Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Design and Field Evaluation of a Solar-Powered CNC-Based Autonomous Seedling Transplanting Robot for Precision Agriculture

Ghada A. Elgamal

Ghada.a.elgamal@gmail.com

Egyptian Chinese University

Omar A. Hashem

Egyptian Chinese University

Nerveen Ehab

University of Hertfordshire by GAF

A. M. Bassiuny

Faculty of Engineering, Helwan, Capital University

Research Article

Keywords: Autonomous seedling transplanting, CNC-based robotics, Solar-powered agricultural systems, IoT precision agriculture, Field robotic automation

Posted Date: May 18th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8649151/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Design and Field Evaluation of a Solar-Powered CNC-Based Autonomous Seedling Transplanting Robot for Precision Agriculture

Ghada A.Elgamal [1*], Omar A.Hashem[2], Nerveen Ehab[3], A.M.Bassiuny[4]

1. *Assistant Professor, Mechatronics Engineering Department, Faculty of Engineering and Technology, Egyptian Chinese University, Cairo, Egypt,* *Ghada.a.elgamal@gmail.com , ghada.abdelzaher@ecu.edu.eg
2. *Teaching Assistant, Mechatronics Engineering Department, Faculty of Engineering and Technology, Egyptian Chinese University, Cairo, Egypt*
3. *Teaching Assistant, Mechatronics and Mechanical Engineering Department, Faculty of Engineering and Computer Science, University of Hertfordshire by GAF, Cairo, Egypt*
4. *Professor of Mechatronics & Control Engineering, Faculty of Engineering, Helwan, Capital University, Cairo, Egypt*

Abstract

Seedling transplantation has a significant impact on crop uniformity, productivity, and resource efficiency. However, conventional manual and electrically driven transplanting systems remain labor-intensive, energy-dependent, and prone to inconsistent planting accuracy under variable field conditions. This paper presents the design and field validation of a solar-powered CNC-based autonomous seedling robot (ASR) for precision agriculture.

The proposed system integrates a three-axis CNC mechanism for accurate seedling placement, IoT-enabled monitoring for real-time operation, and sensor-based autonomous navigation to optimize field coverage. A photovoltaic power system enables fully off-grid operation, enhancing sustainability and reducing operational costs.

Field experiments conducted on various soil types demonstrate that the ASR reduces planting time by approximately 40% compared to manual transplanting while achieving a 95% planting accuracy. The solar-powered architecture enables continuous operation without external energy sources, resulting in zero operational energy cost during field trials.

The results confirm that the ASR effectively addresses key limitations of existing automated transplanting systems, particularly energy dependency and limited adaptability. Beyond technical performance, the proposed system supports sustainable agricultural development by utilizing renewable solar energy, reducing labor dependency, and minimizing environmental impact, offering a scalable solution for next-generation precision agriculture.

Keywords:

Autonomous seedling transplanting; CNC-based robotics; Solar-powered agricultural systems; IoT precision agriculture; Field robotic automation

Abbreviations:

AI – Artificial Intelligence
ASR – Autonomous Seedling Robot
CNC – Computer Numerical Control
DC – Direct Current
DoD – Depth of Discharge
FEA – Finite Element Analysis
GPS – Global Positioning System
IoT – Internet of Things
LIDAR – Light Detection and Ranging
MCU – Microcontroller Unit
MPPT – Maximum Power Point Tracking
PID – Proportional–Integral–Derivative
PV – Photovoltaic (Solar Energy System)
PWM – Pulse Width Modulation
ROS – Robot Operating System
SDGs – Sustainable Development Goals
WSN – Wireless Sensor Network

1. Introduction

Agriculture has been the backbone of human civilization for thousands of years, playing a crucial role in food security, economic development, and employment generation [1]. It contributes approximately 4% to global GDP and employs over 27% of the world's workforce [2]. However, with the world's population expected to reach 10 billion by 2050, food production must increase by at least 70% to meet growing demands [3].

Traditional farming methods rely heavily on manual labor, which is not only time-consuming and costly but also inefficient in large-scale agricultural operations. As a result, precision agriculture technologies have emerged as a solution to optimize farming processes, enhance productivity, and reduce resource waste [4],[5].

One of the major challenges in modern agriculture is the declining availability of skilled labor. Due to urbanization and industrialization, fewer people are willing to engage in physically demanding agricultural work [6]. Studies indicate that by 2030, the agricultural workforce will decline by 20-30% globally [7]. This shortage directly affects planting efficiency and crop yields, making it essential to develop automated solutions [8].

Manual planting methods often result in inconsistent seed spacing, inefficient fertilizer application, and excessive water consumption. According to the World Bank, up to 40% of water used in traditional farming is wasted due to inefficient irrigation systems [1]. In contrast, automated planting robots optimize resource utilization by precisely placing seedlings and applying the required amount of water and nutrients [9].

Traditional transplanting methods lead to inconsistent seedling depth and spacing, which negatively impacts crop growth and yield [10],[11]. Studies show that improper seedling placement can reduce yields by up to 25% [12]. Automated robots ensure uniform seedling placement, leading to higher crop consistency and improved productivity [13].

The following (Table 1) shows comparisons of the challenges of manual seedling Transplantation versus automated solutions

Table 1: Challenges of Manual Seedling Transplantation vs. Automated Solutions

Challenge	Manual Transplanting	Automated Transplanting
Labor Dependence	High	Low
Planting Accuracy	Low (60-70%)	High (90-95%)
Resource Utilization	Inefficient	Optimized
Scalability	Limited	High

With advancements in Industry 4.0, robotics has become a key enabler in modern agriculture [14]. Agricultural robots can perform planting, weeding, harvesting, and monitoring tasks autonomously, reducing dependency on manual labor and improving operational efficiency. Recent studies indicate that robotic automation in agriculture can increase crop productivity by 20–30% while reducing operational costs by up to 40%.

AI-powered algorithms and sensor-based monitoring systems allow real-time crop analysis and precision agriculture [13],[15]. By integrating machine learning models, robots can predict optimal planting patterns, monitor soil health, and adjust nutrient application dynamically [16],[17].

The integration of sensor-based monitoring systems and Internet of Things (IoT) technologies enables real-time data acquisition, remote supervision, and data-driven decision-making in precision agriculture. IoT-enabled platforms support continuous monitoring of soil and environmental conditions, allowing optimized irrigation, planting, and resource management strategies [18].

Over the past decade, robotics and automation have revolutionized agriculture, addressing labor shortages, improving efficiency, and increasing crop yields [19]. Studies show that integrating automated robots in farming can reduce operational costs by up to 40% while boosting productivity by 30% [4].

Agricultural robots are categorized into different types, including:

1) Autonomous tractors for large-scale farming [7].
2) Drone-based monitoring systems for real-time crop assessment [19].
3) Automated seedling transplanters for precision planting [20].

Seedling transplanting is a critical phase in crop cultivation that directly impacts crop uniformity and yield. Traditional manual transplanting is inefficient, leading to inconsistent spacing and improper root establishment [6].

Several automated solutions have been developed:

1) Yang et al. (2021) introduced a belt-driven robotic transplanter, improving seedling positioning accuracy by 25% [20].
2) Wen et al. (2021) designed a double-crank five-bar transplanter, achieving a planting rate of 90 seedlings per minute, demonstrating superior efficiency over manual methods [21].

A comparative summary of representative automated seedling transplanting systems, including their underlying technologies, planting performance, and energy sources, is presented in Table 2.

