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Development of SMART Farm Kit for Experiencing STEM Integrated Education in Biotechnology and Agriculture

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Abstract

Smart farming is a transformative technology addressing food crises in urbanized societies. The SMART farm kit was created to incorporate this concept into education as a practical tool that effectively integrates STEM (Science, Technology, Engineering, and Mathematics) with agriculture and biotechnology. The SMART farm kit, designed using single-board microcontrollers, sensors, and actuators, enables students to explore automation and problem-solving through practical applications. The program was piloted in South Korean middle and high schools, where qualitative data were collected through student and teacher interviews. Results showed that the SMART farm kit enhanced students' understanding of smart farming, STEM concepts, and real-world problem-solving skills. Teachers' and students' responses highlighted its interdisciplinary benefits and potential for curriculum integration. While promising, further optimizations and refinements in hardware design, software functionality, and teacher training are needed to maximize its accessibility and educational impact.

Introduction

Smart farming is regarded as a revolutionary future technology that can address the food crisis in rapidly urbanizing societies [1]. However, in contemporary educational settings, opportunities for students to engage with agriculture and biotechnology are insufficient and limited due to urbanization. At the same time, there is a growing need for an integrated educational approach in schools to prepare future generations. In this context, the SMART farm kit was developed in response to the increasing demand for future global issues. From an educational perspective, the SMART farm kit can be an excellent educational tool that bridges the STEM disciplines, literally integrating science, technology, engineering, and mathematics to provide holistic and authentic learning experiences. By focusing on agriculture, the SMART farm offers a hands-on, practical approach to scientific inquiry, which is often more accessible than other educational tools and experiences. This makes it an ideal STEM integrated education model, particularly for introducing students to biotechnology and agricultural innovation.

Literature review

Research on smart farms commenced with a study introducing the concept of vertical farming technologies, which promises increased crop yields within a reduced footprint of land. This compactness has made the technology particularly innovative for urban environments, where it has been successfully implemented in large-scale structures, such as those in Chicago. [1]. In the industrial sector, research has focused on the development and application of smart farms for vocational education and efficiency innovations [2, 3]. Likewise, in the educational field, there are several efforts to introduce smart-related technologies. For instance, the 2022 revised curriculum for practical arts (technology and home economics)/information subjects incorporates achievement standards for sustainable agriculture education utilizing smart farms at the sixth-grade level, as well as broader standards pertaining to smart cities and devices in middle school [4]. Similarly, the 2022 revised curriculum for science addresses the global food crisis and includes the utilization of smart devices in various domains [5]. Given the timeline for implementing the 2022 curriculum, students will begin learning about smart farm-related technologies starting in 2026.

Nevertheless, research on agricultural and biotechnology education in K-12 is insufficient, both domestically and internationally. For example, Schneller et al. (2015) presented a case study on hydroponics, not smart farms which does not fully align with the concept of smart farms. Other studies in Asia have largely focused on hydroponics in Southeast Asia [6, 7]. In Korea, Kim and Moon [8] developed a kit and program for integrating smart farms into elementary education. However, the kit was designed as a pre-structured tool for younger students in Practical Arts classes, limiting their autonomy. In secondary education, Oh et al. [9] developed a smart farm education program for middle school technology classes, demonstrating improvements in students' engineering problem-solving abilities. These efforts have primarily focused on practical arts or technology education contexts, often utilizing hydroponics or pre-assembled kits with limited flexibility for student-led exploration.

In this context, the primary objective of this study is to develop a highly practical and applicable kit for teaching biotechnology and agriculture through integrated STEM education. The effectiveness of the kit will be evaluated through a comprehensive assessment process.

Research questions

1) How should SMART farm kit for STEM integrated education be designed?
2) What impact does the smart farm kit have on students?

Methodology

Research design

In the initial phase of this study, researchers developed a smart farm kit to support students' learning about smart farming. Subsequently, as a case study, the Smart farm kits were implemented in middle and high schools, and qualitative data were collected from both students and teachers through interviews.

