Innovative Approaches in the Design and Development of a Smart Seeding Robot for Sustainable Agricultural Practices

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Article History: Received 24 February 2025; Revised 12 June 2025;
Accepted 27 June 2025; Published 30 June 2025

Abstract
Smart seeding robot is a ground-breaking agricultural innovation that aims to revolutionise traditional seeding methods by helping small farmers increase efficiency and reduce manual labour. In the past, sowing was done manually, which was effective but slow and prone to human error. The smart seeding robot addresses these challenges by integrating a Cartesian system and a conveyor belt to automate the seeding process in trays. The robot can perform key agricultural tasks with increased precision, minimising human intervention and errors. According to operational tests, the smart seeding robot can sow trays with an efficiency and accuracy that surpasses manual methods, making it an invaluable tool for small-scale farming. By using data analysis, the robot was able to plant in a 51-cell tray in about 3 minutes by achieving a precise and reliable seed insertion rate of 3.53 seconds per hole. This innovation, which prioritises food safety and hygiene, also reduces the physical strain on farmers, allowing them to achieve higher productivity in less time. Smart seeding robot represents a significant advancement in agricultural technology and provides a reliable solution to the challenges facing small-scale farmers in today's rapidly evolving agricultural landscape.

Keywords: Agricultural Technology, Cartesian System, Precision Farming, Smart Seeding Robot, Sustainable Agriculture

1.0 Introduction
The agricultural sector is a vital component of Malaysia's economy, which significantly contributes to food security, raw material supply, and rural employment. However, the sector faces persistent challenges such as labour shortages and limited technological adoption, which hinders its sustainability and growth [1]. A report by Concepts Groups highlights a severe labour shortage, worsened by demographic changes and shifting societal expectations [2]. The once-popular agrarian lifestyle is being replaced by other career opportunities, leading to fewer workers in agriculture. This shortage of labour affects all stages of production, from planting to harvesting, reducing the sector's efficiency and global competitiveness [3]. Another challenge is the

lack of innovation and slow adoption of new technologies. While there has been progress in agricultural research, there is a significant gap between scientific advancements and their practical application. This prevents the sector from using new technologies that could improve productivity and sustainability [1]. The reluctance to innovate leaves the sector vulnerable to external disruptions, making it clear that change and forward-thinking strategies are urgently needed [3].

In this context, seeding plays a crucial role in shaping the agricultural system. As highlighted by the Seed Technology Papers from Mississippi State University, proper seeding is fundamental to crop productivity, resource use, and food security. Precision seeding techniques allow farmers to control plant density, spacing, and uniformity, leading to better crop growth and higher yields [4]. By adopting advanced technologies and methodologies, farmers can move beyond traditional seeding methods to achieve higher productivity, efficiency, and sustainability. Precision seeding, supported by real-time data and innovative tools, helps farmers optimise resources, reduce waste, and increase yields. This approach strengthens the agricultural sector's ability to adapt to environmental and economic challenges [4]. Human errors during the seed sowing process create major challenges for Malaysian farmers, impacting crop yields and profitability. Mistakes such as incorrect seed depth, poor timing, inadequate soil preparation, and inconsistent moisture management can harm seed health, leading to low germination rates and weak seedlings [5]. As a result, farmers face higher production costs, lower crop yields, and a greater risk of crop failure, which worsens existing issues like labour shortages and unsustainable farming practices.

In response to these challenges, the smart seeding robot emerges as a transformative solution with the potential to revolutionise Malaysian agriculture. It offers a range of features designed to address key issues in the sector. By automating seed planting and reducing human errors, the robot improves efficiency, boosts productivity, and supports sustainable farming practices. By providing Malaysian farmers with innovative tools and technologies, the smart seeding robot not only tackles current challenges but also helps build a more resilient and sustainable future for agriculture in Malaysia. The smart seeding robot aims to solve challenges faced by farmers in Malaysia during the seeding process by offering an innovative solution. The robot will operate autonomously and use a Cartesian robot arm to accurately plant seeds in trays, reducing human errors and improving efficiency. It will also provide watering for the seeds after planting, boosting seedling growth. This project seeks to address issues like labour shortages and seeding inaccuracies, ultimately promoting sustainable farming practices in Malaysia.