Table 2: Comparison of Automated Transplanting Systems

Study	Technology	Planting Rate	Energy Source
Yang et al. (2021)	Belt-driven transplanter	Medium	Electrical Grid
Wen et al. (2021)	Double-crank transplanter	High	Electrical Grid
This Research (ASR)	**CNC & IoT-based transplanter**	**High**	**Solar Energy**

Despite advancements, several limitations persist in existing robotic transplanting systems:

1) Limited adaptability to different soil types and planting conditions.
2) High power consumption, restricting long-term field deployment.
3) Lack of real-time monitoring, making it difficult to optimize planting decisions.

These challenges necessitate a more intelligent, adaptable, and energy-efficient solution, which the Autonomous Seedling Robot (ASR) aims to address.

The Internet of Things (IoT) has transformed precision agriculture by enabling real-time monitoring, remote control, and data analytics [22]. Smart farming systems equipped with wireless sensor networks (WSNs) provide insights into soil moisture, temperature, and plant health, helping farmers optimize resource allocation [23],[24],[25].

AI-driven models allow:

1) Predictive analytics for optimal planting conditions.
2) Automated decision-making based on sensor inputs.
3) Machine vision-based plant health assessment for early disease detection.

Selective Seedling Picking & Transplanting Robot (Visual-Perception–Driven System) developed a deep-learning-based perception system for seedling picking and transplanting. Field results showed:

~18.92% improvement in robustness and ~9.91% reduction in missing-planting events compared with conventional automated transplanting systems [26].

Jin et al. (2021) showed Potential analysis of an automatic transplanting method using computer vision and found 96.42% accuracy in detecting empty cells, 98.77% accuracy in identifying healthy seedlings, and 96.38% gripping success rate during the transplanting process. These high recognition and gripping accuracies demonstrate how AI significantly enhances the precision of the overall planting process [27].

A compact robot for seedling transplantation and achieved,[28]:

- 90–95% transplantation success rates for pepper and tomato seedlings.
- Significantly reduced failure and leakage rates compared to traditional automation.

Leafy Vegetable Seedling Detection Method used a computer-vision system for detecting lettuce seedlings and showed up to 100% detection accuracy for early-stage seedlings and the accuracy varies as leaf overlap increases [29].

Research Status and Development Trends of AI in Smart Agriculture showed a broad review summarizing many AI-in-agriculture studies. It highlights positioning accuracy up to 95.5%, also recognized improvements exceeding 98%, the review underscores that AI consistently improves various performance metrics—although exact percentages differ among studies [30].

Energy consumption is a major challenge in autonomous farming systems. Most robotic transplanters rely on grid electricity or fuel-based power, which increases operational costs and carbon footprint [8].

Solar-powered agricultural robots offer:

1) Sustainability by reducing reliance on fossil fuels [31].
2) Cost-effectiveness by eliminating electricity expenses [32].
3) Longer operational time without dependency on external charging stations [31].

A comparative overview of commonly used power sources for agricultural robots, in terms of efficiency, operational cost, and sustainability, is presented in Table 3.

Ghobadpour et. al. review the rise of green-energy-powered and autonomous agricultural robots, highlighting electrification, AI, and digital technologies as key drivers of sustainable and efficient Agriculture 5.0 [33].

Table 3: Comparison of Power Sources for Agricultural Robots

Power Source	Efficiency	Operational Cost	Sustainability
Grid Electricity	High	High	Low
Fuel-based	Medium	Very High	Low
Solar Energy	**High**	**Low**	**High**

To address these challenges, this research introduces the Autonomous Seedling Robot (ASR), a fully automated, solar-powered agricultural robot designed to optimize seedling transplantation efficiency. The ASR integrates:

1) Three-axis CNC-based seedling transmission for precise planting.
2) IoT-enabled remote monitoring and data collection.
3) Solar energy is a sustainable power source.

4) Sensor-based autonomous navigation for optimized field coverage.

Despite the significant progress in automated seedling transplanters, existing systems still suffer from three key limitations:
(1) dependency on grid or fossil-fuel energy,
(2) limited integration between mechanical precision and intelligent monitoring,
and (3) insufficient field-scale validation under varying soil conditions.
To the best of the authors' knowledge, no prior work has experimentally validated a fully solar-powered CNC-based autonomous seedling transplanting robot that combines high-precision mechanical planting with IoT-enabled monitoring under real agricultural field conditions.

Contributions of This Work

This study presents a fully integrated autonomous seedling transplanting platform validated through real-field experiments. The main contributions of this work are summarized as follows:

1) Design and implementation of a solar-powered CNC-based autonomous seedling transplanting robot, enabling fully off-grid agricultural operation.
2) Development of a high-precision three-axis CNC planting mechanism that ensures consistent planting depth and positioning under varying soil conditions.
3) Integration of an IoT-enabled monitoring and control framework for real-time system supervision and performance assessment.
4) Experimental field validation across multiple soil types, demonstrating a 40% reduction in planting time and 95% planting accuracy compared to manual transplanting.
5) Quantitative comparison with existing automated transplanting systems, highlighting the advantages of energy autonomy and CNC-based planting precision.

Beyond technical improvements, this work aims to support sustainable agricultural development by reducing energy consumption, minimizing reliance on conventional power sources, and improving resource efficiency through precision automation.

2. Methodology

This section describes the mechanical, electrical, and control design of the proposed Autonomous Seedling Robot (ASR). The system was developed to automate seedling transplantation through the integration of three main subsystems: a locomotion mechanism, a CNC-based seedling transmission mechanism, and an automated planting mechanism. These subsystems are supported by an electrical power unit, sensor-based control architecture, and IoT-enabled monitoring framework. (see Figure 1 for an illustration of robot parts).

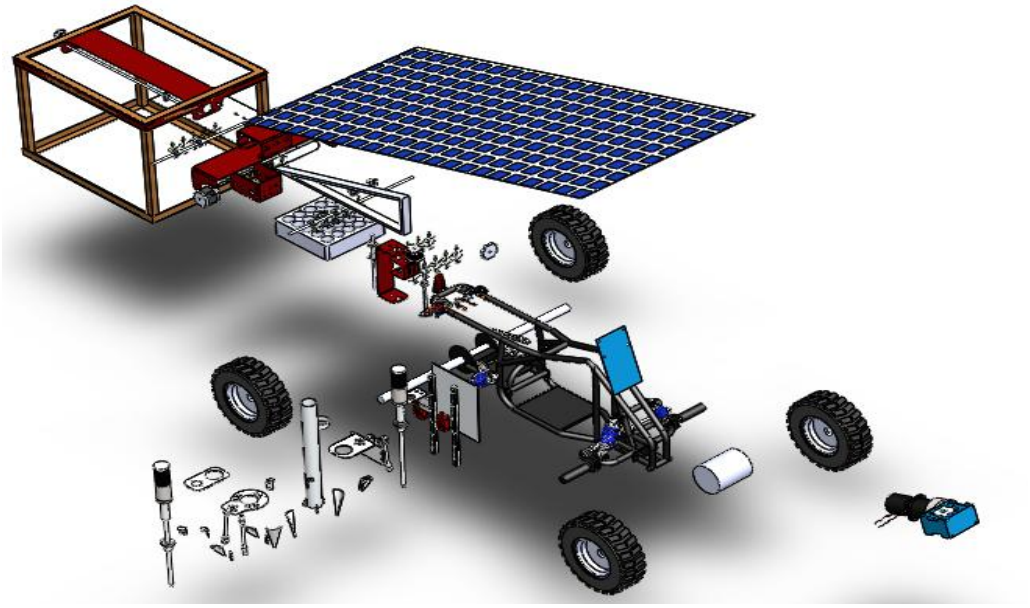


Figure 1: SolidWorks® Disassembly model of Proposed Autonomies seedling robot

2.1. Mechanical Design

2.1.1 Overall structure design

The Autonomous Seedling Robot (ASR) features a modular chassis made of lightweight aluminum alloy, ensuring high durability while maintaining low weight. The robot is designed to operate in various soil conditions, with an adjustable ground clearance mechanism to adapt to rough terrains.

