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# Experiential Learning in Agricultural Robotics and Controlled Environment Agriculture: Integrating FarmBot, Tower Garden, and Freight Farm Technologies

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## Abstract

This paper presents a multi-tiered experiential learning framework integrating robotics, sustainable agriculture, and inclusive STEM education through summer internships, educator workshops, and student academies. The initiative, implemented at the University of Maryland Eastern Shore (UMES), is part of a broader effort to develop a future-ready workforce in Biological and Agricultural Engineering, focusing on the intersection of automation, food systems sustainability, and technology-enhanced learning. The program engaged undergraduate and graduate STEM interns, K–12 students, and educators through hands-on training using FarmBots, Tower Gardens, and Freight Farms representing three levels of emergent agricultural technologies for controlled environment agriculture (CEA). Student interns collaborated on applied research in indoor and urban agriculture, conducting experiments on crop growth in lunar regolith simulants, nutrient management, and automation using FarmBot Express and Tower Garden FLEX systems. The Summer Educator Workshop on Indoor Urban Sustainable Accessible Agriculture (IUSAA) introduced K–12 teachers and university faculty to robotics-based teaching modules and energy-smart urban farming practices. In parallel, the Agricultural Robotics Academy for high school students provided experiential exposure to programming, sensing, and automation, fostering early interest in agri-engineering careers. These activities collectively address three pillars: a) Research and Innovation – advancing sustainable crop production through robotics and resource-efficient systems; b) Education and Workforce Training – developing STEM literacy and practical engineering competencies through discovery-based learning; and c) Extension and Outreach – disseminating knowledge to educators, growers, and community members via workshops and demonstrations. The evaluation and assessment plan incorporated both formative and summative measures using mixed methods: a) pre-and post-assessments to quantify gains in technical knowledge, problem-solving, and self-efficacy; b) reflection journals and focus groups to capture student engagement, teamwork, and inclusivity outcomes; and c) educator surveys to measure confidence in integrating robotics and sustainable agriculture concepts into curricula. Preliminary data indicate measurable improvements in students' understanding of automation, systems thinking, and sustainable design. Educators reported greater confidence in adopting technology-driven agriculture modules, and K–12 participants demonstrated enhanced motivation toward STEM careers. The use of FarmBots for precision planting and irrigation, Tower Gardens for vertical aeroponic cultivation, and Freight Farms for containerized hydroponics served as scalable educational platforms bridging theory with practice. By combining experiential learning, applied research, and inclusive outreach, this program exemplifies a replicable model for cultivating innovation and diversity in the agricultural engineering workforce. The integration of robotics and smart agriculture not only prepares students to address pressing challenges in food security and sustainability but also aligns with NASA's Artemis objectives with national priorities for climate-smart and energy-efficient food system.

## 1. Introduction

### 1.1 Global Challenges in Food Systems and Workforce Preparation

Global food systems are facing unprecedented pressures driven by climate change, population growth, rapid urbanization, labor shortages, and increasing resource scarcity. Agriculture alone accounts for approximately 70% of global freshwater withdrawals and contributes between 20–30% of total anthropogenic greenhouse gas emissions when accounting for land-use change, production, processing, and distribution activities [1], [2]. These pressures are further exacerbated by climate variability, extreme weather events, soil degradation, and disruptions to global supply chains, underscoring the urgent need for more resilient, resource-efficient, and climate-smart agricultural systems [3], [4].

At the same time, the agricultural workforce is undergoing significant structural change. The average age of farmers and agricultural professionals continues to rise, while younger workers with expertise in automation, robotics, data analytics, and systems engineering remain in short supply. [5], [6]. Emerging agricultural sectors particularly controlled environment agriculture (CEA), precision farming, and agri-robotics require interdisciplinary competencies that blend biological sciences, engineering, computer science, and environmental systems analysis.[7]. Industry and government reports consistently identify a growing skills gap in systems-based problem solving, digital literacy, and data-driven decision-making across the food and agricultural sectors.[6], [8]

Controlled environment agriculture, coupled with agricultural robotics and automation, has emerged as a promising response to these converging challenges. CEA systems including hydroponics, aeroponics, vertical farming, and containerized agriculture enable precise control over environmental conditions, optimize water and nutrient use, and reduce land and chemical inputs. [9] [10] [11] Robotic platforms and sensor-driven automation further enhance productivity by enabling precision planting, irrigation, monitoring, and harvesting while reducing labor demands.[12], [13] However, while technological capabilities have advanced rapidly, educational models have not evolved at the same pace. Traditional disciplinary silos and lecture-dominated instruction often fail to prepare students for the complexity and interdisciplinarity of modern agricultural systems. [14], [15]

These gaps point to an urgent need for experiential, integrative learning environments that connect engineering design, biological processes, sustainability metrics, and real-world data. Educational approaches must move beyond conceptual exposure toward authentic engagement with operational systems, where students can explore tradeoffs, constraints, and uncertainties inherent in climate-smart food production [16].