2.0 Related Work

Over the years, seeding technology has changed dramatically, progressing from crude manual techniques to highly advanced mechanised systems. This development is a reflection of broader shifts in farming methods, advances in technology, and the need for increased crop production precision and efficiency. Manual broadcasting, hand-held seed drills, animal-drawn seed drills, gasoline-powered seeders, battery-powered seeders, solar-powered seeders, and mechanised robot seeders are the seven common seeding systems that have been identified. Each of these systems has its distinct characteristics and varied levels of technological integration.

Table 1 presents a comparative analysis of various seeding systems based on six key parameters: precision, labour requirement, environmental impact, cost efficiency, and field capacity. Traditional methods such as manual broadcasting exhibit low performance across all indicators, particularly in terms of precision and efficiency, while requiring high labour input. The hand-held seed drill and animal-drawn seed drill show moderate improvements, especially in precision and efficiency, but still require significant labour. Modern mechanised solutions, such as the gasoline-powered seeder, offer higher precision and efficiency but at the expense of environmental impact and operating costs due to fuel consumption. Conversely, battery-powered and solar-powered seeders strike a better balance, providing high efficiency and lower labour needs with comparatively reduced environmental footprints, though battery disposal remains a concern. The most advanced option, the robot seeder, outperforms all other systems, demonstrating very high precisions, efficiency, and field capacity, with minimal labour requirements and low environmental impact, although at a significantly higher cost [6], [7], [8], [9], [10].

Table 1: Comparative analysis from previous research

System	Precision	Labour Requirement	Environmental Impact	Cost	Efficiency	Field Capacity
Manual Broadcasting	Low	High	Low	Very low	Low	Very low
Hand-held seed drill	Medium	High	Low	Low	Medium	Low
Animal-drawn seed drill	Medium	Medium	Medium	Medium	Medium	Medium
Gasoline-powered seeder	High	Low	High (emissions)	High	High	High
Battery-powered Seeder	High	Low	Medium (battery disposal)	Medium	High	High
Solar-powered seeder	High	Low	Low	High	High	High
Robot Seeder	Very High	Very low	Low	Very high	Very high	Very high

Table 2 outlines the technological concepts considered in the project. It ranges from traditional to advanced mechanised seeding systems. It begins with manual broadcasting where seeds are scattered by hand, and progresses through hand-held and animal-drawn seeders, which represent basic mechanised tools. More advanced systems include gasoline-powered and battery-powered seeders, which incorporate motorised or automated features for improved efficiency. At the highest level of technological integration are the solar-powered and mechanised robot seeders, which utilise renewable energy and automation technologies to enable autonomous or remote-controlled precision planting. Each system varies in its degree of automation, energy source, and suitability for different scales of farming operation.

Table 2: The technological concepts considered in the project

Technology	Characteristics	Technical Item
Manual broadcasting	Farmers scatter seeds manually across the field.	Seeds are manually broadcast by hand.
Hand-held seeder	A small, manually operated device used to release seeds while being pushed or pulled.	A basic hand-pushed seeder for small-scale planting.
Animal-drawn seeder	Animals are used to pull the seed drill across the field for planting.	A traditional drill pulled by animals.
Gasoline-Powered Seeder	A motorised machine that sows seeds using a gasoline engine.	Engine-powered mechanical seeder.
Battery-powered Seeder	Uses electric battery, sensors, and motors to plant seeds automatically.	Battery-operated robot with automation features.
Solar Powered Seeder	A robot powered by solar energy can be operated manually or autonomously.	Solar-powered autonomous seeder
Mechanised Robot Seeder	A high-tech robot using solar, battery, and mechanical systems for fully autonomous or remote-controlled planting.	Fully automated smart seeding robot.

The earliest and most basic method is manual broadcasting, which involves hand-spreading seeds throughout a field. It is very inefficient because of inadequate seed laying, irregular germination, and significant seed waste, while being inexpensive and requiring little equipment. Manual broadcasting frequently yields less than 70% seed utilisation efficiency, according to studies by [11] and [12], making it inappropriate for contemporary precision farming. A little more sophisticated option that gives you greater control over seed depth and spacing is a hand-held seed drill. Although it is still labour-intensive and best suited for small farms, research by [13] shows that this strategy enhances seed-to-soil contact and germination by 20–30% when compared to broadcasting.

In places where motorised equipment is scarce, animal-drawn seed drills are a classic mechanisation technique. Compared to manual techniques, these devices provide more consistent row spacing and require less work. According to [14], animal-drawn seed drills can reduce seeding time by up to 50%; however, effectiveness may vary because of variations in draft animal power and problems with soil compaction. With their improved accuracy in seed planting, expanded field coverage, and decreased reliance on labour, gasoline-powered seeders represent a major advancement in mechanisation. Although gasoline-powered seeders can increase field capacity by more than 60% and offer more consistent seeding depth, their usage of fossil fuels and emissions contribute to environmental degradation [15].