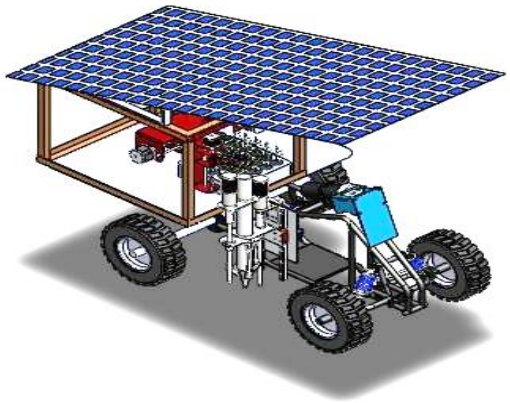


Figure 2: SolidWorks® Design of ASRobot

The autonomous seedling robot, as proposed, has been meticulously engineered with a specific focus: the execution of tasks that encompass the transportation, excavation, planting, and subsequent soil coverage of seedlings to promote their growth.

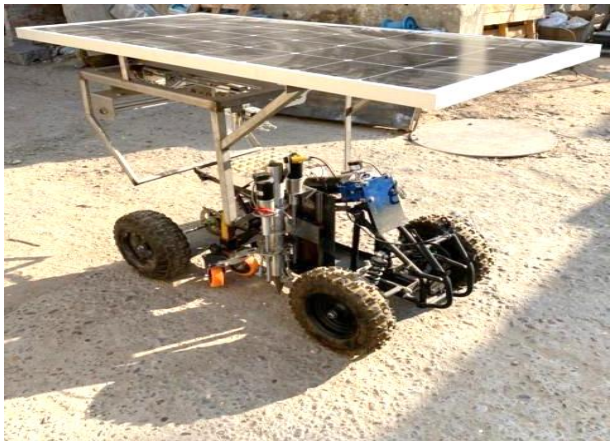


Figure 3: ASRobot Prototype

The mechanical design for each component of the robot has been rigorously executed using SolidWorks® simulation, aimed at achieving the optimal performance of the robotic system. The assemblage of the robot's components is presented in Figure 2, with detailed discussions on each part to be presented in subsequent sections.

Following the design of the robot's constituent parts, a series of performance tests were carried out through multiple simulation processes. Once assurance was gained regarding the model's efficacy, the components were fabricated, assembled, and subsequently subjected to comprehensive testing under standard

operational conditions, as depicted in Figure 3. Elaboration on the description of the proposed robot's components is provided in the ensuing sections, as shown in Figure 4.

2.1.2. Locomotion & Steering Mechanism

The ASR employs a four-wheel drive system, powered by two independent DC motors for differential steering. The front wheels incorporate a servo-based steering mechanism, ensuring precise navigation in the field.

Motors Used:

1) Two DC Motors (24V, 100W) for primary locomotion.
2) Stepper Motors (NEMA 23, 3.2V, 2.8A) for planting mechanism actuation.

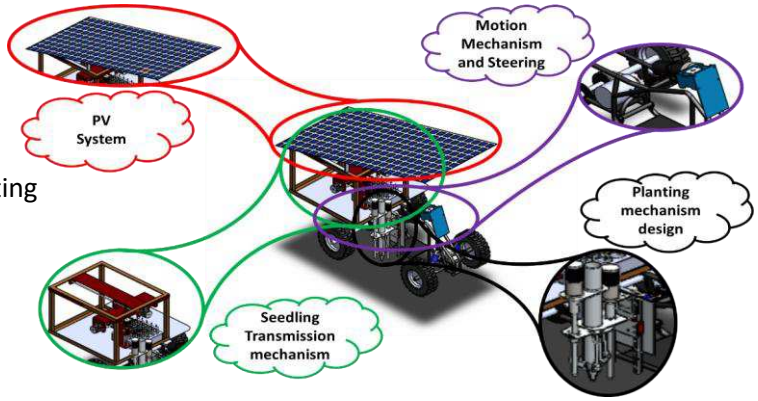


Figure 4: Detailed Mechanisms Drawings

The main motor specifications employed in the locomotion and CNC-based planting mechanisms of the ASR are summarized in Table 4.

Table 4: *Specifications of ASR Motors*

Motor Type	Voltage (V)	Torque (kg.cm)	Purpose
DC Motor	24V	15 kg.cm	Locomotion
Stepper Motor (NEMA 23)	3.2V	19 kg.cm	CNC Planting

This motion mechanism endows the agricultural robot with a high degree of precision, control, and maneuverability, enabling it to proficiently execute its designated tasks. Both motion motors are displayed in Figure 5.

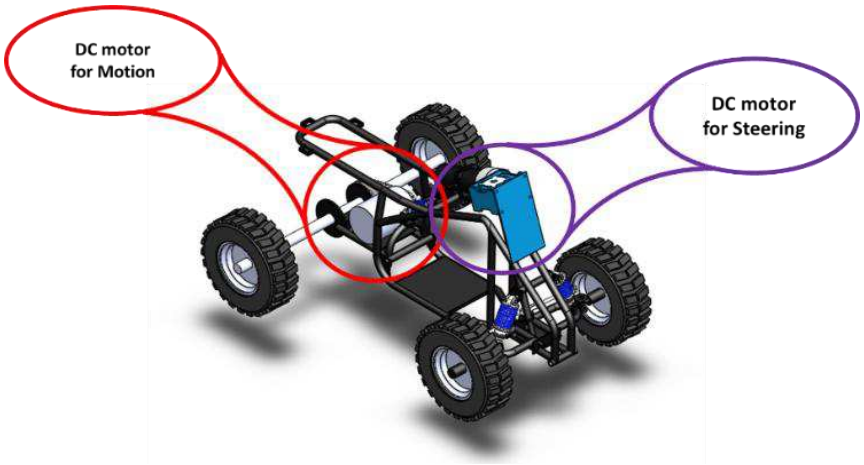


Figure 5: motion steering and forward DC motors

2.2. Seedling Transplantation System

2.2.1 Seedling Transmission Mechanism

The seedling transmission system utilizes a three-axis CNC mechanism, enabling high-precision movement of seedlings from the storage tray to the planting hole. The system operates via:

X-axis: Moves seedlings from the tray to the planting area.

Y-axis: Aligns the seedling with the planting position.

Z-axis: Inserts the seedling into the soil at the correct depth.

Seedling Transmission mechanism Components:

The envisaged robotic mechanism comprises four stepper motors, as visually depicted in Figure 6. In proximity to the seedling transmission mechanisms, there is a designated seedling container from which the seedlings are retrieved.

The motors within the Seedling Transmission mechanism are categorized into two distinct types. The first category encompasses three stepper motors, which are responsible for enabling X-Y-Z motion to maneuver the seedlings along three axes. In contrast, the second type features a fourth motor, intricately connected to a gripper mechanism designed for the precise picking and placing of seedlings.