### 1.2 Experiential Learning as a Pedagogical Imperative

Experiential learning theory, grounded in the foundational work of Dewey and formalized by Kolb, conceptualizes learning as a cyclical process involving concrete experience, reflective observation, abstract conceptualization, and active experimentation. [17], [18] This framework has been widely adopted in engineering and agricultural education as a means of promoting deeper conceptual understanding, adaptive expertise, and professional skill development. [19] [20] [21]

A substantial body of engineering education research demonstrates that experiential, active learning approaches such as project-based learning, problem-based learning, and inquiry-driven laboratories lead to improved learning outcomes, increased retention, and stronger workforce readiness compared to traditional lecture-based instruction [22] [23] [24]. Meta-analyses show that active learning significantly reduces failure rates and improves performance across science and engineering disciplines.[22] In agricultural and biological engineering contexts, experiential learning has been shown to enhance students' ability to integrate engineering principles with biological systems, environmental constraints, and sustainability goals. [25], [26]

Hands-on engagement with real-world systems is particularly critical in domains characterized by complexity, uncertainty, and tradeoffs, such as agricultural robotics and controlled environment agriculture. These systems require learners to navigate interactions among physical infrastructure, biological responses, energy and water flows, and socio-environmental impacts. These dimensions cannot be fully captured through abstract models or isolated laboratory exercises. [27] Experiential learning environments allow students to confront system failures, data variability, and design constraints, fostering resilience, problem-solving capacity, and systems thinking. [28]

Experiential and context-rich pedagogies have been shown to disproportionately benefit students from historically underrepresented groups in STEM. Studies indicate that applied learning environments strengthen STEM identity, sense of belonging, and persistence by making learning relevant, collaborative, and socially meaningful [23], [29], [30]. In the context of land-grant institutions and minority-serving institutions, experiential learning in agriculture and sustainability can serve as a powerful mechanism for broadening participation while addressing workforce needs.

### 1.3 Controlled Environment Agriculture and Space-Inspired Innovation

Controlled environment agriculture technologies including hydroponic, aeroponic, and containerized farming systems enable precise regulation of light spectra, temperature, humidity, carbon dioxide concentration, and nutrient delivery.[9], [31] These systems are increasingly deployed in urban environments, food-insecure regions, and areas with limited arable land or water availability. CEA offers significant advantages in water-use efficiency, yield per unit area, and reduced exposure to pests and climate variability. [10], [11]

Beyond terrestrial applications, CEA technologies are central to space agriculture research and the development of sustainable life-support systems for long-duration missions. National Aeronautics and Space Administration's (NASA) Artemis program emphasizes the ability to "Live and Explore" on the Moon as a critical step toward deep-space exploration, requiring reliable food production systems that operate under extreme resource constraints. [32], [33] Controlled environment systems, combined with automation and robotics, form the backbone of proposed bioregenerative life-support systems for lunar and Martian habitats. [34], [35]

Space agriculture research particularly studies involving lunar and Martian regolith simulants provides a compelling, mission-driven context for experiential learning. These studies expose students to challenges such as nutrient-poor substrates, altered gravity, radiation exposure, and closed-loop resource management. [36] [37] [38] By engaging with space-inspired agricultural challenges, students develop advanced systems thinking skills while exploring technologies that have direct relevance to climate-resilient agriculture on Earth.

Educational initiatives that integrate space agriculture concepts with terrestrial CEA platforms allow learners to simultaneously address global food security, sustainability, and future exploration needs. This dual-use framing not only enhances student motivation but also situates agricultural robotics and controlled environment systems within a broader societal and technological narrative, reinforcing the relevance of experiential learning in preparing the next generation of agricultural and biological engineers. [39], [40].

### 1.4 Purpose and Research Questions

This study seeks to move beyond program description and provide a systematic evaluation of a multi-tiered experiential learning framework integrating agricultural robotics and CEA. While prior sections establish the importance of experiential learning in addressing workforce and sustainability challenges, there remains a need for empirical evidence demonstrating its impact on measurable learning outcomes and higher-order cognitive skills such as systems thinking.

The purpose of this study is to evaluate the effectiveness of an experiential learning program implemented at the University of Maryland Eastern Shore (UMES) in improving technical knowledge, self-efficacy, and systems thinking competency among participants across multiple educational levels. Systems thinking in this study is defined as the ability to identify system components, understand interconnections, recognize feedback mechanisms, and evaluate trade-offs within complex food–energy–water systems.

The study is guided by the following research questions: (1) To what extent does participation in experiential learning activities improve learners' technical knowledge and STEM self-efficacy? (2) How does experiential engagement influence systems thinking competency in the context of agricultural robotics and CEA? and (3) How do participants perceive the relevance of these experiences to career pathways, teaching practices, and real-world problem solving?

## 2. Program Context and Experiential Learning Framework

### 2.1 Institutional Context

UMES is an 1890 land-grant institution with a mission encompassing teaching, research, and extension, with a particular emphasis on serving historically underrepresented and rural communities. As part of the national land-grant system, UMES is charged with translating scientific and engineering knowledge into practical solutions that address societal needs in agriculture, natural resources, and community development. This tripartite mission, which includes education, discovery, and outreach positions the university as an ideal setting for implementing experiential learning models that integrate technical rigor with real-world relevance and public impact [41], [42]. Land-grant institutions have long played a central role in advancing agricultural innovation and workforce preparation, particularly through experiential and applied learning approaches such as cooperative extension, field-based instruction, and undergraduate research. [43] In recent years, scholars have emphasized the need for land-grant universities especially 1890 institutions to modernize these approaches by incorporating emerging technologies such as automation, robotics, and data-driven systems. [44], [45]. Experiential learning frameworks that leverage advanced agricultural technologies can simultaneously address workforce gaps, and broaden participation in STEM, and fulfill the land-grant mission to serve different communities [46].

