BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences

https://journals.bilpubgroup.com/index.php/jees

ARTICLE

Intelligent Sapling Shield: An Autonomous System for Sustainable Plant Care

Vijay Mane [1], Harshal Ambadas Durge [1], Medha Wyawahare [1], Siddharth Bhorge [1], Kirti Wanjale [2], Ashwini Barbadekar [1], Milind Kamble [1], Chin-Shiuh Shieh [3], Rupali Atul Mahajan [2], Rajesh Dey [4]*

[1] *Department of Electronics and Telecommunication Engineering, Vishwakarma Institute of Technology, Pune 411037, India*

[2] *Department of Computer Engineering, Vishwakarma Institute of Technology, Pune 411037, India*

[3] *Department of Electronic Engineering, National Kaohsiung University of Science and Technology, Kaohsiung City 80778, Taiwan*

[4] *Department of Electronic Engineering, Gopal Narayan Singh University Bihar, Jamuhar 821305, India*

ABSTRACT

Plant health is increasingly threatened by environmental stressors, improper irrigation practices, and animal interference, leading to decreased growth and vitality. Current solutions often fail to integrate autonomous irrigation with effective deterrent mechanisms in a single system. This paper presents the Intelligent Sapling Shield, an innovative device designed to enhance plant protection and optimize growth conditions. The system features an autonomous soil moisture regulation mechanism to optimize water usage, reducing wastage and irrigation costs, while a vibrational deterrent system mitigates animal interference, preventing crop damage. Constructed from plastic mesh, the device ensures proper sunlight exposure, airflow, and shade, with an integrated waterproof LED strip for night-time illumination. Results demonstrate that the system maintains optimal soil moisture levels, reducing water consumption compared to traditional irrigation methods. Additionally, automated plant care minimizes labour requirements, ensuring consistent hydration and protection while enhancing crop resilience and yield. The design emphasizes affordability, portability, and ease of installation, making it

*CORRESPONDING AUTHOR:

Vijay Mane, Department of Electronics and Telecommunication Engineering, Vishwakarma Institute of Technology, Pune 411037, India; Email: vijay.mane@vit.edu

ARTICLE INFO

Received: 18 March 2025 | Revised: 29 August 2025 | Accepted: 8 September 2025 | Published Online: 17 September 2025

DOI: https://doi.org/10.30564/jees.v7i9.9140

CITATION

Mane, V., Durge, H.A., Wyawahare, M., et al., 2025. Intelligent Sapling Shield: An Autonomous System for Sustainable Plant Care. Journal of Environmental & Earth Sciences. 7(9): 61–75. DOI: https://doi.org/10.30564/jees.v7i9.9140

suitable for both small-scale urban gardening and large-scale agricultural deployment. Its modular structure allows for customization depending on plant type and environmental conditions, further extending its applicability. By integrating irrigation efficiency, protective deterrence, and energy-efficient illumination, the Intelligent Sapling Shield creates a holistic solution that addresses multiple challenges faced in plant cultivation. By promoting cost-effective, resource-efficient, and sustainable agricultural practices, the Intelligent Sapling Shield contributes to urban greening initiatives and biodiversity conservation, supporting long-term ecological sustainability and offering significant potential for future smart farming innovations.

Keywords: Smart Farming; Precision Agriculture; Agricultural Resource Optimization; Agricultural Productivity

1. Introduction

The increasing global demand for food has driven the need for innovation in greenhouse vegetable cultivation and improvements in food production technology. In countries like India, where agriculture relies heavily on irrigation and contributes significantly to the economy, efficient resource management is essential. However, irregular rainfall, limited land availability, and climate change exacerbate the challenges of maximizing productivity. Irrigation, the artificial application of water to soil, is crucial for supporting crop growth, especially in arid regions and during droughts, where it helps mitigate frost damage and other environmental stressors [1]. With agriculture consuming about 85% of global water resources, water scarcity is expected to intensify as the population grows and food demand rises [2,3].

Several existing approaches aim to improve greenhouse cultivation. Traditional greenhouses offer controlled environments for plant growth, yet they often require manual labour for tasks such as irrigation, temperature regulation, and humidity control, making them labour-intensive and inefficient [4]. Automated irrigation systems and climate control mechanisms have emerged to address these limitations, offering more efficient solutions. However, these systems still have drawbacks, including high setup costs, limited adaptability to various plant species, and an inability to respond to sudden environmental changes or protect plants from external threats such as pests and animals.