Participants

Participants included 168 third-year students enrolled in technology classes at a private middle school, and 15 first- and second-year students enrolled in an after-school program at a private high school. Participants were all male and their age ranged from 14 to 17. Among those, nine middle school students volunteered for the interview, and two high school students volunteered for the interview.

In terms of student background, all participants were members of the general class, irrespective of their academic achievements. In Korea, private schools observe to the national curriculum, ensuring that all students share a common academic foundation. For high school students, they had studied biology in science classes during the ninth grade, and they had engaged in practical arts and technology classes throughout elementary and middle school. They had never taken a kind of prerequisite regarding smart farming since the study was conducted before the generation of 2022 revised curriculum.

The program overview

At the start of the program, students were organized into groups of four members, with each group receiving one smart farm kit. The students also had individual laptops provided by the school. The teaching of the program was conducted directly by the researchers for the middle school, while high school sessions were led by a pre-trained teacher. The teacher in charge of the program was responsible for managing all aspects of the sessions, including the overall process and student engagement.

Table I. The Program Plan for Implementation

Middle School		High School	
Lesson	Course Description	Lesson	Course Description
1-6	▪ Learning embedded programming and basic electronic circuit operation using microcontrollers ▪ Practicing 3D design using Sketchup app	1	▪ Understanding the basics of smart farming ▪ Introduction to the smart farm project Team building Setting your own goal of the project
7	▪ Introduction to the smart farm project Team building Setting your own goal of the project	2	▪ Setting up the physical computing environment Reviewing software coding and 3D design for building smart farms
8-10	▪ Software design for their projects reconstructing the Arduino code scaffolded by the teacher	3-4	▪ Hardware design 3D printing and leveraging various materials (e.g., aluminum, pvc, wood) to build smart farms ▪ Hardware troubleshooting
11-13	▪ Hardware design of their own smart farms using the Sketchup app	5-7	▪ Software design and integration with hardware Utilization of various softwares (including A.I., Arduino code, and more) for problem-solving ▪ Hardware and software troubleshooting
14-15	▪ Troubleshooting (problem-solving; adjusting the software and hardware)	8	▪ Analysis of problems and discussion of improvements
16	▪ Presentation and peer evaluation		

The program was structured differently for middle and high school students according to levels of achievement (Table I). The middle school program consisted of 16 lessons, which was roughly double the time required for the high school program. This was because high school students had prior knowledge of physical computing and did not require additional learning on microcontrollers, resulting in shorter lesson times. Both programs began with an introduction to smart farming, and the hardware and software components were taught separately, although the order varied oppositely. Middle school students generally progressed more slowly than high school students. In the final stage, students identified issues and engaged in discussions to address them.

Data collection and analysis

Two methods were used for data collection: student interviews and teacher interviews. Qualitative data was collected through interviews to validate the efficacy of the developed SMART farm kit and identify areas for enhancement. To achieve this, the interview subjects were restricted to a subset of participating students, and all two instructors who utilized SMART farm kits during the lesson were required to participate in the interviews. The student interviews were conducted as semi-structured focus group interviews, lasting approximately 30 minutes. Teacher interviews were conducted individually and lasted around 20 minutes. The interview questions are summarized in Table II. The student interview questions consisted of five open-ended questions, while the teacher interview questions included four detailed inquiries about their observations, applicability, and other relevant insights.

Table II. The Questions on SMART Farm Kit Application

Teacher Version	Student Version
1. Tell me about the utilization/application of the SMART Farm kits in your class. - In which subject and class types did you utilize the SMART Farm kits? - Which grade level did you target? - How many students were in your class? - Over how many sessions was the class taught? 2. Tell me about in what ways the SMART Farm kits were helpful for students' learning in terms of learning STEM subjects. 3. Do you think the SMART Farm kits are applicable in STEM-integrated courses from a teacher's perspective? Reflect on the following aspects. • Preparation and instruction difficulty • Cost • Time management • Student evaluation • Collaboration with colleagues 4. What challenges did you face when using and teaching SMART Farm kits?	[Student] 1. Tell me what SMART Farm is. Describe in your own words. 2. What was your goal when using SMART Farm kits? 3. Do you think the SMART Farm kits were helpful for learning? Tell me more about what you learned through using the kits. 4. What challenges did you face when making and utilizing SMART Farm kits? 5. Can you share your reflection on the utilization of SMART Farm kits?