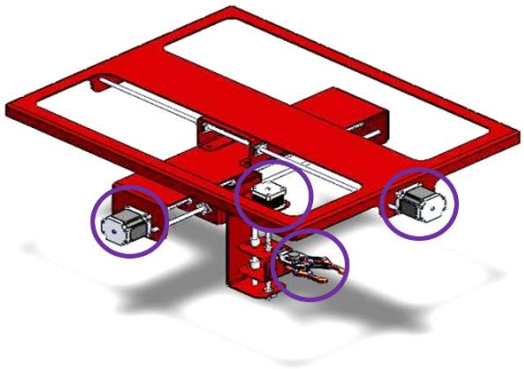


Figure 6: Transmission Mechanism

2.2.2 Planting Mechanism

The planting mechanism consists of a servo-controlled drill unit, which creates a planting hole, followed by a pneumatic gripper that securely holds the seedling and inserts it into the soil.

A quantitative comparison between manual planting and the proposed automated planting mechanism, in terms of operational time and planting accuracy, is presented in Table 5.

Table 5: *Performance Metrics of the Planting System*

Parameter	Manual Planting	ASR Automated Planting
Time per Seedling	10 sec	4 sec
Accuracy (%)	60%	95%

The proposed robot features an innovative automated planting mechanism that has superseded the previous manual process, resulting in a significant enhancement of operational efficiency. The Planting mechanism encompasses two distinct operations: soil drilling and seedling insertion.

Various forms of planting mechanism cones and head shapes are available, including rectangular, circular, and slender wheel configurations.

Conventional manual planting mechanisms typically rely on spring-loaded cone structures operated by human force, which often result in inconsistent planting depth and spacing, as illustrated in Figure 7. In the proposed system, this manual process was transformed into an automated planting mechanism through the integration of DC motors, encoders, and sensor feedback, enabling precise soil drilling and controlled seedling insertion.



Figure 7: Manual drilling mechanism

Thus, by applying contemporary engineering principles to the conventional manual drilling mechanism, the implemented design has effectively realized this transformation. It has converted the manual planting mechanism into an automated drilling and planting system through the integration of a carefully orchestrated system featuring two DC motors, encoders, and sensors.

The depicted planting mechanism, as presented in Figure 8, comprises two DC motors, each with its specific role. One of these motors facilitates the elevation and descent of the mechanism, while the other governs the opening and closing of the planting cone.

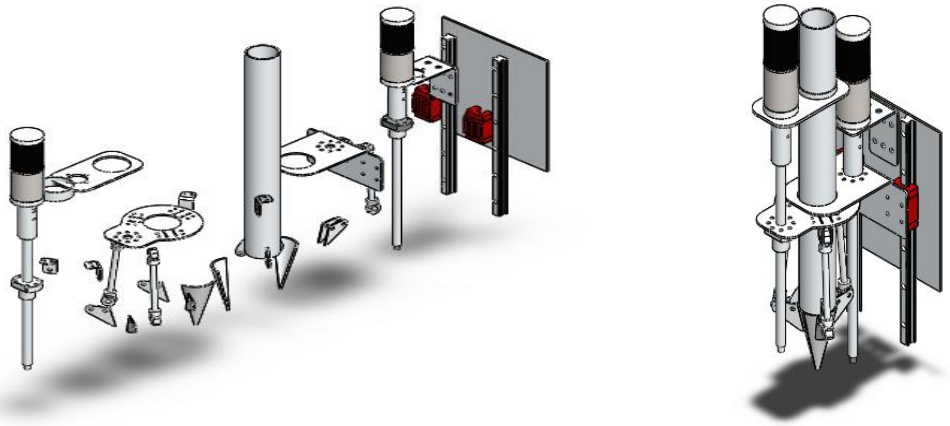


Figure 8: Planting Mechanism Design: a) planting mechanism disassemble b) planting mechanism assemble

The main electromechanical components used in the assembly of the Autonomous Seedling Robot (ASR) are summarized in Table 6.

Table 6: *Components Used in ASR Assembly*

Component	Specification	Function
CNC Mechanism	3-Axis System	Seedling Transport
DC Motors	24V, 100W	Locomotion
Stepper Motors	NEMA 23	CNC Actuation

2.3 Electrical & Control System

2.3.1 Power Supply Architecture

- The ASR is powered by a photovoltaic energy system designed for fully off-grid agricultural operation. A 150 W monocrystalline solar panel is used to supply system loads and charge a 24 V lithium-ion battery pack (30 Ah) through an MPPT-based charge controller rated at 30 A.
- Lithium-ion batteries were selected due to their high energy density, reduced weight, and improved depth-of-discharge characteristics compared to conventional lead-acid batteries, making them more suitable for mobile robotic applications.
- Although the total connected electrical load reaches 568 W, the system components do not operate simultaneously. Based on duty-cycle analysis and experimental operation, the effective power consumption during planting operations was approximately 300 W, allowing stable autonomous operation under typical field conditions.
- The actual power consumption of the robot was experimentally evaluated using an inline power meter during field operation. The results confirmed an operational duration of approximately 3–4 hours under real field conditions with solar power assistance, enabling off-grid operation with zero reliance on external energy sources during the experimental trials.
- System Integration：After completing the design and optimization of the electronic circuits, all components were integrated into a single final schematic diagram. Figure 9 presents the complete electrical schematic of the ASR, including the control unit, motor drive units, sensor modules, and power supply components. The schematic was designed to ensure electrical compatibility among all subsystems and to minimize potential electrical interference.

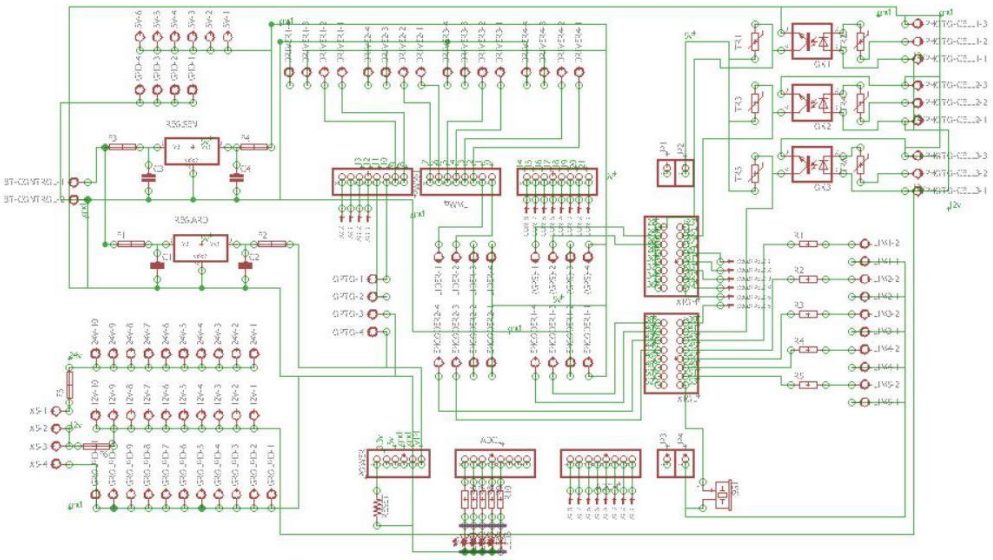


Figure 9: Final schematic of the proposed system

2.3.2 Sensors & Feedback Control

The ASR is equipped with a multi-sensor feedback system, including:

1) Lidar Sensor: For obstacle detection and navigation.
2) Ultrasonic Sensors: To measure planting depth.
3) Limit Switches: For CNC motion control.
4) Humidity & Temperature Sensors: For environmental monitoring.

The main sensors integrated into the ASR for navigation, planting depth control, and environmental monitoring are summarized in Table 7.