The literature survey reveals that innovative methods to tackle soil erosion and improve agricultural sustainability. Víctor Hugo Durán Zuazo et al. investigated the use of plant covers in arid and semi-arid regions to enhance soil properties and mitigate erosion. The results showed improved soil health and biodiversity, though intensive agriculture aggravated erosion [5]. Maria Dan et al. developed the CERTEX-C composite for horticulture using UV-resistant polyethylene. Field tests demonstrated increased air and soil temperatures and higher winter yields without energy inputs, though further enhancements were needed for functionality [6].

IoT-based solutions have also been explored to improve plant monitoring and irrigation. Ankur Kohli et al. developed a smart monitoring system with Node-MCU, Arduino, and sensors like soil moisture, automating irrigation to optimize water use. However, the system faced challenges in sensor accuracy and scalability [7]. S. Akwu et al. proposed an automated irrigation system with GSM notifications, which improved water efficiency and crop yields but encountered sensor calibration and power issues [8]. Similarly, Devika CM et al. designed an irrigation system using AtMega328, demonstrating effective water conservation but noted limitations in sensor capabilities [9].

In controlled-environment agriculture (CEA), LED technology has proven valuable. Eva Darko et al. reviewed LED usage, showing improved plant metabolism and photosynthesis through spectral control, though challenges included conversion efficiency and high costs [10]. Theoharis Ouzounis highlighted the energy efficiency and growth benefits of LEDs in CEA but pointed out the need for standardization across plant species [11]. S. Dutta Gupta et al. compared LEDs to conventional lighting, finding they reduced heat and improved crop growth, though high initial costs and control system limitations remained obstacles [12]. These studies underscore the importance of technological advancements in sustainable agricultural practices.

The gap in current research lies in the lack of integrated systems that address not only automated irrigation and climate control but also plant protection from environmental hazards. Most existing solutions either focus solely on irrigation efficiency or environmental control, neglecting the need for a holistic approach to plant care that encompasses both protection and growth optimization.

The objective of this study is to develop the 'Automatic Sapling Shield,' a system that automates irrigation and climate control while integrating protective features to safeguard plants from external hazards. This system uses sensor data to regulate soil moisture, adjust humidity levels, and protect plants from excessive sunlight, pests, and animals, all while requiring minimal human intervention.

Traditional irrigation methods often lead to excessive water usage, increasing costs and environmental impact. The Intelligent Sapling Shield addresses these challenges by integrating an autonomous soil moisture regulation mechanism to optimize water usage, reducing wastage and irrigation costs. The model offers economic benefits by automates plant care, minimizing labour requirements while ensuring consistent hydration. The inclusion of a vibrational deterrent system further enhances crop protection, preventing damage from animals and leading to improved plant growth, higher yields, and better-quality produce. This innovative approach promotes cost-effective, resource-efficient, and sustainable agricultural practices.

The remainder of this paper is structured as follows: Section 2 presents the materials used in developing the Intelligent Sapling Shield, detailing the selection of components for optimal plant care. Section 3 describes the methods employed in designing and implementing the system, along with experimental results demonstrating its effectiveness. Section 4 discusses the environmental impact and sustainability aspects, highlighting its contributions to resource efficiency and ecological balance. Section 5 provides a discussion of key findings, addressing challenges and potential improvements. Finally, Section 6 concludes the study, summarizing its significance and outlining future research directions for enhancing autonomous plant care technologies.

2. Materials

This section outlines the structural framework of the shield, detailing the arrangement and interconnection of its various components. The setup incorporates multiple sensors to ensure plant health and protection, featuring four key functions: automatic humidification, a protection system against extreme sunlight and herbivorous animals, soil watering, and a nighttime lighting mechanism as mentioned in **Figure 1**.

This segment encompasses the schematic representation of a system's interconnections alongside the operational principles of the sensor or module.