The experiential learning framework described in this paper is aligned with UMES's land-grant mission by embedding agricultural robotics and controlled environment agriculture (CEA) into curricular, co-curricular, and outreach activities. Rather than treating experiential learning as an add-on, the program integrates hands-on research, instruction, and extension activities into a cohesive educational ecosystem. This approach reflects national calls for engineering and agricultural education programs to align institutional missions with contemporary challenges in sustainability, food security, and climate resilience [47], [48].

Importantly, the UMES context enables the program to address both local and global challenges. Students engage with technologies relevant to urban agriculture, sustainable food production, and resource-limited environments while simultaneously exploring applications to extreme and space-constrained systems, such as lunar and Martian agriculture. This dual-use framing strengthens student motivation and reinforces the societal relevance of engineering and environmental science education. [49]

## 2.2 Three-Pillar Experiential Learning Framework

The experiential learning program is structured around three interconnected pillars: (1) Research, (2) Education and Workforce Development, and (3) Extension and Outreach. These pillars ensure vertical integration across educational levels and horizontal integration across disciplinary boundaries, consistent with best practices in experiential engineering education.[50], [51]

**Research and Innovation**.

The first pillar emphasizes student engagement in applied research related to sustainable agriculture, agricultural robotics, and controlled environment systems. Undergraduate and graduate students participate in hands-on research activities involving FarmBot robotic platforms, Tower Garden aeroponic systems, and containerized farming technologies. These research experiences expose students to experimental design, data collection, system troubleshooting, and iterative optimization through skills that are central to engineering practice and innovation [52], [53]. Embedding students in authentic research contexts has been shown to enhance conceptual understanding, scientific reasoning, and persistence in STEM fields, particularly when research topics are connected to pressing societal challenges such as access to arable lands and food security. [54]

**Education and Workforce Development**.

The second pillar focuses on developing technical, professional, and transferable competencies through experiential learning embedded within coursework and structured programs including internships. Students acquire skills in applied agricultural sciences, automation, programming, sensor integration, data analysis, and systems thinking while also developing teamwork, communication, and reasoning abilities. These competencies align closely with ABET student outcomes and workforce expectations in agricultural and biological engineering, environmental engineering, and related disciplines.[41], [55]. Experiential learning environments that integrate engineering design with biological and environmental systems are particularly effective in preparing students for interdisciplinary careers in agri-tech, sustainability, and climate-smart infrastructure. [56]

**Extension and Outreach.**

The third pillar emphasizes dissemination of knowledge beyond the university through educator workshops, K–12 academies, and community demonstrations. Extension-oriented activities introduce educators and pre-college students to agricultural robotics and CEA technologies, supporting early STEM engagement and curricular innovation. Extension scholarship has increasingly recognized the importance of engaging learners across the educational pipeline to build a diverse and resilient workforce. [57], [58] By connecting university-based research and instruction with community partners, the program reinforces the land-grant mission while creating feedback loops that inform curriculum design and research priorities [59].

Collectively, the three-pillar framework supports a systems-based approach to experiential learning. Students move fluidly between research, instruction, and outreach contexts, reinforcing learning through multiple perspectives and applications. This integrated structure enables scalability, sustainability, and adaptability as key considerations for experiential learning initiatives in large-enrollment and resource-constrained institutional settings. [60], [61]

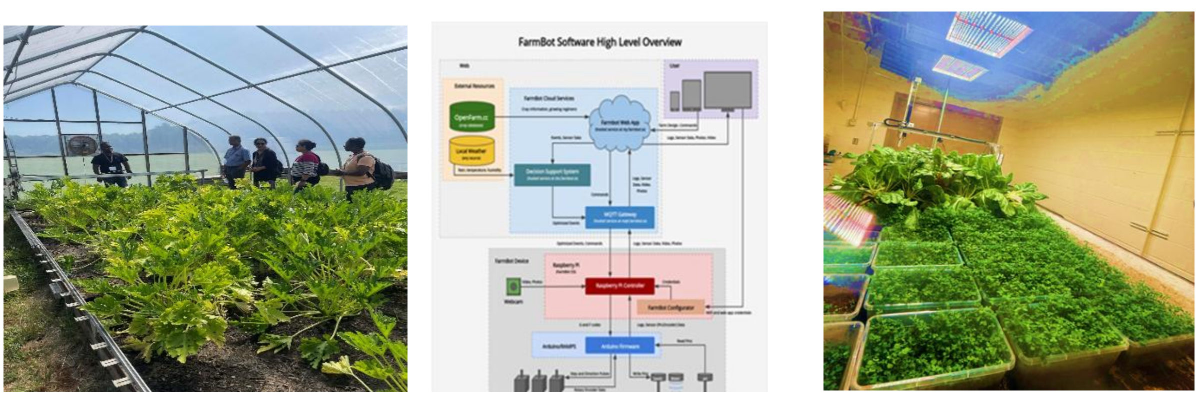
## 3. Materials and Methodology: Experiential Learning Platforms

