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STEAM-BASED SMART MICROGREEN SYSTEM WITH LIGHT AND MOISTURE SENSORS TO SUPPORT THE SUSTAINABLE DEVELOPMENT GOALS (SDGS)

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Abstract

This study aimed to develop a smart, sensor-driven microgreen cultivation system aligned with the Sustainable Development Goals (SDGs). Using the ADDIE model, including Analysis, Design, Development, Implementation, and Evaluation, the research integrated scientific inquiry, engineering design, and digital technology under a Science, Technology, Engineering, Arts, and Mathematics (STEAM) framework. The system used moisture and light sensors controlled by an ESP32 microcontroller. Results showed better microgreen growth compared to conventional methods. These improvements occurred because automation provided precise control over irrigation and lighting, optimizing conditions while minimizing water and energy use. Internet of Things (IoT) connectivity and the Message Queuing Telemetry Transport (MQTT) protocol enabled real-time data transmission and monitoring. This project supports SDG 2 (Zero Hunger), SDG 4 (Quality Education), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Overall, the system advances sustainability, enhances STEAM-based learning, and contributes to innovative, environmentally conscious agricultural practices.

Keywords: Automation, Microgreen, Oisture sensor, SDGs, STEAM.

1. Introduction

Microgreens have attracted increasing attention due to their rich phytochemical content and distinctive flavour profile [1]. Studies indicate that their concentrations of vitamins and carotenoids are approximately 30-40 times higher than those of mature vegetables and fruits [2]. These miniature greens are also rich in antioxidants, including phenols, vitamins A, C, and E, and essential minerals such as copper, magnesium, and zinc [3]. Owing to these bioactive compounds, microgreens are commonly consumed in the form of juices, smoothies, shakes, and salads [4]. Research using *in vitro* and *in vivo* models has confirmed their health benefits, demonstrating anti-inflammatory, antimicrobial, anticancer, and antihyperglycemic properties [5]. Consequently, microgreens are gaining popularity in commercial markets, particularly among high-end restaurants and premium grocery outlets, where consumer perception significantly influences demand [1].

Although microgreens are relatively easy to grow, improper cultivation practices (such as excessive humidity or insufficient lighting) can lead to issues like mold growth [6]. Germination is typically enhanced by pre-soaking seeds and sowing them in substrates such as soil, cocopeat, or vermiculite, under controlled humidity and extended photoperiods ranging from 12 to 16 hours per day [1]. Their adaptability to small, controlled environments makes them suitable for urban farming systems with limited land availability.

To achieve high-quality yields, it is essential to optimize critical environmental factors, including light, temperature, and humidity. This has led to the application of agricultural intelligence systems that utilize the Internet of Things (IoT) and sensor technologies to monitor substrate humidity [7] and light conditions. These technologies support data-driven decision-making, improving resource efficiency and contributing to sustainability. Their application aligns with the Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger), SDG 4 (Quality Education), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Given that agriculture consumes approximately 70% of global freshwater resources, the development of water-efficient food production systems has become imperative. Recent advances in sensor technologies offer solutions for improving irrigation efficiency and mitigating the effects of overwatering, with automated systems enabling precise regulation of water based on real-time crop performance [8]. These innovations reduce waste and increase productivity, laying the groundwork for sustainable agriculture. In response to these global challenges, the integration of Science, Technology, Engineering, Arts, and Mathematics (STEAM) and digitalization into agricultural practices presents new opportunities for innovation and education [9].

This research aims to design a sensor-based automated microgreen cultivation system using STEAM principles, evaluate the performance of light and moisture sensors, and assess the system's impact on supporting the SDGs. Guided by the ADDIE model, which encompasses Analysis, Design, Development, Implementation, and Evaluation, the study presents a novel integration of STEAM pedagogy with sensor-based automation, yielding a water- and energy-efficient farming solution that addresses food security, sustainability, and educational objectives.

2. Method

This research employed a multidisciplinary framework grounded in STEAM, which stands for Science, Technology, Engineering, Arts, and Mathematics. The aim was to develop an automated microgreen farming system that supports the SDGs through the integration of scientific investigation, engineering design, and project-based learning. Each STEAM component was applied in the following ways:

(i) Science: Investigated photosynthesis, soil moisture, light intensity, and growth requirements of microgreens.

