IoT

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Evaluating the Impact of Controlled Ultraviolet Light Intensities on the Growth of Kale Using IoT-Based Systems

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Abstract: Incorporating Internet of Things (IoT) technology into indoor kale cultivation holds significant promise for revolutionizing organic farming methodologies. While numerous studies have investigated the impact of environmental factors on kale growth in IoT-based smart agricultural systems, such as temperature, humidity, and nutrient levels, indoor ultraviolet (UV) LED light's operational efficiencies and advantages in organic farming still need to be explored. This study assessed the efficacy of 15 UV light-controlling indoor experiments in three distinct lighting groups: kale cultivated using conventional household LED lights, kale cultivated using specialized indoor UV lights designed for plant cultivation, and kale cultivated using hybrid household and LED grow lights. The real-time IoT-based monitoring of light, soil, humidity, and air conditions, as well as automated irrigation using a water droplet system, was employed throughout the experiment. The experimental setup for air conditioning maintained temperatures at a constant 26 degrees Celsius over the 45-day study period. The results revealed that a combination of daylight household lights and indoor 4000 K grow lights scored the highest, indicating optimal growth conditions. The second group exposed to warm white household and indoor grow red light exhibited slightly lower scores but larger leaf size than the third group grown under indoor grow red light, likely attributable to reduced light intensity or suboptimal nutrient levels. This study highlights the potential of indoor UV LED light farming to address challenges posed by urbanization and climate change, thereby contributing to efforts to mitigate agricultural carbon emissions and enhance food security in urban environments. This research contributes to positioning kale as a sustainable organic superfood by optimizing kale cultivation.

Keywords: internet of things; indoor cultivation; IoT system; kale; light intensity; Raspberry Pi; UV light

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1. Introduction

An increase in the need for efficient resource management and food security has led to a surge in the demand for sustainable and regulated agricultural practices [1]. Kale has gained significant attention as a superfood due to its exceptional health benefits and culinary versatility [2] and has been recognized as a nutritional powerhouse. Kale, rich in phytonutrients, antioxidants, vitamins, and minerals, is a nutrient-dense addition to any diet [3]. Despite its nutritional value, kale cultivation encounters numerous obstacles in the contemporary agricultural environment. The adverse effects of climate change on weather patterns, including increased temperatures and unpredictable precipitation, pose considerable challenges for kale cultivators [4,5]. Increased temperatures have the potential to induce heat stress in plants, which can have detrimental effects on both growth rates and crop yields [6]. Agricultural practices that utilize toxic residues from herbicides and pesticides raise inquiries regarding kale production's environmental sustainability and food safety [7,8]. Given the obstacles mentioned earlier, it is critical to investigate novel approaches and environmentally sound resolutions to guarantee the ongoing production and accessibility of kale as a superfood for subsequent generations.

Integrating Internet of Things (IoT) technology into indoor kale cultivation presents significant potential for a paradigm shift and the advancement of organic farming methodologies. Particularly those enhanced by IoT technology, indoor cultivation systems present a promising resolution to those challenges [9–11]. IoT technology in precision agriculture enables the exact regulation of growing conditions, including light, temperature, and humidity, which are critical for the kale plant's growth. By incorporating sensors and actuators into indoor farming systems, IoT technology facilitates automated adjustments and continuous monitoring, guaranteeing ideal growth conditions that may increase nutritional value and yields. In addition, IoT technology enables organic farming to be more traceable and transparent by providing comprehensive data on crop cultivation methods, spanning from sowing to harvest [12]. By leveraging the IoT, farmers can enhance crop quality and productivity while advocating for sustainable and organic farming methods that prioritize consumer health and environmental stewardship [13,14].

IoT-based technologies have been the subject of extensive research and application in diverse agricultural sectors to augment productivity, sustainability, and resource efficiency within smart farming. The extant body of literature contains a multitude of studies that concentrate on the conception and advancement of automated systems intended to regulate environmental factors [14], including air quality [15–17], water [13,14,18,19], and soil [15,18–20], within a variety of crop cultivation environments [13,14]. The effectiveness of IoT-enabled sensors and actuators in optimizing crop growth parameters and reducing resource wastage is demonstrated in these studies [14,21]. For example, scholarly investigations into precision irrigation systems have demonstrated substantial water conservation and enhanced agricultural productivity by utilizing automated irrigation scheduling and real-time monitoring of soil moisture levels [10,22]. The utilization of IoT sensors for soil health monitoring has also allowed farmers to evaluate microbial activity [21], nutrient levels [23], pH balance [23,24], humidity [25,26], and temperature [25,26]. As a result, targeted fertilization and soil management practices have become more feasible. Furthermore, research on air quality monitoring has underscored the significance of IoT sensors in identifying contaminants and optimizing ventilation systems to establish ideal conditions conducive to crop growth [21,27].

Existing studies have concentrated on kale solutions in numerous IoT-related domains. Noer et al. [28] investigated the analysis of kale growth utilizing IoT devices and sensors to enhance the smart farming agricultural system. Two primary environments (soil moisture, air temperature, and humidity) were linked to a Raspberry Pi. A dashboard was implemented to display the environmental parameters on a web database powered by a Firebase server. Wongprasadpetch et al. [29] extended many IoT sensors to facilitate real-time monitoring to manage and analyze kale's data. This research utilized an LDR (light-dependent resistor) as an environmental sensor. Tachi et al. [30] implemented a kale-specific intelligent farm management system enabled by the IoT. Four primary functions comprise the proposed system: automated fertilization, reporting, detection of cutworms and aphids, and automatic irrigation triggered by weather forecasts. Wu et al. [31] utilized semantic segmentation to develop kale recognition. The qualities of kale were gathered and subsequently extracted. Although prior research has examined the effects of environmental variables on IoT-based smart farming systems, including temperature, humidity, lighting, pest detection, and kale growth characteristics, there is a notable research void concerning the application of controlled ultraviolet (UV) light intensities within these systems despite the progress made in IoT and IoT-based applications. UV light, which alters plants' phytochemical composition and morphology, can substantially impact kale's growth and nutritional value [29,32]. Nevertheless, the comprehensive investigation of UV light integration's operational efficiencies and distinct advantages in indoor IoT-based cultivation systems remains unattained. The existing knowledge gap provides a potential avenue for additional investigation into the advantages of customizing light conditions to optimize kale yield and nutritional value in enclosed spaces. This study is driven by the objective of determining the optimal light requirements for kale cultivation in indoor environments by integrating IoT technology with advanced lighting systems.

By applying a robust IoT system architecture, the main objectives of this study are as follows:

- To determine the impact of controlled UV light intensities on the growth of kale in an indoor environment. The authors hypothesize that the precise regulation of UV light exposure throughout the growth stages of kale will enhance both growth rates and health benefits.
- To provide actionable insights for indoor farming practices, contributing valuable knowledge to the broader domain of agricultural sciences and advancing the goals of sustainable agriculture and resource efficiency using IoT technology.
- To address existing agricultural obstacles in controlled environments by implementing sophisticated IoT technologies, optimizing and mechanizing agricultural processes to make indoor farming more adaptable, efficient, and aligned with the requirements of contemporary agricultural production.

This article thoroughly examines the innovative cultivation of kale indoors using IoT technology, emphasizing the impact of environmental factors and UV light on plant growth, and comprehensively describes the experimental setup, IoT system architecture, UV LED lighting configurations, and ecological control mechanisms. The 15 UV light-controlling experiments have yielded results that underscore the potential impact of various lighting groups on the nutritional content, plant health, and growth of kale. This study also highlights the potential findings of IoT and UV LED technology in indoor agriculture, sparking optimism and intrigue. The conclusion suggests exciting future research directions that have the potential to influence the future of indoor agriculture.

2. Theoretical Background

The literature review identifies research gaps that this study intends to fill and provides a comprehensive overview of the key areas pertinent to this study, including indoor kale cultivation, the application of IoT technologies in agriculture, the effects of UV light on plant growth, and all the above subjects.

2.1. Indoor Kale Cultivation

Agricultural research has centered on the indoor cultivation of kale due to the ability of the indoor system to regulate environmental benefits, such as prolonged growing seasons and diminished pest populations. Indoor farming can increase yield per unit area and provide precise microclimate control over the plant, as demonstrated by Ahamed et al. [33]. Chowdhury et al. [5] and Lee et al. [34] emphasized the significance of optimizing environmental conditions, including light, temperature, humidity, and CO_2, to improve kale growth and nutritional value. However, most of these studies have concentrated on aeroponic and hydroponic systems, integrating advanced IoT technologies in these environments that are receiving less attention.

The potential of indoor kale cultivation, which falls under the broader domain of controlled-environment agriculture (CEA), to yield vegetables of superior quality irrespective of external climatic conditions has generated significant attention [35,36]. Cultivating kale indoors entails the establishment of structures, including growth chambers, indoor vertical farms, and greenhouses, where environmental variables, including light, temperature, humidity, and nutrient provision, are carefully regulated. The study of indoor kale cultivation unveils many aspects, encompassing its merits, difficulties, and diverse cultivation methodologies, such as the distinction between organic and non-organic approaches [8].

An essential benefit of indoor kale cultivation is the capacity to generate crops throughout the year [37]. This feature significantly improves productivity and yield predictability, which is especially advantageous in regions characterized by unfavorable climates. Indoor plant cultivation also reduces reliance on pesticides by establishing a controlled environment that effectively mitigates the risk of pest and disease infestation [38]. In addition, indoor farming facilitates accurate resource management by employing recirculating systems to decrease water consumption and targeted fertilization techniques to minimize nutrient wastage [39]. The practice of cultivating kale indoors presents notable advantages and obstacles. The initial investment and ongoing operational expenses can be significant, including installing regulated environmental systems and continuous energy consumption, specifically for climate control and lighting.

Thorough management is imperative to ensure the success of indoor kale cultivation due to many factors. The significance of light intensity and spectrum concerning phytonutrient synthesis and plant growth rates cannot be overstated [29,32]. Maintaining precise temperature and humidity levels is critical to optimizing plant vitality and preventing the growth of pathogens [28]. Elevating CO_2 levels is also imperative due to their impact on photosynthesis rates and growth [5].