Table 7: *Sensors Used in ASR*

Sensor Type	Function
Lidar	Obstacle Detection
Ultrasonic Sensor	Planting Depth Control
Temperature Sensor	Climate Monitoring

- **Manual Control Stage**

the robot operates in **manual open-loop mode** using a joystick, without any sensor feedback. The microcontroller receives control signals from the joystick through the driver and executes predefined motion and manipulation commands as shown in figure 10.

Basic movement commands are defined as follows: The **Up**, **Down**, **Right**, and **Left** buttons control forward motion, backward motion, and right and left turning, respectively. Combined button commands are used to control the gripper and planting mechanisms. These commands allow the gripper to move toward the seedling disk, grasp and lift the seedling, transfer it to the planting mechanism, release it, and finally perform the planting action in the soil before returning to the initial position.

This stage is mainly intended for system testing, calibration, and manual operation prior to implementing sensor-based or autonomous control modes.

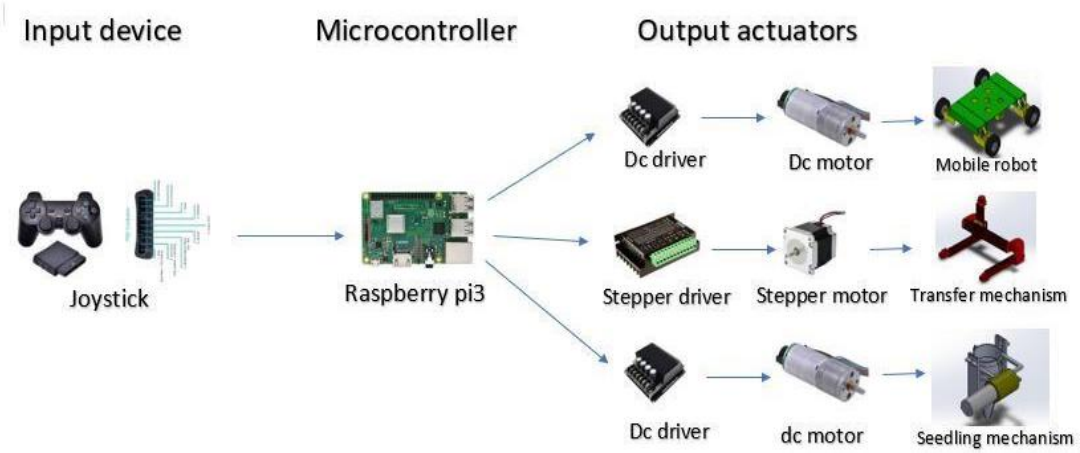


Figure 10: Manual Control

- **Autonomous Control Phase**

The robot performs the complete task **autonomously** using sensor feedback. A single start command is sent to the microcontroller via a joystick, mobile phone, or PC through a cloud-based IoT system, as shown in figure 11.

Upon receiving the command, the robot moves forward for a fixed distance of **30 cm** using encoder feedback, then stops. The camera mounted on the seedling transfer mechanism detects the presence of seedlings. Once a seedling is detected, the gripper moves downward to grasp it, then lifts and transfers it forward to the planting mechanism. The seedling is then released into the planting mechanism, which lowers it into the soil to complete the planting process. Afterward, the planting mechanism returns to its initial position, the gripper resets to its starting position, and the cycle is repeated.

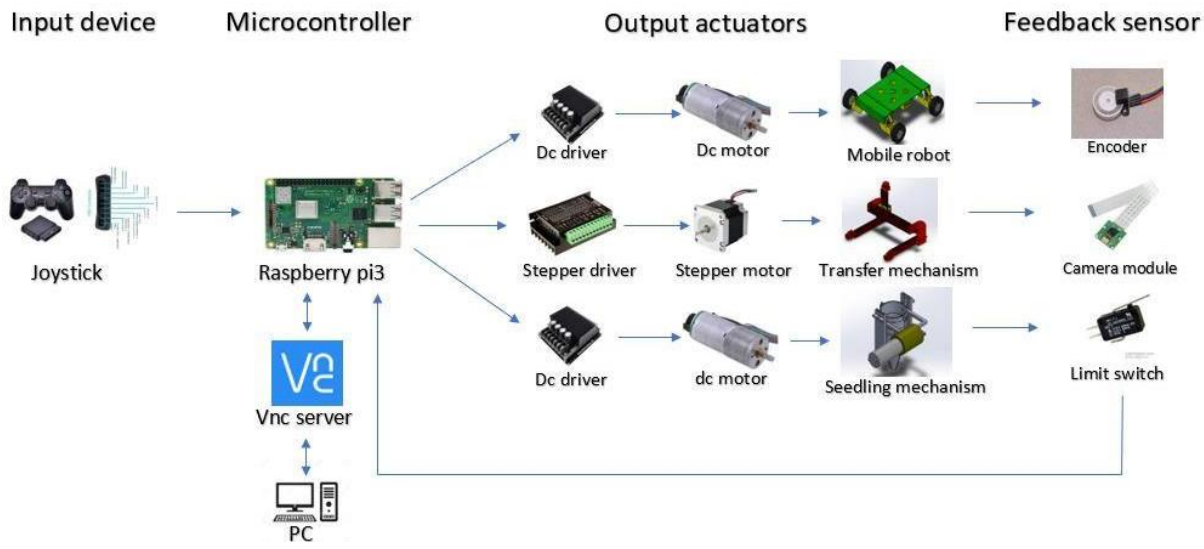


Figure 11: Semi-automatic control with IoT

2.3.3 Microcontrollers & IoT Integration

The ASR utilizes two microcontrollers to manage system operation and communication. A Raspberry Pi 3 Model B is employed for high-level task coordination, data handling, and IoT-based communication, while an Arduino Mega 2560 is responsible for low-level motor control and real-time sensor feedback processing.

2.3.4 Software & IoT Integration

The ASR software architecture was developed to support sensor-based control, data communication, and real-time monitoring. The software framework is implemented using:

1) Python & C++ for embedded programming.
2) MQTT Protocol for cloud-based communication.
3) Blynk & ThingSpeak for real-time IoT monitoring.

Unity-Based Simulation

Unity Simulation is a cloud-based platform that enables efficient execution of parameterized simulation scenarios for engineering applications. By creating virtual representations of real-world environments and running simulations faster than real time, it supports rapid performance evaluation and system analysis.

In this project, Unity was used to develop a virtual simulation of the Autonomous Seedling Robot to monitor its motion and performance in real time without physical presence at the operation site. This enables assessment of planting efficiency and verification of correct seedling handling.

The simulation was developed through three main stages: the robot was first modeled in **SolidWorks**, then exported in **STL format** to **Blender** for processing, and finally converted to **FBX format** and integrated into **Unity3D,** figure 12.

