Design, fabrication, and testing of an air-pressurized cannon for agricultural seed pods

Edrick Vyner Lawrence Jaya[1], Faris Haziq Azharudin[1], Omar Faruqi Marzuki[1,2*], Ellie Yi Lih Teo[1,2], Azmin Shakrine Mohd Rafie[3]

(1. Department of Science and Technology, Universiti Putra Malaysia, 97008 Bintulu, Sarawak, Malaysia;
2. Institut EkoSains Borneo, Universiti Putra Malaysia, Jalan Nyabau, 97008 Bintulu, Sarawak, Malaysia;
3. Department of Aerospace Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia)

Abstract: This study presents the design, fabrication, and testing of an air-pressurized cannon developed to enhance precision and efficiency in agricultural seed planting. Traditional sowing methods are often labor-intensive and ineffective in challenging terrains, leading to uneven seed distribution and suboptimal crop yields. To address these issues, the air-pressurized cannon was tested under controlled field conditions with varying launch angles (30°, 40°, and 50°), air pressures (30, 40, and 50 psi), and three seed pod designs: round-nose cylindrical (AL), mortar shell (CL), and cluster bomb (TL). The results demonstrated that the AL pod achieved the maximum distance of 85.1 meters at a 40° angle and 40 psi, emphasizing the importance of weight and aerodynamic design. Germination tests confirmed the system's capability to maintain seed integrity and promote healthy growth, with CL pods exhibiting the fastest germination rates. These findings highlight the cannon's potential to improve planting accuracy, reduce labor, and enhance sustainability, particularly in regions where traditional methods are less effective. Future work will focus on refining seed pod designs and conducting field tests under diverse environmental conditions to further optimize the system's performance.

Keywords: Air-pressurized cannon, seed pod design, agricultural mechanization, germination performance, precision seed planting

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1 Introduction

The increasing demand for efficient and sustainable agricultural practices has spurred the development of innovative technologies aimed at enhancing planting operations. Traditional manual and mechanical methods of seed sowing are labor-intensive, time-consuming, and often inefficient, particularly in areas with difficult terrain or limited accessibility (Liu et al., 2023). Moreover, these conventional methods frequently result in uneven seed distribution and suboptimal germination rates, impacting crop yields and resource utilization (Soyoye, 2020).

To address these challenges, recent advancements in mechanized planting technologies, such as air-pressurized seeding systems and drone-assisted sowing, have demonstrated significant potential. Air-pressurized systems offer precision in seed placement, optimizing spacing and depth, which are critical for

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***Corresponding author: Omar Faruqi Marzuki, PhD.** Department of Science and Technology, Universiti Putra Malaysia, 97008 Bintulu, Sarawak, Malaysia. Email: omar_faruqi@upm.edu.my.

enhancing germination and crop establishment (Liu et al., 2023). Similarly, unmanned aerial vehicle (UAV) based technologies have been explored for their ability to navigate complex terrains and deliver seeds with high accuracy and efficiency (Marzuki et al., 2021).

In addition, to UAV technologies, the development of specialized machinery, such as low-cost drum seeders for paddy fields, has significantly improved planting efficiency in labor-constrained environments. These devices enable precise row spacing and reduce seed waste, making them suitable for smallholder farmers in developing regions (Mamun et al., 2024). Similarly, multi-row seeders for crops like onions and maize have been designed to increase planting capacity and reduce labor costs while maintaining optimal seeding depth and spacing (Idago et al., 2019; Samoy-Pascual et al., 2021). These innovations ensure uniform seed distribution, improve seedling establishment, and enhance overall crop yield.

Such developments highlight the pressing need for adaptable and efficient planting systems, particularly in regions where traditional machinery fails to perform adequately. Air-pressurized cannons, in particular, provide a unique advantage by enabling the planting of seeds in hard-to-reach areas and offering adjustable parameters to suit various crop types and field conditions (Soyoye, 2020). This study aims to design, fabricate, and test an air-pressurized cannon for agricultural seed pods, contributing to the ongoing efforts to modernize planting methods and improve agricultural productivity.