Results

The current section describes the development of SMART farm kit and teachers' and students' interview responses according to key components of the project.

The design of SMART farm kit

Hardware implementation

The hardware was centered around a controller and was divided into two main parts (See Fig. 1): actuator and sensor parts. To ensure accessibility, the system was designed to use popular microcontrollers such as Arduino, which are affordable and widely supported with reference materials available online.

The sensor components included a CdS (cadmium sulfide, photoresistors) sensor to detect sunlight, a soil moisture sensor for monitoring soil humidity or water level in the vase, and a temperature/humidity sensor to regulate the overall environment. The actuator components included a water pump, which activated based on readings from the soil moisture sensor to maintain appropriate soil hydration. In addition to the sensors, an LCD (liquid crystal display) monitor was integrated to provide users with a visual status of the smart farm. A LED (light-emitting diode) was set in the smart farm to provide an appropriate amount of light inside in addition to natural sunlight considering class setting. A DC (direct current) fan was also included, based on research suggesting that artificial stress environments can affect crop growth [10, 11]. This setup allowed students to control and manipulate variables that could have positive or negative effects on the system by themselves.

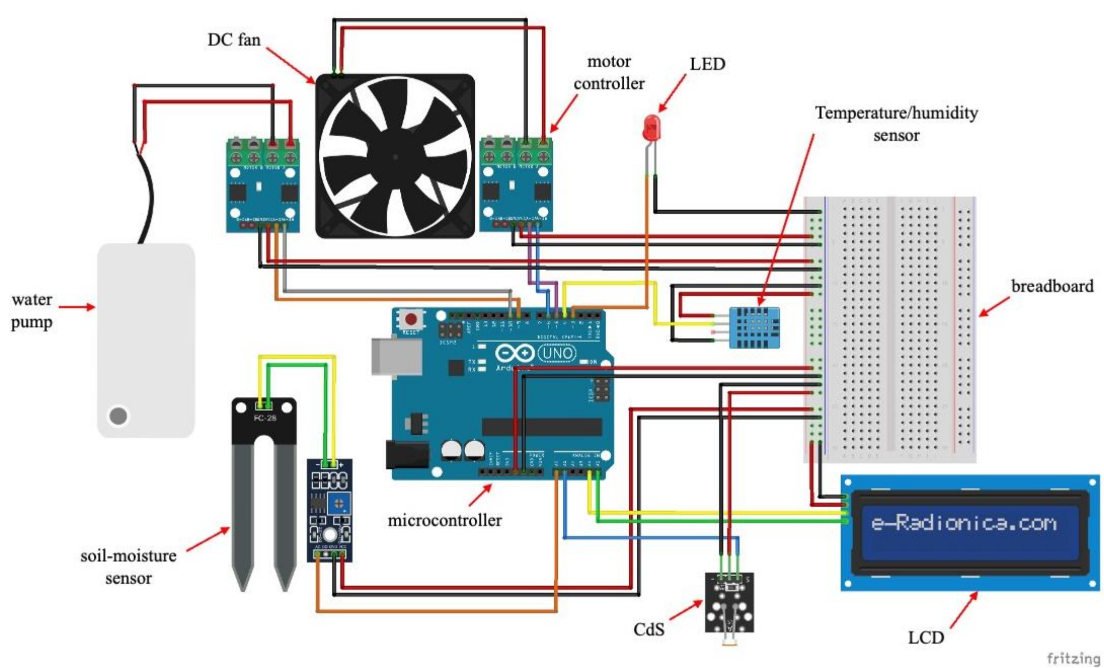

Fig 1. The Circuit and Hardware of SMART Farm Kit

Software Implementation

The software control was implemented using Arduino's free software, which utilized a C/C++ language-based IDE (integrated development environment) platform. Arduino served as the main controller, and basic algorithms and code samples are shown in Fig 2 and 3. For user convenience, the system displayed overall status messages on the LCD monitor. A continuous loop syntax controls the data from the temperature and humidity sensors, soil moisture sensor, and light sensor. When specific thresholds were exceeded or errors occurred, the actuators responded accordingly.

