Youth Innovation Journal
YIJ–2025–0002F

YIJ
YOUTH INNOVATION JOURNAL

An Efficient Micro-Agriculture System for Cruciferous Crops Promoting Polyculture

*Authors contributed equally

Nithin Aruswamy[1*]
Nilasha Naveen[2*]
Nirupa Rao[1*]
Krishna Eduri[1*]
Anusha Sundar[3*]
Shlok Powar[2*]
Sayansh Gupta[4*]
Hari Kathrani[4*]

Joshua Amaladass[5]
Alex Colin[5]

[1]Dublin High School
Dublin, California

[2]Washington High School
Fremont, California

[3]Amador Valley High School
Pleasanton, California

[4]California High School
San Ramon, California

[5]Dublin Robotics
Dublin, California

Received: 08/20/25
Accepted: 09/15/25
Published: 10/29/25
Corresponding:
innovation@robolabs.org

Abstract— **This paper introduces SHIELD (Sustainable Harvesting and Integrated Efficient Land Defense), a solution designed to address inefficiencies, labor shortages, environmental degradation, and safety hazards inherent in traditional agriculture. This invention aims to automate the agricultural cycle for cruciferous and other nutrient-rich crops, significantly enhancing sustainability, productivity, and overall efficiency. It consists of a main vehicle equipped with advanced robotics systems, LiDAR, multispectral cameras, and electrochemical sensors, in addition to modular attachments specifically designed for planting, irrigation, pest control, and harvesting. SHIELD operates through precise navigation and real-time data analytics, utilizing AI-driven sensors and robotics to optimize farming tasks. Its unique approach integrates autonomous planting systems, targeted laser weed control, and precision harvesting methods in order to minimize chemical usage and improve overall yield and crop quality. The broader impact of SHIELD extends to environmental preservation, economic resilience, and public health. Its closed-loop resource management reduces soil degradation and chemical runoff, preserving ecosystems and decreasing greenhouse gas emissions compared to conventional farming.**

Keywords: Agtech, Nutrient-Dense Crops, Sustainable Agriculture, Precision Fertilization, Laser Weed Control, Autonomous Farming Systems.

I. Introduction

Agriculture, a vital element of human survival, has remained one of the least automated industries despite playing a tremendous role in global food security. In 2022, less than 5% of farmers worldwide were using applied automation strategies (Bland et al., 2023). Historically, agriculture has transitioned from a labor-intensive activity to one that is executed by fewer workers. In the US, the number of active farms declined by 4.7% between 2011 and 2018, further demonstrating the significant shifts in the industry (Spangler et al., 2020). While these automations have transformed industries like manufacturing and healthcare, agriculture continues to rely heavily on manual execution, leading to limited scalability and efficiency.

The labor force of the agricultural sector has seen a significant shortage due to the innate intensive physical demand, hazardous work conditions, and wages well below the median. Workers often face severe risk, such as injuries from heavy equipment, handling chemicals, and health problems linked to pesticide exposure (De-Assis et al., 2021). These common yet imposing challenges accompanying the already low wages found in agricultural work, have been the lead causes of labor shortages found in the industry. Automation offers an ideal solution to the challenges in agricultural work by both greatly reducing workplace hazards and alleviating workforce shortages (Hayden et al. 2022). As technology advances and cohesively integrates into the agricultural sector automation will increase efficiency, provide a safer work environment, and simulate aggregate output.

Current industrial farm models heavily utilize large machinery to maximize their production output. Consequently, reliance on large machinery diminishes efficiency with concerns to resource consumption, precision, and ultimately sustainability. Although the current technologies employed in the agricultural field have led to a substantial increase in global food production, they do so by exhausting natural resources and significantly contributing to both pollution and environmental degradation. For instance, agricultural tractors in the U.S. emit 33 million metric tons of carbon each year (EPA, 2025). Additionally, large scale harvesting and heavy tillage has negatively affected both soil health and root growth, lowering water absorption and air flow. Despite the notable increase in production efficiency, precision equipment such as GPS enabled equipment is only utilized by 25% of farms worldwide (*McFadden et al. 2023*). The low adoption rate of precision equipment is directly related to high costs and limited access which prevent farmers from converting to more efficient machinery. As global demand for agricultural products rises, ensuring the implementation of precision equipment is fundamental in achieving higher productivity and greater sustainability.

Widespread use of chemical fertilizers and pesticides in commercial agriculture has huge environmental and health implications. Pesticides, such as neonicotinoids, have been linked to a 43.3% decline in populations of pollinators, that are essential for crop production and biodiversity (Guzman et al., 2024). Additionally, excessive fertilizer use causes environmental degradation, namely the 6,000-square-mile "dead zone" in the Gulf of Mexico, where nutrient runoff has severely harmed the aquatic environment (NOAA, 2022). Fertilizers also release nitrous oxide, a greenhouse gas 300 times more potent at trapping heat than carbon dioxide, which hastens climate change (UCAR, 2024). Long-term exposure to these chemicals has been connected to endocrine disruption and reproductive issues in humans and animals. Cumulatively, they degrade soil fertility, destabilize ecosystems, and pose serious barriers to sustainable agriculture.