2 Materials and methods

2.1 Air-pressurized cannon design and fabrication

The air-pressurized cannon was designed to enhance seed planting efficiency by leveraging pneumatic technology. The system's key components include a pressurized air tank, a solenoid valve for controlled air release, and a launch barrel designed to accommodate various seed pod types. The design process was conducted using CAD software to ensure precise alignment of components and optimal aerodynamics for seed pods (Figure 1). Similar methodologies have been adopted in developing mechanized planting systems, emphasizing precision and adaptability to diverse agricultural contexts (Soyoye, 2020; Liu et al., 2023).

The fabrication process involved the use of lightweight yet durable materials, such as Polyvinyl Chloride (PVC) for the barrel and aluminum for structural supports, ensuring portability and resistance to field conditions (Figure 2). The PVC pipe used complies with MS 628, MS 762, and JIS K 6741 (JIS Standard), which are intended for pressure applications in cold water services. PVC is a high-strength thermoplastic material, offering excellent durability and resistance to environmental factors, making it suitable for air-pressurized applications. The aluminum structural components were fabricated using an extruded aluminum standardized profile (flat bar) in alloy EN AW-6060 T66 (AIMgSi), which provides superior mechanical strength, corrosion resistance, and lightweight properties, ideal for the cannon's structural framework. Additionally, a 3D printer was employed to produce the 30 mm diameter seed pods, inspired by innovations in seed pods and UAV-based seeding mechanisms (Marzuki et al., 2021).

2.2 Testing procedures

The performance of the air-pressurized cannon was evaluated through controlled field tests, designed to assess its effectiveness across several operational parameters. The experimental site was a grassy field inside Universiti Putra Malaysia Campus Bintulu, Sarawak, Malaysia, which experiences a tropical climate with hot and wet weather year-round. The site is located at latitude 3.205450 and longitude 113.085603, providing a suitable environment to assess the cannon's performance under real-world agricultural conditions. The study was conducted from July 29, 2024, to November 10, 2024, allowing for comprehensive testing across different weather conditions to evaluate the system’s reliability and efficiency. One of the key variables examined was the launch angle, with tests conducted at 30°, 40°, and 50°. These angles were chosen to determine their impact on the horizontal distance and accuracy of seed pod delivery. Identifying the optimal launch angle is crucial for maximizing the coverage area while ensuring precise seed placement.

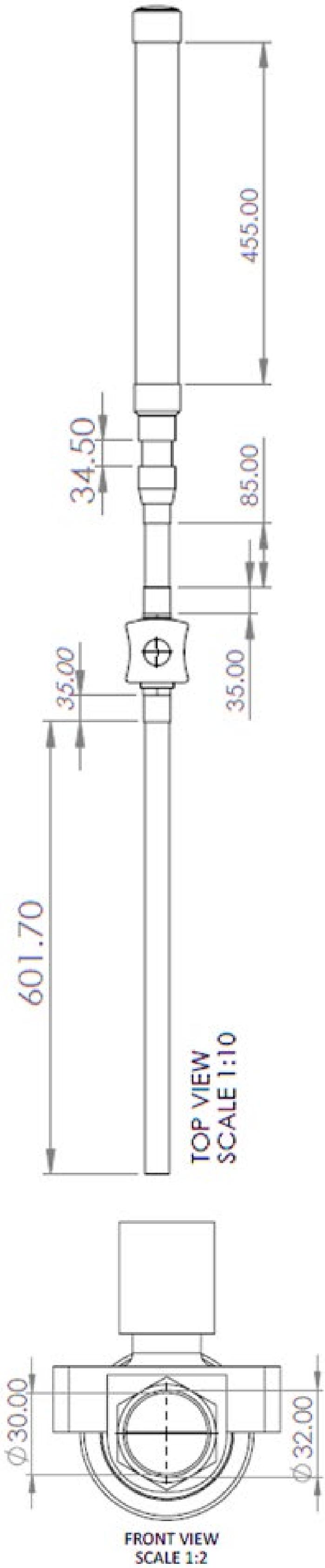


Figure 1 CAD drawing of the air-pressurized cannon: 30 mm inner diameter barrel and 57 mm inner diameter air tank