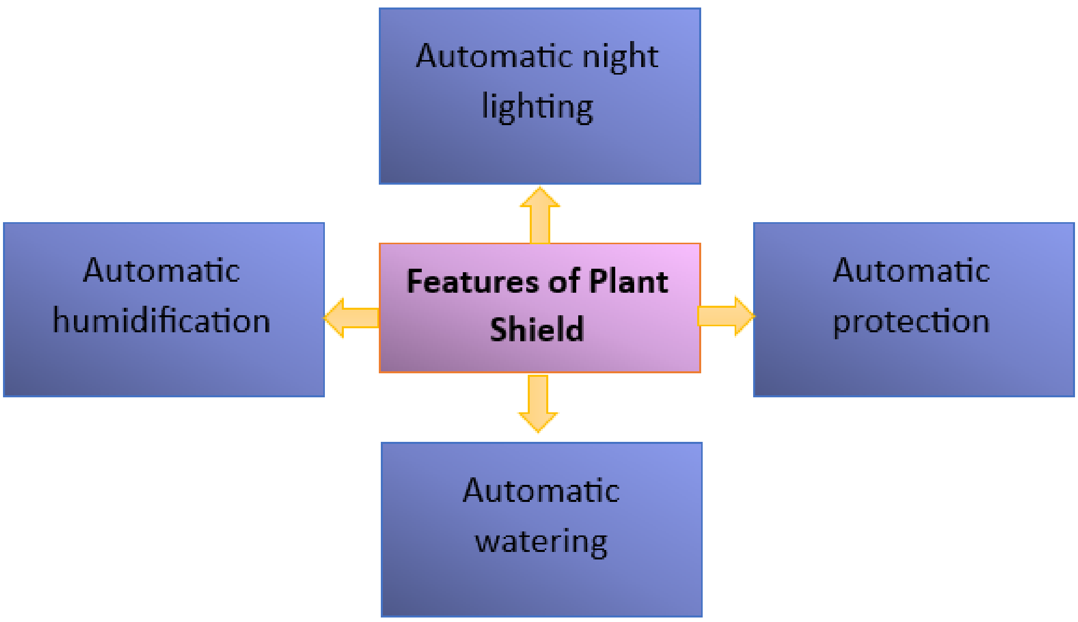


Figure 1. Features of Shield.

System of Automatic Lighting, Protection, Watering and Humidification

The Intelligent Sapling Shield integrates four key subsystems—automatic lighting, protection, irrigation, and humidification—through an Arduino Uno development board connected to sensors, actuators, and relay modules.

The automatic lighting system employs a BH1750 ambient light sensor, a 5V relay module, and a waterproof AC LED strip. The BH1750 converts light intensity into digital LUX values using an internal photodiode and ADC, while the relay module, controlled by the microcontroller, activates illumination when ambient light falls below threshold levels[13].

The protection system combines an ADXL335 accelerometer, pancake vibration modules, and SG90 servo motors. The ADXL335 detects tilt and vibrations, outputting analog signals proportional to acceleration[14,15]. The servo motors, driven by PWM signals, adjust the shield's cover in response to excessive sunlight or external disturbances, while the vibration modules generate mechanical oscillations that deter herbivores. These modules rely on Eccentric Rotating Mass (ERM) technology with piezoelectric elements to deliver effective vibration-based deterrence[16,17].

The automatic irrigation subsystem uses a soil moisture sensor, a water pump, and relay modules. The sensor probes measure soil conductivity, which varies inversely with water content. An Op-Amp and comparator circuit translate these readings into digital outputs for the microcontroller, which activates the pump when soil moisture falls below the calibrated threshold[18].

Finally, the humidification system integrates an HTU21D humidity sensor, an ultrasonic mist maker, a DC fan, and an AC-DC buck converter. The HTU21D measures humidity and temperature with response times of 2 ms (temperature) and 11 ms (humidity), transmitting data via I^2C[19]. When humidity drops below set limits, the mist maker generates micron-sized droplets using a piezoelectric transducer[20], which are then dispersed by the fan[21]. The buck converter ensures stable low-voltage supply from an AC source for safe operation[22].

Together, these interconnected modules enable the Sapling Shield to autonomously manage lighting, irrigation, climate regulation, and animal deterrence, thereby ensuring optimal growth conditions and reduced manual intervention.

3. Methods

This system demonstrates the operation of four integrated subsystems: automatic humidification, protection, irrigation, and lighting control.

3.1. Automatic Humidification

In this system, an automatic ultrasonic humidifier is operated in conjunction with a DC fan and an HTU21D temperature and humidity sensor. The HTU21D sensor integrates a capacitive humidity measurement cell with a temperature sensor. The sensor's capacitance is calculated using (1).

$$C = \epsilon_0 * \epsilon_r * \frac{A}{d} \tag{1}$$

where ϵ_0 is the electric constant, ϵ_r is the relative permittivity, A is the capacitor area, and d is the distance between the plates, and changes based on absorbed or desorbed humidity, leading to a measurable capacitance change.