Monoculture farming involves successive cultivation of the same crop, which depletes the soil of its original nutrients and destabilizes the ecosystem balance. In the long term, it depletes the organic nutrients in the soil, reducing the soil's ability to support healthy crops. For instance, in the long-term rye cultivation experiment, there was an increase in soil CO_2 emissions by 32.8% and a decline in earthworm populations, both direct measures of soil degradation (Bogužas et al., 2020). Corn, wheat, and soybean crops propel world agriculture and exaggerate these issues. For instance, maize fields have been estimated to have lost 23% of their organic carbon, leading to reduced yields and increased reliance on artificial fertilizers. Over-reliance on fertilizers also destabilizes soil pH and microbial populations, with environmental consequences far and wide. In Brazil, nitrogen and phosphorus leaching from monoculture sugarcane has been blamed for water pollution and encouraging algal blooms. Rice monoculture has also been blamed for emitting more greenhouse gas emissions, in this case methane, due to the continuous flooding of the fields that prevent the soil from absorbing atmospheric oxygen, leading to anaerobic fermentation of organic matter (Rajendran et al., 2024). These instances explain how monoculture degrades land and exacerbates climate change by reducing opportunities for carbon storage and increasing harmful emissions.

Although monoculture farming has increased output at reduced costs, it has also caused severe long term negative effects for human health. The nature of monoculture farming has created an abundance of low quality crops, generally based in wheat, soy, or corn. The increased availability of food has led to a proportional increase in the intake of high calorie, nutrient poor food. Diets lacking nutrient diversity are directly linked to an increased risk of chronic illnesses such as obesity, cardiovascular diseases, and type 2 diabetes (Clemente-Suárez et al., 2023). Additionally, within households experiencing food insecurity, adults are 21% more likely to develop clinical hypertension (Seligman et al., 2010). Diets dominated by these foods lack nutritional diversity, contributing to nutrient deficiencies that now affect nearly 2 billion people worldwide (FAO, 2022). Such deficiencies impair immune function, reduce quality of life, and elevate the risk of chronic illnesses. Improving nutrition requires diversifying foods and reducing dependence on the same few commodities that form the basis for most ultra-processed foods.

Globally, the demand for several types of crops has greatly increased over recent years, straying away from the reliance on the “big three”: corn, wheat, and soy. This phenomenon is in part driven by the change in consumer preferences with more nutritious food and health trends such as gluten-free, paleo, and low-carb diets dominating in newer generations. Different crops, such as quinoa and sorghum, are popular options as alternatives to traditional wheat products. An expansion in the different types of crops consumed throughout the world demonstrates how unsustainable the dependence on a few crops is. The nutritional demands of our diverse and growing population would not be met on this limited dependence. For example, crop diversification has been shown to improve nutritional diversity, which directly impacts nutritional security. Studies indicate that crop diversification has increased food security scores by 40% (Nahar, 2024). While we see this trend being prominent in developed countries, it represents a larger movement toward food security and improved global nutrition.

Growing and cultivating nutritious crops presents several challenges compared to traditional crops such as corn and wheat. Based on their previous popularity, these crops have not been optimized for large-scale farming, making their production more complex and resource-demanding (Khoury et al., 2014). Nutrient-dense crops require very specific growing conditions, continued care, and sustainable fertilization practices to achieve optimal yields that satisfy global demands (Hernandez et al., 2024). Current technologies in the agricultural field, particularly designed for the staple crops, are highly inadequate for newer, more nutritious crops, creating intensive labor and inefficient production systems (Foley et al., 2011). To address these challenges, an innovative solution is key to streamlining the farming process and maintaining the quality of our crops. Systems such as SHIELD propose a transformative step forward in agriculture by enabling a scalable and efficient production of diverse crops that meet current dietary needs.

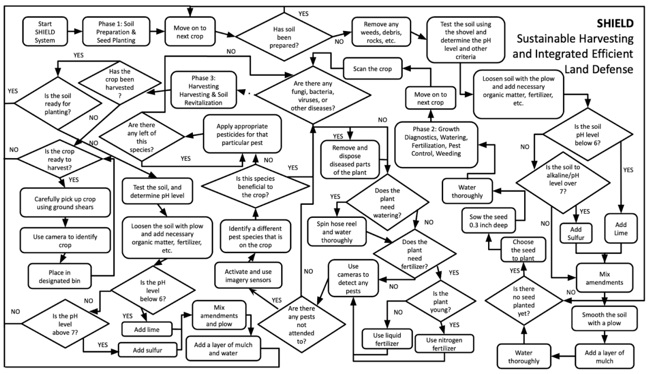
Robotics solutions in agriculture have progressed significantly over the past decade, with a focus on intensive labor farming of crops such as fruits, vegetables, and cruciferous plants like broccoli and cauliflower. Sensors, robotics, and advancements in AI have greatly contributed to an efficient farming industry. Despite these advancements, most technologies available remain within their niche and perform narrow human-supervised tasks. For example, tractor companies such as John Deere or harvesting robots from companies such as Tortuga AgTech perform tasks advertised to be highly autonomous but require heavy human supervision. In the same fashion, many drone sprayers, which apply pesticides efficiently, are limited to environmental factors. While platforms in agriculture, which are very precise, lower labor costs and increase crop yield, the adaptability of these technologies across different environments remains a notable challenge that requires holistic and flexible solutions.