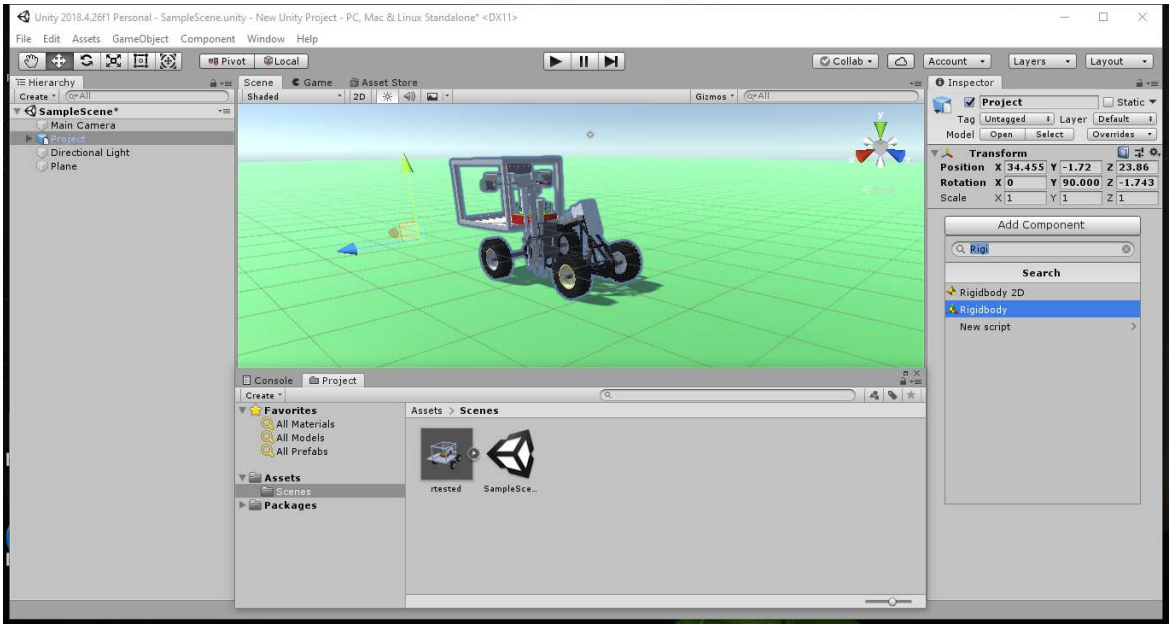


Figure 12: Simulation using Unity

2.4. System Control and Data Flow Architecture

The control and data flow architecture of the solar-powered, IoT-enabled Autonomous Seedling Robot (ASR) is designed to ensure reliable data transmission, precise system control, and efficient field operation. Sensor data collected from the robot—such as environmental parameters and positional feedback—is transmitted to a database for structured storage and processing.

The stored data is then communicated through an IoT server platform (e.g., ThingSpeak or Cayenne), allowing access to a client-side dashboard for real-time system monitoring, manual actuation commands, and performance evaluation. This architecture enables continuous supervision of the planting process and supports rule-based operational control, improving planting accuracy and overall system efficiency. Figure **13** illustrates the adopted system data flow and control architecture.

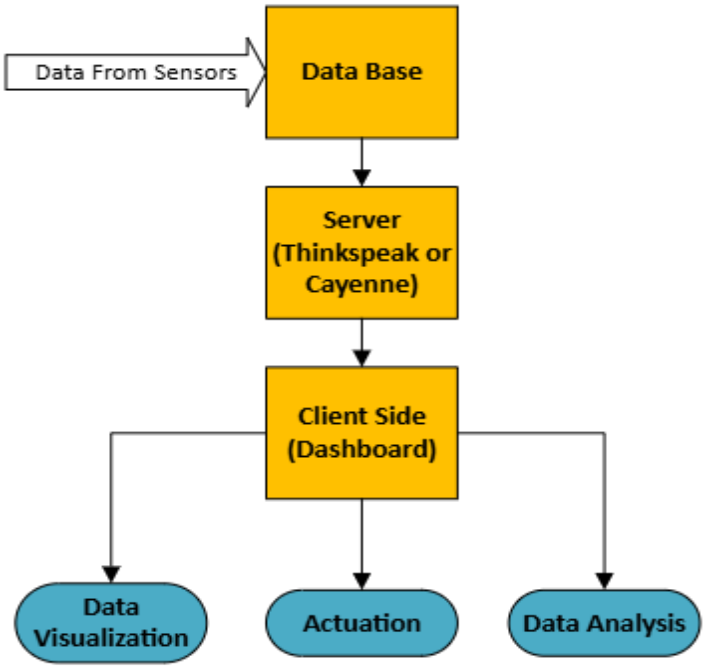


Figure 13: Flow of Data

3. Results and Discussion

Each experimental scenario was repeated multiple times under identical field conditions to ensure the consistency and reliability of the obtained results. The reported planting accuracy, operational time, and soil performance metrics represent average values obtained from repeated field trials, with observed variations remaining within acceptable operational limits for agricultural field robotics.

3.1. Performance Analysis Compared to Manual Transplanting

The experimental results demonstrate that the proposed Autonomous Seedling Robot (ASR) significantly outperforms conventional manual transplanting methods in terms of planting speed, accuracy, and labor efficiency. As summarized in Table 8, the ASR reduced the time required to transplant 100 seedlings from 50 minutes to 30 minutes, corresponding to an improvement of approximately 40%, while achieving a planting accuracy of 95% compared to 60% for manual transplanting.

This performance improvement can be attributed to the precise motion control provided by the CNC-based planting mechanism, which ensures consistent planting depth and spacing while minimizing human-induced variability commonly observed during manual operations. In addition to speed and accuracy improvements, the ASR substantially reduces labor dependency, enabling a more efficient planting process with minimal human intervention.

Table 8: *ASR vs. Manual Planting Performance*

Metric	Manual Transplanting	ASR Automated Transplanting	Improvement
Time per 100 seedlings	50 min	30 min	40% faster

Accuracy (%)	60%	95%	35% improvement
Labor Dependency	High	Low	80% reduction

3.2. Energy Performance Evaluation

Energy performance represents a key advantage of the proposed ASR system. Unlike conventional transplanting methods that rely on grid electricity, fuel-based machinery, or intensive human labor, the ASR operates using an integrated solar-powered energy system that enables fully off-grid agricultural operation.

Field experiments confirmed that the ASR was capable of continuous operation without external energy sources, resulting in zero operational energy cost during the conducted trials. This energy autonomy significantly reduces long-term operational expenses and contributes to environmentally sustainable agricultural practices by minimizing greenhouse gas emissions associated with fossil fuel consumption.

Table 9 summarizes the comparative energy cost between manual planting, fuel-based agricultural machinery, and the proposed ASR system.

Table 9: *Energy Consumption of ASR vs. Traditional Machines*

System	Power Source	Energy Cost (per hour)
Manual Planting	Human Labor	High
Fuel-Based Machines	Diesel	$2.5/hr
ASR (This Study)	**Solar Energy**	**$0/hr**

3.3. Soil Adaptability and Environmental Performance

To evaluate system adaptability under varying field conditions, the ASR was tested across three different soil types: sandy, loamy, and clayey soils. The experimental results indicate that the ASR maintained consistent planting depth and seedling positioning accuracy across all tested soil conditions.

As presented in Table 10, the planting depth variation achieved by the ASR remained within ±2–4 mm across different soil types, whereas manual transplanting exhibited significantly higher variability, reaching up to ±12 mm in clayey soils. This enhanced consistency is primarily attributed to the controlled vertical motion of the CNC-based planting mechanism, which compensates for soil resistance and surface irregularities during planting operations.

Improved planting consistency directly contributes to better crop uniformity during early growth stages, which is a critical factor for achieving higher yields and efficient resource utilization.

Table 10: *Soil Adaptability Performance*

Soil Type	Manual Planting Variance (Depth ± mm)	ASR Variance (Depth ± mm)	Improvement
Sandy Soil	±10 mm	±3 mm	**70% more consistent**
Loamy Soil	±8 mm	±2 mm	**75% more consistent**
Clayey Soil	±12 mm	±4 mm	**66% more consistent**

3.4. Comparison with Existing Automated Transplanting Systems

To further validate the effectiveness of the proposed ASR, its performance was compared with previously reported automated transplanting systems from the literature. Table 11 presents a

comparative summary of selected studies focusing on planting accuracy, technology type, and energy source.