Implementing an IoT-enabled indoor cultivation environment enables the efficient regulation of the environmental conditions that promote the growth and development of kale. Understanding and controlling various conditions is essential to maximizing the yield and quality of the produce. Table 1 delineates the essential components for cultivating kale indoors.

Table 1. Factors for growing kale indoors.

Factor Concerns	Description
Soil and nutrition [40,41]	Kale thrives in well-drained, fertile environments with a pH between 6.0 and 7.5. In indoor hydroponics, soil is replaced with nutrient solutions or inert substrates such as coco coir or rock wool. Nutrients must include essential elements like nitrogen, phosphorus, potassium, calcium, and magnesium.
Temperature [42]	Optimal growth occurs at temperatures between 60 and 70 °F (15 and 21 °C). Kale can tolerate cooler temperatures and light frosts, but high temperatures above 80 °F (27 °C) can lead to bolting, which affects leaf flavor and texture.
Humidity [5,43]	The ideal relative humidity is between 60 and 70%. Excessive humidity can increase the risk of fungal diseases like powdery mildew, hence the need for good ventilation and air circulation to manage humidity effectively.
Light intensity [44]	Kale requires high light intensity, which is best provided by LED or fluorescent grow lights mimicking the full sun. The daily light requirement is about 12–16 h, focusing on the blue and red parts of the light spectrum.
UV levels [32,45]	UV light enhances kale's nutritional content by boosting the synthesis of vitamins and antioxidants. The optimal UV exposure needs careful management to avoid plant tissue damage while enhancing plant stress responses that benefit growth.
Growing cycle [46]	Depending on the variety and conditions, kale generally takes 55 to 75 days from seed to harvest. Indoor systems can accelerate this cycle. Kale allows for progressive harvesting by clipping outer leaves, letting the inner leaves continue to grow.

It is imperative to comprehend and efficiently oversee all of these variables in indoor kale cultivation to guarantee the plants' optimal health, productivity, and nutritional composition. Thus, the findings of this research permit the precise regulation of growing conditions via UV LEDs. An essential advantage of indoor farming that this study examines is the variety of lights utilized; this may result in higher yields and higher-quality produce than conventional outdoor farming.

2.2. IoT in Agriculture

The IoT in agriculture enables more data-driven and automated farming practices [9,14]. This technology signifies a paradigm shift. Smart farming technology based on the IoT enables real-time monitoring and control of agricultural environments, substantially improving operational efficiency and decision-making. It was a concern to investigate the benefits, drawbacks, and various facets of IoT implementation in agriculture, including instances of actual success. Emerging IoT technologies in the agricultural sector have brought about a paradigm shift in farming practices, favoring precision agriculture guided by data. In their study, Pereira et al. [25] described the effective utilization of IoT applications to monitor soil moisture and climate conditions, directly influencing irrigation practices and resource management. Real-time data collection and analysis have been made possible by IoT technologies, enabling immediate adjustments to be made to enhance plant health and productivity [47]. Agriculture gains numerous advantages from IoT technologies, including increased productivity and efficiency, decreased environmental impacts, and enhanced resource management. IoT devices in precision agriculture facilitate the precise administration of water, fertilizers, and pesticides, thereby diminishing expenditures and the ecological impact [13,47]. Furthermore, implementing IoT systems enables the ongoing surveillance of soil and crop conditions, thereby facilitating the timely identification of pests and diseases and mitigating the risk of extensive crop damage [48–50].

Moreover, the advantages of IoT in agriculture are confronted with several obstacles. The substantial upfront and ongoing expenses are particularly prohibitive for small- to medium-sized farms [51]. Additionally, concerns arise concerning data privacy and security, given the potentially sensitive nature of agricultural data and the potential ramifications for farm competitiveness or security [52]. Moreover, in remote or rural regions, the reliance on uninterrupted power supply and internet connectivity can pose a substantial obstacle, diminishing the dependability of IoT solutions [53]. As shown in Table 2, aspects of concern about implementing the IoT in agriculture encompassed a more comprehensive array of issues that could potentially impact the effectiveness and triumph of IoT systems.

Table 2. Factors influencing the implementation of IoT in agriculture.

Factor Concerns	Description
Microcontroller compatibility [9–15]	IoT devices must be compatible with microcontrollers that offer sufficient computational power, energy efficiency, and connectivity options to handle real-time data processing.
Automated control [10,13]	Systems require robust algorithms and reliable actuators for timely adjustments based on sensor data, which is crucial for managing irrigation systems and climate controls in greenhouses.
Data logging and processing [54]	Effective data logging is essential for tracking long-term trends, while advanced processing capabilities are needed for predictive analytics and optimizing responses.
Network stability and connectivity [53]	Stable network connections are critical to ensure continuous data transmission and system reliability, especially in remote or rural areas where connectivity issues occur.
Energy efficiency and management [13]	IoT devices and systems must optimize energy use to enhance sustainability and reduce operating costs, particularly in large-scale deployments.

User training and support [55]	Adequate training for farm personnel on IoT system operation and troubleshooting is necessary to maximize the benefits and minimize disruptions in agricultural processes.
Scalability of IoT solutions [56]	The ability to scale IoT solutions efficiently as the farm grows or as new technologies emerge is crucial for the long-term viability and expansion of IoT applications in agriculture.
Regulatory compliance [57]	IoT implementations must comply with local and international regulations regarding technology use in agriculture, which can vary significantly by region.

2.3. Role of UV Light in Plant Growth

The development and physiology of plants are significantly impacted by UV light, which affects growth patterns and resistance to pests and diseases [58]. To enhance commercial factories, Yoon et al. [59] examined the advantages of UV light for plant growth, with a specific focus on kale, which maximizes UV light exposure. The complexities surrounding the operation of UV-B radiation in plant biology have been the subject of extensive investigation. Burana et al. [60] examined the concentrations of flavonoids in kale regarding the effects of specific UV–C irradiation. This discovery suggests that light spectra could be manipulated to delay the nutritional value of chlorophyll degradation. Notwithstanding this, most previous studies have solely concentrated on the impacts of UV radiation under typical circumstances, with a limited inquiry into the regulated implementation of UV in the IoT-enabled indoor farming environments.

UV light, specifically UV-B, elicits many beneficial responses in plants. UV light can improve the color and flavor of plants, including leafy greens like kale, which is crucial for their commercial viability [60]. Research has demonstrated that under-controlled UV exposure can enhance the thickness and waxiness of plant leaves, consequently fortifying their drought resistance and overall robustness [61]. However, it is important to note that excessive exposure to UV radiation may result in detrimental consequences such as leaf scorching, inhibited development, and impaired photosynthesis. Plants exposed to elevated levels of UV radiation may demonstrate leaf bleaching and a decline in foliage density as stress indicators [6,32]. These detrimental effects can significantly impair photosynthetic efficiency and growth [62]. It is therefore crucial to exercise caution and ensure the efficient control of UV radiation, considering the fine line that distinguishes advantageous and detrimental impacts on the well-being and output of plants.

In light of this, UV light must be strictly regulated in agriculture in terms of wavelength, intensity, and duration. Additionally, the plant's developmental stage can affect its susceptibility to UV light damage; younger plants are more vulnerable. Control system rigor is not just necessary but crucial to optimize a plant's lifecycle UV exposure, ensuring the safety and productivity of indoor farming environments.

Table 3 details the factors concerning the use of UV light in plant growth, specifically in indoor kale cultivation with IoT integration.

Table 3. UV factors in IoT-enabled indoor kale cultivation.

Factor Concern	Requirement of IoT-Enabled Cultivation Process
UV light intensity [63]	Precise management of UV light intensity is required. An inadequate amount will fail to elicit the plant's intended responses, whereas an excessive amount may result in detrimental consequences like leaf scorching and stunted development. Adjustable systems regulate intensity following plant growth stages and environmental conditions.
Duration of exposure	Additionally, the duration of UV light exposure must be strictly regulated. Prolonged exposure has the potential to cause harm.

[64]	Therefore, it is recommended that IoT systems be programmed to regulate light periods by daily and seasonal demands.
UV light wavelength [62]	Variations in UV wavelength have distinct impacts on plant physiology. It is of utmost importance to dynamically adjust specific wavelengths emitted by UV light sources. In this regard, IoT systems can provide valuable assistance by continuously monitoring plant health.
Plant developmental stage [62,65]	UV light sensitivity is dependent on the plant's developmental stage. Younger plants may be more susceptible to UV damage; therefore, variable light management strategies that adjust as the plants develop may be required.
Environmental interactions [25,26]	UV light interacts with other environmental elements, including temperature and humidity. IoT systems must integrate data from all environmental sensors to optimize UV exposure while preventing the exacerbation of stress conditions.
System integration and automation [25,26]	Communication between devices and sensors must be seamless for agricultural IoT systems to incorporate UV light management. Automated control systems must possess robustness and dependability to manage these intricacies effectively.
Energy consumption [66]	UV lighting systems may require considerable amounts of energy. Succinct energy management that balances energy consumption and agricultural gains necessitates revolutionary IoT solutions.

IoT technology can significantly enhance the management of UV light in agricultural settings. Sensors can continuously monitor UV intensity and duration, and actuators can adjust UV light sources in real time based on the plant's observed responses. Jiang et al. [66] showed that IoT systems can be programmed to increase UV exposure incrementally based on real-time weather data. UV light has also been explored for its potential to manage crop pests. Specific UV wavelengths are known to repel insects or inhibit fungal growth, offering a non-chemical pest control method. Integrating UV light into pest management strategies, particularly in an IoT-enabled system, could reduce pesticide reliance and promote a more sustainable cultivation approach [67].

In conclusion, while the application of UV light in agriculture offers many potential benefits, the management systems require fully leveraging advantages without harming the plants. IoT technology offers promising solutions to these challenges, providing the tools necessary to precisely monitor and control UV light exposure for optimal plant health and productivity.

3. Materials and Methods

The novel methodology introduced in this study, which combines state-of-the-art UV LED lighting with a highly responsive IoT-driven environmental control system, not only improves the sustainability and productivity of indoor kale cultivation but also paves the way for future precision agriculture applications. The system's technological sophistication and statistical robustness underscore its potential to significantly contribute to sustainable agriculture and food security by revolutionizing indoor farming practices. The findings of this investigation have far-reaching implications for the field of controlled-environment agriculture, instilling a sense of hope and optimism, suggesting that the integration of IoT technology and UV LED lighting has the potential to revolutionize the optimization of crop production in indoor environments.