SHIELD represents a new generation of agricultural robotics, providing a complete system for the entire cultivation process. In contrast to other technologies, SHIELD facilitates planting, monitoring, pest protection, and harvesting. SHIELD is intended for cruciferous and nutrient-dense crops, leveraging high-tech sensors, AI-powered monitoring, and robotic modules to ensure sustainable and accurate crop growth. The flexibility of the design supports various types of crops and environments, which makes the technology more versatile and efficient in comparison with conventional technologies that execute one task on a single type of crop. SHIELD minimizes costs by automating time-consuming processes, optimizes yields, and ensures low environmental impact to address the increasing demand for sustainable and healthy food sources.

II. Methodology

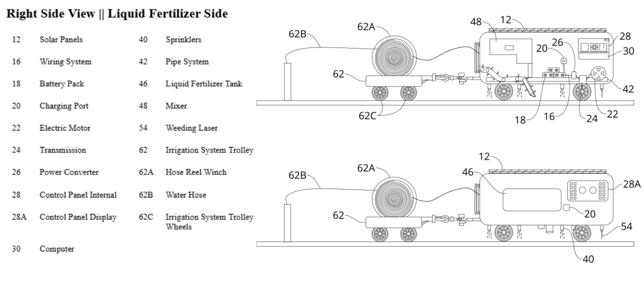
The Sustainable Harvesting and Integrated Efficient Land Defense *(SHIELD)* system consists of two primary components: a Main Vehicle that performs core agricultural tasks such as planting, monitoring, and harvesting, and a series of Attachments that enhance its functionality for specific farming operations. These components are integrated into a comprehensive, fully automated solution designed to streamline the entire crop cultivation cycle, from soil preparation to harvesting, while minimizing labor requirements and environmental impact.

A. SHIELD Deployment

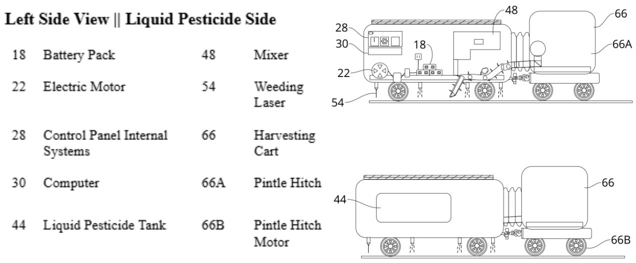


1. SHIELD Operational Logic

B. General Idea Being Proposed



2. SHIELD Robot Right Side Schematic



3. SHIELD Robot Left Side Schematic

C. System Architecture

The SHIELD systems integrate autonomous robotics and precision agriculture to manage the full lifecycle of cruciferous crops. Central to its operation is the solar/battery powered robotic platform with LiDAR, multispectral cameras, and electrochemical sensors for real-time soil and crop data. During soil preparation, a plow tills the earth while a linear drill plants seeds at optimal depths, adjusting soil pH via lime or sulfur based on sensor feedback. For growth management, retractable irrigation hoses and AI-guided sprinklers deliver water and fertilizers tailored to soil moisture and nutrient levels, while targeted lasers eliminate weeds without herbicides. At harvest, AI-driven shears cut mature crops, and a conveyor belt transfers them to storage, with plant waste recycled as compost. Modular attachments (soil prep, irrigation, and harvesting units) are autonomously swapped via a magnetic hitch system, enabling seamless task transitions. SHIELD's logic-driven workflow (ex., "If pests detected → activate laser") ensures minimal chemical use, reduced labor, and maximal yield, prioritizing sustainability through closed-loop resource efficiency.

D. Functionality of System

The SHIELD system's functionality centers on its Main Vehicle, the core platform is equipped with advanced robotics, sensors, and navigation systems designed to autonomously manage agricultural tasks such as planting, fertilizing, applying pesticides and monitoring crop health across fields. This goal is accomplished through several integrated subsystems operating in unison. Initially, the Drivetrain allows mobility across various terrains, ensuring the vehicle can operate efficiently in diverse farming environments. Next, the Sensors Array System monitors soil moisture, nutrient levels, and crop health in real time, providing data-driven insights for precision farming. Lastly, the Energy & Navigation System integrates GPS and LiDAR for precise navigation, obstacle detection, and optimized routing, while efficiently managing the combination of solar and battery power for sustainable energy consumption.

Table 1: Systems in CORALS and Their Functions

E. Systems Applied in SHIELD

	System	***Function***
Main Vehicle	Drivetrain	Core platform for field operations (planting, watering, chemical application). Features GPS, automated controls for precise movement across varied terrains. Built for durability and environmental adaptability.
	Sensor Array System	Real-time monitoring of soil, moisture, and crop health. Integrates data to optimize irrigation, fertilization, planting, and chemical applications for enhanced crop management decisions.
	Energy & Navigation System	GPS/Lidar integration for precise navigation and obstacle detection. Manages battery/solar power, optimizes routing, adjusts power usage, and handles automated recharging for continuous operation.
Robotics Systems	Fertilizer & Pesticide	Stores and dispenses fertilizers/pesticides in separate compartments. Sensor-monitored levels with flow adjustment during application. Ensures accurate distribution and prevents over-application.
	Water Irrigation System	Delivers water with real-time flow adjustments based on soil moisture. Route-integrated for optimized delivery, conserving resources while ensuring proper crop hydration.
	Precision Planting System	GPS and soil data-guided seed placement. Vehicle-synchronized for even distribution, maximizing land usage and crop density with minimal waste.
	Harvesting System	Ground shears and conveyor belt system for crop cutting and collection. Vehicle-integrated for efficient harvesting with minimal damage and optimized collection-to-storage transition.