Figure 2 Setup of the air-pressurized cannon during field testing

The tests were also conducted under varying pressure levels, specifically 30, 40, and 50 Psi, to evaluate the influence of air pressure on the launch performance. The relationship between air pressure and seed pod velocity is a critical factor in achieving desired launch distances and maintaining seed integrity. By testing multiple pressure settings, the study aimed to identify the most effective pressure range for different planting scenarios.

Three distinct seed pod designs were tested to further explore the impact of weight and aerodynamics on the cannon's performance. These designs included round-nose cylindrical (AL), mortar shell (CL), and cluster bomb (TL) shapes (Figure 3). Each design varied in its weight and aerodynamic properties, which are crucial for determining the optimal trajectory and stability during flight. The round-nose cylindrical (AL) design features a hemispherical nose, which is known to influence aerodynamic characteristics significantly. Studies have shown that projectiles with hemispherical noses experience different aerodynamic forces compared to those with sharp noses, particularly at higher Mach numbers. For instance, research indicates that the Robins–Magnus effect is 15% greater for hemispherical nose shells than for sharp nose configurations at Mach 3. This effect can impact the stability and accuracy of the projectile during flight (Lijin and Jothi, 2018).

Additionally, the shape of the bullet's arc curve affects its aerodynamic characteristics, influencing flight stability and resistance. The design of the arcuate curve must consider factors such as resistance and lift to optimize projectile performance. Incorporating these aerodynamic considerations into the AL seed pod design is essential for achieving the desired flight stability and accuracy in seed dispersal applications (Hao et al., 2024). These configurations are comparable to those used in UAV seeding devices, which are designed to adapt to diverse terrains and environmental conditions (Liu et al., 2023). Similar principles are applied in the aerodynamic design of nose cones, where shapes are optimized to minimize drag and enhance stability across different flight regimes, demonstrating how aerodynamic optimization can significantly improve performance (Prajapati et al., 2022).

2.3 Data collection and analysis

Field trials were conducted to measure critical performance metrics, including seed distribution patterns, maximum launch distances, and accuracy. For each combination of pressure level, launch angle, and seed pod type, 45 trials were performed to ensure the reliability of the results. The data collected during these trials were analysed to assess the cannon's capability to achieve consistent and precise seed placement, thereby contributing to its overall efficacy as a mechanized planting tool.

Table 1 presents the one-way ANOVA summary for the whether pod type (CL, AL, TL) has a statistically significant effect on pod weight. The table point out an ANOVA calculation, including sums of squares (SS), degrees of freedom (df), mean squares (MS), the F-statistic, and the corresponding *p*-value. The one-way ANOVA shows that there is a statistically significant difference in pod weight among the three pod types (CL, AL, and TL) with $F(2,12) = 35.39$ and $p < 0.001$. This result implies that the design of the seed pod substantially influences its weight. Specifically, the AL pods are significantly lighter compared to the CL pods, with the TL pods showing intermediate weights.