This segment has been organized logically to facilitate comprehension by deconstructing the intricate elements of the proposed system. The proposed framework for supporting the experiments is the IoT-based kale cultivation architecture, detailed in Section 3.1. The authors describe the comprehensive material design of the architecture of our IoT-based kale cultivation system in Section 3.2, emphasizing its layered and integrated structure. Section 3.3 establishes the groundwork for a comprehensive experimental configuration and intricacy within the procedure ecosystem. The methodology for collecting the data is detailed in Section 3.4. In Section 3.5, the analysis methodology is delineated, illustrating the impact of kale growing conditions on the efficacy of UV lights. Each subsection builds upon the previous one by comprehensively understanding the system's architecture, components, and performance evaluation.

3.1. IoT-Based Kale Cultivation Architecture

The use of IoT technology to cultivate kale signifies a substantial progression in agricultural methodologies, specifically in how the IoT augments precision in farming. This methodology enables the exhaustive monitoring and ongoing modification of all environmental factors that impact the growth of kale, including soil pH, light exposure, temperature, and humidity. By utilizing automated systems and real-time data, this type of precision agriculture allows farmers to consistently maintain ideal growing conditions, thus optimizing the genetic potential of the crops. The proposed IoT system's scalable and adaptable architectural framework accommodates modest indoor operations and extensive commercial agricultural undertakings. The proposed system guarantees scalability, enabling effortless expansion or modification without requiring substantial redesigns. In addition, its adaptability permits its implementation on a wide range of crops by modifying particular parameters or modules to suit the particular requirements of each plant species. This adaptability is paramount in contemporary agriculture, where crop rotation and diversification are essential for addressing soil health, air pollution, and pest management.

In the context of the IoT, automated systems substantially improve operational efficacy. The decreased dependence on manual monitoring and adjustments reduces labor expenses typically associated with conventional farming practices. By automating processes such as climate control, lighting adjustment, and irrigation, labor force reduction and human error are mitigated, resulting in more consistent and dependable agricultural output. In conclusion, collecting and analyzing data from various sensors yields profound insights into the ideal conditions that promote plant growth and development during cultivation. The utilization of a data-driven methodology promotes streamlined agricultural methodologies and enables advancements in the field of plant science. One can utilize data analytics by experimenting with and implementing new cultivation techniques that are more in tune with the physiological requirements of plants. These innovations possess the capacity to fundamentally transform agricultural practices, rendering them more productive and sustainable in light of the shifting global climate and escalating food requirements.

Aspect–component layering, as described in reference [68], is utilized to organize the architecture of an IoT-based kale cultivation system into a coherent structure that extends from the most concrete elements, such as hardware, to the more conceptual components, such as business processes. As illustrated in Figure 1, this architectural design enables a methodical progression in constructing and overseeing the IoT cultivation ecosystem, guaranteeing that every element operates harmoniously to attain maximum plant development and effective farm administration. The diagram depicts a comprehensive framework for a kale cultivation system that utilizes the IoT to optimize indoor plant growth. This structure has been meticulously designed to ensure that all technological components are in unity.

The hardware layer comprises fundamental physical components, including Raspberry Pi, sensors, relays, UV lights, solenoids, and power supply mechanisms. This configuration facilitates smooth communication between the system and its tangible surroundings, wherein actuaries promptly modify conditions in alignment with data gathered by sensors to accommodate the plant's requirements.

The hardware architecture layer provides an overview of the possible computing architectures implemented by the system, including hybrid, distributed, edge, client–server, and cloud computing. These architectural designs establish the guidelines for data processing and management throughout the system, allowing computations to be performed locally (edge computing) or in the cloud, thereby improving scalability and dependability.

The system software layer comprises the requisite software platforms and operating systems that facilitate the operation of the hardware. Operating systems such as Windows IoT, Linux, RIOT, NOS, and Tiny are essential for the efficient management of devices and the execution of applications, thereby ensuring that their security and performance are optimized.

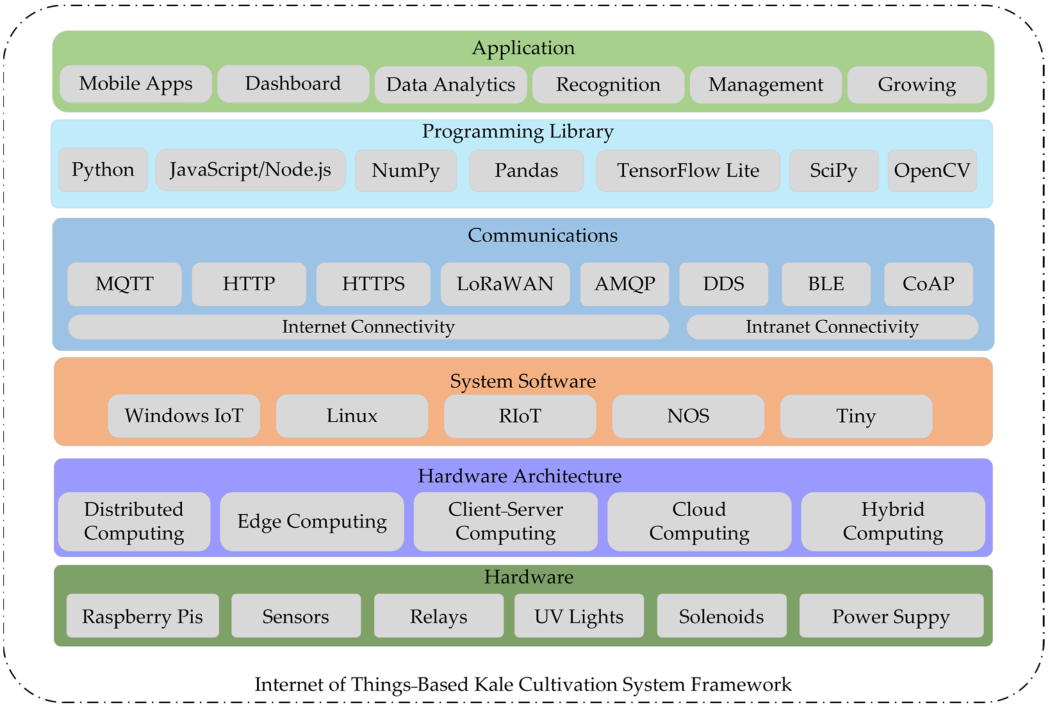


Figure 1. IoT-based kale cultivation system framework.

Communication protocols such as Message Queuing Telemetry Transport (MQTT), HyperText Transfer Protocol (HTTP), HTTP Secure (HTTPS), Long-Range Wide-Area Network (LoRaWAN), Advanced Message Queuing Protocol (AMQP), Data Distribution Service (DDS), Bluetooth Low Energy (BLE), and Constrained Application Protocol (CoAP) are implemented at the Network Layer to facilitate resilient and adaptable communication throughout the IoT infrastructure. These protocols enable data transfer between servers and devices, accommodating diverse specifications for range, bandwidth, and power consumption. As a result, they guarantee dependable connectivity, even in extensive or complex setups.

The programming library layer provides a variety of software libraries, including TensorFlow Lite, SciPy, OpenCV, Python, JavaScript/Node.js, NumPy, and Pandas, to the system. These libraries facilitate advanced data manipulation, machine learning, statistical analysis, and image processing, thereby empowering users to conduct sophisticated data analysis and make informed decisions by utilizing both real-time and historical data that have been gathered. TensorFlow Lite and OpenCV, integral components of our IoT-based kale cultivation architecture, offer significant benefits. These powerful tools leverage advanced image processing and machine learning techniques, leading to substantial improvements in plant health and development.

TensorFlow Lite, a potent instrument in our IoT-based kale cultivation architecture, is utilized to develop machine learning models that optimize UV light exposure and irrigation schedules with unparalleled precision. Initially, a machine learning model is trained using historical data that encompass a variety of parameters, including light intensity, humidity, temperature, soil moisture, and the corresponding plant growth metrics. This model is trained on a more powerful machine using TensorFlow and subsequently converted to TensorFlow Lite format for deployment on the Raspberry Pi. The data collected from sensors deployed in the cultivation environment could eventually be used to make real-time inferences using the lightweight TensorFlow Lite model. The TensorFlow Lite model can predict the requisite adjustments when the sensors detect that the light intensity or soil moisture levels deviate from the optimal range. For instance, it may optimize soil moisture levels by adjusting the irrigation schedule or increasing UV light exposure during specific growth phases of the kale to facilitate photosynthesis. This dynamic adjustment aids in preserving optimal growing conditions, fostering more robust and healthier plant growth.

OpenCV, a versatile tool, is employed in our IoT-based kale cultivation architecture to analyze images and monitor plant health and growth. It can extract valuable information about plant health and development by processing images of the plants at regular intervals using cameras connected to the Raspberry Pi. For instance, OpenCV can detect indications of nutrient deficiencies, disease, or pest infestations by examining changes in leaf color, shape, and texture using techniques such as edge detection, color analysis, and contour detection. It can also be used in conjunction with convolutional neural networks (CNNs) to tackle more complex image analysis tasks. CNNs can be trained to identify specific patterns associated with healthy and unhealthy plants, enhancing the system's diagnostic capabilities.

Once trained, the CNN model can be deployed on the Raspberry Pi by integrating it with OpenCV. For instance, the system employs image analysis to proactively diagnose and classify plant health issues. The growers are promptly notified if the system detects early signs of a fungal infection through leaf spots or discoloration patterns, allowing for timely intervention. A comprehensive and intelligent system that optimizes the growing environment and guarantees the plants' well-being through continuous, automated assessment and adjustment is obtained by combining TensorFlow Lite for predictive analytics and OpenCV for visual monitoring. The integration of machine learning and image processing technologies not only enhances the efficiency of indoor kale cultivation but also promotes sustainable agricultural practices by minimizing resource wastage and maximizing crop yield.