A central feature of the experiential learning framework is the use of multiple agricultural technology platforms that span research-scale, instructional-scale, and commercial-scale systems. These platforms allow students to engage with agricultural robotics and controlled environment agriculture (CEA) at increasing levels of complexity. The use of multiple platforms also supports comparative analysis, systems thinking, and workforce alignment by exposing students to technologies used in academic research, education, and industry. [62]

### 3.1 FarmBot Robotic Agriculture Systems

FarmBot is an open-source, computer numerically controlled (CNC) agricultural robot capable of precision planting, irrigation, sensing, and monitoring [63]. Designed originally as a low-cost, accessible platform for precision agriculture, FarmBot combines mechanical motion systems, embedded controllers, and cloud-based software to automate key farming operations (Figures 1a-c). Its open-source architecture makes it particularly well suited for educational environments, as students can engage directly with both hardware and software components. [64] FarmBot systems were used as a primary pedagogical platform for introducing students to agricultural robotics and automation. Instructional activities were designed to develop competencies in robotic kinematics and spatial reasoning, as students learned to translate Cartesian coordinate systems into physical movement across a planting bed. These activities provided a practical introduction to automation logic and control systems within an agricultural context [65].

Precision irrigation and resource optimization were emphasized through experiments that required students to adjust watering duration, and frequency, along with treatments like applications of seaweed biostimulants and controls. By analyzing plant responses through morphological measurements such as plant biomass, leaf area indices, plant height, the crop performance was documented. The biochemical data especially on antioxidants following harvesting of plants were also recorded. Data collection further reinforced systems thinking, as students connected environmental inputs to biological outcomes. [66] The students were actively involved in system calibration, troubleshooting, and performance optimization. These experiences mirror real-world agricultural and engineering practice, where systems rarely function perfectly and iterative problem solving is required.[67] Prior research in engineering education has shown that engagement with system failure and troubleshooting is critical for developing adaptive expertise and professional confidence [68].




a b c

Figure 1a. Outdoor Farmbot inside a tunnel house with zucchini; 1b. Farmbot software assembly; 1c. Indoor Farmbot Express with alfalfa microgreens in the martian regolith simulant (MGS-1)

### 3.2 Tower Garden Aeroponic Systems

Tower Garden FLEX units represent a vertical aeroponic controlled environment agriculture system designed for space efficiency, water conservation, and accessibility [69]. Unlike soil-based systems, Tower Gardens suspend plant roots in air and deliver nutrients via a recirculating mist or spray, allowing for precise control over nutrient availability and water use (Figures 2a-b). These characteristics make aeroponic systems particularly relevant for sustainability education and resource-constrained environments. [70]

Within the experiential learning framework, Tower Garden systems were used to introduce learners to soil-free cultivation principles and the fundamentals of nutrient solution formulation and management. Students examined macronutrient and micronutrient requirements for leafy greens and herbs, monitored plant growth under controlled conditions, and compared aeroponic production to traditional soil-based approaches. These activities reinforced concepts in plant physiology, including nutrient uptake, transpiration, and growth responses to environmental variables [71]. Tower Gardens also provided a platform for introducing sustainability metrics such as water-use efficiency, yield per unit area, and labor requirements. Studies have shown that vertical aeroponic systems can reduce water use by up to 90% compared to conventional field agriculture, while significantly increasing productivity per square meter [72].

Due to their modular design, minimal maintenance requirements, and relatively low operational complexity, Tower Garden systems were particularly effective for engagement with K–12 educators and students. The accessibility of the platform enabled participants to engage meaningfully with food production technologies, supporting STEM education goals [73]. From a pedagogical perspective, Tower Gardens served as an entry point into CEA concepts.

a b

Figure 2. a. Tower Garden FLEX with bibb and gourmet lettuce when first transplanted; b. Bib lettuce after one month.

### 3.3 Freight Farms Containerized Systems

Freight Farms are fully enclosed, climate-controlled hydroponic systems housed within standard shipping containers and designed for commercial-scale food production [74]. These systems integrate advanced environmental controls, LED lighting, hydroponic nutrient delivery, and digital monitoring to enable year-round crop production independent of external climate conditions. Freight Farms represent a mature, industry-deployed CEA technology and are increasingly used in urban agriculture, institutional food systems, and food-insecure regions (Figure 3). [75].

While Freight Farms were not used for direct experimental manipulation in this study, they served as an important commercial-scale reference platform within the experiential learning framework. The site demonstrations enabled students to analyze system design, and operational logistics associated with containerized agriculture. Discussions focused on energy consumption, load management, and the tradeoffs between system control, productivity, and operating costs. [76].

Freight Farms also provided a context for examining commercial food production logistics, including supply chain considerations, labor requirements, and food safety regulations. By comparing FarmBot and Tower Garden systems with Freight Farms, students developed an understanding of how agricultural technologies scale from educational and research contexts to industry applications. This comparative analysis reinforced workforce awareness by highlighting the diverse roles available in advanced agri-tech industries, including systems engineering, data analytics, operations management, and sustainability consulting. [77] Exposure to Freight Farms helped bridge the gap between classroom learning and industry practice, a connection that has been identified as critical for improving workforce readiness in engineering and agricultural education [78]. By situating small-scale experiential platforms within a broader commercial landscape, the program enabled students to contextualize their learning within real-world agricultural systems and career pathways.