Table 1 One-way ANOVA

Source	SS	df	MS	F	*p*-value
Between groups	302.78	2	151.39	35.39	< 0.001
Within groups	51.33	12	4.28		
Total	354.11	14			

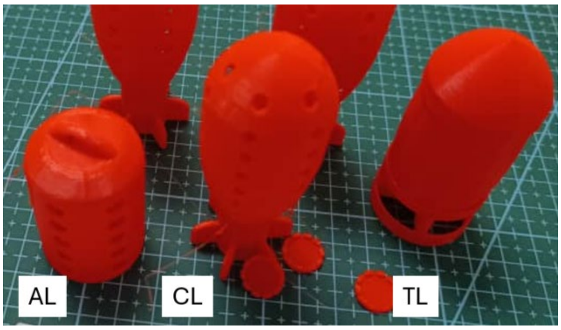


Figure 3 3D-printed seed pods fabricated using PLA material

3 Results and discussion

The experimental data indicate a significant relationship between launch angles, air pressure, and the resulting distances achieved by the seed pods. At moderate pressure levels (40 psi), the optimal launch angle for maximum distance was 40°, with the AL seed pod type achieving a maximum distance of 85.1 meters. This finding aligns with studies on UAV seeding systems, where an optimal angle is critical for maximizing horizontal coverage (Liu et al., 2023). At higher pressures (50 psi), distances began to decrease, particularly at larger angles, likely due to aerodynamic drag and suboptimal launch trajectories, as observed in the CL pods, which achieved only 41.2 meters at a 50° angle (Figure 4).

Figure 4 illustrates that at lower angles (30°), distances were consistent across different pressures, indicating that the air-pressured system performed effectively at launching seeds over shorter trajectories, useful for dense planting areas. These results are comparable to observations in multi-crop planter designs, where optimal conditions ensured even seed distribution (Samoy-Pascual et al., 2021).

The weight of the seed pods was inversely proportional to the distance traveled, with lighter AL pods consistently outperforming the heavier CL pods. For instance, AL pods with an average weight of 24 grams reached distances exceeding 80 meters at 40 psi and 30°-40° angles, while the heavier CL pods (35 grams) peaked at 70.6 meters under the same conditions (Figure 5). These findings are consistent with the results from drone seeding technologies, where seed pod aerodynamics and weight significantly influenced seeding range and precision (Marzuki et al., 2021). Additionally, ANOVA confirmed significant differences between pod types ($p < 0.05$), emphasizing the influence of weight and design on planting efficiency.