The application layer combines all functionalities into user-accessible applications, such as dashboards for real-time monitoring and control and mobile applications. Furthermore, it encompasses sophisticated applications for data recognition, management, cultivation, and analytics, which leverage the data to optimize environmental management, forecast plant growth, and enhance cultivation techniques.

In practical applications, the Business Layer, which is not explicitly illustrated but presumed to exist, would leverage the operational capabilities and insights obtained from the IoT system to propel business decisions, streamline processes, and potentially introduce novel business models or services predicated on the system's performance data and capabilities.

The implementation of this layered architecture promotes scalability and operational efficiency while also enabling sophisticated data analytics that have the potential to revolutionize agricultural methodologies. The system facilitates kale cultivation in a sustainable, efficient, and highly controllable environment through IoT technology. The system's outcome can increase crop yields and enhance nutritional quality.

3.2. Material Design

The material regarding the IoT methodology for kale cultivation establishes an all-encompassing framework that incorporates both hardware and software components. Priority has been given in the design of the integrated framework to environmental monitoring, which enables precise control of critical variables such as light, air, and water quality—all of which are necessary for kale growth optimization. As demonstrated in Table 4, the system design highly emphasizes adaptability and scalability. Moreover, it facilitates the seamless integration of additional sensors required for environmental monitoring, thereby obviating significant redesigns. By placing adaptability as a top priority, this framework ensures its capacity to integrate technological advancements in smart agriculture practices and efficiently respond to evolving demands.

Table 4. Overview of key hardware and software components employed in this study.

Component		Description
Hardware	Raspberry Pi 4 (8 GB RAM)	The Raspberry Pi is designed with considerable processing power and ample memory capacity to facilitate integration with various sensors, IoT devices, and data streams. Functioning as the primary processing unit to oversee numerous signals simultaneously, it permits data processing in real time across a wide range of applications.
	Temperature and humidity sensor (RS485)	RS485 signals are generated from the environmental temperature and humidity sensors by employing a dependable digital processing circuit and a superior-quality industrial-grade integrated transducer.
	Four-channel relay	A relay with four channels is a device that incorporates four discrete relay switches in a single unit. Each relay switch can autonomously regulate the establishment or termination of an electrical circuit.
	Solenoid valve	A solenoid valve is an electromechanical apparatus that regulates water flow within a system. Applying an electric current to the solenoid induces the generation of a magnetic field, which in turn causes the movement of the plunger. This movement can either open or close a valve mechanism.
	Pump	A pump is a mechanical apparatus that transfers water from a water reservoir to plots of kale.
	Drip emitters	Drip emitters transport water directly to plants referred to as water drops.
	Water tank	A water tank is a receptacle utilized for water storage.
	Air conditioner	An air conditioner is a device that manages and adjusts the temperature, humidity, and overall air quality in an indoor space.
	LED UV source	Lighting technology has significantly advanced, offering a wide range of LED sources. Every light source possesses distinct attributes of energy efficiency, color rendition, longevity, and ecological footprint. The following light sources were used: • Household cool white: 18 W; 1600 lumens; temperature 4000 K. • Household warm white: 18 W; 1600 lumens; temperature 3000 K. • Household daylight: 18 W; 1600 lumens; temperature 5700 K. • Indoor grow lights—full spectrum: 25 W; sunshine: 144 Pcs (warm light—108 Pcs; red light—18 Pcs; blue light—12 Pcs; UV—3 Pcs; and IR—3 Pcs). • Indoor grow red lights: 25 W; 380–780 nm; 144 Pcs. • Indoor 4000 K grow lights: 25 W; 4000 K; 144 Pcs.
	Soil moisture sensor detector	The design is based on the LM393 and is used to detect and measure moisture humidity levels.

Operating system	Raspbian OS 64-bit kernel 6.6	The software is specifically designed to maximize performance on Raspberry Pi hardware, allowing for efficient multitasking and compatibility with a wide range of libraries necessary for integrating sensors, controlling relays, managing lights, operating solenoid valves, and controlling air systems.

As illustrated in Figure 2, the IoT-enabled kale cultivation framework is an all-encompassing solution intended to optimize kale cultivation growth conditions via cutting-edge IoT technology. The framework under consideration incorporates many elements, such as solenoid valves, pumps, water tanks, four-channel relay IoT sensors, a microcontroller, and control modules designed to regulate air, light, and water. The solenoid valves and pumps facilitate the precise watering of the kale plants, controlling the water flow from the water tank to the plants using IoT sensors to gather real-time soil moisture data. Many devices can be controlled under the relay's four channels, enabling automated modifications to water, light, and air parameters. The Raspberry Pi microcontroller can facilitate data processing, analysis, and control by orchestrating the interactions between various components for optimal kale growth. The framework allows growers to oversee and control crucial environmental variables, including light intensity, temperature, humidity, and water availability. This system design enables them to optimize kale yield and quality while reducing the labor and resources required. The actual IoT-driven kale cultivation system is depicted in Figure 3.

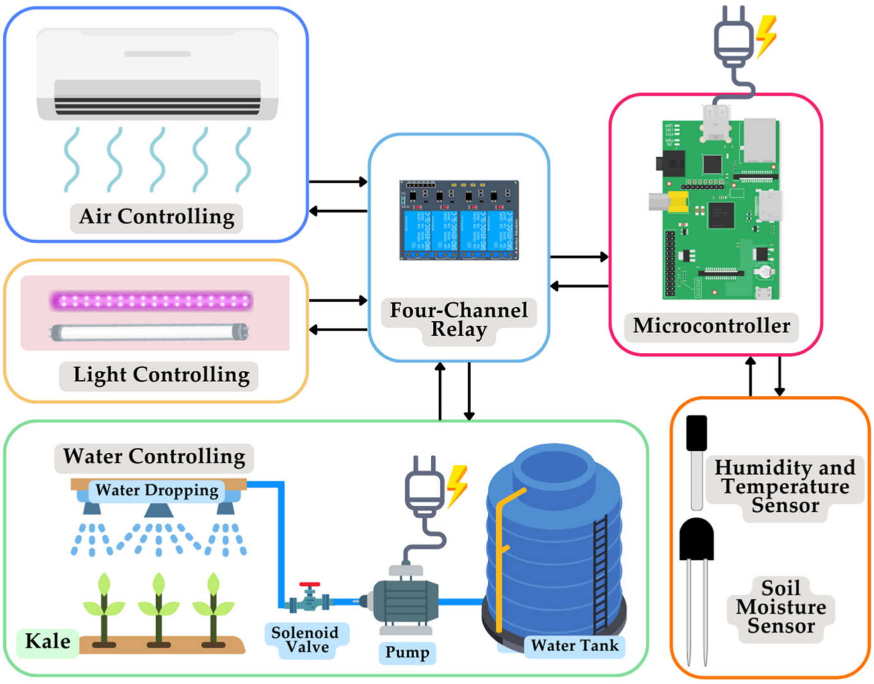


Figure 2. Overall system architecture and workflow of the IoT-driven kale cultivation system.

Figure 3. Actual system architecture and design of the IoT-driven kale cultivation system.

3.3. Experimental Setting and Procedure

A controlled indoor environment measuring 6 × 5 m was utilized to conduct an experimental analysis of the effects of various lighting conditions on the growth of curly kale in this study. An 18,000 BTU air conditioner was installed in the room to ensure consistent temperature levels. The investigation was structured into three discrete groups: the first group (T1) comprised three experimental sets; the second group (T2) comprised three sets as well; and the third group (T3) contained nine experimental sets for a cumulative sum of fifteen experimental sets. As shown in Figure 4, each set comprised three curly kale plants, with forty-five plants in the experiment. Vinyl partitions measuring 62 cm in width and 60 cm in height were positioned between each row, 30 cm apart, to promote consistency and reduce variances among the sets. The primary objective of the experiment was to assess the efficacy of UV light control in three distinct lighting conditions: kale cultivated using conventional household LED lights, kale cultivated using specialized UV lights designed for indoor plant cultivation, and kale cultivated using a hybrid system of household and LED grow lights. Three household types of LED lights—daylight, warm white, and cool white—and three grow light types—full-spectrum indoor grow lights, indoor grow red lights, and indoor grow lights set to 4000 K—were employed. The configurations mentioned above are elaborated upon in the cited figures, which visually represent the experimental arrangement. Figures 5 and 6a depict the actual surroundings and configurations.

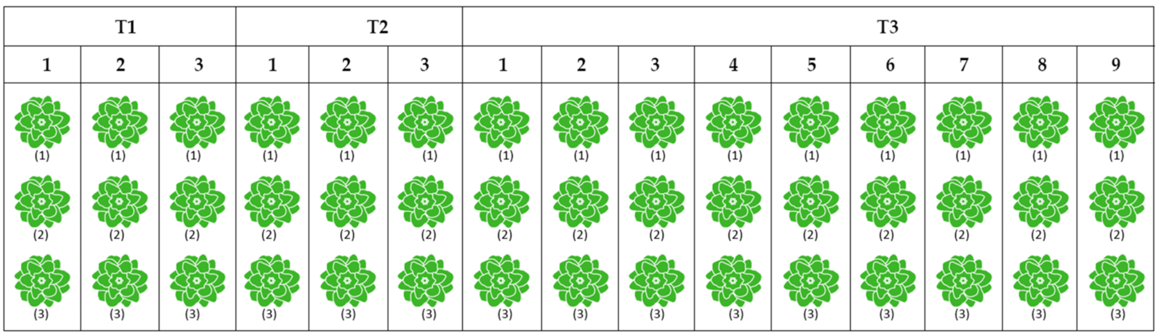


Figure 4. Top view design of kale's layout.