Figure 3. Freight Farm with spinach

## 4. Implementation: Applied Research and Learning Activities

Applied research and structured learning activities formed the core of the experiential learning framework, providing authentic contexts in which students, educators, and pre-college participants engaged with agricultural robotics and CEA. Activities were intentionally designed to align with experiential learning theory, undergraduate research best practices, and workforce development goals while remaining scalable across educational levels [79], [80] [81]

### 4.1 Undergraduate Internships

Undergraduate internships constituted the primary mechanism for deep technical engagement with agricultural robotics and CEA systems. A total of ten interns (including one summer intern from Aerospace Engineering through exchange program) were recruited from biology, environmental science, agriculture, engineering, computer science, through competitive application processes including interviews emphasizing academic preparation, interest in sustainability or automation, and commitment to interdisciplinary learning. Priority was given to students from historically underrepresented backgrounds, consistent with land-grant and inclusive STEM education objectives [82], [83].

Student interns conducted applied research focused on crop growth, nutrient management, and automation using FarmBot robotic platforms and Tower Garden aeroponic systems. Research activities included designing experiments using lunar regolith simulants to examine plant response under resource-limited and nontraditional growing conditions. These experiments required students to formulate hypotheses, identify control and treatment groups, and justify experimental parameters such as regolith concentration, irrigation frequency, and nutrient composition. Automation and data acquisition were central components of the research experience. Students programmed automated irrigation and imaging routines using FarmBot's Lua-based scripting environment, enabling time-lapse monitoring and precision water delivery.

These activities align closely with established best practices in undergraduate research, which emphasize student ownership of inquiry, iterative problem solving, and dissemination of findings [79, 84]. Prior studies demonstrate that participation in undergraduate research enhances retention, scientific reasoning, self-efficacy, and graduate school aspirations, particularly for students from underrepresented groups in STEM [29], [30], [85]. By embedding research within operational agricultural systems, the program enabled students to connect theory with practice while developing competencies relevant to careers in agri-tech, sustainability, and engineering research.

### 4.2 Summer Educator Workshop: Indoor Urban Sustainable Agriculture with Emergent Technologies (IUSAET)

The Indoor Urban Sustainable Agriculture with Emergent Technologies (IUSAET) workshop served as a professional development mechanism for scaling the impact of agricultural robotics and CEA education. A total of six participants included K–12 teachers and university faculty selected through an application process that prioritized teaching role, potential for curriculum integration, and commitment to outreach. Participation requirements stated that attendees were expected to integrate selected workshop content into their teaching, curriculum, outreach, or professional practice, reinforcing transfer and sustainability of impact. The two-day workshop combined hands-on training, field-based demonstrations, and reflective curriculum design activities using Farmbot webapp (Figures 4a-b).

Activities included guided demonstrations of FarmBot robotic systems, where participants explored how automation supports precision planting, irrigation, and monitoring in indoor food production. Aeroponics modules using Tower Garden systems introduced soil-free vertical cultivation, emphasizing pesticide-free production and suitability for classrooms and urban educational spaces.

A distinctive feature of the workshop was the inclusion of culturally grounded and accessible activities, such as a hands-on Kokedama (Japanese moss ball gardening) demonstration, which participants created as take-home projects for classroom or outreach use. Additional modules on food packaging and preservation addressed food safety, nutrition, and shelf-life considerations, linking agricultural production to downstream food systems and public health. Field tours further expanded participant exposure to real-world applications, including Freight Farms containerized systems, outdoor and indoor FarmBots, and climate-resilient alley cropping demonstrations The workshop concluded with design-your-own-Farm activities and participant reflections, reinforcing experiential learning cycles and encouraging curricular adaptation.

Teacher professional development is widely recognized as a critical leverage point for scaling STEM education innovations. Research shows that educator confidence and perceived relevance strongly predict classroom adoption of new technologies and pedagogies [31], [32], [86]. By combining technical exposure, curriculum-ready activities, and peer networking, the IUSAET workshop supported both pedagogical competence and sustained implementation**.**


a

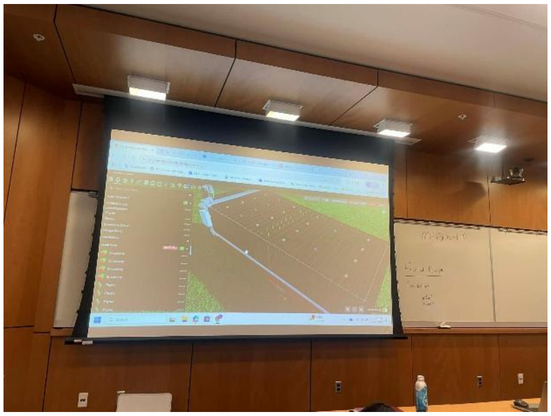

b

Figure 4 a Kokedama presentation at the IUSAET; b: Designing of a sustainable farm by the participant using the Farmbot WebApp

### 4.3 Agricultural Robotics Academy for High School Students (SEASAR)

The Summer Enrichment Academy in Sustainable Agriculture and Robotics (SEASAR) provided early, immersive exposure to agricultural robotics and sustainability for four high school students. Participants were recruited regionally through school partnerships and outreach materials emphasizing interest in STEM, agriculture, or environmental issues. Selection aimed to broaden participation by engaging students from diverse socioeconomic and educational backgrounds.