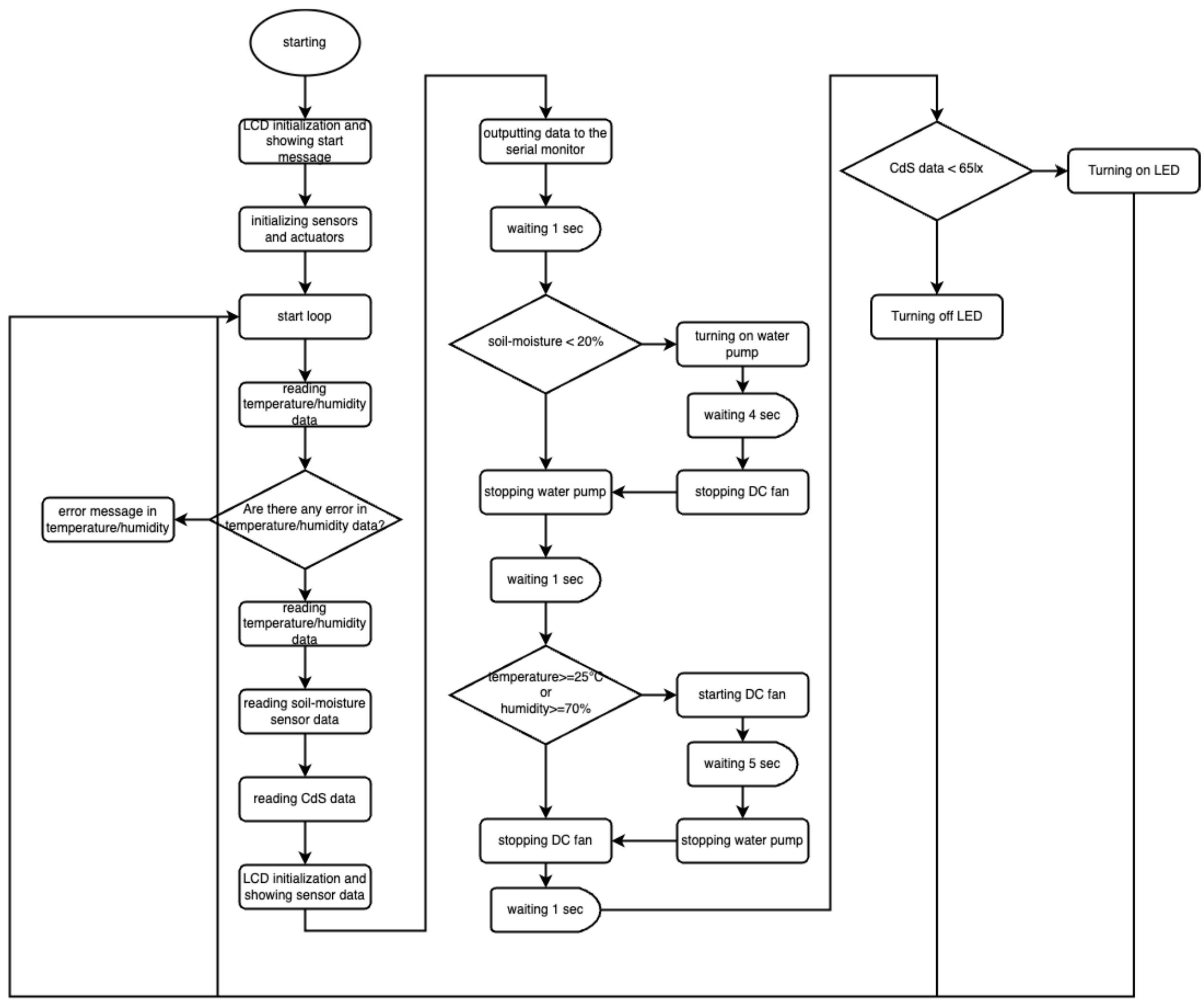

Fig 2. The Algorithm of SMART Farm Kit

```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <DHT.h>
#define DHTPIN 4
#define DHTTYPE DHT11
#define B_1A 9
#define    B_1B 10
#define    A_1A 6
#define    A_1B 5
#define SOIL_HUMI A0

LiquidCrystal_I2C lcd(0x27, 16, 2);
DHT dht(DHTPIN, DHTTYPE);

int cds_pin = A1;
int cds_ledpin=3;
int soil, psoil;
int val, ledval, pledval;

void setup() {
  lcd.init();
  lcd.clear();
  lcd.backlight();
  lcd.setCursor(3,0);
  lcd.print("SmartFarm");
  lcd.setCursor (5,1);
  lcd.print("Start");
  Serial.begin(9600);
  Serial.println("SmartFarm START!");
  delay(3000);
  dht.begin();
  pinMode(A_1A, OUTPUT);
  pinMode(A_1B, OUTPUT);
  digitalWrite(A_1A, LOW);
  digitalWrite(A_1B, LOW);
  pinMode(B_1A, OUTPUT);
  pinMode(B_1B, OUTPUT);
  digitalWrite(B_1A, LOW);
  digitalWrite(B_1B, LOW);
  pinMode(cds_ledpin, OUTPUT);
}

void loop() {
  float h = dht.readHumidity();
  float t = dht.readTemperature();
  if (isnan(h) || isnan(t)){
    Serial.println("Failed to get the data from
DHT sensor!");
    return;
    }
  soil = analogRead(SOIL_HUMI);
  psoil = map(soil, 1023, 0, 0, 100);
  val = analogRead(cds_pin);
  ledval = map(val,0, 1023, 250, 0);
  pledval = ledval*0.4;
  lcd.init();
  lcd.clear();
  lcd.backlight();
  lcd.display();
  lcd.setCursor(0,0);
  lcd.print("M: "); lcd.print(psoil);
lcd.print("%");
  lcd.setCursor(8,0);
  lcd.print("D: "); lcd.print(pledval);
lcd.print("lx");
  lcd.setCursor(0,1);
  lcd.print("T: "); lcd.print(t,0);