(ii) Technology: Programmed microcontrollers to interpret sensor inputs and control water pumps and light-emitting diode (LED) lights.

(iii) Engineering: Designed and assembled the automation system, including physical layout, wiring, and component integration.

(iv) Arts: Emphasized aesthetic aspects of the cultivation system, data visualization, and documentation.

(v) Mathematics: Processed sensor data created humidity and lighting graphs and analysed plant growth statistics.

To systematically guide the development process, the study adopted the ADDIE model, comprising Analysis, Design, Development, Implementation, and Evaluation stages [10]. The system was programmed using the Arduino Integrated Development Environment (IDE). The ESP32 microcontroller was coded to read input data from the BH1750 light sensor and a capacitive humidity sensor. Threshold-based logic was applied using *if–else* conditions to trigger output responses via a relay module. For example, when the substrate humidity dropped below a predefined threshold, the system activated the mini water pump. Similarly, low light intensity prompted the system to turn on the LED lamp. Additional programming functions enabled wireless communication through Wi-Fi, allowing the ESP32 to transmit real-time sensor data to an IoT-based monitoring platform.

To validate and verify the system's reliability, the automated microgreen setup was tested under various configurations. The validation phase ensured the program's ability to accurately read sensor inputs, perform logical operations, and activate the correct actuators. Verification involved repeated trials to assess performance stability during irrigation, illumination, and data transmission cycles.

Through these tests, the system was confirmed to be both functionally accurate and operationally reliable. The ESP32's programmed logic successfully implemented the design concept and fulfilled the requirements for practical application in automated microgreen farming and STEAM-based learning environments. Table 1 outlines the specific activities conducted during each stage.

Table 1. ADDIE model research procedure.

Stages	Activity
Analyse	Identified problems and needs related to microgreen cultivation and STEAM learning.
Design	Created a STEAM-based system incorporating light and moisture sensors and basic Internet of Things (IoT) integration.
Develop	Constructed the prototype based on the proposed system design.
Implement	Conducted trials to observe microgreen growth, automation responses, and educational relevance within the STEAM framework.
Evaluate	Assessed system performance and reflected on how well STEAM and SDG objectives were achieved.

3. Result and Discussion

At the analysis stage, the findings revealed that the main challenges in STEAM-based microgreen cultivation are the lack of interactive media and technical limitations in monitoring plant growth. The identified need was for an automated system that could integrate science, technology, engineering, arts, and mathematics while also fostering sustainability awareness.

The design stage produced a STEAM-based prototype system that integrates IoT, sensors, and actuators for automated microgreen cultivation. The main purpose of this design is to provide a hands-on learning medium that combines scientific observation, technological application, and system engineering in a simple yet effective framework.

Figure 1 illustrates the hardware architecture, in which the ESP32 microcontroller functions as the central processing unit. It processes input from the BH1750 light sensor and the capacitive planting medium humidity sensor, then transmits the processed data to a monitoring platform via Wi-Fi. The system design ensures that both analogue and digital signals from the sensors are correctly interpreted by the ESP32.

On the output side, the design integrates a relay module that controls the activation of the mini water pump for irrigation and a set of LED lights to provide artificial illumination when needed. This actuator control ensures that the cultivation system responds automatically to environmental conditions. For the power supply, the design incorporates a step-down converter to regulate the voltage before it is distributed to the actuators, ensuring stable and safe operation.

Through this design, the system not only fulfils functional requirements for automated microgreen growth but also serves as an accessible and illustrative tool to demonstrate STEAM concepts, from circuit design and coding to sustainability applications.

Figure 2 presents the hardware flow implemented on the ESP32 in the form of a flowchart that translates sensor readings into automatic actions. In this flow, the system will take data on light intensity and substrate humidity (planting media) at certain intervals. After that, it will evaluate each reading against a predetermined threshold at the humidity threshold used in this study is 40%, and execute control commands, where the LED light will be turned on when the ambient light intensity is below the predetermined setpoint, while the mini water pump is activated if the substrate humidity is below the threshold until the setpoint value is reached again. Error mechanisms and time constraints are integrated to avoid oscillatory behaviour and ensure stable environmental regulation.

