depth. The average planting depth ranged between 4.8 and 4.9 cm. Variations in planting depth are generally influenced by forward speed (Li et al., 2024) and soil surface roughness. Previous studies have shown that maximum seedling emergence rates are achieved when the nominal sowing depth is maintained between 40 and 60 mm (Özmerzi et al., 2002).

The singulation efficiency observed in the field experiments was slightly lower than that recorded in the bench tests. In the field trials, the maximum singulation efficiency reached 98% at the Low-1 tractor speed with a blower rotational speed of 6000 rpm. These results are comparable to or better than those reported in previous studies (Ha et al., 2017; Zhang et al., 2021; Liu et al., 2023; Sharma et al., 2023; Huang et al., 2023; Zhu et al., 2024; Ding et al., 2024), and they also surpass the performance of the staggered seedling belt soybean precision planter developed by Ma et al. (2024).

At higher tractor speeds (Low-2), a decrease in singulation efficiency was observed, likely due to increased vibrations induced by the faster movement of the tractor (Wang et al., 2024). Increased vibration can impair the ability of the seed holes to retain the seeds, leading to seed loss. Kowalczuk et al. (2017) recommended an operating speed range of 2.5–3.0 $km \cdot h^{-1}$ for sowing with a four-wheel tractor. However, since this study employed a two-wheel tractor, the average forward speeds were 1.19 $km \cdot h^{-1}$ (Low-1) and 2.38 $km \cdot h^{-1}$ (Low-2).

ANOVA results indicated that the tractor forward speed did not significantly affect the singulation efficiency. However, blower rotational speed showed a significant effect ($p < 0.05$) on singulation performance. At the higher tractor speed (Low-2), singulation efficiency could be improved by increasing vacuum pressure, a finding consistent with previous studies showing that increased vacuum pressure reduces the miss rate (Vučajnk et al., 2020; Wang et al., 2024). Nevertheless, higher blower speeds may lead to increased fuel consumption (Lauriano et al., 2017). Additionally, the retention of seeds on the seed holes could be further improved by incorporating a seed position adjustment device, as proposed by Zhao et al. (2023).

Moreover, no damaged seeds were observed during the entire experiment. Future improvements to the measurement system could include the application of real-time monitoring methods, as demonstrated by Bai et al. (2022). The experimental results indicated that the germination rate ranged from 86% to 91% at the Low-1 tractor speed, whereas at the Low-2 speed, the germination rate was slightly lower, between 83% and 89%. These results are comparable to those reported by Gbabo et al. (2017). Although seed germination can be influenced by planting depth (Grace et al., 2020), in this experiment, it was primarily affected by the seed viability, which was 93%.

Table 5.
Summary of field performance test results.

Tractor speed	Blower rotational speed (rpm)	Seed spacing (cm)	Planting depth (cm)	Singulation efficiency (%)	Germination (%)
Low-1	5000	19.6±0.78^{a}	4.9±0.6^{a}	93.0±2.0^{a}	86.3±1.2^{a}
Low-1	5500	19.5±0.64^{a}	4.9±0.4^{a}	97.0±2.0^{b}	89.0±2.0^{b}
Low-1	6000	19.5±0.63^{a}	4.9±0.6^{a}	98.0±2.3^{b}	90.7±1.5^{b}
Low-2	5000	19.2±0.65^{b}	4.8±0.6^{a}	90.0±4.0^{a}	83.7±1.5^{a}
Low-2	5500	19.2±0.76^{b}	4.9±0.4^{a}	95.0±2.0^{ab}	88.3±1.5^{ab}
Low-2	6000	19.2±0.66^{b}	4.8±0.5^{a}	96.0±3.3^{b}	88.7±1.5^{b}

Note: Values in the same column with the same letter are not significantly different *($p < 0.05$)*.

At the Low-1 tractor speed, the average theoretical field capacity and effective field capacity were measured at 0.52 $m^2 \cdot s^{-1}$ (0.19 ha h^{-1}) and 0.46 $m^2 \cdot s^{-1}$ (0.16 ha h^{-1}), respectively, resulting in a field efficiency of 87.9%. At the higher Low-2 speed, the effective field capacity increased to 0.85 $m^2 \cdot s^{-1}$ (0.31 ha h^{-1}), although the field efficiency decreased to 78.0%. This increase in field capacity was primarily due to the doubling of the tractor's forward speed from 0.33 $m \cdot s^{-1}$ (Low-1) to 0.66 $m \cdot s^{-1}$ (Low-2). However, since the turning time at the end of each plot remained relatively constant between the two speeds, the effective field capacity did not increase proportionally with forward speed, leading to a reduction in field efficiency. Nevertheless, the machine's field capacity significantly outperformed that of the previously developed two-row seeder (Hermawan et al., 2016).

The design and performance evaluation demonstrated that the four-row soybean seeder could be effectively operated by an 8.5 hp walking tractor. The developed seeding system exhibited strong performance in seed placement accuracy, singulation efficiency, and germination rate, confirming its suitability and effectiveness for field application. With further development, the seeder could be manufactured by local industries and adopted for widespread use by farmers nationwide. Additionally, the design could be adapted for other crops, such as corn, peanuts, or mung beans, with appropriate modifications to the seed metering system.