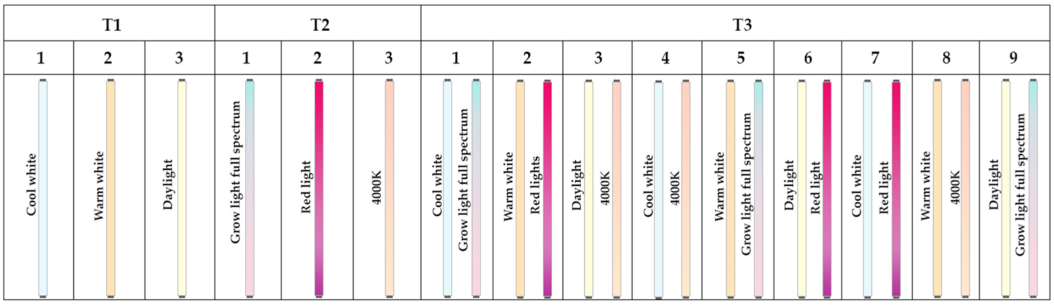
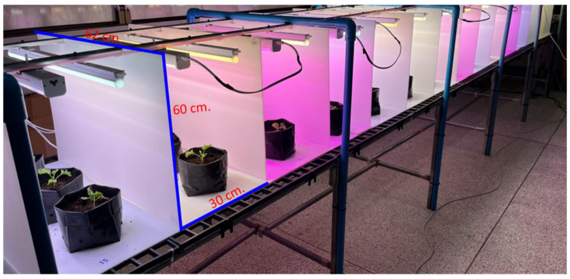


Figure 5. Layout of LED light settings at various positions.



(**a**)

(**b**)

Figure 6. Actual experimental setting of kale pot area: (**a**) pot experimental area; (**b**) pot watering and soil sensor.

The experimental investigation commenced with the seedling phase, which spanned an estimated duration of 30 days. Throughout this time, the kale seedlings grew in height from 5 to 7 cm. Experiments were conducted using seedlings that exhibited consistent size and leaf count while being in optimal health. Following this, the chosen seedlings were meticulously transplanted into the indicated experimental plots. The temperature of the cultivation environment was maintained at an exacting 26 degrees Celsius. The IoT system was employed to regulate the air temperature in the cultivation area. Air conditioning maintained temperatures between 26 and 27 degrees Celsius, with the controller temperature limited to 28 degrees Celsius.

Because of the substantial lighting needs of kale, the plants were illuminated with UV LED lights, automatically controlled by an IoT-based kale cultivation system as previously illustrated in the system architecture of Section 3.1, from 06:00 in the morning to 18:00 in the evening to ensure optimal growth. Daily watering was carried out at 07:00 using an activated water dropper system, which commenced operation when soil moisture sensors indicated that humidity levels had decreased to the desired range of 60–70%. As depicted in Figure 6b, this automated irrigation system ensured that every kale pot obtained adequate hydration. The IoT system played a crucial role in maintaining these optimal conditions, showcasing the innovative technology used in our experiment.

In addition, the IoT system contributes to environmental stability. When the relative humidity falls below a predetermined threshold, the plants are automatically irrigated, and the air conditioning is activated in response to temperatures exceeding the predetermined limits. After the seedlings' emergence, fertilization was initiated when the kale had grown to approximately 2 inches in height. The kale plants were subsequently fertilized every two weeks with nutrient-dense organic substances to stimulate vigorous development. By following a systematic approach, the conditions for kale development were intended to be optimized, thereby ensuring the health and productivity of the plants throughout the experiment.

3.4. Data Collection

A careful and methodical strategy was implemented to gather data for this investigation to guarantee the precision and dependability of the findings. Many parameters, including light intensity, air temperature, humidity, and water distribution, were rigorously monitored via an IoT system during the research conducted in a controlled indoor environment. The main aim of this study was to investigate the effects of varying intensities of UV light on the development of curly kale.

Light intensity data were collected using sensors that monitored light intensity (LUX) levels at regular intervals from 06:00 to 18:00. These readings accurately reflected the artificial lighting conditions applied to the kale plants. The cultivation area was outfitted with temperature and humidity sensors to monitor environmental conditions continuously. The sensors implemented measures to maintain the temperature within the 26–27 degrees Celsius range. They initiated the air conditioning system's operation automatically if the temperature rose above the upper threshold of 28 degrees Celsius. Similarly, relative humidity levels were regulated to 60–70%, and automated watering was activated when they dropped below this threshold.

The quantitative evaluation of plant growth involved the measurement of the kale's height, leaf size, and branch size at three critical growth stages: 15, 30, and 45 days after transplantation, as visually depicted in Figure 7. The data obtained from these measurements analyzed the physical growth responses of the plants in response to different lighting conditions. Additionally, before transplantation, the seedlings' health and uniformity were evaluated to ensure that the experimental sample was consistent. By employing this thorough data collection method, a thorough examination of growth patterns was possible, and these patterns could be correlated with the controlled environmental parameters. As a result, valuable insights were gained regarding the most favorable conditions for cultivating curly kale indoors.

Figure 7. Actual experimental conditions and the data collection of indoor kale pots.

The methodology employed for data collection in this study was meticulously devised to ensure consistency, validity, and reliability—the pillars upon which experimental results in plant growth studies depend for their credibility.

Consistency maintenance was ensured by applying standardized treatment conditions and uniformly selecting seedlings across all experimental groups. The reduction in initial variability among the plants was achieved by selecting seedlings that exhibited comparable size and health. This approach ensured that any discernible variations in growth and development could be ascribed to the experimental treatments alone rather than to genetic variability or pre-existing condition differences. In addition, external variables such as light, temperature, and humidity remained constant in the controlled environment, except for the intentional fluctuations planned for this research. By rigorously regulating environmental conditions, every plant was exposed to an identical set of conditions replicated throughout all experimental runs. This approach significantly improved the consistency of the collected data.

The data collection process was conducted with utmost precision, and the instruments were meticulously calibrated. Situated strategically, light intensity, temperature, and humidity sensors were configured to precisely replicate the environmental conditions to which every plant was subjected. Generally, these instruments exhibit high sensitivity and accuracy, thereby delivering precise measurements directly associated with the plant's growth environment. Additionally, IoT technology enabled adjustments and monitoring in real time, which assisted in maintaining the ideal environmental conditions required for valid experimental manipulation. The selection of monitoring parameters, including light intensity and humidity levels, is well established to impact plant growth substantially; therefore, this guarantees that the data gathered are pertinent and directly associated with the research aims.

By the automated and continuous nature of data collection, dependability was significantly enhanced. By enabling continuous data logging, the IoT system increased the data's dependability and decreased the likelihood of human error during data collection. Constant temperature regulation and watering under soil moisture levels and real-time readings, respectively, ensured that the plants remained within the optimal growth parameters at all times. The dependable data and realistic conditions simulated by this methodology pertained to the application of automated systems in the agricultural sector. The reliability was further enhanced by conducting repeated measurements during critical growth stages, which enabled the consistent tracking of data and the observation of trends over an extended period.

Furthermore, incorporating automated systems, accurate instrumentation, and regulated environmental conditions significantly enhanced the data collection process in this investigation by ensuring its high consistency, validity, and dependability. These characteristics are critical in guaranteeing the reliability, scalability, and practicality of this study's results in agricultural environments.

3.5. Data Analysis

The authors of this study determined the optimal light settings for kale growth by conducting an exhaustive analysis of the plant's development under various indoor UV LED lighting conditions. Over 45 days, the research team methodically divided the experimental configurations into numerous segments, with each segment subjected to controlled environmental conditions, including variations in light intensity and branch development. The objective was to examine the resulting impacts on these variables.

Critical growth metrics were meticulously recorded at three distinct growth stages for each experimental group: 15, 30, and 45 days. The parameters that were assessed to evaluate the overall growth and health of the plants comprised the initial and final heights, leaf width and length at each time point, and branch dimensions (which were additionally averaged at the 45-day mark). The systematic methodology employed to examine the effects of various indoor UV LED lights on plant growth inspires trust in the dependability of our results. Analysis of Variance (ANOVA) is an especially suitable statistical method for this objective, as it enables researchers to ascertain whether disparities between the means of three or more unrelated (independent) groups are statistically significant. In evaluating various UV LED lights, every light setting or intensity level corresponds to a distinct treatment group. ANOVA facilitates the simultaneous comparison of these multiple groups to determine whether variations in light intensity led to distinct growth outcomes, including variations in the plants' height, leaf area, and branch diameter. The dataset provided was subjected to ANOVA to determine the effects of UV LED light settings on various growth parameters across experimental groups. Significant differences exist between the groups for each measured parameter, as indicated by the ANOVA results.

As an illustration, there were substantial differences in the light intensity that plants acquired among the groups, as indicated by an *F*-statistic of 28.69 and a *p*-value deemed to be highly significant (1.40×10^{-8}). The findings indicate that the varying UV LED light configurations substantially influence the light intensity supplied to each plant group. Similarly, there were notable variations in the height of plants after 45 days between the groups, as indicated by an *F*-statistic of 13.94 and a *p*-value of 2.30×10^{-5}. This result indicates that variations in lighting may affect the vertical development of plants over the same period.

In addition, there were substantial leaf and branch size variations among the experimental groups at the 45-day mark (*p*-values of 1.59×10^{-11} and 3.61×10^{-9}, respectively). The results of this study indicate that the UV LED light parameters impact the plants' overall growth height, leaf expansion, and branch outgrowth, among other developmental characteristics.

In brief, the ANOVA outcomes confirm that the various UV LED lights employed in the experiments exert a statistically significant impact on the plants' growth parameters. This analysis possesses practical implications beyond its scientific merits, as it aids in identifying optimal light conditions that promote plant growth. This knowledge has the potential to significantly contribute to the optimization of indoor farming practices, thereby enhancing plant health and yield. As such, it has a direct application in agriculture and indoor farming.

In addition to comparing the mean values of growth metrics among various experimental groups, the analysis employed variance analysis to ascertain the influence of each lighting configuration on the variability in plant growth. This methodology assisted in identifying the particular lighting conditions that promoted optimal conditions for kale development, thus offering potentially useful insights for agricultural methodologies, particularly in controlled settings where light can be meticulously regulated. This comprehensive analysis not only facilitates the enhancement of agricultural technologies and methodologies but also presents novel prospects for innovation, propelling the potential of indoor farming systems forward and motivating the audience with notions of expansion and progress.