In the hardware system described previously, sensor data will be generated, which will then be displayed for monitoring. Therefore, a method for sending data is needed, and in this study, the MQTT protocol is used to send data from the ESP32 to the application used to display it. Figure 3 shows the telemetry and remote control path using the publish and subscribe methods in MQTT. Where publish is a command to send data to the MQTT broker, then subscribe itself is a command to request data that matches a predetermined topic and is provided by the person who publishes it, while the MQTT broker itself is a temporary database that will store data until new data is published. The ESP32 functions as an MQTT client that publishes time-stamped sensor data payloads to the MQTT broker and subscribes to relevant control topics so that it can carry remote commands or configuration updates. The client application (IoT MQTT Panel) also subscribes to the same sensor topic to get data sent to the MQTT broker, so that the IoT MQTT panel enables asynchronous monitoring, lightweight remote observation, and basic reconfiguration while maintaining device automation for critical control functions.

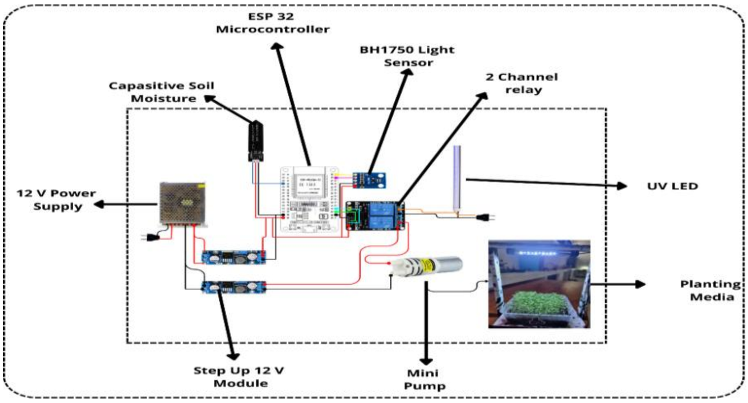

Fig. 1. Circuit design schematic.

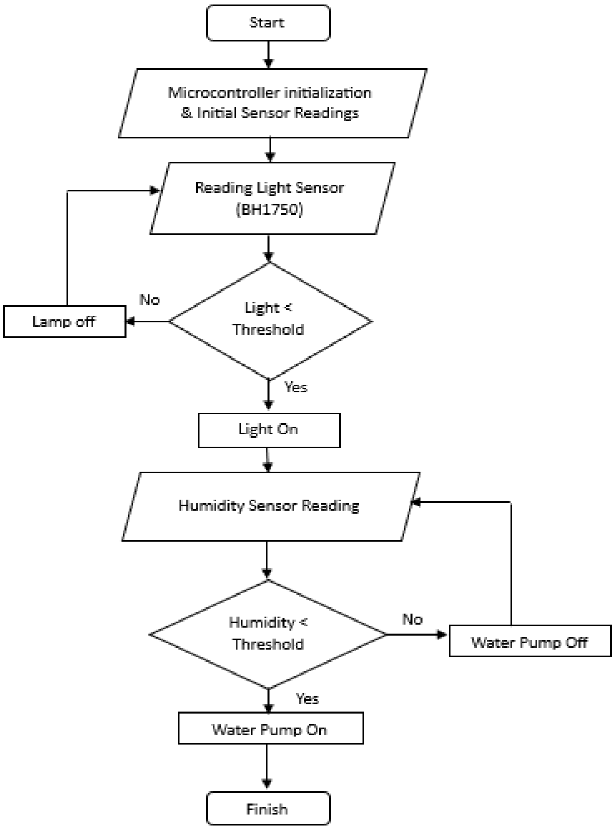

Fig. 2. Automatic system work flowchart.