Table 1: Systems in SHIELD and Their Functions

F. Hardware Design Description

Central to the system's structure is the housing, which provides a protective framework for all internal and external components. The battery pack serves as the primary power source for the vehicle, distributing energy via the wiring system to ensure that all components operate smoothly. The charging port is used to recharge the battery by connecting the vehicle to an external power outlet, with the power converter managing the efficient distribution of this power across the vehicle's systems. While the solar panels are installed to power certain electronics on board, their role is supplementary to the main power source.

The vehicle's movement is facilitated by the main vehicle wheels, which are powered by the electric motor and managed by the transmission. The system's operations are governed by the control panel internal systems, which interface with the computer to control the vehicle's various tasks, providing feedback and allowing adjustments through the control panel display. The system's sensors, including cameras, proximity sensors, a lidar module, and electrochemical sensors, collect and relay data to optimize the vehicle's functions such as navigation, irrigation, and spraying.

For irrigation tasks, the system uses the irrigation system trolley, equipped with a hose reel winch, water hose, and irrigation system trolley wheels. This system ensures precise water delivery, complemented by the sprinklers connected to the pipe system. The liquid pesticide tank and liquid fertilizer tank store the necessary chemicals, which are mixed by the mixer and mixing blades before being evenly distributed across the crops. The weeding laser provides an efficient method for weed control, reducing the need for chemical herbicides. For harvesting, the ground shears are used to cut the cruciferous crops from the stem, with the conveyor belt aiding in the efficient movement of harvested materials. The harvesting cart, complete with its storage tank and harvesting cart wheels, is used to collect and transport crops. The soil preparation and revitalization cart frame is another critical attachment, featuring a drill linear slide for creating holes for seed planting, a seed and chemical container for holding seeds, a drill motor to power the drilling process, and a seed dispenser with a trapdoor for placing seeds into the prepared soil. The plow is used to prepare the soil for planting, while the soil preparation and revitalization cart frame wheels provide mobility for the attachment.

The locking mechanism plays a crucial role in enabling the system to switch between different attachments, such as the irrigation system, soil preparation module, and harvesting cart. This mechanism is controlled by the pintle hitch motor, which vertically opens the pintle hitch like a claw, and the sway adjustment motor, which allows for horizontal rotation. The lunette ring serves as the connection point for these mechanisms, ensuring secure and efficient attachment and detachment. Supporting the vehicle's autonomous operations are additional components like the internal pipes, which facilitate fluid distribution, and the gates/valves, which control the flow of liquids within the system. The ground shears also assist in clearing the way for the vehicle, while the connecting tunnel plays a role in integrating various system components, ensuring the vehicle functions as a cohesive unit.

G. Components of SHIELD and their Functions

	Components	***Function***
Main Vehicle	Housing (Protolabs, USA)	Protects the robot's internal components and provides structure.
	Solar Panels (San Tan Solar, USA)	Captures sunlight and converts it into electrical energy.
	Main Vehicle Wheels (Harbor Freight, USA)	Enables robot mobility across various terrain surfaces.
	Wiring System (RobotShop, Canada)	Transfers electricity between robot components.
	Battery Pack (Blue Robotics, USA)	Stores electrical energy to power the entire robot.
	Charging Port (WiBotic, USA)	A charging port transfers electricity to the robot's battery.
	Electric Motor (Buggies Unlimited, USA)	An electric motor drives the robot's wheels.
	Transmission (Reman Transmission, USA)	Transmits power from the electric motor to the power converter.
	Power Converter (Powermax, USA)	A device that's used to convert electrical energy between AC or DC.
	Control Panel (SuperLogics, USA)	Allows the user to configure the robot's mechanics.
	Computer (Thinkmate, USA)	Controls each part, performing functions based on control panel input.
	Cameras (DigiKey, USA)	Collects visual data on what happens around the robot.
	Electrical Chemical Sensors (DigiKey, USA)	Converts electrochemical reaction data into quantitative signals.
	Lidar Module (SparkFun, USA)	Measures the distance from the robot to the nearest object it's facing.
	Proximity Sensor (DigiKey, USA)	Detects nearby objects without physical contact.
	Sprinklers (Hunter, USA)	Spray water in a pattern to other objects near the robot.
	Pipe System (Charlotte Pipe, Depot, USA)	A series of pipes that deliver water from one place to another.
	Liquid Pesticide Tank (ChemWorld, USA)	A tank filled with pesticides.
	Liquid Fertilizer Tank (ChemWorld, USA)	A tank filled with fertilizer in liquid form.
	Mixer (US Plastic Corporation, USA)	Blends fertilizer, pesticide, and water into one solution.