The three-day academy combined hands-on laboratory activities, field tours, and project-based learning. Activities included introductory programming and automation exercises using FarmBot systems, where students observed and interacted with robotic irrigation processes. Sensor-based monitoring modules introduced students to data interpretation, allowing them to connect environmental conditions to plant growth outcomes. Students participated in structured field tours of Tower Garden installations, Freight Farms, and FarmBot systems across campus, providing exposure to both research-scale and commercial-scale CEA technologies. Complementary sessions addressed food processing, preservation, and sustainability, linking agricultural production to nutrition and public health. Laboratory activities, such as analysis of total phenolic content (TPC) in plant samples, introduced students to basic analytical techniques and the concept of functional foods. Pre- and post-assessments were administered to evaluate learning gains, and certificates of completion were awarded upon program completion

Early exposure to authentic, hands-on STEM experiences has been shown to significantly increase students' likelihood of pursuing STEM majors and careers, particularly when activities emphasize real-world relevance and career pathways [33], [87], [88]. The academy therefore functioned as a critical pipeline component, reinforcing interest in agricultural and biological engineering before college entry.

## 5. Results and Discussion

A mixed-methods evaluation framework was employed to assess learning outcomes, engagement, and transfer of knowledge across participant groups, including undergraduate and graduate research interns, K–12 educators participating in the IUSAET workshop, and high school students enrolled in the SEASAR Agricultural Robotics Academy. This approach is consistent with best practices in engineering education research, which recommend combining quantitative measures of learning with qualitative evidence of engagement, motivation, and applicability [79], [80].

### 5.1 Evaluation Design and Data Collection

A convergent mixed-methods research design was employed to evaluate the impact of the experiential learning program across participant groups, including undergraduate interns (n = 10), educators participating in the IUSAET workshop (n = 6), and high school students enrolled in the

SEASAR academy (n = 4). All participants completed at least one form of assessment, resulting in a participation rate of 100% across groups. Participant demographics and participation rates are summarized in Table 1.

| Group | N | Completed Assignments | Participation Rate |
|---|---|---|---|
| Undergraduate interns | 10 | 10 | 100% |
| Educators (IUSAET) | 6 | 6 | 100% |
| High School Students (SEASAR) | 4 | 4 | 100% |

Table 1 Participant demographics and participation rates

Multiple data sources were used to capture cognitive, affective, and behavioral outcomes. Quantitative data were collected using a 30-item multiple-choice pre- and post-assessment instrument designed to measure knowledge in agricultural robotics, controlled environment agriculture, food systems, and sustainability concepts.

To explicitly evaluate systems thinking, a structured rubric was developed based on established literature, incorporating four dimensions: identification of system components, understanding of interconnections, recognition of feedback loops, and evaluation of trade-offs. Each dimension was scored on a five-point scale. The rubric used for evaluation is shown in Table 2.

| Dimension | Description | Scale |
|---|---|---|
| Components | Identification of System Elements | 1-5 |
| Interconnections | Understanding relationships | 1-5 |
| Feedback loops | Recognition of system dynamics | 1-5 |
| Trade-offs | Evaluation of competing factors | 1-5 |

Table 2. Systems Thinking Rubric

Qualitative data were collected through reflection journals, focus-group discussions, and open-ended survey responses. Reflection prompts included questions such as: “Describe a challenge encountered and how you resolved it” and “Explain how water, energy, and nutrient systems interact in controlled agriculture.” Focus groups were conducted with 3–5 participants per group, each lasting approximately 30–45 minutes.

### 5.2 Outcomes

#### 5.2.1 SEASAR (High School Students)

All four SEASAR participants demonstrated improved post-test performance relative to their pre-test scores when assessed using the identical 30-question instrument covering food safety (GAPs and GMPs), food preservation and packaging, robotics fundamentals, automation, FarmBot, Tower Garden, Freight Farms, drones, and plant phenolic compounds. The post-test content assessed both foundational knowledge (e.g., definitions of robots, sensors, actuators, and autonomy) and applied understanding (e.g., purpose of FarmBot, aeroponics in Tower Gardens, hydroponics in Freight Farms, and interpretation of Total Phenolic Content assays). Gains across all students indicate that the academy's short-duration, immersive format was effective in supporting conceptual learning across multiple STEM domains.

Quantitative analysis of pre- and post-assessment scores revealed substantial learning gains among SEASAR participants. The mean pre-test score was 48.5% (±6.2), while the mean post-test score increased to 82.3% (±5.8), representing an average gain of 33.8 percentage points. A paired t-test indicated that this improvement was statistically significant ($p < 0.01$), suggesting that even a short-duration experiential intervention can yield meaningful learning gains. A summary of these results is presented in Table 3. These results indicate strong improvement in both foundational and applied knowledge areas, supporting the effectiveness of immersive, hands-on STEM learning environments.

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| **Metric** | **Pre-Test (%)** | **Post-Test (%)** | **Gain** | **p-value** |
|---|---|---|---|---|
| Knowledge Score | 48.5 ± 6.2 | 82.3 ± 5.8 | +33.8 | <0.01 |

Table 3. Pre- and Post-Assessment Results for SEASAR Participants

In addition to cognitive gains, qualitative observations during the academy indicated increased confidence in discussing STEM topics, greater curiosity about agricultural and biological engineering careers, and improved ability to connect food production technologies to health, sustainability, and environmental outcomes. These findings are consistent with prior research showing that early exposure to authentic, hands-on STEM experiences significantly increases students' likelihood of pursuing STEM majors and careers [87], [88].