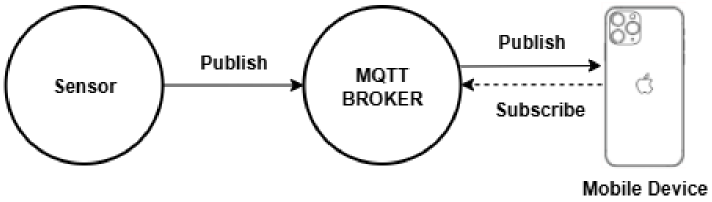

Fig. 3. MQTT flow system.

Figure 4 shows the complete data flow of how the data is sent through a hardware device, which is then received by software, namely the IoT MQTT panel. In the process, the ESP32 will initiate the MQTT client and MQTT broker so that it can connect to the MQTT broker. Then, after connecting, the ESP32 will publish the data with a predetermined topic periodically. Where the data is sent in the form of a payload, which is usually in the form of a JSON file, so it is more concise and faster in delivery. Then, the IoT MQTT panel will initiate the MQTT client to be able to connect to the MQTT broker so that it can run the subscribe command to request data that matches the topic that was initiated and previously determined. Then the data obtained will be decrypted into UTF-8. After that, the data will be broken down according to sensor data, which will then be displayed in the form of gauges and graphs on the IoT MQTT panel.

After explaining the hardware and software systems, the next step will be applied to microgreens, where the microgreen seeds used in this experiment are Spinacia oleracea (spinach), planted in sterile cocopeat media. System testing was carried out in the growth phase from day 3 to day 10 with two treatments: (1) the use of the STEAM-smart automated system (BH1750 light sensor and media humidity sensor with ESP32 control that regulates lighting and irrigation), and (2) control without automation. The parameters observed included average plant height, plant condition (turgor, stem elasticity), and leaf colour; observations were made daily and analysed descriptively-qualitatively to compare the performance of the two treatments. In addition, aspects of pedagogical implementation within the STEAM framework were recorded as part of the evaluation of the system's application in the learning environment.

During the development stage, the prototype was assembled according to the design plan. The results showed that the system functioned as intended, successfully monitoring light intensity and moisture levels while also activating an automatic water pump. Based on the trial results, light and humidity sensor data were obtained, which are presented in Table 2.

Table 2. Light and humidity sensor data.

Day to	Average Light (%)	Light	Average Humidity (%)	Automatic Watering
3	25%	Light up	87%	Off
4	20%	Light up	64%	Off
5	28%	Light up	45%	Off
6	29%	Light up	32%	Water flow
7	23%	Light up	76%	Off
8	16%	Light up	57%	Off
9	22%	Light up	30%	Water flow
10	18%	Light up	80%	Off

Note: Average Light (%) was obtained from the BH1750 light sensor readings throughout the day (every 2 hours). Humidity (%) was taken from the planting media humidity sensor using cocopeat.

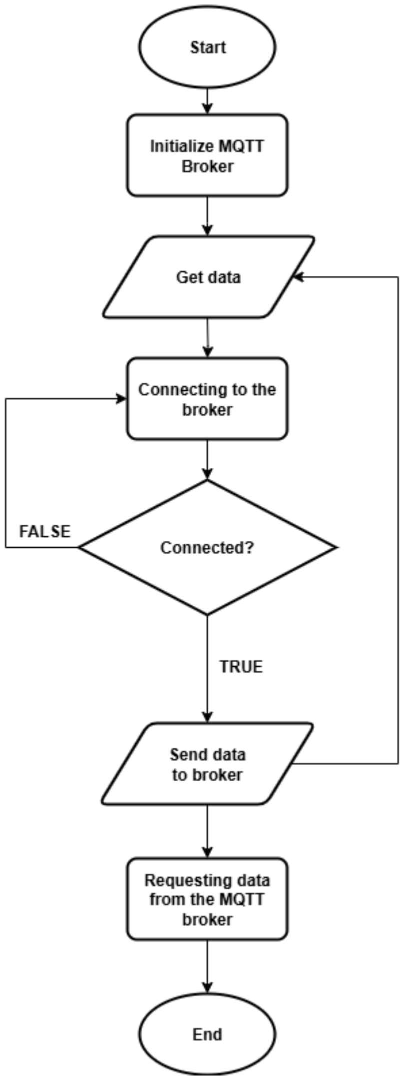

Fig. 4. Data communication flowchart.