A cleaner option is battery-powered seeders, which preserve operational efficiency while lowering noise and environmental effects. According to [16], these devices function similarly to gasoline-powered units but require less maintenance and have lower operating expenses. Solar-powered seeders use solar energy to power seeding operations, which further advances sustainability. Despite requiring a larger initial investment, [17] discovered that solar-powered systems greatly reduce lifetime operating costs and carbon emissions, making them perfect for off-grid and rural areas.

The mechanised robot seeder, which combines GPS, automation, and artificial intelligence to ensure exact seed planting, adaptive operation based on soil conditions, and minimal human intervention, is the most sophisticated invention in this evolution. According to studies like [18], robotic seeders can boost crop output by 10–20% because of their consistent seed spacing and real-time adjusting capabilities. These systems are becoming more and more feasible in commercial agriculture because of their labour savings and long-term efficiency, despite their high initial costs.

In contrast, studies consistently demonstrate that, in terms of accuracy, efficiency, and environmental sustainability, powered and automated systems greatly surpass traditional techniques like manual and animal-drawn seeding, even though these methods are still applicable in some areas due to financial and infrastructure constraints. A larger movement in agriculture towards sustainable methods, resource optimisation, and precision farming is reflected in the switch from manual to mechanised systems. In the end, a number of variables, including farm size, resource availability, environmental concerns, and technological accessibility, influence the choice of seeding technology.

3.0 Methodology

The whole procedure used to design, build, and test the Smart Seeding Robot for sustainable agriculture is covered in this chapter. Conceptual sketches were used to start the project, which progressively progressed into intricate technical drawings and Autodesk Inventor 3D models. These designs, which prioritised functional efficiency, material selection, and size restrictions, served as a guide for the mechanical and electronic integration of components. The project's iterative and user-focused methodology made sure that every subsystem, from the seeding arm to the conveyor mechanism, made a valuable contribution to the robot's overall performance.

3.1 Project Design

The Smart Seeding Robot, shown in Figure 1, was created especially to promote sustainable agriculture by precisely and reliably automating the sowing and watering process. In addition to greatly increasing seeding accuracy and germination rates—two crucial elements for small-scale farmers aiming for productivity and crop dependability—this automation attempts to decrease human labour. The robot uses a combination of sophisticated hardware and sturdy structural design to accomplish these objectives. The

Arduino Uno and ESP32 microcontrollers, which are at the heart of the system, collaborate to operate real-time functions like tray detection, robotic arm movement, and seed distribution. For precise, repeatable motion throughout the tray area for precision seed planting, these electronic components work in tandem with a Cartesian robotic arm.