lcd.print("C");
  lcd.setCursor(8,1);
  lcd.print("H: "); lcd.print(h,0);
lcd.print("%");
  Serial.print("humidity: ");
  Serial.print(psoil);
  Serial.print("    lx: ");
  Serial.print(pledval);
  Serial.print("    temp: ");
    Serial.print(t);
    Serial.print("    humid: ");
    Serial.print(h);
    Serial.println();
    delay(1000);

if(psoil < 20) {
  analogWrite(B_1A, 200);
  digitalWrite(B_1B, LOW);
  delay(4000);
  digitalWrite(B_1A, LOW);
  digitalWrite(B_1B, LOW);
  digitalWrite(A_1A, LOW);
  digitalWrite(A_1B, LOW);
  }
  else{
  digitalWrite(B_1A, LOW);
  digitalWrite(B_1B, LOW);
}
  delay(1000);
if(t >= 25 || h >= 70) {

  analogWrite(A_1A, 230);
  digitalWrite(A_1B, LOW);
  delay(5000);
  digitalWrite(A_1A, LOW);
  digitalWrite(A_1B, LOW);
  digitalWrite(B_1A, LOW);
  digitalWrite(B_1B, LOW);
}
else{
  digitalWrite(A_1A, LOW);
  digitalWrite(A_1B, LOW);
}
  delay(1000);
  if (pledval <65) {
    analogWrite(cds_ledpin, ledval);
  }
    else{
    analogWrite(cds_ledpin, LOW);
  }
}
```

Fig 3. The Software Code of SMART Farm Kit

The effects of SMART farm kit implementation

Understanding smart farming and agriculture

Students generally showed a good understanding of smart farming concepts. The interviews with middle school students (M5 and M6) reflect their understanding of smart farming not merely as hydroponics but as a concept involving "automation" and "minimal intervention." Their use of terms such as "minimal labor" and "necessary elements" indicates they grasped the efficiency goals of smart farming.