This STEAM-based automated microgreen farming system was tested using sensors embedded in the microgreens. The system can be monitored via an IoT MQTT Panel Android app, monitoring plant conditions, including humidity and light. When light levels fall below 100%, the lights will automatically turn on and off when they reach 100%. Likewise, when humidity levels fall below 40%, the pump will turn on, and water will be automatically supplied. The physical setup of the system, including sensors, actuators, and an ESP32 microcontroller, is shown in Fig. 5, while the monitoring interface is presented in Fig. 6.

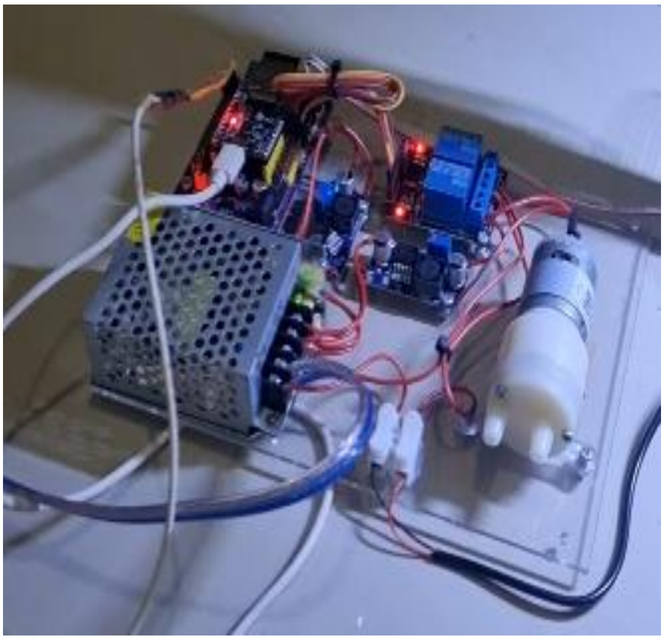

Fig. 5. Prototype of the STEAM-based microgreen automated system.

Fig. 6. IoT MQTT panel application view.

IoT technology can effectively reduce human intervention by automating vertical farming processes through computer-assisted monitoring, data processing, and reporting. IoT has advanced the concept of urban agriculture [11, 12]. IoT systems not only assist in anticipating and reducing crop failures but also employ sensors to monitor key environmental variables (light, temperature, pH) and transform them into data for analysis [13]. Artificial lighting incurs high costs, but its use in extending photoperiods within closed systems can render production both economically and environmentally sustainable [14].

In the implementation stage, trials were conducted using microgreen cultivation in cocopeat media over a set growth period. The automation system responded well to environmental changes, such as activating the pump when the moisture decreased. To provide clearer evidence of these findings, the results of observations on microgreen growth, condition, and leaf colour in both variations are systematically presented in Table 3. Visual comparisons of the cultivation outcomes are also illustrated in Fig. 7.

Table 3. Results of observations of microgreen growth, leaf condition, and colour.

Day to	Treatment	Control
3	Average height 1 cm, curved stem	Average height 1 cm, curved stem
4	Average height 1.2 cm, stem straight up following the LED light, fresh green leaves.	Average height 1.5 cm, curved stem, yellowish-green leaves
5	Average height 1.5 cm, stem straight up following the LED light, fresh green leaves.	Average height 1.8 cm, stem tilted and fallen, yellowish leaf colour.
6	Average height 1.7 cm, stem straight up following the LED light, fresh green leaves.	Average height 2.2 cm, fallen stems wither and leaves dry up.
7	Average height 2.1 cm, stem straight up following the LED light, fresh green leaves.	Average height 2.4 cm, stems are almost all collapsed and wilted.
8	Average height 2.2 cm, stem straight up following the LED light, fresh green leaves.	Average height 2.5 cm, fallen stems dry out and die.
9	Average height 2.6 cm, stem straight up following the LED light, fresh green leaves.	Average height 2.9 cm, fallen stems dry out and die.
10	Average height 2.8 cm, stem straight up following the LED light, fresh green leaves.	Average height 3 cm, most of the stems fall and dry up

The cultivation of microgreens is affected by various abiotic parameters, including substrate choice, fertilization, humidity, light intensity, and temperature, each of which plays a crucial role in determining post-harvest quality and shelf life [15, 16]. Based on the study's results, it was found that microgreens grown using a STEAM-based automated farming system exhibited better growth. This finding aligns with the results of research by [17], which revealed that experimental observations under dual growth settings showed that microgreens performed optimally under elevated light intensity.