### 5.2.2 Undergraduate Interns

Quantitative outcomes for undergraduate interns further demonstrate the effectiveness of experiential learning in developing technical and cognitive competencies. As shown in Table 4, interns exhibited significant gains in knowledge, self-efficacy, and systems thinking. These improvements reflect increased confidence, deeper conceptual understanding, and enhanced ability to analyze complex agricultural systems.

| Metric | Pre | Post | Gain |
|---|---|---|---|
| Knowledge (%) | 62 | 88 | +26 |
| Self-Efficacy (1-5) | 2.8 | 4.4 | +1.6 |
| Systems Thinking (1-5) | 2,5 | 4.2 | +1.7 |

Table 4. Undergraduate Intern Learning Outcomes

### 5.2.3 IUSAET Workshop (Educators)

Analysis of the IUSAET Workshop Evaluation Forms revealed consistently positive outcomes across participants. Responses to open-ended questions indicated that the most valuable components of the workshop included: Hands-on interaction with FarmBot robotic systems, which demystified automation and increased confidence in using robotics for instructional purposes. Tower Garden aeroponic demonstrations, which participants identified as immediately transferable to classrooms, school gardens, and outreach programs. The Kokedama hands-on activity, frequently cited as an accessible, culturally engaging, and low-cost tool for introducing plant science and sustainability concepts. Participants reported strong intentions to apply workshop content in teaching, curriculum development, extension programming, and community outreach. Many respondents referenced plans to integrate FarmBot demonstrations, Tower Garden modules, and food systems activities into lesson plans, STEM clubs, or professional training programs. Sessions on food packaging, preservation, and safety, which participants noted as filling a gap in existing curricula and strengthening connections between agriculture, nutrition, and public health.

Overall, educator responses reflected increased confidence in integrating robotics-enabled agriculture and CEA concepts into educational settings, aligning with research demonstrating that teacher confidence and perceived relevance are key predictors of sustained classroom adoption of new technologies [31], [32], [86].

Educator survey results indicated strong positive outcomes, particularly in confidence and intent to implement learned concepts. These findings are summarized in Table 5.

| Metric | Mean (1–5) |
|---|---|
| Confidence in teaching Robotics | 4.6 |
| Ability to integrate CEA | 4.5 |
| Likelihood of implementation | 4.7 |

Table 5. Educator Workshop Outcomes

### 5.2.4 Systems Thinking Development

To directly address the role of systems thinking, this study evaluated changes using a structured rubric. Results indicate substantial improvements across all dimensions. Changes in systems thinking scores are shown in Table 6. These findings demonstrate that experiential learning environments facilitate higher-order cognitive development, enabling participants to understand complex interdependencies within agricultural systems.

| Dimension | Pre | Post |
|---|---|---|
| Components | 2.6 | 4.3 |
| Interconnections | 2.3 | 4.1 |
| Feedback Loops | 2.1 | 3.9 |
| Trade-offs | 2.4 | 4.0 |

Table 6. Systems Thinking Development Across Dimensions

Key qualitative themes identified through thematic analysis are summarized in Table 7. These themes reinforce quantitative findings and provide deeper insight into participant experiences.

| Theme | Description | Example Quote |
|---|---|---|
| Systems Thinking | Understanding system interactions | "Everything is connected…" |
| Confidence | Increased technical confidence | "I can program now…" |
| Relevance | Real-world application | "This felt real…" |
| Engagement | Increased interest in STEM | "This changed my perspective…" |

Table 7. Summary of Qualitative Themes

### 5.2.5 Cross-Cutting Outcomes

Across participant groups, several common outcomes emerged:

a) Improved understanding of automation and systems thinking, particularly in relation to food–energy–water interactions.

b) Increased confidence in data-driven reasoning, including interpretation of sensor data, experimental results, and sustainability metrics.

c) Enhanced motivation toward STEM and engineering pathways, especially among high school students and early-career undergraduates.

d) Educator readiness to implement curriculum-ready modules involving agricultural robotics, aeroponics, and sustainable food systems.

These outcomes align with documented benefits of experiential and active learning in engineering and sustainability education [22], [23], [56].

## 6. Discussion

The results of this study demonstrate that experiential learning centered on agricultural robotics and controlled environment agriculture (CEA) can effectively advance technical learning, systems thinking, and workforce readiness across multiple educational levels. By integrating applied research, educator professional development, and pre-college engagement within a single, coherent framework, the program illustrates how experiential learning can be scaled while maintaining depth, rigor, and inclusivity.

### 6.1 Experiential Learning as a Catalyst for Systems Thinking

A central contribution of this work is the demonstration that hands-on engagement with agricultural robotics and CEA systems fosters systems thinking, an essential competency for addressing complex food, energy, and environmental challenges. Across participant groups, learners were required to reason about interdependencies among biological processes, automation, resource flows, and sustainability outcomes. Whether through programming FarmBot irrigation routines, analyzing plant responses in aeroponic systems, or interpreting food safety and preservation data, participants engaged with authentic system constraints rather than simplified abstractions.