To determine the experiments' ranking, the overall average for each metric is computed and subsequently added together to yield a cumulative score for each experiment, as illustrated in Equation (1).

$$\text{Total Score} = \text{Avg. Height} + \text{Avg. Leaf Size} + \text{Avg. Branch Size} \tag{1}$$

By utilizing the formula to rank experiments [69], complex plant growth data can be consolidated into a single, quantifiable metric. This methodology is founded upon the premise that a more comprehensive assessment of the growth performance of a plant can be obtained through the amalgamation of numerous crucial growth indicators. In this instance, the light conditions influence the physiological responses of plants, which are represented by the dimensions of the plant's stem, leaves, and branches. The authors generate a composite score that represents the overall growth performance under each experimental condition by summing these values for each experiment.

The method's validity is contingent upon the supposition that height, leaf area, and branch magnitude are pivotal metrics for evaluating the plant's overall growth and vitality and serve as critical indicators thereof. By this presumption, these metrics can be utilized interchangeably in the computation of the overall score. Every element comprising the overall score represents a fundamental facet of plant development: branch size determines structural biomass, leaf size impacts overall growth, and height influences photosynthetic capacity.

This approach's simplicity and consistency constitute its reliability. By applying the same formula to each experimental group, the authors guarantee that all experimental groups are evaluated according to the same criterion. Nevertheless, inaccuracies in recording measured parameters or the precise control of experimental conditions may compromise reliability. It is imperative to utilize consistent measurement techniques and experimental variables under control to guarantee that the overall scores faithfully represent the variations in plant growth caused by the diverse light conditions.

Employing this formula efficiently transforms intricate data into a format that is straightforward to examine and contrast. By utilizing the cumulative score of the experiments, the authors can determine the most effective lighting conditions that stimulate optimal growth in kale. This information will serve as a guide for the development of future lighting technologies and agricultural practices in controlled environments. This approach provides a clear and concise metric that can facilitate evidence-based decision-making in the context of agricultural research and production.

4. Results and Discussion

4.1. Analysis Results

The dataset being analyzed results from a comprehensive examination of the growth patterns of kale in response to varying light conditions. This research was executed with extreme accuracy, as each entry in the dataset was characterized by several parameters that rigorously monitor the development and growth of kale in particular controlled environments. The light intensity, quantified in lux, is a critical factor that sheds light on the varying degrees of exposure to each plant group.

The height of the plants at the 45-day mark is a crucial element of the data, as it directly indicates vegetative growth over a specified period. In addition to this metric, the average width and length of the leaves, as determined at the 45-day interval, are also included. The insights provided by these measurements pertain to the photosynthetic surface area, which is vital for the plant's energy production. Furthermore, the dataset monitors the progression of the plant's structural elements by calculating the mean width and length of branches during the identical period. The biomass accumulation of these branches indicates the plant's capacity to sustain and uphold the leaf canopy.

These parameters possess the potential to optimize the growth of kale and are not merely numerical values. The extensive range of data enables scientists to investigate the diverse effects of light intensity on the structure and function of plants, with the ultimate goal of establishing ideal circumstances for the advancement and maturation of plants in controlled agricultural systems. By utilizing this dataset, lighting conditions can be precisely adjusted to improve plant health, yield, and overall productivity. These outcomes are pivotal in optimizing agricultural practices, especially in environments with strictly regulated environmental conditions, as illustrated in the Appendix A, Tables A1 and A2.

Table A1 presents a comprehensive summary of growth-related measurements from an experimental investigation involving kale plants. These data are organized diversely, utilizing a range of metrics to represent seven distinct variables. The dataset for each variable comprises 45 observations, signifying its completeness in the absence of any missing values.

As presented in Table A2, the 'Plot Number' is a categorical identifier for experimental plots, denoting three distinct plot configurations within the experiment ranging from 1 to 3. The variable 'Light Intensity (lux)' quantifies the extent of light exposure experienced by the plants. It exhibits a substantial range of values from 1826 to 13,136 lux, with an average intensity of 6535.76 lux. This broad range denotes the considerable variation in light conditions observed across the experimental configurations.

Several variables represent the physical characteristics of the kale plants. Significant variation in plant growth is evident in the 'Height (cm)' of the plants, which varies from 3 cm to 29 cm, with an average height of nearly 13.66 cm. The average measurements for the parameters 'Average Width Leaf Size (cm)' and 'Average Length Leaf Size (cm)' are 8.39 cm and 10.65 cm, respectively. The variation in length from 4.17 cm to 16.33 cm and width from 3.5 cm to 13.67 cm indicates that the sample contains varying-sized leaves.

The average width and length of branches are specified in the variables 'Average Width Branch Size (cm)' and 'Average Length Branch Size (cm),' which are 17.54 cm and 21.02 cm, respectively. The observed branch widths and lengths, ranging from 5 cm to 27.67 cm and 7.33 cm to 33.5 cm, respectively, indicate the plants' diverse growth conditions or genetic variations.

The complex variation in the growth responses of kale plants under distinct experimental conditions is highlighted by the statistical data. This intricacy serves as evidence of this study's meticulousness, potentially with the intention of investigating light intensity's influence on the plants' growth. In addition to illuminating the dispersion and central tendency of the data, these statistics provide a glimpse into the intricate interplay between environmental variables and plant morphology as it pertains to this research.

Figure 8 illustrates the correlation between the growth parameters of kale (height (measured in centimeters), leaf size (length and width, measured in millimeters), branch size (length and width, measured in centimeters), and light intensity (measured in lux)) during four growth stages: 25%, 50%, 75%, and maximum growth. As the light intensity increases from approximately 4.3 K lux to 13.1 K lux, all growth metrics experience a corresponding dramatic improvement. Moderate growth is observed at the 25% stage. In contrast, the 50% stage indicates a significant increase in all parameters, suggesting that increased light intensity positively impacts development. This trend is maintained in the 75% stage, which exhibits substantial growth enhancements. Lastly, kale achieves its most significant growth metrics when subjected to the highest light intensity during maximum growth. These data emphasize the positive correlation between increased light intensity and improved kale growth, underscoring the efficacy of UV LED lights that are managed by an IoT system in optimizing indoor cultivation conditions.

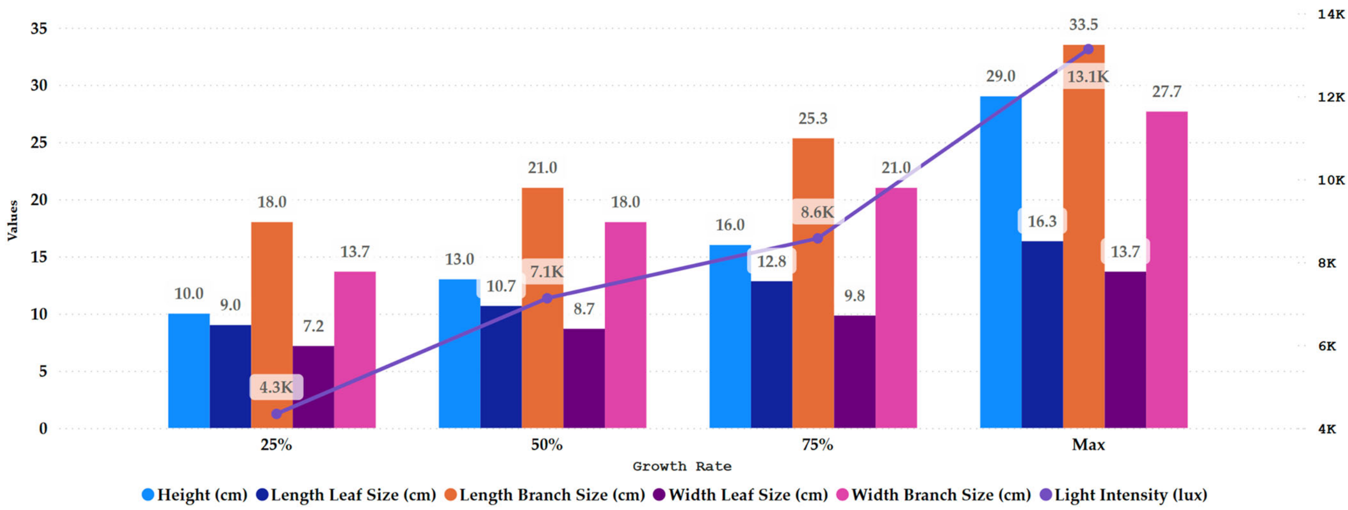


Figure 8. Kale across different growth stages, highlighting the effectiveness of UV LED lights controlled by an IoT system.

Figure 9 presents a comparative analysis of various kale growth parameters, such as height, leaf size (length and width), and branch size (length and width), across different experimental groups, designated T3-3 to T1-2, under varying light intensities measured in lux. The maximum height, leaf size, and branch size values are achieved in group T3-3, where the light intensity peaks at approximately 30 K lux. This group exhibits the highest growth metrics. Group T3-2 exhibits substantial growth, albeit with slightly lower light intensity and corresponding growth parameters. Conversely, groups subjected to significantly lower light intensities, including T1-3, T1-1, and T1-2, demonstrate diminished growth metrics in all the measured parameters. The graph emphasizes the positive correlation between increased light intensities and improved growth parameters, with groups exposed to optimal light conditions exhibiting superior plant development. This trend emphasizes the efficacy of UV LED lights managed by an IoT system in optimizing indoor cultivation conditions, resulting in enhanced kale plant growth and health. The data support the hypothesis that the precise regulation of light intensity is essential for maximizing kale's health benefits and growth potential in indoor farming environments.

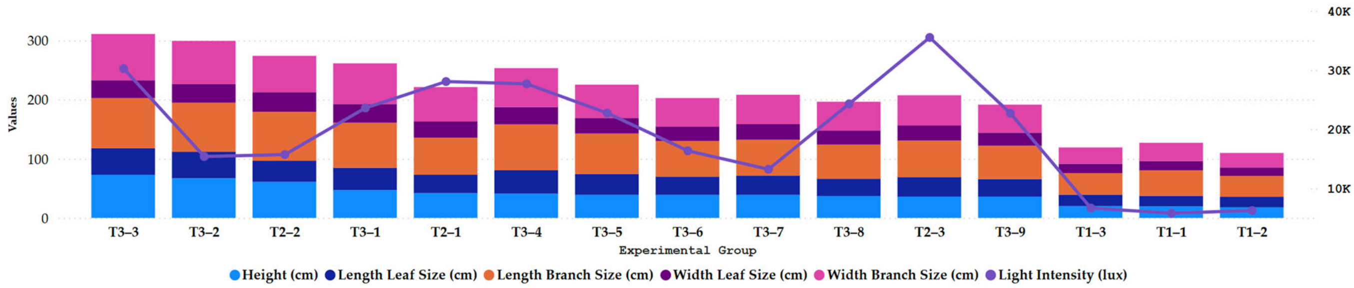


Figure 9. Comparative growth parameters of kale across different experimental groups under varying light intensities.