	Components	Function
	Gates/Valves (Boshart, USA)	Used to allow or stop the flow of liquids in the robot.
	Weeding Laser (Carbon Robotics, USA)	Eliminates weeds with a laser beam.
	Internal Pipes (Grainger, USA)	Carries liquids between robot components.
	Conveyor Belt (Uline, USA)	Allows objects to go in and out of the robot.
	Ground Shears (Zoro, USA)	Ground Shears cut the weed under the robot.
	Connecting Tunnel (T-Rex Rubber International, Netherlands)	Allows the conveyor belt to transport objects through the robot.

Table 2: Components of SHIELD-Main Vehicle and Their Functions

	Components	Function
	Irrigation System Trolley (FIMCO, USA)	Attached is the order to water crops.
	Hose Reel Winch (Uline, USA)	Keeps the water hose elevated to prevent soil dragging.
	Water Hose (Abbot Rubber Inc, USA)	Connects to the irrigation system for direct plant watering.
	Irrigation System Trolley Wheels (Sentry Tires, USA)	Allows for the trolley's mobility.
	Soil Prep and Revitalization Cart Frame (FIMCO, USA)	Used for the soil preparation and revitalization phases.
Attachment	Drill (Elevator/Linear Slide) (Vevor, USA)	Used to drill a hole in the ground to plant seeds.
	Seed and Chemical Container (Wuxi Nanquan Pharma)	Stores seeds and soil preparation chemicals.
	Drill Motor (Misumi, USA)	Turns the drill.
	Seed Dispenser with Trapdoor (All States Ag Parts, USA)	Used to dispense the required seed when planting.
	Plow (John Deere, USA)	Used to loosen soil to plant and sow seeds.
	Soil Prep and Revitalization Cart Wheels (Sentry Tires, USA)	Allows the cart to be moved.
	Harvesting Cart (Astro Meta Craft, USA)	Used for the harvesting phase of the crop growth.
	Storage Tank (Global Industrial, USA)	Stores plants after harvesting them.
	Harvesting Cart Wheels (Sentry Tires, USA)	Allows the cart to be moved.
	Locking Mechanism (Southco, USA)	Secures carts/trolleys to the pintle hitch connection.
	Pintle Hitch (Premier Manufacturing, USA)	Heavy-duty hook mechanism that connects carts to the main robot.
	Pintle Hitch Motor (Bodine Electric Company, USA)	Motorized Pintle Hitch.
	Sway Adjustment Motor (Oriental Motor, USA)	Used to rotate the cart.
	Lunette Ring (Etrailer, USA)	Metal component that connects trailer to pintle hook.

Table 3: Components of SHIELD-Attachments and Their Functions

H. Assembly of Innovation

The assembly of SHIELD system involves constructing the Main Vehicle Platform and configuring its Modular Trolley Attachments, which carry out the core agricultural functions. Begin by securing the chassis frame to a set of all-terrain wheels, ensuring ground clearance and stability for operation on uneven farm surfaces. Install the electric drivetrain, including the motor, transmission, and power converter, which powers the vehicle's movement and auxiliary systems.

Next, mount the battery pack centrally for balanced weight distribution and connect it to the power management hub, which routes electricity to all operational components. On the roof of the chassis, install the solar panels, angled to maximize exposure, and connect them to the battery for continuous trickle charging. Integrate the charging port into the rear panel to allow autonomous docking and recharging. Install the central control computer and sensor network, including the LiDAR module, multispectral cameras, electrochemical soil sensors, and proximity sensors. These should be securely mounted on shock-absorbing brackets to minimize disruption from terrain vibrations. Wire the sensors into the control hub, where the onboard computer runs the autonomous navigation and data-processing algorithms.

Attach the control panel display near the vehicle's top or front panel for operator configuration and emergency stop access. At the rear of the main vehicle, mount the pintle hitch and motorized locking system. This mechanism allows SHIELD to connect and disconnect from various trolley modules using a claw-like motion and horizontal sway adjustment for precise alignment. Each modular trolley (for soil preparation, watering/diagnostics, or harvesting) is assembled separately. Begin with the trolley frame and add the respective wheels. Mount each trolley's specific components: the plow, drill, and seed dispenser for planting; sprinklers and fluid tanks for crop care; or ground shears, conveyor belt, and storage tank for harvesting. Connect each module's wiring harness and liquid delivery lines to match with the SHIELD vehicle interface ports.

Once fully assembled, the robot undergoes a calibration process to align sensor inputs, verify motor functions, and test attachment mechanisms. The final step is pairing the system with the docking station, which supports autonomous recharging and maintenance routines. Once assembly and system checks are complete, SHIELD is ready for deployment in the field.

I. Mechanism of Components

SHIELD operates through an integrated network of sensors, actuators, power systems, and control algorithms that collectively enable autonomous agricultural functions across all stages of crop cultivation. Each component is designed for seamless interaction, allowing smooth transitions between tasks such as planting, watering, harvesting, and soil revitalization. Central to SHIELD's operation is its electric-vehicle-inspired power management system. A high-capacity battery powers the entire system, while onboard solar panels provide supplemental energy to essential subsystems like localization and communication. When battery levels are low, SHIELD autonomously docks at a charging station, where a built-in port ensures reliable recharging.