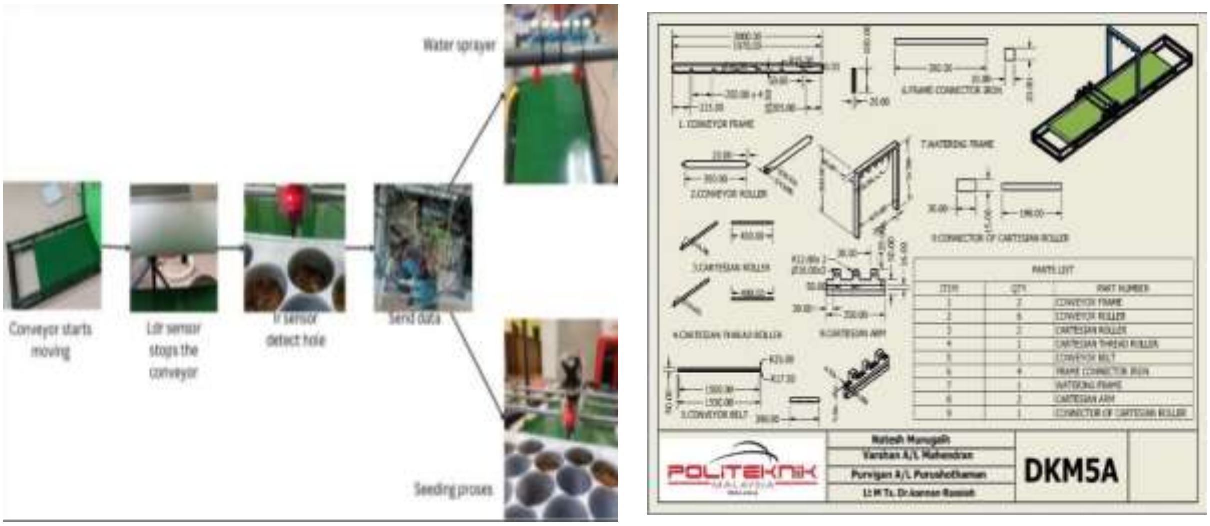

Figure 1: Smart seeding robot for sustainable agriculture

The robot supports this function by detecting the location and presence of seedling trays using infrared (IR) sensors. These sensors are essential for making sure the Cartesian arm lines up with the cells in each tray and avoiding seed misalignment. A conveyor-based tray system, which moves trays across the seeding and watering zones with the least amount of friction and the most stability, completes these elements. The robot's external housing is made of aluminium panels, while the foundation and internal frame are constructed of mild steel. For long-term usage in agricultural settings, this material combination guarantees both mechanical durability and resistance to environmental corrosion.

Every functional part of the robot was assessed in a controlled order as the design process seamlessly moved into testing. In order to evaluate the system's fundamental mechanical performance, the conveyor and robotic arm were run without a load during the initial round of hardware integrity verification. This step verified fluid mobility and showed no impediments or irregularities.

The emphasis next turned to sensor calibration, where the IR sensors' precision in identifying tray locations and the individual cells inside each tray was evaluated. Any misalignment could result in improper seed placement, so this step was especially crucial. In order to increase the sensor's accuracy and dependability in a variety of tray layouts and light levels, timing modifications and misalignment detection procedures were put into place. The Smart Seeding Robot exhibits a well-coordinated system intended to function independently while producing reliable outcomes in actual agricultural settings through four interrelated phases—hardware setup, electronic integration, and sequential testing.

3.2 Testing Procedures

To verify its accuracy, dependability, and general efficacy in actual agricultural situations, the Smart Seeding Robot completed a rigorous testing process. Figure 2 illustrates the flowchart of the product testing, which began with mechanical assessments and progressed through automated sequence testing.