> *"I think a smart farm is a type of farm where, as long as it keeps supplying elements like electricity and water, crops can grow without certain intervention" (M5)*

> *"A smart farm integrates modern technology with farming, automating processes to operate the farm with minimal labor while maintaining stable conditions for cultivation" (M6)*

Smart farm learning has also been demonstrated to be beneficial for agricultural education. The responses of high school students effectively articulate the concept of smart farming using precise terminology. Simultaneously, they demonstrate an improvement in their understanding of agriculture by comprehending the interactions between crops and factors such as temperature and environmental conditions. Furthermore, they acknowledge the environmental impact and demonstrate an understanding of the rationale behind their education in the field of future agriculture, particularly smart farms.

> *"A smart farm is a system that uses ICT technology to enhance productivity and efficiency in agriculture. For example, if temperature or environmental conditions fall below a certain threshold, connected devices are activated to adjust the conditions back to optimal levels, creating an ideal environment for crop growth" (H1)*

> *"Smart farming, a concept briefly defined as utilizing cutting-edge technologies to enhance crop yields, reduce costs, and minimize the environmental impact of agriculture, offers numerous benefits to the agricultural sector." (H2)*

Support for STEM learning and career

The smart farm kit proved particularly effective in broadening prior knowledge, interconnecting concepts, and facilitating real understanding of previously unclear ideas.

> *"I didn't know how to connect certain sensors or where to place resistors, but I searched online, went through trial and error, and eventually figured it out" (M2)*

> *"While this activity didn't involve Arduino, I've previously used Micro:bit and sensors to make an automatic trash can. Back then, block coding made me the process quite complicated, but this time, coding in C/C++ text gave me a real understanding of programming, which felt fresh." (M8)*

> *"Before making the smart farm kit, I participated in a school project researching 'optimal light wavelengths and intensities for plant growth.' Based on that, we adjusted LEDs. I think adding a small manual explaining how to set up LEDs for different plants would improve the kit" (H1)*

Although students had prior experiences with sensors, resistors, and physical computing, they often lacked confidence. However, they overcame challenges through independent internet searches and experimentation, ultimately understanding more complex programming languages like C. The high school student even connected the activity to prior science lessons, offering future directions for improving the kit.

Additionally, during the interview with the middle school student, he expressed his aspirations for a career in the STEM field. Furthermore, he mentioned that gaining knowledge about smart farms instilled in him confidence and assurance in selecting their major.

“The smart farm project really helped me with my studies. I’m hoping to go to a university in STEM field, and this project taught me about electronic circuit configuration, coding, and automation systems. It made me feel more confident about choosing my major and future career.” (M7)

Problem-solving skills

The ′seeking problem-solving′ and ′flexible and unstructured′ natures of the smart farm activity encouraged students to confront and solve problems by themselves. While schools typically teach about electricity without delving into problem-solving, students demonstrated the ability to troubleshoot power issues on their own. The high school students′ use of ChatGPT for efficient problem-solving highlights how technology was leveraged.

"While building the smart farm, we faced an issue with insufficient power supply. Specifically, we couldn’t operate the LCD, motor, and water pump simultaneously. To solve this, we separated the power supply into one unit powered by Arduino and another using an external power source." (M5)

"When writing code for the smart farm device, errors often occurred. To solve these efficiently, we often used ChatGPT to debug and optimize the code." (H2)

Advantages of smart farming

Teachers highlighted the advantages of the smart farm compared to more structured models or hydroponics. Teacher 1 emphasized that the kit's greatest strength lies in enabling students to engage in self-directed learning. Teacher 2 noted that the kit supports interdisciplinary learning by integrating various engineering elements with science and technology, making it highly beneficial for pursuing integrated STEM education.