The ANOVA results for each variable are presented in Table 5. The table illustrates the variation in degrees of freedom, representing residuals and groups, the *F*-statistic (calculating the ratio of variance between groups to variance within groups), the *p*-value (assessing the likelihood that the observed F-statistic would occur under the null hypothesis), and the sum of squares (which quantifies the variation within the data) across various measurements of the kale plants. Significant variations among experimental groups are underscored by each result, indicating that these conditions influence growth parameters and environmental factors. In the ANOVA table, the degrees of freedom (DF) are divided into two components: one is allocated to the 'Experimental Group' (comprising within-group variance), while the other is designated for the residuals. The values 14 and 30 for the dataset and ANOVA test conducted were computed using 15 test groups. Table 5 shows the degrees of freedom for the experimental group. This value signifies the number of levels absent in the experimental group. As the unique counts in Table A1 indicate, if there are 15 distinct experimental groups, then the experimental group's degree of freedom is $15 - 1 = 14$ because degrees of freedom for effect in ANOVA are computed by subtracting one from the number of levels of the categorical variable. The determination of degrees of freedom for residuals involves subtracting the number of levels in the experimental group from the total number of observations. The dataset comprises a total of 45 observations. Therefore, $45 - 15 = 30$ degrees of freedom are assigned to the residuals, denoting the portion of the variance present in each group that cannot be accounted for solely by group differences.

Table 5. ANOVA results.

Variable	Sum of Squares	Degrees of Freedom (DF)	*F*-Statistic	*p*-Value	Significance
Light intensity (lux)	393362200	14, 30	39.19	0.000	Highly significant
Height (cm)	1215.74	14, 30	9.54	0.000	Highly significant
Average width leaf size (cm)	168.05	14, 30	5.78	0.000	Highly significant
Average length leaf size (cm)	341.42	14, 30	8.60	0.000	Highly significant

Average width branch size (cm)	1195.09	14, 30	7.94	0.000	Highly significant
Average length branch size (cm)	1208.96	14, 30	9.35	0.000	Highly significant

Listed below are the top three experiments as determined by the total score derived from Equation (1), which is composed of average height, leaf size, and branch size. As shown in Table 6, the cumulative score for each experiment was calculated by adding the mean values of average height, average leaf size (comprising leaf width and length), and average branch size.

Table 6. Top three UV light conditions across all experimental groups.

Experimental Group	Average Height (cm)	Average Leaf Size (cm)	Average Branch Size (cm)	Total Score	Impact Explanation
T3-3 (household daylight and indoor 4000 K grow lights)	24.33	12.47	27.17	63.98	Highest scores across all parameters suggest optimal light and nutrient conditions, potentially including enhanced UV light exposure, promoting robust growth and larger biomass accumulation.
T3-2 (household warm white and indoor grow red lights)	22.33	12.69	25.99	61.03	Slightly lower height but greater leaf size may indicate a balance between light intensity and quality, with conditions fostering broad leaf development beneficial for photosynthetic efficiency.
T2-2 (Indoor grow red lights)	20.33	11.47	24.02	55.83	Lower scores in all categories could reflect less intensive light conditions or suboptimal nutrient availability, impacting overall growth rates and structural development.

As shown in Figure 10, it is conceivable that the T3-3 group was exposed to the most favorable conditions, which included optimal UV LED light exposure. It is well known that UV light induces particular defensive and growth responses in plants. The experimental conditions promoted the development of taller plants with larger leaves and branches, as evidenced by the high total score, which suggests robust overall growth. The observed result is ascribed to the synergistic effect of elevated light intensity and advantageous wavelengths, specifically wavelengths that are known to be beneficial for plant growth. These wavelengths facilitate a more substantial biomass accumulation and improve nutrient quality.

Group T3-2, in contrast to T3-3, presented unique advantages despite being marginally shorter in height. The observed increase in mean leaf size suggests that the light quality may have been optimized for leaf expansion, potentially through a particular spectrum or intensity. This attribute, beneficial to kale, directs development towards the plant's consumable components, a potential avenue for further research. The environmental conditions may have been modified to prioritize the expansion of leaf surface area rather than vertical growth, thus maximizing the yield of leaves, a finding that could have significant implications for agricultural practices.

The T2-2 group, while obtaining the lowest rankings among the top three, still provided valuable insights. Their findings indicate that although the conditions were favorable for growth, they may not have been as optimally optimized as those observed in T3-3 or T3-2. The marginal reduction in height, leaf, and branch dimensions may suggest diminished light intensity or less effective light spectra. The nutritional delivery of this system may have been slightly more conservative or variable, a factor that could be further explored. These findings contribute to our understanding of plant growth and development under different light conditions, highlighting the importance of comprehensive research in this field.

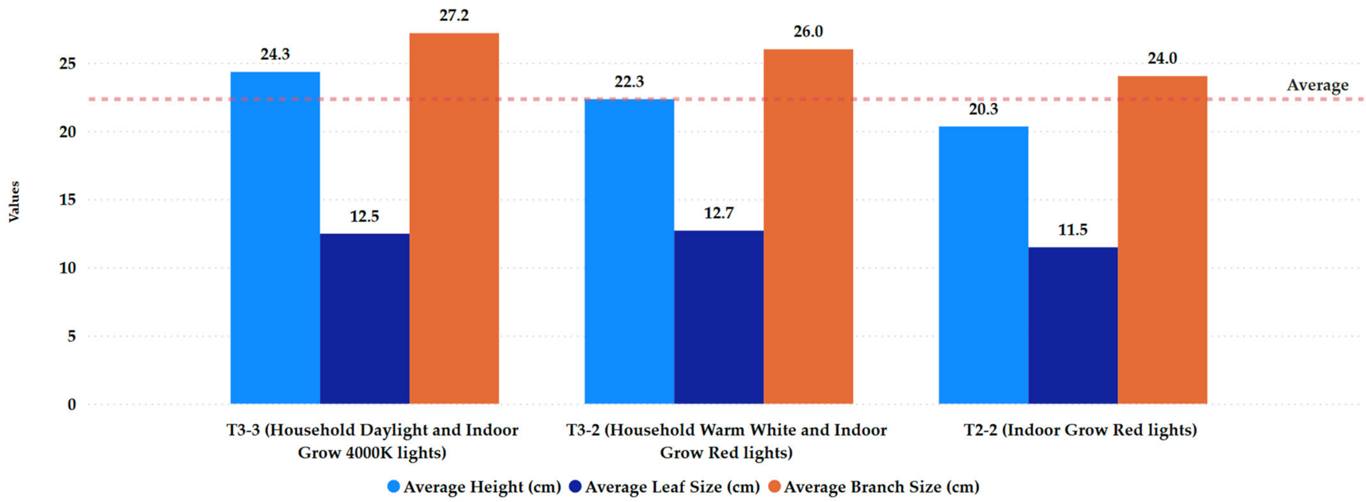


Figure 10. The average height, leaf size, and branch size of kale grown under the top three UV light conditions.

4.2. Discussion

This section is divided into three primary subsections. The initial subsection, theoretical contributions, explores the conceptual advancements and foundational knowledge that our study provides to agricultural IoT systems and UV light applications in horticulture. The second subsection is the benefits and limitations of indoor IoT-controlled UV LED lights, which assesses our experimentation's practical advantages, challenges, and constraints. It emphasizes the innovative aspects and areas for improvement. Lastly, the third subsection, future work, delineates potential avenues for additional research, underscoring the collaborative nature of these endeavors and the importance we attach to your input to refine and expand upon the current findings to improve the efficacy and sustainability of innovative agricultural practices.

4.2.1. Theoretical Contributions

This research presents an IoT-enabled kale cultivation framework and operational system that utilized controlled UV LED light intensities indoors. This work established a scalable model that holds potential for future indoor farming initiatives and has contributed to understanding various critical insights and developments in precision agriculture. Kale's growth metrics and nutritional quality have been significantly enhanced through rigorous experimentation, which involved precisely regulating the growth environment using cutting-edge IoT controlling systems and a range of spectral intensities of indoor UV LED lights. This study's results provided valuable information regarding the appropriateness of particular indoor UV LED light varieties and the significance of suitable light spectra in promoting kale growth and nutrient content in controlled indoor environments. This finding is particularly relevant for cultivating kale, a crop that is gaining an understanding of its nutritional advantages.

Examining various configurations of indoor UV lighting highlighted the efficacy of full-spectrum LEDs, which emulate the characteristics of natural sunlight and deliver a well-rounded illumination that spans an extensive spectrum of wavelengths. The application of this spectrum to kale resulted in enhanced growth and a greater abundance of phytonutrients, which are vital for both plant defense mechanisms and human health. In particular, it was observed that an optimal growth environment was cultivated under daylight white and full-spectrum light (indoor 4000 K grow lights), which resulted in increased biomass and heightened concentrations of antioxidants and vitamins in kale leaves. Adapting light conditions to correspond with the developmental phases of kale has resulted in increased rates of growth and enhanced nutritional composition. The result supports the hypothesis that meticulous environmental regulation can elevate the quantity and quality of agricultural output.

This study further enhances the body of knowledge in agronomic engineering and plant physiology by providing a comprehensive analysis of how diverse light spectra can impact the biochemistry and morphology of plants. This result contributes to advancing knowledge regarding photomorphogenesis, the mechanism through which plants regulate their growth and development in response to light signals. This research illustrates how precise light quality and intensity regulation can be accomplished by integrating IoT technology with sophisticated lighting systems to control the growing environment. The result allows for adapting environmental conditions to suit the distinct requirements of kale at various phases of the kale's growth cycle. UV LED lights in indoor farming effectively tackle the obstacles presented by urbanization and climate change, thereby contributing to the overarching objectives of mitigating agricultural carbon emissions and bolstering food security in urban environments.