Reduced light availability induces plants to enlarge their leaf surface and elongate in height, thereby maximizing light interception to sustain photosynthetic efficiency. Meanwhile, when light intensity is increased, plant leaf diameter and thickness are reported to increase due to the growth of palisade tissue to avoid excessive sunlight and promote photosynthesis [18]. As the primary energy source for photosynthesis, light is essential for plant growth and development, with its effects mediated by photoreceptors including phytochromes, chlorophyll, and related molecules.

However, the light source must meet the plant's needs for photosynthesis, so the ideal spectrum and irradiance vary by species [19]. Therefore, microgreens can also be produced indoors with supplemental lighting. The use of *light-emitting diodes* (LEDs) that emit photosynthetically active radiation can improve seedling growth in air-conditioned environments [20], as well as influence the production of pigments beneficial to human health, such as chlorophyll and carotenoids.

Based on recent findings, microgreen cultivation requires a photoperiod of 12–16 hours to support optimal growth. These crops have a short cultivation cycle and demonstrate high adaptability to vertical farming systems, particularly those implemented indoors using vertically stacked shelves and artificial lighting. Light-emitting diodes (LEDs), including white light (400–700 nm) and combinations of red (660 nm) and blue wavelengths, are widely used in such controlled environments to stimulate growth and developmental processes in plants [21, 22]. Compared to conventional lighting, LEDs offer greater energy conversion efficiency and are thus preferred in modern cultivation systems [22, 23].

(a) **(b)**

Fig. 7. (a) Microgreens without a system and (b) Microgreens with a system.

In this study, cocopeat was used as the primary growing medium. Observations revealed that humidity could be maintained for approximately two to three days before the sensor detected a level below 40%, triggering the automatic pump to activate. This outcome supports prior findings that cocopeat is highly suitable for microgreen production due to its excellent water retention, efficient drainage, weed- and pathogen-free characteristics, slow decomposition rate, acceptable pH range, strong cation exchange capacity, and stable electrical conductivity [17, 24].

As such, cocopeat is widely recognized as an effective substrate for soilless vegetable cultivation.

Proper regulation of humidity and temperature is essential for optimal plant development, as different species require specific conditions to maximize photosynthetic activity [25]. Deficiencies in water or nutrients can adversely affect the growth, visual quality, and yield of microgreens [16]. Water loss, in particular, contributes to accelerated deterioration and shortens shelf life. During postharvest storage, physiological responses such as ethylene-induced wilting and senescence further degrade pigment quality, reducing overall aesthetic and nutritional appeal [26]. An automated microgreen farming system based on the Science, Technology, Engineering, Arts, and Mathematics (STEAM) approach offers a viable solution by maintaining consistent moisture levels in the growing medium, thereby supporting healthy growth, and extending shelf life under controlled agricultural conditions.

Evaluation showed that the project supports the achievement of the SDGs, particularly Goal 2 (Zero Hunger), Goal 4 (Quality Education), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action). The outcomes highlighted improvements in sustainability awareness, collaborative innovation, and environmentally responsible practices. Building upon these results, each element of STEAM is integrated into the development of a practical and functional automated microgreen farming system. The application of this multidisciplinary framework not only supports technological innovation but also strengthens the cross-disciplinary approach required for addressing sustainability issues. The integration of STEAM with the SDGs provides significant added value, particularly in advancing sustainable practices, enhancing technological literacy, and optimizing resource use. The project's contributions to the SDGs are outlined below.