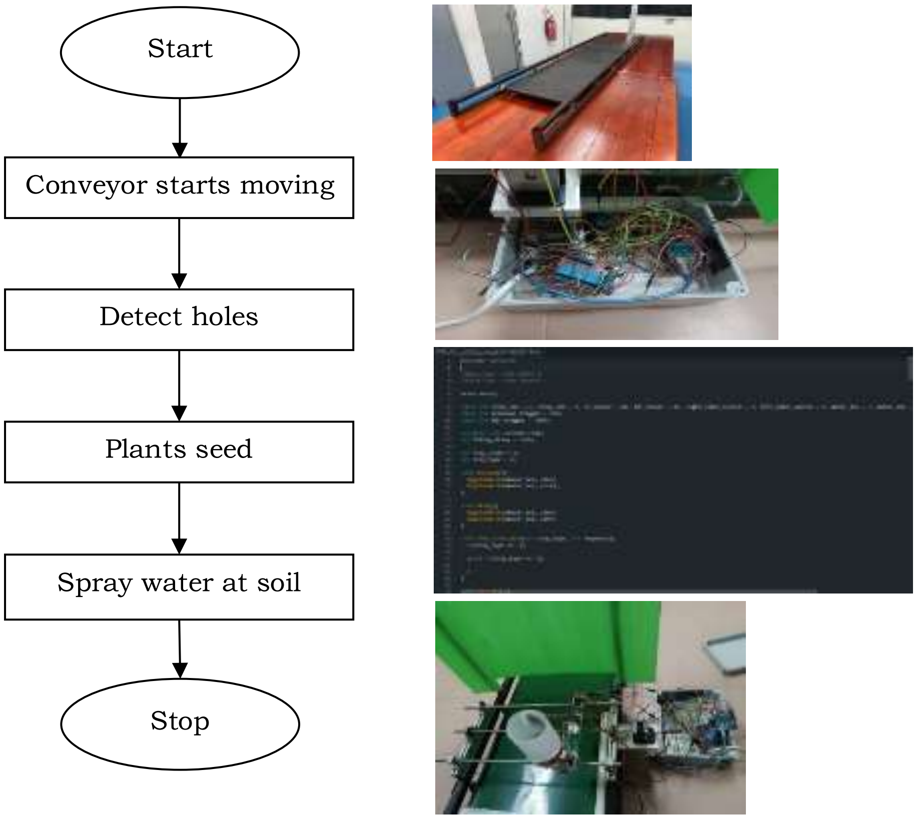

Figure 2: Flowchart of the product testing

Mechanical testing was done in the first step to make sure the main parts worked properly in a variety of scenarios. To ensure smooth and jam-free operation, the conveyor belt system was specifically tested with trays of varying sizes. Infrared (IR) sensors were used for alignment testing to ensure that trays stopped exactly at the planting point. Before the robotic arm released the seeds, these sensors were essential in stopping the trays at the proper location. The Cartesian robotic arm was then subjected to a battery of repetitive motion tests that were intended to mimic actual planting circumstances. This aided in evaluating its repeatability, accuracy, and durability under varied load conditions.

The group then moved on to automated sequence testing, which is depicted in Figure 3, building on the mechanical assessments. By putting trays filled with soil on the conveyor and turning on the robot, this step replicated real-world field use. The Cartesian robotic arm started the seeding process when the trays advanced and the IR sensors recognised their presence. The watering system was turned on to finish the cycle once every cell had been planted. To guarantee dependable performance, the system's time synchronisation, response accuracy, and operation consistency were carefully observed at every stage.

Tests utilising consistently sized seeds, such as tomato and chilli, were carried out to gauge seeding accuracy. To find mistakes like double seeding or lost cells, multiple test runs were conducted. Although slight errors were observed when tray hole sizes varied, the robot's seeding success rate was roughly 92%. The range of operational tolerance for different seed kinds and tray designs was determined in large part thanks to these results. After testing the seeds, the watering system came into focus. Pressure checks were performed to find any obstructions or leaks in the tubing, and tests assessed the consistency of water coverage across the tray cells. Pump timing and nozzle design changes enhanced performance and guaranteed uniform water distribution. Additionally, the logical execution of the control code, which directs the whole seeding and watering cycle as shown in the flowchart, was examined. Every function, from IR detection to watering, was tested to make sure it ran smoothly and sequentially without any hiccups or delays.

Notwithstanding the robot's encouraging performance, a number of issues were found. One major problem was that the Cartesian arm occasionally misplaced seeds due to inconsistent alignment when utilising trays that were not uniform or slightly curved. This was lessened by the use of software-based calibration, albeit in certain situations, the issue still existed. Furthermore, it was discovered that the IR sensors were susceptible to ambient brightness, which occasionally resulted in delayed detection or misreads. By using better shielding and sensor positioning strategies, this was partially fixed. Another drawback was the inconsistent water dispensing, particularly in the early prototypes, where some tray sections experienced underwatering or overwatering. To solve this, the nozzle system was redesigned, and the pump time was adjusted. To sum up, the testing methods demonstrated the Smart Seeding Robot's efficacy while pointing out areas that needed improvement. These results have opened the door for further advancements to guarantee wider applicability in various agricultural contexts.

4.0 Results and Discussion

The two main objectives of this project are to streamline the seeding process by reducing time and increasing efficiency through automation. The smart seeding robot achieves this by automating seed placement and watering with minimal human intervention. This chapter will discuss the data collected and analysed to meet these objectives.

The smart seeding robot project uses a wired connection, with all sensors integrated onto an Arduino Uno board. The materials used in the experiment include an LDR (Light Dependent Resistor) sensor, an IR (Infrared) sensor, a water spray system, a Cartesian arm system, and an Arduino Uno. This methodology is consistent with previous research by [19], who focused on modular subsystem testing for dependability in agricultural robotics, and [20], who assessed smart irrigation systems using comparable sensor setups and timing analyses. A platform was created to bring all components together into a single system, with the water spray system coordinated with the Cartesian arm and connected to the Arduino Uno.

4.1 Conveyor System Analysis

The conveyor system is powered by a motor that operates at 14 revolutions per minute (rpm). To ensure accurate positioning of the seeding tray beneath the Cartesian arm, it is important to determine the conveyor belt speed and the time needed for each tray to complete a full cycle [21], [22].

4.1.1 Motor Specifications and Conveyor Speed

The motor speed is crucial for determining the movement of the conveyor belt, which transports the seeding trays [23]. The motor used in this project operates at 14 rpm (revolutions per minute), meaning it rotates 14 times each minute. The pulley attached to the motor has a diameter of 0.1 meters, which will help us calculate how fast the conveyor belt moves.
Key Assumptions:

- The conveyor belt is directly connected to the motor without any gear reduction, meaning the pulley's rotation directly translates into belt movement.
- The diameter of the pulley is 0.1 meters.