These findings reinforce prior research showing that experiential learning environments are particularly effective for developing systems-level reasoning because they expose learners to non-linear relationships, tradeoffs, and uncertainty inherent in real-world systems. Importantly, the observed learning gains were not limited to technical knowledge but extended to students' ability to contextualize engineering decisions within broader environmental and societal frameworks. This aligns with national calls for engineering education to prepare graduates who can evaluate the broader impacts of their work rather than focusing solely on technical optimization.

### 6.2 Workforce Preparation and Career Pathway Development

The program's multi-tiered structure supports workforce development by creating vertically integrated learning pathways from high school through undergraduate and graduate research experiences. SEASAR participants demonstrated measurable gains in foundational knowledge related to robotics, food systems, and sustainability, suggesting that short-duration, immersive experiences can effectively build early interest and competence. Such early exposure is particularly critical in agricultural and biological engineering, fields that often remain underrepresented in pre-college STEM pipelines.

For undergraduate interns, and graduate students who worked as their immediate mentors, the applied research experiences mirrored professional engineering and scientific practice, emphasizing experimentation, automation, data analysis, troubleshooting, and communication. These competencies directly align with workforce needs in emerging agri-tech sectors, including precision agriculture, indoor farming, and climate-smart food systems. The proposed intern evaluation framework further strengthens this alignment by explicitly assessing technical skills, systems thinking, communication, and professional identity development.

Educator participants represent a multiplier effect for workforce preparation. By increasing educator confidence and providing curriculum-ready tools, the IUSAET workshop extends program impact beyond the university and into K–12 and community learning environments. This finding underscores the importance of professional development as a mechanism for sustaining and scaling workforce-relevant STEM education innovations.

### 6.3 Implications for Engineering Education Practice

From an engineering education perspective, this work offers several actionable insights:

a) Experiential platforms matter: Open-source, scalable technologies such as FarmBot and Tower Garden enable meaningful engagement without prohibitive cost or infrastructure.

b) Assessment must be multi-dimensional: Combining cognitive, affective, and professional skill measures provides a more complete picture of learning outcomes.

c) Vertical integration strengthens impact: Linking pre-college, undergraduate, graduate, and educator experiences reinforces learning pathways and workforce pipelines.

d) Context drives engagement: Sustainability- and space-inspired framing enhances relevance, motivation, and systems-level thinking.

These implications suggest that similar experiential frameworks could be adapted across engineering and environmental science programs seeking to address sustainability, automation, and workforce development challenges.

### 6.4 Limitations

Several limitations should be considered when interpreting these findings. The relatively small sample sizes, particularly for SEASAR participants, limit generalizability. The short duration of program interventions restricts long-term assessment of learning retention. Additionally, some measures relied on self-reported data, which may introduce bias. Future research will include longitudinal tracking, larger cohorts, and comparison groups to strengthen validity.

## 7. Conclusions and Future Directions

This work demonstrates that experiential learning grounded in agricultural robotics and CEA provides a powerful, scalable approach for advancing systems thinking, workforce readiness, and inclusive STEM participation. By integrating FarmBot robotic platforms, Tower Garden aeroponic systems, and commercial-scale Freight Farm technologies across undergraduate research, educator professional development, and pre-college enrichment, the program successfully bridged theory and practice while aligning with workforce development missions.

The findings indicate that hands-on engagement with automation, sensing, and food production systems supports measurable gains in technical knowledge, confidence, and motivation across participant groups. High school students demonstrated improved conceptual understanding through pre- and post-assessments, educators reported increased readiness to integrate robotics-enabled agriculture into curricula, and undergraduate and graduate interns engaged in authentic research experiences that mirrored professional engineering and scientific practice. Collectively, these outcomes reinforce the value of experiential, systems-based pedagogies for preparing learners to address complex challenges in food security, sustainability, and climate resilience.

A key contribution of this work is the demonstration of a vertically integrated experiential learning framework that connects K–12 students, educators, undergraduates, and graduate researchers within a shared ecosystem of technologies and learning objectives. This structure not only strengthens educational pathways into agricultural and biological engineering but also amplifies impact through educator professional development and community engagement.

The incorporation of space-inspired agricultural challenges, including lunar regolith-based experiments and closed-loop production concepts, further enhanced student engagement and broadened perceptions of agriculture as a technologically advanced and future-oriented field. This dual-use framing addressing both terrestrial and extraterrestrial food systems offers a compelling model for motivating students while maintaining relevance to pressing Earth-based sustainability needs.

Future work will focus on strengthening assessment rigor through longitudinal tracking of student persistence, career trajectories, and graduate school enrollment. Planned enhancements include expanded use of artificial intelligence and advanced sensing, deeper evaluation of systems thinking development, and broader dissemination of curriculum modules through extension networks and educator communities. Additional emphasis will be placed on formalizing mentor training and refining intern assessment rubrics to ensure consistency and scalability.

In summary, this program illustrates how experiential learning in agricultural robotics and controlled environment agriculture can serve as a transformative platform for engineering and STEM education. By intentionally integrating research, education, and outreach, the framework provides a replicable model for institutions seeking to prepare a diverse, future-ready workforce capable of addressing global food system challenges on Earth and beyond.

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