- SDG 2 (Zero Hunger). This project provides a small-scale farming solution that can be easily implemented at home or school. Cultivating highly nutritious microgreens can provide a healthy and affordable food source. The automated system allows anyone (including children and urban communities) to grow fresh vegetables without complex farming skills, contributing to reducing dependence on industrial food distribution.
- SDG 4 (Quality Education). This project promotes discovery-based, collaborative, and contextual learning based on the STEAM approach. Students develop 21st-century skills: critical thinking, problem-solving, technological literacy, and creativity. Connecting academic knowledge to real-world problems makes learning more relevant and meaningful. It provides opportunities for students to become innovators and problem-solvers in local contexts.
- SDG 12 (Responsible Consumption and Production). The automated system waters plants based on actual moisture, thus avoiding water waste. Microgreen cultivation also does not require large areas of land, excessive pesticides, or chemical fertilizers, uses simple and energy-efficient materials, and can be integrated with recycled materials (if further developed), thereby promoting wise and responsible consumption and production practices from an early stage.
- SDG 13 (Climate Action). The project raises awareness of climate-friendly agricultural practices by promoting localized food production, reducing dependency on resource-intensive supply chains, and highlighting innovation for environmental resilience.

STEAM, with its holistic and integrated approach, aligns closely with the SDGs and fosters resilience, environmental stewardship, and equitable development within the global agricultural sector [27]. The integration of STEAM and the SDGs further reinforce innovation and sustainability awareness, thereby driving solutions to real-world challenges such as hunger, responsible consumption, and sustainable production [28]. This study adds new information regarding SDGs, as reported elsewhere (Table 4).

Table 4. Previous studies on SDGs.

No.	Title	Ref
1	Sustainable development goals (SDGs) in engineering education: Definitions, research trends, bibliometric insights, and strategic approaches	[29]
2	Sustainable packaging: Bioplastics as a low-carbon future step for the SDGs	[30]
3	Production of wet organic waste ecoenzymes as an alternative solution for environmental conservation supporting SDGs	[31]
4	HIRADC for workplace safety in manufacturing: A risk-control framework and bibliometric review to support SDGs	[32]
5	Techno-economic analysis of production ecobrick from plastic waste to support SDGs	[33]
6	Techno-economic analysis of sawdust-based trash cans and their contribution to Indonesia’s green tourism policy and the SDGs	[34]
7	Definition and role of sustainable materials in reaching global SDGs completed with bibliometric analysis	[35]
8	Bibliometric insight into materials research trends and innovation to support SDGs	[36]
9	Physical adaptation of college students in high-altitude training to support SDGs	[37]
10	Enhancing job satisfaction through HRIS and communication: A commitment-based approach to SDGs	[38]
11	Enhancing innovative thinking through theory-based instructional model to support SDGs	[39]
12	Influence of self-efficacy on affective learning outcomes in social studies education toward achieving SDGs	[40]
13	Enhancing occupational identity and self-efficacy through self-education in art/design aligned with SDGs	[41]
14	Integrating generative AI-based multimodal learning in education to enhance literacy aligned with SDGs	[42]
15	Dataset on Sulawesi schools and cultural implications to support SDGs	[43]
16	Enhancing professional readiness in vocational education aligned with SDGs	[44]
17	School feeding program and SDGs in education: Linking food security to learning outcomes	[45]
18	Influence of eco-friendly packaging on consumer interest to meet SDGs	[46]

4. Conclusion

This research demonstrates that integrating STEAM-based technology with light and humidity sensor systems controlled by an ESP32 microcontroller enables the development of an automated, efficient, and environmentally sustainable microgreen cultivation system. The light sensor regulates optimal illumination levels, while the humidity sensor manages irrigation to conserve water and minimize resource waste. Experimental results show that the system successfully maintains favourable environmental conditions for microgreen growth, thereby enhancing both quality and productivity.

Moreover, this approach aligns with the SDGs, particularly SDG 2 (Zero Hunger), SDG 4 (Quality Education), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), by combining digital technology, sustainability awareness, and educational value. Consequently, this system holds strong potential as an innovative technological solution to support urban agriculture, enrich educational practices through STEAM-based learning, optimize resource efficiency, and contribute to global sustainability efforts.

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