Conclusions

A prototype four-row vacuum-type soybean seeder was successfully developed and evaluated. The seeder units were mounted on, and powered by, a walking tractor. The tractor's engine simultaneously drove a vacuum blower, which provided sufficient suction to operate all four seed metering devices effectively. Seed disks were driven via a chain-and-sprocket transmission system connected to the tractor's wheel shaft.

Bench tests demonstrated that vacuum pressure significantly influenced seed singulation performance. Higher vacuum pressures (above 1.70 kPa) improved singulation efficiency and reduced the rate of missed seeds, particularly at lower seed disk rotational speeds (12.7

rpm). Under optimal conditions, singulation efficiencies of 99–100% were achieved for both *Anjasmoro* and *Argomulyo* varieties, with a minimal occurrence of missed and double seeds (less than 1.25%), and no seed damage was observed. Although improvements in singulation efficiency with increased vacuum pressure were observed, statistical analysis indicated that these differences were not significant. Conversely, increasing the seed disk rotational speed (26.1 rpm) significantly reduced singulation efficiency due to decreased seed pickup time.

In field trials, the achieved average seed spacing and planting depth were closely aligned with the target values of 20 cm and 5 cm, respectively. Minor reductions in seed spacing were primarily attributed to higher-than-anticipated wheel slip, which resulted in more frequent seed drops and slightly reduced spacing. The average planting depth remained within the optimal range of 4.8–4.9 cm and was not significantly affected by either tractor forward speed or blower rotational speed. The highest singulation efficiency, reaching up to 98%, was recorded at the Low-1 tractor speed and a blower speed of 6000 rpm. Although singulation performance declined slightly at higher tractor speeds, likely due to increased vibration, no seed damage was observed. Increasing the tractor's forward speed from Low-1 to Low-2 significantly enhanced the effective field capacity, from 0.16 $ha \cdot h^{-1}$ to 0.31 $ha \cdot h^{-1}$. Overall, the developed seeding system demonstrated strong performance in terms of seed placement accuracy, singulation efficiency, and germination rate, confirming its suitability and effectiveness for field application.

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PROJEKTOWANIE I OCENA PARAMETRÓW EKSPLOATACYJNYCH CZTERORZĘDOWEGO SIEWNIKA PODCIŚNIENIOWEGO NAPĘDZANEGO CIĄGNIKIEM JEDNOOSIOWYM DO PRECYZYJNEGO WYSIEWU SOI

Streszczenie. Wcześniej opracowany dwurzędowy siewnik podciśnieniowy wykazywał obiecującą skuteczność wysiewu pojedynczych nasion, jednak jego wydajność eksploatacyjna była ograniczona ze względu na małą liczbę rzędów roboczych. Celem badań było zaprojektowanie, wykonanie oraz ocena czterorzędowego podciśnieniowego siewnika do soi aby zwiększyć wydajność, a jednocześnie zachować precyzję siewu. Siewnik, montowany na ciągniku jednoosiowym i napędzany nim, wykorzystywał promieniową dmuchawę ssącą do wytwarzania podciśnienia dla czterech aparatów wysiewających. Tarcze wysiewające były napędzane mechanizmem łańcuchowo-zębatym połączonym z wałem koła ciągnika. Badania stanowiskowe przeprowadzono dla dwóch prędkości obrotowych tarcz wysiewających (12,7 oraz 26,1 obr·min^{-1}) oraz sześciu prędkości obrotowych dmuchawy (3500, 4000, 4500, 5000, 5500 oraz 6000 obr·min^{-1}), z wykorzystaniem dwóch odmian soi. Rejestrowano skuteczność wysiewu pojedynczych nasion oraz odsetek wysiewów podwójnych i braków. Wyniki wykazały, że wyższe wartości podciśnienia (>1,70 kPa) przy niższej prędkości obrotowej tarczy (12,7 obr·min^{-1}) istotnie poprawiały skuteczność wysiewu pojedynczych nasion, umożliwiając uzyskanie efektywności na poziomie 99–100%, przy minimalnym udziale braków i wysiewów podwójnych (<1,25%) oraz braku uszkodzeń nasion. Zwiększenie prędkości obrotowej tarczy (26,1 obr·min^{-1}) powodowało obniżenie dokładności wysiewu. Badania polowe przeprowadzone dla trzech prędkości obrotowych dmuchawy (5000–6000 obr·min^{-1}) oraz dwóch prędkości jazdy ciągnika (Low-1 i Low-2) potwierdziły równomierne rozmieszczenie nasion w rzędzie (19,2–19,6 cm) oraz optymalną głębokość siewu (4,8–4,9 cm), przy niewielkich odchyleniach wynikających z poślizgu kół. Najlepsze parametry pracy w warunkach polowych (98% skuteczności wysiewu pojedynczych nasion) uzyskano przy prędkości ciągnika Low-1 oraz prędkości obrotowej dmuchawy 6000 obr·min^{-1}. Zwiększenie prędkości jazdy ciągnika spowodowało wzrost wydajności polowej z 0,16 do 0,31 ha·h^{-1}. Uzyskane wyniki potwierdzają skuteczność prototypu w zakresie precyzyjnego i wydajnego siewu soi.

Słowa kluczowe: parametry eksploatacyjne, siewnik podciśnieniowy, wysiew pojedynczych nasion, soja, ciągnik jednoosiowy