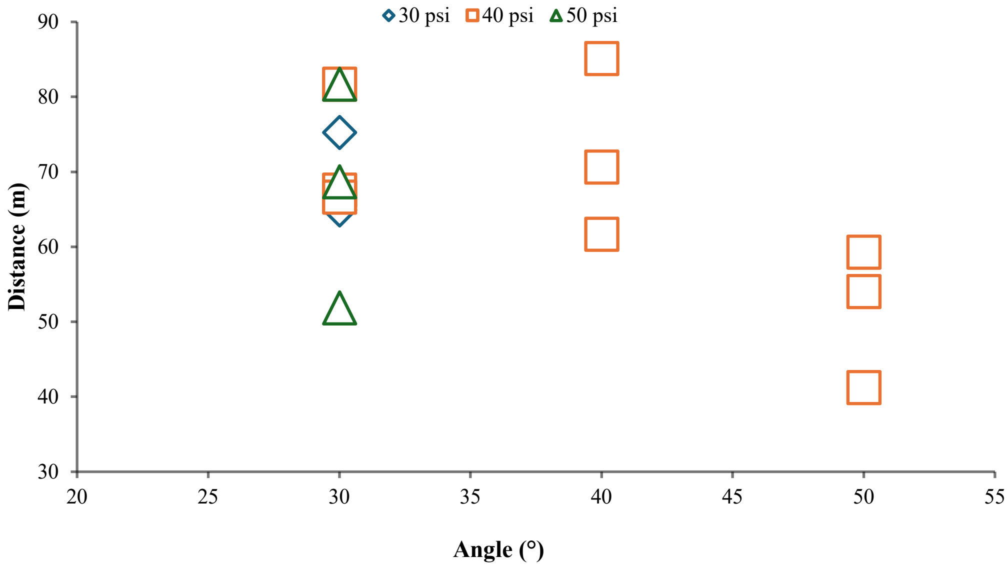


Figure 4 Distance vs. angle for different pressures

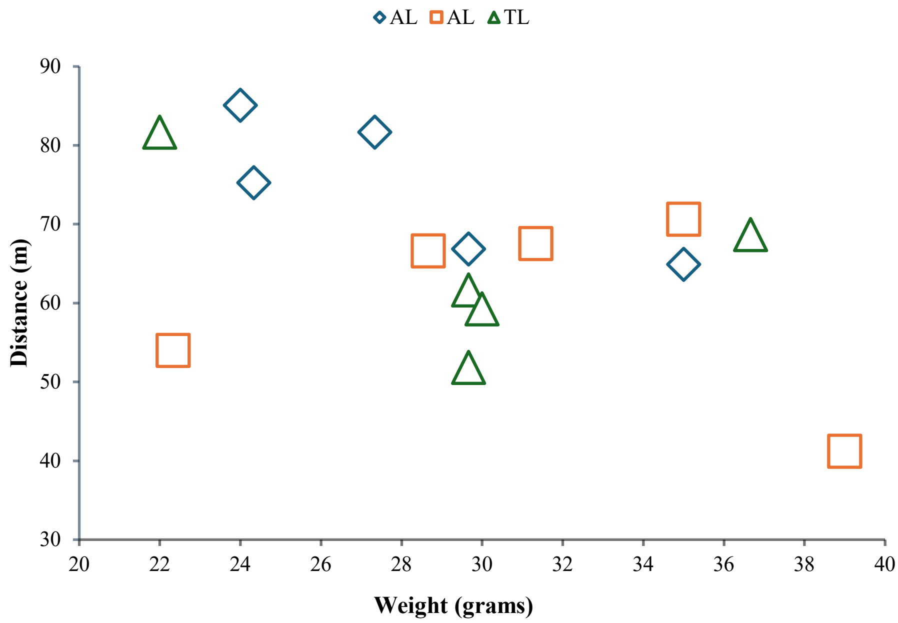


Figure 5 Distance vs weight for different seed pod types

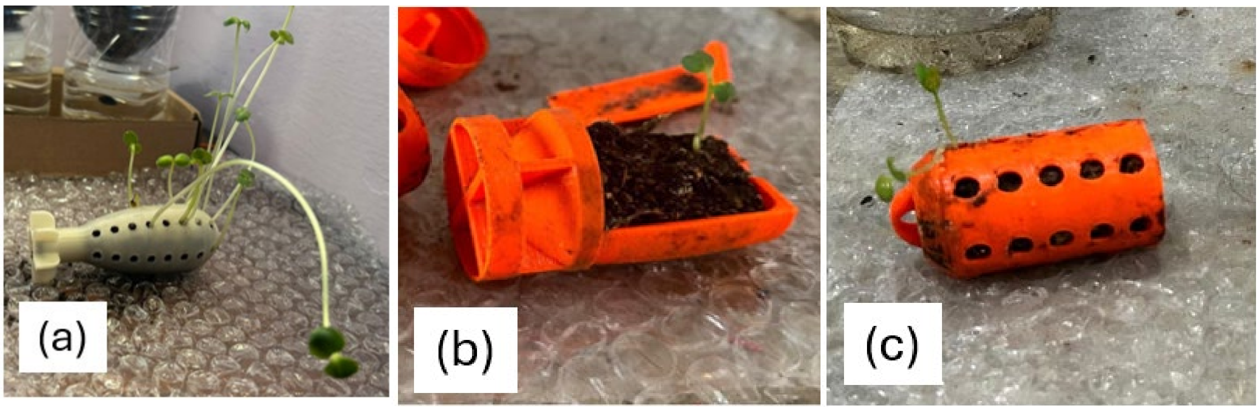
Figure 5 highlights the disparity in performance due to pod weight, reinforcing the need for design considerations that optimize weight distribution and shape. The AL pod's streamlined cylindrical shape likely contributed to its superior aerodynamics, as noted in other mechanized planting studies where pod design played a pivotal role in enhancing efficiency (Soyoye, 2020).