A key feature of SHIELD is its modular attachment system, which allows for quick switching between tools specialized for different farming phases. This is accomplished through a combination of locking mechanisms, a motorized pintle hitch, and a sway adjustment motor that aligns attachments horizontally. Embedded magnets guide and secure the connection, enabling fully autonomous coupling without manual input.

SHIELD's operations rely on a comprehensive sensor suite that includes LiDAR for terrain mapping, electrochemical sensors for soil analysis, cameras for crop monitoring, and proximity sensors for obstacle detection. These sensors feed real-time data into a central control algorithm that interprets environmental conditions and coordinates system responses. During the soil preparation and planting phase, tools such as a drill, plow, and seed dispenser work in tandem to evaluate soil conditions, adjust treatments, and plant seeds at optimal depth and spacing. In the growth management phase, sprinklers, fertilizer tanks, and a laser weeder are deployed to nourish crops and eliminate weeds with minimal chemical use. The harvesting phase involves ground shears that cut crops at the stem, followed by a conveyor system that transports the yield to onboard storage. After harvesting, SHIELD enters a soil revitalization phase, using existing tools to restore soil conditions for the next planting cycle.

To ensure safety and reliability, SHIELD is equipped with a master stop button on its control panel and built-in error-handling protocols. If a component fails or an obstruction is detected, the system can halt operations, notify the operator, and attempt to resolve the issue before resuming.

This sophisticated coordination of components enables SHIELD to deliver highly efficient, precise, and autonomous agricultural performance with minimal human oversight.

J. Applications of CORALS

SHIELD is designed to autonomously perform end-to-end agricultural tasks across various crop cycles, minimizing the need for human intervention while maximizing efficiency and precision. The system is deployed in three primary phases: setup, active fieldwork, and maintenance.

1) Setup

To initiate SHIELD, operators first configure the system using the control panel display. Field dimensions, crop type (such as specific varieties of cauliflower), and soil treatment preferences are entered into the interface. Once the data is submitted, the appropriate modular trolley is selected, either the soil preparation, watering and diagnostics, or harvesting trolley. The trolley is attached using the vehicle's automated locking mechanism and pintle hitch system, which ensures accurate alignment and secure coupling. SHIELD is then positioned at the designated start point in the field. Upon activation, it begins autonomous navigation using integrated GPS and LiDAR systems to follow a predefined path and continuously assess its environment.

2) During Fieldwork

In the planting phase, SHIELD evaluates the soil using built-in sensors to assess pH, moisture levels, and any obstructions. If preparation is necessary, the plow tills the soil, the drill creates holes at optimized depths, and the seed dispenser places seeds accurately. Sprinklers then apply water to support initial germination. Each action is regulated in real-time by the control algorithm, ensuring optimal seeding conditions. In the growth management phase, SHIELD switches to the watering and diagnostics trolley. Cameras, proximity sensors, and electrochemical soil sensors monitor plant health, moisture, and nutrient levels. If deficiencies or pests are detected, the system responds by activating appropriate modules—sprinklers for irrigation, tanks for liquid fertilizer, or pest control tools such as targeted sprayers or lasers. All actions are precisely measured based on sensor feedback. In the harvesting phase, SHIELD engages the harvesting trolley. Ground shears cut the crops at their base, and a conveyor belt transports the produce into an onboard storage container. The robot systematically covers the field section by section, minimizing crop damage and ensuring gentle handling of harvested goods.

3) Maintenance

Once the assigned tasks are complete, SHIELD autonomously returns to its docking station. It recharges its battery, performs self-checks, and prepares for the next deployment. Operators can access data collected during operation, review field performance, refill pesticide or fertilizer tanks, and conduct any necessary maintenance or part replacements. Once serviced and recharged, SHIELD is ready to begin a new cycle of fully autonomous, precision-guided farming.

III. Results and discussions

The expected implementation of SHIELD offers several important benefits for farming. It is projected to improve food safety by reducing the need for harmful pesticides, and to help lower labor costs by automating tasks that would usually require a lot of manual work. Additionally, by relying less on traditional methods that use a lot of chemicals, it is expected to help grow healthier crops with higher nutritional value. The robot is designed to be powered by solar panels, making it a sustainable energy source that's better for the environment. Its design, which includes wheels and trolleys, allows it to easily move across different types of fields, making it adaptable for various farming needs. Overall, the robot is projected to make farming more efficient, safer, and environmentally friendly.

A. Minimized Soil Degradation

SHIELD's lightweight robotic systems stand to reduce soil compaction, preserving the soil structure for delicate crop roots. By collecting and processing data, SHIELD would apply the right amount of fertilizer at optimal times, maximizing soil nutrition. In other words this minimizes soil degradation, allowing crops to grow efficiently with fewer resources. The approach also promotes long-term soil health, ensuring sustainable land productivity for future generations through faster soil regeneration.