Compared to belt-driven and mechanically actuated transplanting systems, the proposed ASR demonstrates higher planting accuracy while offering the additional advantage of solar-powered operation. This combination of CNC-based precision and renewable energy utilization distinguishes the ASR from existing solutions and highlights its suitability for sustainable and large-scale agricultural deployment.

Table 11: *ASR vs. Other Automated Transplanters*

Study	Technology	Planting Rate	Power Source	Accuracy (%)
Yang et al. (2021)[34]	Belt-driven transplanter	Medium	Electrical Grid	80%
Wen et al. (2021) [21]	Double-crank transplanter	High	Electrical Grid	85%
This Research (ASR)	CNC & IoT-based transplanter	High	Solar Energy	95%

3.5. Technical Challenges and System Refinements

During the development and testing phases, several technical challenges were encountered. Initial CNC alignment issues resulted in minor seedling placement inaccuracies, while prolonged operation led to motor overheating under continuous load conditions. In addition, intermittent connectivity was observed in the IoT-based monitoring system when operating in remote agricultural environments.

These challenges were systematically addressed through CNC recalibration procedures, the integration of additional heat dissipation mechanisms, and the evaluation of improved communication protocols. The implemented refinements contributed to the stable and reliable system performance observed during the final field trials summarized in the previous sections.

3.6. Implications for Sustainable Agriculture

Beyond the immediate performance improvements, the proposed ASR demonstrates strong potential for contributing to sustainable agricultural development. By integrating sensor-based automation, IoT-enabled monitoring, and solar-powered energy systems, the ASR reduces carbon emissions, minimizes resource wastage, and lowers labor dependency in farming operations.

The system aligns with key sustainable development objectives by enhancing agricultural productivity, promoting clean energy utilization, and advancing smart farming infrastructure. These characteristics position the ASR as a scalable and environmentally responsible solution for next-generation precision agriculture applications.

Table 12 summarizes the alignment of the proposed ASR with selected Sustainable Development Goals (SDGs).

Table 12: *Alignment of ASR with Sustainable Development Goals (SDGs)*

Sustainable Goal	ASR Contribution
Zero Hunger	Improves agricultural productivity
Affordable & Clean Energy	Uses solar power for zero energy cost
Industry, Innovation & Infrastructure	Advances smart farming technology

4. Conclusion & Recommendations

The Autonomous Seedling Robot (ASR) offers a scalable and fully autonomous solution for precision farming, capable of enhancing planting efficiency and accuracy. By integrating sensor-based automation and IoT-enabled monitoring, the system achieves reliable and consistent field operation under varying agricultural conditions. Furthermore, the adoption of solar-powered operation contributes to significant reductions in long-term operational costs while minimizing environmental impact, supporting sustainable and eco-friendly agricultural practices.

5. Future Recommendations

Future developments for the Autonomous Seedling Robot (ASR) may focus on enhancing system capabilities and operational versatility. The integration of computer vision and artificial intelligence techniques for seedling quality assessment prior to planting could further improve crop performance. Expanding the robot's operational capacity to support multi-species cultivation would increase its applicability across diverse agricultural environments. Additionally, the application of artificial intelligence for agricultural data analysis may enhance decision-support functions and overall system efficiency.

Declarations:

Funding: This research was funded by Heliopolis University (Abouleish Award), But No funding was received to support publishing this study.

Clinical Trial Registration: Not applicable.

Ethics Approval: Not applicable. This study does not involve human participants, animals, or identifiable or sensitive data.

Consent to Participate: Not applicable.

Consent to Publish: Not applicable.

Conflicts of Interest: There are no conflicts to declare.

Author Contributions:

Ghada A. Elgamal: Project supervision and oversight of project implementation; conceptualization; writing the original draft of the manuscript; and manuscript review and editing.

Omar A. Hashem: Experimental and hands-on work on the developed device; contribution to manuscript writing and preparation; assistance in structuring the manuscript; and support during the editing process.

Nerveen Ehab: Experimental and hands-on work on the developed device.

Abdel Halim M. Bassiuny: Project supervision and guidance during implementation; technical review and validation of the work; and manuscript review.

Data Availability Statement: All data generated or analysed during this study are included in this published article.

Acknowledgments

The authors acknowledge the support of Heliopolis University for Sustainable Development. The Abouleish Award is gratefully acknowledged for supporting the establishment of the experimental setup used in this research. The authors confirm that no external funding was received for the publication of this manuscript, and the award did not influence the study design, data analysis, interpretation of results, or the decision to publish.

References

[1] Food and Agriculture Organization of the United and (FAO), "The future of food and agriculture: trends and challenges," *Futur. food Agric. trends challenges*, vol. 4, no. 4, pp. 1951–1960, 2014, [Online]. Available: www.fao.org/publications%0Ahttp://www.fao.org/3/a-i6583e.pdf%0Ahttp://siteresources.worldbank.org/INTARD/825826-1111044795683/20424536/Ag_ed_Africa.pdf%0Awww.fao.org/cfs%0Ahttp://www.jstor.org/stable/4356839%0Ahttps://ediss.uni-goettingen.de/bitstream/han

[2] H. N. Azmi, S. S. H. Hajjaj, K. R. Gsangaya, M. T. H. Sultan, M. F. Mail, and L. S. Hua, "Design and fabrication of an agricultural robot for crop seeding," *Mater. Today Proc.*, vol. 81, no. 2, pp. 283–289, 2021, doi: 10.1016/j.matpr.2021.03.191.

[3] D. F. Yépez-Ponce, J. V. Salcedo, P. D. Rosero-Montalvo, and J. Sanchis, "Mobile robotics in smart farming: current trends and applications," *Front. Artif. Intell.*, vol. 6, no. 2018, 2023, doi: 10.3389/frai.2023.1213330.

[4] G. G. R. d. Castro *et al.*, "Adaptive Path Planning for Fusing Rapidly Exploring Random Trees and Deep Reinforcement Learning in an Agriculture Dynamic Environment UAVs," *Agric.*, vol. 13, no. 2, 2023, doi: 10.3390/agriculture13020354.

[5] S. A. Bhat, I. Hussain, and N. F. Huang, "Soil suitability classification for crop selection in precision agriculture using GBRT-based hybrid DNN surrogate models," *Ecol. Inform.*, vol. 75, no. September 2022, p. 102109, 2023, doi: 10.1016/j.ecoinf.2023.102109.

[6] A. Khadatkar, C. P. Sawant, A. P. Magar, and V. Kumar, "Agricultural robots and automated machinery for handling of nursery seedlings with special reference to the transplanting devices," *Discov. Appl. Sci.*, vol. 7, no. 8, 2025, doi: 10.1007/s42452-025-06736-5.

[7] M. Fontani *et al.*, "A Systematic Review of 59 Field Robots for Agricultural Tasks: Applications, Trends, and Future Directions," *Agronomy*, vol. 15, no. 9, pp. 1–30, 2025, doi: 10.3390/agronomy15092185.

[8] C. Lytridis and T. Pachidis, "Recent Advances in Agricultural Robots for Automated Weeding," *AgriEngineering*, vol. 6, no. 3, pp. 3279–3296, 2024, doi: 10.3390/agriengineering6030187.

[9] C. Han, X. Hu, J. Zhang, J. You, and H. Li, "Design and testing of the mechanical picking function of a high-speed seedling auto-transplanter," *Artif. Intell. Agric.*, vol. 5, pp. 64–71, 2021, doi: 10.1016/j.aiia.2021.02.002.

[10] Q. Yang, X. Du, Z. Wang, Z. Meng, Z. Ma, and Q. Zhang, "A review of core agricultural robot technologies for crop productions," *Comput. Electron. Agric.*, vol. 206, no. December 2022, p. 107701, 2023, doi: 10.1016/j.compag.2023.107701.