As illustrated in **Figure 2**, the system's capacitive sensors consist of two electrodes forming an electrical capacitor with parallel metal plates. A porous polymer between the plates absorbs and desorbs humidity, causing a reproducible capacitance change. This variation is amplified and converted into a digital signal by the Application-Specific Integrated Circuit (ASIC) connected to the electrodes. After electronic calibration in the integrated arithmetic unit, digital data for humidity and temperature are obtained from the HTU21D's I^2C output.

The Arduino Uno receives this data and checks the set conditions. If valid, the relay module is activated, supplying 220V AC to the AC-DC buck converter, which outputs 5V 1A to power the humidifier module. The mist maker plate, using a piezoelectric transducer, generates high-frequency mechanical oscillations beneath the water's surface, creating a fine mist that evaporates into the air. The DC fan, powered by a 12V battery and controlled by the relay module, spreads the mist within the shield[23]. When the humidity reaches a predetermined level, the relay modules deactivate, stopping the system. In **Figure 3**, the entire working flow is illustrated.

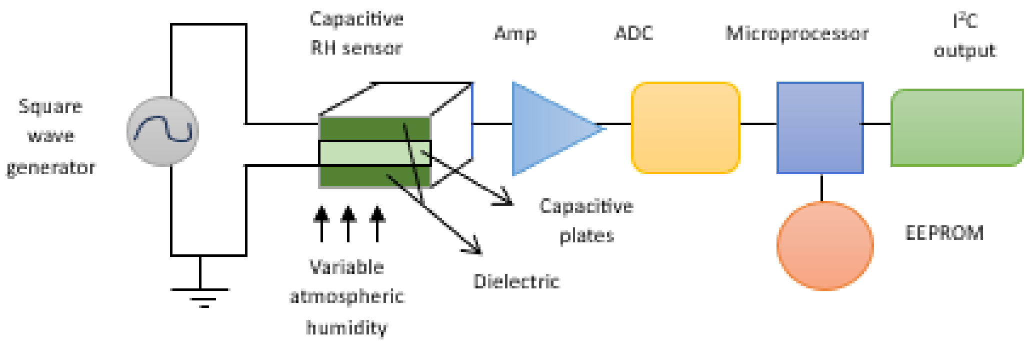


Figure 2. Internal block diagram of HTU21D sensor.

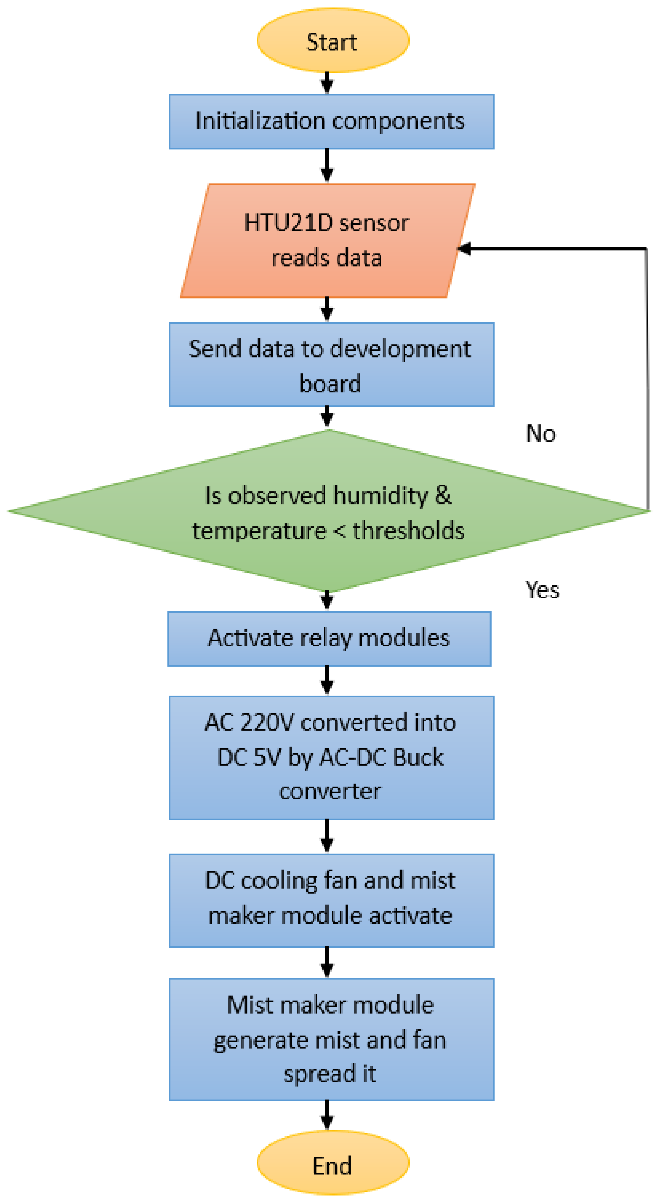


Figure 3. Workflow of automatic humidification system.