B. Reduced Labor Costs & Alleviating Labor Shortages

SHIELD's autonomous capabilities are projected to drastically lower labor costs by automating many laborious human tasks such as planting, monitoring and harvesting. This is especially beneficial for large-scale farms that struggle with labor shortages and rising wages. The use of robotics eliminates the variability in human labor, ensuring consistency by contributing a 24/7 operation that is economically viable and never scarce or seasonal.

C. Zero-waste Harvesting

SHIELD's advanced robotic harvesting system is designed to eliminate crop waste by utilizing precision cutting tools and sensors that detect optimal ripeness. This ensures that only fully matured crops are harvested, avoiding under- or over-harvesting. Additionally, SHIELD's technology is expected to allow for the use of every part of the plant, minimizing waste left in the field. By maximizing the utility of all harvestable material, SHIELD would increase farm profitability and support the move toward a zero-waste agricultural model.

D. Enhanced Food Safety

SHIELD's advanced sensor system stands to detect contaminants/pathogens to ensure crops are as safe as possible. Through the automation of planting, monitoring and harvesting, SHIELD would significantly decrease chances of foodborne illnesses, like listeria and cyclosporiasis. Its meticulous data collection and cross-referencing is designed to ensure safety concerns as quickly as possible, improving product quality and ensuring consumer health.

E. Scalability for Large-Scale Operations

The SHIELD system is inherently scalable and is expected to efficiently manage large-scale agricultural operations through its modular, robotic architecture. Multiple SHIELD units could autonomously collaborate, optimizing several tasks such as soil preparation, planting, irrigation, weed control, and harvesting across extensive areas. Powered by renewable solar energy, SHIELD is projected to minimize operational costs and environmental impact, offering a sustainable, scalable solution for large-scale cruciferous crop production.

F. Nutritional Efficiency in Cruciferous Plants

SHIELD's intelligent systems are designed to monitor and deliver precise amounts of water, nutrients, and fertilizers, tailored specifically for cruciferous crops like broccoli, cauliflower, and cabbage. By ensuring plants receive exactly what they need at the right time, SHIELD would boost their growth rates and enhance the concentration of essential nutrients like vitamins, antioxidants, and fiber. This optimized nutrient delivery results in healthier crops that are more resilient to pests and diseases, all while using fewer chemical inputs, thus promoting both plant vitality and consumer health.

G. Reduced Greenhouse Gas Emissions & Sustainable Energy Source

By integrating electric-powered systems and renewable energy sources (ex. solar panels), SHIELD is expected to drastically cut down the use of greenhouse gas emissions. Its energy-efficient machinery along with AI-powered optimized routes would reduce emissions, using energy only where needed. This increases productivity and reduces waste through minimizing use of energy.

H. Water Conservation

The sensors implemented in SHIELD are designed to allow the robot to detect when a crop needs watering and determine the exact amount of water required to keep the plant healthy. This reduces room for human error in judging how much to water a plant. Additionally, the crop would not receive excessive amounts of watering when it requires little to no water.

I. Data Collection & Crop Forecasting

With a network of sensors integrated throughout the farm, SHIELD is expected to continuously collect vast amounts of data on soil moisture, nutrient levels, weather conditions, and plant growth. This data would be processed by advanced AI algorithms to provide farmers with actionable insights into crop performance and potential yield forecasts. By using predictive analytics, SHIELD is designed to enable proactive decision-making, helping farmers anticipate weather changes, adjust irrigation, and prevent crop diseases. These insights result in higher crop yields, better resource management, and reduced financial risk due to unforeseen variables.

J. Reduced Pesticide & Fertilizer Use

SHIELD is designed to employ precision farming technology through its many different components such as its lidar module and electrochemical sensors, in order to deliver the exact amount of pesticides & fertilizers needed. Eliminating excess chemicals and reducing environmental impact allows farms to reduce chemical runoff on surrounding ecosystems, improving biodiversity and soil health all while maintaining crop enrichment. This method also minimizes consumers' exposure to synthetic chemicals.

K. Optimized routes for energy-efficient farming

SHIELD's AI-driven navigation system is expected to calculate the most efficient routes for its robotic vehicles, reducing fuel and energy consumption while maximizing field coverage. By avoiding unnecessary paths, SHIELD would save time and resources, which helps improve operational efficiency while reducing its carbon footprint.

IV. Conclusion

The SHIELD system is a transformative approach to addressing the pressing challenges of traditional farming: labor shortages, environmental degradation, and resource inefficiency. Through the integration of robotics, AI-driven sensors, and a modular design, SHIELD allows farmers to automate the entire cultivation process (from planting to harvesting) while prioritizing precision and sustainability. Also, SHIELD's adaptability to numerous crops, primarily nutrient-rich cruciferous varieties, aligns with shifting consumer demands for healthier, sustainable food systems.

The self-sustaining capability of the system not only minimizes labor reliance but also enhances food safety, water efficiency, and nutritional value of crops through data-based decision-making. Based on renewable energy and zero-waste principles, SHIELD offers scalable technology for mitigating the carbon footprint of agriculture without lowering productivity. With increasing climatic pressures and global populations, such innovations as SHIELD emphasize the central role robotics will play in ensuring food security without compromising environmental equilibrium. Future growth must focus on maximizing crop compatibility and accessibility, transforming the technology into a mainstay of sustainable, equitable food systems worldwide.