[11] A. Sharma and S. Khar, "Design and development of a vegetable plug seedling transplanting mechanism for a semi-automatic transplanter," *Sci. Hortic. (Amsterdam).*, vol. 326, no. December 2023, p. 112773, 2024, doi: 10.1016/j.scienta.2023.112773.

[12] V. Paradkar, H. Raheman, and K. Rahul, "Development of a metering mechanism with serial robotic arm for handling paper pot seedlings in a vegetable transplanter," *Artif. Intell. Agric.*, vol. 5, pp. 52–63, 2021, doi: 10.1016/j.aiia.2021.02.001.

[13] M. Wakchaure, B. K. Patle, and A. K. Mahindrakar, "Application of AI techniques and robotics in agriculture: A review," *Artif. Intell. Life Sci.*, vol. 3, no. November 2022, p. 100057, 2023, doi: 10.1016/j.ailsci.2023.100057.

[14] L. R. R. da Silva, D. Y. Pimenov, R. B. da Silva, A. Ercetin, and K. Giasin, "Review of Applications of Digital Twins and Industry 4.0 for Machining," *J. Manuf. Mater. Process.*, vol. 9, no. 7, pp. 1–29, 2025, doi: 10.3390/jmmp9070211.

[15] G. A. Z. Elgamal and A. M. Gomaa, "AI and Smart Water Treatment: A Bibliometric Perspective on Emerging Technologies in Water Purification," *Adv. Sci. Technol. J.*, vol. 0, no. 0, pp. 0–0, 2025, doi: 10.21608/astj.2025.371920.1055.

[16] T. Adamo, D. Caivano, L. Colizzi, G. Dimauro, and E. Guerriero, “Optimization of irrigation and fertigation in smart agriculture: An IoT-based micro-services framework,” *Smart Agric. Technol.*, vol. 11, no. September 2024, p. 100885, 2025, doi: 10.1016/j.atech.2025.100885.

[17] C. L. Nkwocha *et al.*, “A Comprehensive Review of Sensing, Control, and Networking in Agricultural Robots: From Perception to Coordination,” *Robotics*, vol. 14, no. 11, pp. 1–67, 2025, doi: 10.3390/robotics14110159.

[18] A. L. Duguma and X. Bai, “How the internet of things technology improves agricultural efficiency,” *Artif. Intell. Rev.*, vol. 58, no. 2, pp. 1–26, 2025, doi: 10.1007/s10462-024-11046-0.

[19] A. Bin Rashid, A. K. Kausik, A. Khandoker, and S. N. Siddque, “Integration of Artificial Intelligence and IoT with UAVs for Precision Agriculture,” *Hybrid Adv.*, vol. 10, no. March, p. 100458, 2025, doi: 10.1016/j.hybadv.2025.100458.

[20] Q. Yang, I. Ahmad, M. Faheem, B. Siddique, H. Xu, and M. Addy, “Development and assessment of belt-drive seedlings transmission device for fully-automatic vegetable transplanter,” *Comput. Electron. Agric.*, vol. 182, no. September 2020, 2021, doi: 10.1016/j.compag.2020.105958.

[21] Y. Wen *et al.*, “Design of a traction double-row fully automatic transplanter for vegetable plug seedlings,” *Comput. Electron. Agric.*, vol. 182, no. February, p. 106017, 2021, doi: 10.1016/j.compag.2021.106017.

[22] A. Bin Rashid, A. K. Kausik, A. Khandoker, and S. N. Siddque, “Integration of Artificial Intelligence and IoT with UAVs for Precision Agriculture,” *Hybrid Adv.*, vol. 10, no. January, p. 100458, 2025, doi: 10.1016/j.hybadv.2025.100458.

[23] A. Khadatkar *et al.*, “Cable-driven agribot prototype: Enabling precision agriculture through innovative design,” *Mater. Today Proc.*, vol. 13, no. 1, p. 108938, 2025, doi: 10.1016/j.compag.2024.108938.

[24] H. Kabir *et al.*, “Fabrication of a spider-legged agricultural spraying and grass cutting robot using Klann-mechanism with green energy-based obstacle detection,” *Mater. Today Proc.*, vol. 258, no. August, pp. 819–832, 2025, doi: 10.47857/irjms.2025.v06i01.02736.

[25] N. P. More, V. Venkataramanan, M. O. Kumar, M. S. Padaya, and F. Solanki, “IoT-Based Precision Farming Robot for Agricultural Automation,” *Int. Res. J. Multidiscip. Scope*, vol. 6, no. 1, pp. 819–832, 2025, doi: 10.47857/irjms.2025.v06i01.02736.

[26] M. Li *et al.*, “Visual perception enabled agriculture intelligence: A selective seedling picking transplanting robot,” *Comput. Electron. Agric.*, vol. 229, no. November 2024, p. 109821, 2025, doi: 10.1016/j.compag.2024.109821.

[27] X. Jin, L. Tang, J. Ji, C. Wang, and S. Wang, “Potential analysis of an automatic transplanting method for healthy potted seedlings using computer vision,” *Int. J. Agric. Biol. Eng.*, vol. 14, no. 6, pp. 162–168, 2021, doi: 10.25165/J.IJABE.20211406.6638.

[28] A. Khadatkar, A. P. Pandirwar, and V. Paradkar, “Design, development and application of a compact robotic transplanter with automatic seedling picking mechanism for plug-type seedlings,” *Sci. Rep.*, vol. 13, no. 1, pp. 1–12, 2023, doi: 10.1038/s41598-023-28760-4.

[29] W. Fu, J. Gao, C. Zhao, K. Jiang, W. Zheng, and Y. Tian, “Detection Method and Experimental Research of Leafy Vegetable Seedlings Transplanting Based on a Machine Vision,” *Agronomy*, vol. 12, no. 11, 2022, doi: 10.3390/agronomy12112899.

[30] C. Ge, G. Zhang, Y. Wang, D. Shao, X. Song, and Z. Wang, “Research Status and Development Trends of Artificial Intelligence in Smart Agriculture,” *Agric.*, vol. 15, no. 21, pp. 1–41, 2025, doi: 10.3390/agriculture15212247.

[31] E. M. Barhoumi, P. C. Okonkwo, I. Ben Belgacem, M. Zghaibeh, and I. Tlili, “Optimal sizing of photovoltaic systems based green hydrogen refueling stations case study Oman,” *Int. J. Hydrogen Energy*, vol. 47, no. 75, pp. 31964–31973, 2022, doi: 10.1016/j.ijhydene.2022.07.140.

[32] Y. B. Muna and C. C. Kuo, “Feasibility and Techno-Economic Analysis of Electric Vehicle Charging of PV/Wind/Diesel/Battery Hybrid Energy System with Different Battery Technology,” *Energies*, vol. 15, no. 12, 2022, doi: 10.3390/en15124364.

[33] A. Ghobadpour, G. Monsalve, A. Cardenas, and H. Mousazadeh, “Off-Road Electric Vehicles and Autonomous Robots in Agricultural Sector: Trends, Challenges, and Opportunities,” *Vehicles*, vol. 4, no. 3, pp. 843–864, 2022, doi: 10.3390/vehicles4030047.

[34] T. Liu *et al.*, “Unmanned aerial vehicle and artificial intelligence revolutionizing efficient and precision sustainable forest management,” *J. Clean. Prod.*, vol. 311, no. April, p. 127546, 2021, doi: 10.1016/j.jclepro.2021.127546.