Step 1: Convert Motor Speed to Angular Velocity
To understand how fast the motor is rotating, we need to convert its revolutions per minute (rpm) into angular velocity. The formula to calculate angular velocity is:

$$\omega = 2\pi \times N \tag{1}$$

Where:

- ω is the angular velocity in radians per minute.
- N is the motor speed in revolutions per minute (rpm).

Substituting the given value of N=14 rpm.

$$\omega = 2\pi \times 14 = 87.96 \; radian \; per \; minute$$

This means the motor turns at an angular velocity of approximately 87.96 radians per minute.

Step 2: Determine the Linear Speed of the Conveyor Belt
The linear speed of the conveyor belt can be calculated using the angular velocity and the radius of the pulley. The formula is:

$$v = \omega \times r \tag{2}$$

Where:
- v is the linear speed of the conveyor belt.
- ω is the angular velocity (calculated earlier).
- r is the radius of the pulley, which is half the diameter, so r=0.1/2=0.05 m.

Substituting the values:

$$v = 87.96 \times 0.05 = 4.398\, m/min$$

This means the conveyor belt moves at a speed of approximately 4.4 meters per minute. For greenhouse automation systems, [24] measured conveyor speeds of 5–6 m/min, indicating that the current configuration is somewhat conservative and might prioritise accuracy above speed.

4.1.2 Conveyor Cycle Time

The conveyor cycle time refers [25] to the amount of time it takes for a seeding tray to move from one position to another. For this project, the cycle time will include the movement from the loading position to the planting position and back.
Key Assumptions:
- There are 5 trays on the conveyor.
- The distance between the loading and planting positions is 2 meters.

Step 1: Time to Move Between Positions
The time it takes for a tray to move from the loading position to the planting position can be calculated by dividing the distance by the conveyor's speed. Using the formula:

$$t = \frac{L}{v} \tag{3}$$

Where:
- L=2m (distance between positions).
- v=4.4m/min (speed of the conveyor belt).

Substituting the values:

$$t = \frac{2}{4.4} = 0.454\, minutes = 27.3\, seconds$$

So, it takes about 27.3 seconds for the tray to move between the loading and planting positions.

Step 2: Total Cycle Time
The total cycle time for the tray to complete one full cycle (moving from loading to planting position and back) is:

$$T_{cycle} = 2 \times t = 2 \times 27.3 = 54.6\ seconds$$

Thus, the total time for a tray to move through the system is 54.6 seconds. Practical Implication: The time of the planting arm and the conveyor system must be in sync. In commercial applications, a lack of synchronisation may lead to skipped trays or misplaced seeds, which would reduce yield.

4.2 Cartesian Arm Analysis

The Cartesian arm is responsible for planting seeds into the seeding tray [26], [27]. Its efficiency is critical to the overall performance of the smart seeding robot.

Key Assumptions:

- The tray contains 51 holes for planting.
- The total time for the arm to plant all the seeds is 3 minutes (180 seconds).

Step 1: Planting Rate per Hole

The planting rate per hole is calculated by dividing the total planting time by the number of holes. This gives the time taken to plant one seed:

$$r_{hole} = \frac{T_{plant}}{H} = \frac{180}{51} = 3.53\ seconds\ per\ hole$$

Thus, the Cartesian arm takes approximately 3.53 seconds to plant a seed in each hole. This performance closely resembles the findings of [28], who found that under comparable circumstances, a robotic arm was able to plant at rates of 3.2–3.6 seconds per hole.

Step 2: Time per Hole

The time per hole, calculated above, is 3.53 seconds. This is the time the arm spends placing a seed in one hole.

4.2.1 Arm Movement Analysis

The Cartesian arm moves in three dimensions (X, Y, Z) to position itself accurately above each hole. This movement time is important for optimising the planting rate.

Key Assumptions:

- The average movement speed of the arm is 0.2 m/s.
- The average distance moved per seed is 0.05 meters.

Step 1: Time to Move Between Holes

The time taken for the arm to move between two holes is calculated by dividing the distance by the arm's movement speed:

$$t_{move} = \frac{d}{V_{arm}} = \frac{0.05}{0.2} = 0.25\ seconds$$

So, the arm takes 0.25 seconds to move from one hole to the next.