In addition to elucidating the practical design, system, applications, and theoretical contributions of employing particular varieties of UV LED lights to cultivate kale indoors, this study provides growers and agronomists with actionable insights. It serves as a precursor to further research that may investigate the intricate interplay between light and plant health, IoT technology, and precision agriculture. Such investigations may result in developing more sophisticated agricultural methodologies and technologies, directly benefiting the indoor farming community.

4.2.2. Benefits and Limitations of Indoor IoT-Controlled UV LED lights

The innovative approach to indoor kale cultivation, which incorporates UV LED lights and IoT technology, is a testament to our commitment to pushing the boundaries of agricultural practices. This method offers a range of benefits and constraints that are worth exploring. Controlling environmental conditions with precision is one of the most significant benefits, as it is a critical factor in optimizing plant growth. The experimental results indicate that kale can be cultivated in as little as 45 days, substantially improving the traditional 55–60 day harvesting period. The real-time monitoring and automated adjustment of parameters, including temperature, humidity, light intensity, and soil moisture, are facilitated by IoT technology. This results in an optimized growing environment that can improve kale plants' health and growth rate. Additionally, UV LED lights can improve the synthesis of vitamins and antioxidants, thereby enhancing the nutritional content of kale and resulting in a higher-quality crop. This approach also improves resource efficiency by reducing water and nutrient waste through targeted irrigation and fertilization.

However, it is crucial to acknowledge that this method, despite its potential economic advantages, has its own set of constraints. The high initial setup cost is a significant drawback, primarily due to the necessity of specialized equipment such as UV LED lights, sensors, irrigation systems, and IoT infrastructure. The ongoing operational costs, encompassing energy consumption for climate control and lighting, can also be substantial. The system's complexity is another potential challenge that requires technical expertise for installation, maintenance, and troubleshooting. This complexity may challenge farming operations that are less technologically advanced or smaller.

While the experimental configuration is robust, it simulates a controlled and somewhat idealized setting, which may not fully represent the complexities of large-scale commercial agriculture. Furthermore, the specific configurations of indoor UV light intensities and spectra used in this research may only be universally applicable to certain crop varieties or indoor farming environments. This suggests a potential for variability in the replicability and scalability of the experiments, highlighting the need for further research in this area.

Managing UV light exposure is a critical aspect of this method. It is essential to exercise extreme caution to avoid potential adverse effects on plant growth. This study underscores the need for precise control over the intensity and duration of UV light, ensuring that the plants receive the right amount of UV radiation without any harm.

4.2.3. Future Work

The potential for future research on the proposed control of UV LED lights for indoor kale cultivation using the IoT method is immense. Incorporating sophisticated IoT technologies, such as machine learning algorithms, could facilitate the development of more intelligent and adaptive control systems. These systems would automatically optimize plant growth conditions by analyzing real-time data from multiple sensors and adjusting environmental parameters. Additionally, the potential to extend the application of this IoT-controlled UV LED lighting method to other crops could offer valuable insights into its versatility and broader agricultural benefits, thereby facilitating the development of customized lighting protocols for a diverse array of crops.

Another critical area for future research is implementing the system in larger-scale commercial operations. This step is essential because it will enable us to assess the system's performance in real-world scenarios. Practical insights will be obtained by expanding the technology from a controlled experimental environment to commercial indoor farms and observing its effects on economic viability, resource usage, and productivity. These insights could be subsequently employed to develop best practices and guidelines for deploying IoT-controlled UV LED lighting systems in various agricultural settings. Moreover, the system's sustainability can be significantly improved by incorporating renewable energy sources, such as solar panels, and implementing energy-efficient lighting and climate control strategies. This will not only reduce operational costs but also lessen our environmental impact. The objective of future research and development endeavors should be to optimize the advantages of IoT-controlled UV LED lighting for indoor agriculture by refining the technology, expanding its applicability, and improving its sustainability.

5. Conclusions

This study's distinctiveness stems from its sophisticated integration of UV LED lighting and IoT technology, designed to optimize indoor kale cultivation. This innovative approach utilizes the precise control capabilities of UV LEDs to emit specific wavelengths tailored to meet kale's PAR requirements, ensuring optimal light quality, intensity, and exposure duration. This customized light spectrum enhances photosynthetic efficiency and robust plant health. Rigorous statistical validation further bolsters confidence in this methodology's scientific rigor and reliability.

This research leverages an IoT-driven system to meticulously monitor and adjust critical real-time environmental variables, including temperature, humidity, light intensity, and soil moisture. This dynamic control, facilitated by a network of sensors and actuators, ensures optimal growing conditions throughout the plant's developmental stages. The system's automated nature guarantees consistent and optimal plant health while minimizing resource wastage, presenting a promising solution for sustainable agriculture. The precision and efficiency of this system inspire confidence in its efficacy, suggesting the potential for a new era of controlled-environment agriculture.

Empirical evidence strongly supports the system's efficacy, with statistical analysis, including ANOVA examination, demonstrating the effectiveness of specific light intensities and spectra in promoting kale growth. During a 12 h photoperiod, light intensities of

6535.76 lux, approximately 98.04 μmol/m²/s PAR, significantly increased the plants' nutritional content and biomass compared to conventional lighting setups. This statistically significant increase in growth metrics further bolsters confidence in the approach's potential.

The IoT-based kale cultivation architecture incorporates advanced technological capabilities. The MQTT protocol ensures efficient and low-latency data transmission for real-time monitoring and control. At the same time, LoRaWAN extends connectivity for large-scale agricultural operations. The cloud-based architecture optimizes growth conditions through real-time analysis and seamless data integration. These IoT system features provide a robust and scalable precision agriculture platform, furthering this study's objectives and highlighting its potential for advancing sustainable agricultural practices.

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Appendix A

Table A1. Summary statistics for kale data for 45 days.

Statistic	Plot Number	Light Intensity (lux)	Height (cm)	Average Width Leaf Size (cm)	Average Length Leaf Size (cm)	Average Width Branch Size (cm)	Average Length Branch Size (cm)
Count	45	45	45	45	45	45	45
Mean	2.00	6535.76	13.66	8.39	10.65	17.54	21.02
Std	0.83	3070.64	5.82	2.29	3.11	5.87	5.81
Min	1.00	1826.00	3.00	3.50	4.17	5.00	7.33
25%	1.00	4340.00	10.00	7.17	9.00	13.67	18.00
50%	2.00	7128.00	13.00	8.67	10.67	18.00	21.00
75%	3.00	8573.00	16.00	9.83	12.83	21.00	25.33
Max	3.00	13,136.00	29.00	13.67	16.33	27.67	33.50

Table A2. Dataset on effects of light intensity on kale growth for 45 days.

Experimental Group	Plot Number	Light Intensity (lux)	Height (cm)	Average Width Leaf Size (cm)	Average Length Leaf Size (cm)	Average Width Branch Size (cm)	Average Length Branch Size (cm)
T1-1	1	1826	6.0	5.83	7.00	10.33	15.00
T1-1	2	1968	6.5	4.17	4.67	8.67	11.67
T1-1	3	2005	7.0	5.83	6.17	11.83	16.33
T1-2	1	1946	7.0	5.83	7.83	8.83	12.67
T1-2	2	2302	8.0	4.83	5.83	10.83	15.17
T1-2	3	1997	3.0	3.50	4.17	5.00	7.33

T1-3	1	2130	7.0	5.33	7.00	11.67	14.33
T1-3	2	2236	6.0	4.67	6.17	7.50	11.50
T1-3	3	2294	7.0	5.67	6.17	8.50	10.67
T2-1	1	7505	16.0	11.50	12.83	21.67	23.33
T2-1	2	10,101	15.0	8.50	9.17	19.83	20.67
T2-1	3	10,440	11.0	7.50	9.00	16.5	18.67
T2-2	1	4335	17.0	9.67	10.50	20.67	23.83
T2-2	2	5567	28.0	13.67	14.50	27.67	33.50
T2-2	3	5800	16.0	9.83	10.67	13.12	25.33
T2-3	1	9417	11.0	7.17	9.67	14.67	18.00
T2-3	2	13,136	12.0	9.83	12.33	20.50	23.33
T2-3	3	12,944	13.0	8.83	11.00	15.67	20.33
T3-1	1	7638	14.0	9.00	12.17	19.83	23.00
T3-1	2	8248	19.0	11.83	13.33	26.50	27.67
T3-1	3	7709	14.0	10.83	12.33	22.33	25.33
T3-2	1	5247	23.0	9.17	15.17	23.33	29.00
T3-2	2	5254	22.0	12.33	16.33	24.83	26.00
T3-2	3	4883	22.0	9.83	13.33	24.83	28.00
T3-3	1	9390	29.0	9.83	15.33	27.67	29.00
T3-3	2	11,202	24.0	10.17	14.83	26.67	29.50
T3-3	3	9659	20.0	10.00	14.67	24.00	26.20
T3-4	1	9465	11.0	8.33	10.50	18.50	20.33
T3-4	2	8573	16.0	11.67	15.50	26.33	30.00
T3-4	3	9627	14.0	9.33	13.67	21.00	27.00
T3-5	1	7864	13.0	7.67	9.83	17.33	22.00
T3-5	2	7649	12.0	10.5	14.33	19.83	24.00
T3-5	3	7209	14.0	8.00	11.00	19.33	22.50
T3-6	1	5711	10.0	8.50	10.83	20.00	20.00
T3-6	2	5330	11.0	8.67	9.50	13.83	21.00
T3-6	3	5305	18.0	7.17	10.50	14.33	19.33
T3-7	1	4757	11.0	8.83	10.33	15.67	19.33
T3-7	2	4340	14.0	8.17	11.00	18.00	18.67
T3-7	3	4132	14.0	9.50	11.33	15.83	22.50
T3-8	1	8975	13.0	9.00	10.17	16.17	20.67
T3-8	2	7128	9.0	6.17	7.67	13.67	15.83
T3-8	3	8174	15.0	8.83	11.33	18.67	21.17
T3-9	1	8420	9.0	5.17	7.17	10.67	13.33
T3-9	2	7243	15.0	8.33	12.50	20.00	22.50
T3-9	3	7028	12.0	8.50	10.00	16.83	20.50

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