The findings also reveal that accuracy in seed placement varies significantly depending on the combination of pressure, angle, and seed pod speed. At higher pressures and moderate angles, such as 50 psi and 30°, accuracy peaks at 96%, indicating precise seed delivery over consistent distances. Similarly, an angle of 40° with 40 psi also showed high accuracy levels, reaching up to 92%, further supporting the effectiveness of moderate angles in optimizing seed placement.

The germination and seed vigor results of the chili (Capsicum annuum) seed pods (CL, TL, and AL) demonstrated varied performance in seedling emergence and growth. These findings align with studies on sugar pine seeds, which emphasize the critical role of protective structures in maintaining seed viability during adverse conditions. Shen and Cho (2021) identified that intact seed structures provide mechanical and physiological protection, contributing to improved germination outcomes when external conditions are favorable. Similarly, our results show that CL pods, with their robust protective design, yielded the fastest germination rates and significant growth by Day 14, underscoring the importance of seed coat protection.

Moreover, innovations like 3D-printed hydrogel-based seed planters, as explored by Huang et al. (2022), highlight the influence of substrate design on germination efficiency and seedling vigor. In these systems, seed orientation and substrate properties significantly impacted water absorption and seedling development, which parallels the observed performance differences among our pod designs. The AL and TL seed pods, despite slower germination, exhibited uniform growth, suggesting that design optimization could further enhance their protective and nurturing capabilities during the germination phase. These results collectively emphasize the potential of leveraging advanced material designs to improve agricultural outcomes

The findings demonstrate the effectiveness of the air-pressurized cannon in achieving precise seed placement across varying distances and angles. The results confirm that lighter seed pods with optimized shapes can achieve greater distances, similar to advancements seen in UAV-based afforestation systems that emphasize precision and efficiency in diverse terrains (Liu et al., 2023). These results also align with findings in multi-crop planter evaluations, highlighting the importance of adaptive technologies for improving planting accuracy and reducing seed wastage (Idago et al., 2019). Furthermore, the germination tests confirmed that the seed pods provide a protective environment, maintaining seed integrity and vigor, which is a critical factor for successful field performance.



(a) CL on Day 14 (b) TL on Day 10 (c) AL on Day 10

Figure 6 Germination and seed vigor observed within seed pods

Future improvements could focus on refining pod designs to further enhance aerodynamics and reduce weight, thereby extending planting range while maintaining accuracy. The design principles of artillery firing accuracy, as discussed by Qian et al. (2022), emphasize the importance of balancing structural dynamics and projectile performance to optimize flight stability and target precision. This parallels the need for precision in seed delivery systems, where design refinements in seed pod aerodynamics can minimize deviations and improve planting efficiency. Additionally, incorporating sensitivity analysis to identify key design parameters could enhance the robustness of seed dispersal systems in varying environmental conditions.

4 Conclusion

This study successfully designed, fabricated, and tested an air-pressurized cannon for the precise and efficient planting of agricultural seed pods. The cannon demonstrated optimal performance in terms of seed distribution, with the AL seed pods achieving the highest launch distances due to their lighter weight and aerodynamic design. The results highlight the importance of launch angle and air pressure, with a 40° angle and moderate pressure (40 psi) providing the best performance for most seed pod types.

The germination tests further validated the effectiveness of the system, showing high seed vigor and germination rates across all seed pod types, particularly the CL and AL designs. This highlights the cannon's capability to not only ensure effective seed placement but also maintain seed integrity and promote healthy plant growth.

The air-pressurized cannon offers a promising solution for precision agriculture, especially in areas with challenging terrains where traditional planting methods are less effective. By enhancing planting accuracy and reducing labor requirements, this innovation contributes to improving agricultural productivity and sustainability. Future work could focus on refining seed pod designs for specific crop types and conducting field tests under varied environmental conditions to further optimize the system's performance.

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