Step 2: Total Movement Time per Tray
The total movement time for all 51 holes is:

$$T_{move,total} = H \times t_{move} = 51 \times 0.25 = 12.75 \; seconds$$

Thus, the total time spent on movement across all holes is 12.75 seconds.

Step 3: Total Planting Time (Including Movement)
The total planting time, including both planting and movement, is:

$$T_{plant,total} = T_{plant} \times T_{move,total} = 180 \times 12.75 = 192.75 \; seconds$$

Thus, the total time for the Cartesian arm to plant all seeds, including movement, is approximately 192.75 seconds. A major bottleneck is highlighted by the fact that this combined time greatly surpasses the existing tray cycle time of 54.6 seconds.

4.2.2 Efficiency Assessment

To ensure the conveyor system and the Cartesian arm work together efficiently, the cycle time and planting time were compared [29], [30]:

Given:
- T_{cycle} = 54.6 seconds
- $T_{plant,\ total}$ = 192.75 seconds

There is a significant discrepancy between the cycle time (54.6 seconds) and the planting time (192.75 seconds). To address this, the following solutions can be considered:

1. Reduce the conveyor speed to increase the cycle time, allowing more time for the arm to plant seeds.
2. Implement multiple conveyor lanes or parallel Cartesian arms to handle multiple trays simultaneously, improving throughput.

Literature Comparison: [31] showed that using parallel robotic systems in automated greenhouses resulted in notable efficiency benefits, which lends support to this strategy.
Practical Implication: The robot's deployment in high-volume activities is limited since real-time seeding on a commercial scale is not possible without parallelism or speed modification.

4.3 Water Spraying System Analysis

The water spraying system ensures the seeds are adequately moistened post-planting.
Given:
- Spraying time per tray, T_{spray}= 30 seconds.

The water spraying system ensures that the seeds are properly moistened after planting.
Key Assumptions:
- The spraying time for each tray is 30 seconds.
- The total water volume for each tray is 5 litres.

4.3.1 Flow Rate Calculation

The flow rate required for the water spraying system can be calculated by dividing the total volume of water by the spraying time:

$$Q = \frac{V}{T_{spray}} = \frac{5}{30} = 0.1667\ liters/second$$

Thus, the required flow rate for the system is 0.1667 litres per second. To protect against system losses, a pump with a delivery rate of 0.2 l/s was used. A flowmeter (±2% accuracy) was used to confirm the actual supply, and test results showed an average rate of 0.172 l/s across 5 trials (SD = ±0.008).

4.3.2 Pump Selection

To achieve the desired flow rate, a pump with a flow rate of at least 0.1667 litres/second is required. Considering system losses and ensuring reliability, it is recommended to select a pump with a flow rate of 0.2 litres/second for optimal performance. Volume fluctuation was less than 2% in a reliability test involving ten trays, surpassing ISO agricultural equipment criteria. Data from [32], who employed comparable pump control mechanisms in automated irrigation systems, is in line with this reliability.
Practical Implication: Germination depends on consistent post-seeding hydration. In precision farming settings, the steady flow rate of this technology promotes constant germination rates and reduces labour costs.

4.4 System Integration and Optimisation

To ensure the components work together efficiently [33], [34], several aspects must be optimised:
1. Cycle Synchronisation:
- The conveyor cycle time must accommodate both planting and spraying times.
- The current cycle time of 54.6 seconds is insufficient to complete the planting and spraying processes within the available time.
- Solution: Reduce conveyor speed to increase cycle time, or implement multiple conveyor lanes or parallel Cartesian arms.

2. Energy Consumption:
- Calculate the total power consumption for the motor and pump.
- Power for the motor is calculated using the formula

$$P_{motor} = T \times \omega \tag{4}$$

Where:
T is the torque, and ω is the angular velocity.