V. Acknowledgments

We would like to express our sincere gratitude to our mentors, Alex Colin, who provided invaluable guidance and support throughout every step of the SHIELD project. Their expertise and encouragement were instrumental in helping us overcome challenges and achieve our goals. We extend special thanks to Dublin Robotics for their generous collaboration and technical resources. Their technical expertise made it possible to bring this project from concept to reality. We also acknowledge the dedication and hard

work of our fellow researchers and team members who played essential roles in this endeavor.

References

1. Bland, R., Ganesan, V., Hong, E., & Kalanik, J. (2023, May 31). Trends driving automation on the farm. McKinsey & Company. https://www.mckinsey.com/industries/agriculture/our-insights/trends-driving-automation-on-the-farm#
2. Bogužas, V., Skinulienė, L., Butkevičienė, L. M., Steponavičienė, V., Petrauskas, E., & Maršalkienė, N. (2022). The Effect of Monoculture, Crop Rotation Combinations, and Continuous Bare Fallow on Soil CO2Emissions, Earthworms, and Productivity of Winter Rye after a 50-Year Period. Plants, 11(3), 431. https://doi.org/10.3390/plants11030431
3. Clemente-Suárez, V. J., Beltrán-Velasco, A. I., Redondo-Flórez, L., Martín-Rodríguez, A., & Tornero-Aguilera, J. F. (2023). Global Impacts of Western Diet and Its Effects on Metabolism and Health: A Narrative Review. Nutrients, 15(12), 2749. https://doi.org/10.3390/nu15122749
4. De-Assis, M. P., Barcella, R. C., Padilha, J. C., Pohl, H. H., & Krug, S. B. F. (2021). Health problems in agricultural workers occupationally exposed to pesticides. Revista brasileira de medicina do trabalho : publicacao oficial da Associacao Nacional de Medicina do Trabalho-ANAMT, 18(3), 352–363. https://doi.org/10.47626/1679-4435-2020-532
5. FAO, IFAD, UNICEF, WFP and WHO. 2022. The State of Food Security and Nutrition in the World 2022. Repurposing food and agricultural policies to make healthy diets more affordable. Rome, FAO.
6. Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., & Zaks, D. P. M. (2011). Solutions for a cultivated planet. Nature, 478(7369), 337–342. https://doi.org/10.1038/nature10452
7. Guzman, L.M., Elle, E., Morandin, L.A. et al. Impact of pesticide use on wild bee distributions across the United States. Nat Sustain 7, 1324–1334 (2024). https://doi.org/10.1038/s41893-024-01413-8
8. Hayden, M. A., Barim, M. S., Weaver, D. L., Elliott, K. C., Flynn, M. A., & Lincoln, J. M. (2022, December 8). *Occupational Safety and health with technological developments in livestock farms: A literature review*. International journal of environmental research and public health. https://pmc.ncbi.nlm.nih.gov/articles/PMC9778243/
9. Hernandez, L. E., Ruiz, J. M., Espinosa, F., Alvarez-Fernandez, A., & Carvajal, M. (2024). Plant nutrition challenges for a sustainable agriculture of the future. Physiologia plantarum, 176(6), e70018. https://doi.org/10.1111/ppl.70018
10. Khoury, C. K., Bjorkman, A. D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., ... & Struik, P. C. (2014). Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences, 111*(11), 4001–4006. https://doi.org/10.1073/pnas.1313490111
11. McFadden, B., Gonzalez, M., & Wu, T. (2023). *Global adoption of precision agriculture technologies: Trends and barriers*. Elsevier.
12. Nahar, N., Rahman, M.W., Miah, M.A.M. et al. The impact of crop diversification on food security of farmers in Northern Bangladesh. Agric & Food Secur 13, 9 (2024). https://doi.org/10.1186/s40066-023-00463-z
13. National Oceanic and Atmospheric Administration (NOAA). (2022). *Dead zone in the Gulf of Mexico*. Ocean Today. https://oceantoday.noaa.gov/deadzonegulf/welcome.html
14. Rajendran, S., Park, H., Kim, J., Park, S. J., Shin, D., Lee, J.-H., … Kim, C. M. (2024). Methane Emission from Rice Fields: Necessity for Molecular Approach for Mitigation. *Rice Science*, *31*(2). https://doi.org/10.1016/j.rsci.2023.10.003
15. Seligman, H. K., Laraia, B. A., & Kushel, M. B. (2010). Food insecurity is associated with chronic disease among low-income NHANES participants. *Journal of Nutrition, 140*(2), 304–310. https://doi.org/10.3945/jn.109.112573
16. Spangler, K., Burchfield, E. K., & Schumacher, B. (2025, August 6). *Past and current dynamics of U.S. Agricultural Land Use and policy*. Frontiers. https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2020.00098/full
17. UCAR. "Some Greenhouse Gases Are Stronger than Others | UCAR Center for Science Education." Scied.ucar.edu, 2024, scied.ucar.edu/learning-zone/how-climate-works/some-greenhouse-gases-are-stronger-others.
18. United States Environmental Protection Agency. "Inventory of U.S. Greenhouse Gas Emissions and Sinks." US EPA, 15 Jan. 2025, www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.