"Previously, students would follow instructions to assemble kits, but the smart farm kit requires them to understand its basic structure and algorithms, allowing them to modify and experiment independently. As a result, students felt like developers, solving problems in real-time, which significantly enhanced learning outcomes." (T1)

"Through this project, students learned basic concepts of electrical and electronic systems, communication, material selection and application, and biotechnology, which helped integrate multiple fields." (T2)

Improvement for SMART farm kit

Feedback on potential issues was gathered from both students and teachers. Students suggested that using graphs and data visualization would help them better understand the concepts. Teacher 1 pointed out that for those without a coding background, additional learning time and prerequisite courses would be necessary, highlighting the lack of electrical and electronic education in standard school curricula. Teacher 2 noted that the smart farm kit was still a prototype, emphasizing the need for improvements in cost-efficiency and further alignment with student curricula. In response to the complaints, he proposed that many teachers require assistance in implementing and developing lesson plans and materials to address the identified issues. He also suggested that sharing the knowledge and ideas would help teachers implement these improvements effectively in the educational field. Furthermore, two teachers emphasized the need for cost-effective solutions to actively implement these improvements in the classroom.

> *"If we could visualize the data in graphs and compare it with the actual results from the kit, the activity would feel much more engaging and help students better understand." (H2)*
>
> *"For beginner students in coding, more time is needed to learn the basics. Additionally, to make sure stable implementation of SMART farm kit, learning for foundational knowledge of coding, hardware functionality, and electronics is required." (T1)*
>
> *"This is a prototype rather than a fully developed smart farm. Improvements are needed in cost-efficiency, student preparation, and curriculum alignment. To address the complaints, we should try the kits and lessons in various settings. Teachers should share their knowledge and ideas." (T2)*

Discussion

Enhancing authentic problem-solving skills

An analysis of the students' responses revealed that they not only developed an understanding of smart farming but also expanded and interconnected their prior knowledge. While students were already familiar with the individual concepts of "smart" and "farm," the integrated activity of smart farming allowed them to synthesize biology, agriculture, electrical and electronic engineering, and computer engineering on their own. Teachers facilitated this learning process by encouraging self-directed group activities with the kit instead of traditional one-sided lectures.

Moreover, students demonstrated growth in areas where they previously lacked confidence. For example, they gained an understanding of advanced text coding languages such as C/C++, resolved confusion about sensors, and they even suggested visual graphing to analyze data for the future improvements for the kit. This shows that the smart farm kit effectively helped students not only grasp fundamental concepts but also expand and deepen their knowledge.

Differentiating from previous smart farming programs

The smart farm kit stands out compared to previous programs. Earlier research focused on incorporating well-established technologies, such as hydroponics, into education. On the other hand, these approaches were limited in addressing future food challenges or stimulating students' learning motivation. Additionally, previous smart farming programs were too structured to offer opportunities for autonomous learning.

In contrast, the smart farm kit enabled students to engage in various extended activities to solve problems, such as reorganizing power alignment structures, adjusting variables for plant growth, or using different programming languages. This flexibility allowed students to employ higher-order cognitive skills in STEM learning, enabling them to analyze and solve real-world problems effectively.

Future directions

While introducing smart farming into education, several challenges were identified. Both teachers and students pointed out issues with coding and circuit design. Although the teachers successfully managed to resolve these problems, minimizing obstacles, optimizing circuits, and reducing time wasted will be essential for smooth implementation and clear learning objectives. These efforts could also contribute to lowering the kit's production costs.

Additionally, challenges related to curriculum integration were evident. Prerequisite knowledge was an issue, as students individually varied in their physical computing skills and familiarity with computer activities, resulting in differing learning paces. Fortunately, no further steps in the program exceeded the curriculum's scope. Nevertheless, further research is needed to determine the appropriate grades, subjects, and units in which smart farming should be learned and taught. Given the interdisciplinary nature of STEM education and smart farming, collaboration with biology or agriculture teachers within schools will ultimately be necessary as well.

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