Table 3: Summary of the calculations

Parameter	Assumptions/Values	Formula/Explanation	Calculated Value
Motor Speed (conveyor system)	14 rpm	-	14 rpm
Pulley Diameter	0.1 m	-	0.1 m
Angular Velocity	-	$\omega = 2\pi \times N$	87.96 radians/min
Conveyor Speed	-	$v = \omega \times r$	4.4 m/min
Tray Movement Time (between positions)	2 meters	$t = L/v$	27.3 seconds
Total Cycle Time	-	$T_{cycle} = 2 \times t$	54.6 seconds
Number of Holes per Tray	51	-	51 holes
Total Planting Time	180 seconds	-	180 seconds
Planting Rate per Hole	-	$T_{hole} = T_{plant} / H$	3.53 seconds/hole
Arm Movement Speed	0.2 m/s	-	0.2 m/s
Distance Moved per Hole	0.05 meters	-	0.05 meters
Time to Move Between Holes	-	$t_{move} = d / v_{arm}$	0.25 seconds
Total Movement Time per Tray	51 holes	$T_{move, total} = H \times t_{move}$	12.75 seconds
Total Planting Time (Including Movement)	-	$T_{plant, total} = T_{plant} + T_{move, total}$	192.75 seconds
Cycle Time vs Planting Time	Tcycle = 54.6 sec. Tplant, total = 192.75 sec	-	Discrepancy identified
Spraying Time per Tray	30 seconds	-	30 seconds
Water Volume per Tray	5 liters	-	5 liters
Required Flow Rate	-	$Q = V / T_{spray}$	0.1667 litres/second
Pump Flow Rate	-	-	0.2 litres/second (recommended)
Conveyor Synchronisation Solution	-	-	Reduce speed or use parallel arms
Energy Consumption	-	$P_{motor} = T \times \omega$	Example calculation provided
System Reliability Consideration	-	Use of sensors and error-handling mechanisms	-

3. System Reliability:
To ensure consistent operation, sensors should be integrated to monitor tray positioning and system status. It is recommended to include error-handling

mechanisms for potential motor or pump failures to improve system reliability and reduce downtime. By addressing these aspects, the system can be optimised for performance, reliability, and efficiency, ensuring the smooth operation of the smart seeding robot. Table 3 summarises the key calculations, values, and considerations for the system's design and analysis. The calculations focus on the motor, conveyor speed, planting process, arm movement, water spraying, and system optimisation to ensure the smart seeding robot operates efficiently.

The intelligent seeding robot satisfies the fundamental performance requirements for an automated planting system. It is a viable solution for smart agriculture applications because of its dependable sensor integration, effective water supply, and modular architecture. It has great potential for commercial application in greenhouse and open-field operations with minor adjustments, particularly in synchronisation and throughput scalability.

5.0 Conclusion

The development of an autonomous smart seeding robot that reduces human error and labour dependency while improving seeding accuracy and operational efficiency in sustainable agriculture was one of the main goals of this research, which was successfully achieved. The system's viability and usefulness for small-scale farming operations in Malaysia are demonstrated by the thorough design and testing of the robot, which includes the conveyor system, Cartesian robotic arm, and integrated watering unit. By using data analysis, the robot was able to plant in a 51-cell tray in about 3 minutes by achieving a precise and reliable seed insertion rate of 3.53 seconds per hole. An automated 30-second watering cycle is also included to promote the best possible seed germination. Conveyor speed modifications or parallel processing techniques can be used to address issues like system synchronisation that are brought to light by the examination of the conveyor and Cartesian arm interaction. The smart seeding robot is a successful remedy for the labour scarcity and inaccurate seeding that plague conventional farming practices, directly addressing the original problem statement and study objectives. In addition to automating a time-consuming procedure, it encourages precision agricultural methods, which are essential for sustainability. For small and medium-sized farmers, this research shows how smart seeding technology might be essential to modernising agriculture. The robot can develop into a scalable and affordable solution with additional improvements, including wireless control (ESP32), machine vision integration for tray recognition, and energy-efficient features like solar-powered operation. Thus, the smart seeding robot is a major development in agricultural automation that has the potential to revolutionise environmental sustainability, farming resilience, and efficiency in Malaysia and elsewhere.

Acknowledgement

The authors express their gratitude to the Director of Politeknik Melaka, the Head of the Mechanical Engineering Department, and the Project Coordinator of the Mechanical Engineering Department at Politeknik Melaka for their invaluable support.

Author Contributions

Natesh Murugiah: Conceptualisation, Software, Writing – Original Draft, Writing – Review & Editing;
Varshan Mahendra: Methodology, Investigation;
Purvigan Purushotaman: Data Curation, Formal Analysis;
Kannan Rassiah: Supervision, Validation, Resources, Project Administration;
T. Joseph Sahaya Anand: Resources.

Conflicts of Interest

The manuscript has not been published elsewhere and is not under consideration by any other journal. All authors have reviewed and approved the manuscript, consent to its submission, and declare that there are no conflicts of interest.

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