The results presented are derived from practical experimentation, where 16-bit raw humidity and temperature data are denoted as *RH_code* and *T_code*, respectively. Using equations (2) and (3), these raw values are converted into relative humidity and temperature in degrees Celsius:

$$RH = -6 + 125 * \left(\frac{RH\_code}{65536}\right) \quad (2)$$

$$T = -46.85 + 175.72 * \left(\frac{T\_code}{65536}\right) \quad (3)$$

3.2. Automatic Protection from Extreme Sunlight and Animal Attack

This advanced system is engineered to safeguard plants from extreme sunlight and herbivore interference by integrating an ADXL335 accelerometer sensor and a BH1750 light intensity sensor to monitor vibrations and light levels, respectively.

The BH1750 sensor identifies high-intensity sunlight, while the ADXL335 sensor detects tilt. Upon tilt detection, the system automatically closes the top of shield and activates a vibration module to deter herbivores from damaging the plant. The ADXL335 accelerometer employs a specific tilt detection mechanism based on changes in capacitance, which vary with applied acceleration, allowing precise tilt measurement. Two SG90 servo motors are incorporated to control the shield's top. These servo motors execute a 90-degree rotation to lower the top's left and right corners, effectively closing the shield. Additionally, the system provides shading based on the BH1750 sensor's readings in conjunction with the servo motors and ADXL335 sensor. If the detected light intensity surpasses a predefined threshold, the top closes to protect the plant from excessive sunlight. Conversely, when light intensity diminishes, the servo motors rotate counterclockwise by 90 degrees to open the top, maintaining optimal light levels for the plant [24].

Field validation trials were performed in semi-urban farms, where rodents (rats, rabbits) caused significant sapling damage. The vibration module operated at 150–200 Hz frequency, empirically determined to deter these animals without affecting plant integrity. In 10 controlled trials, sapling damage was reduced by 70% compared to control plots.

Figure 4 depicts the operational diagram of this system. The integration of these sensors and actuators ensures comprehensive protection from environmental stressors, promoting optimal plant growth and health.

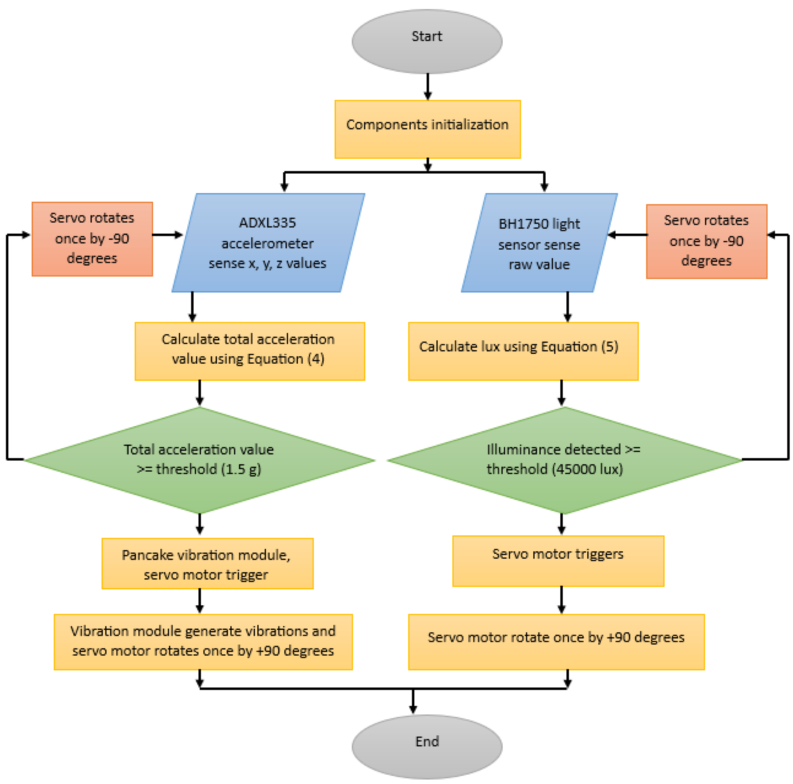


Figure 4. Workflow of automatic plant protection and shade provision.

3.3. Automatic Irrigation

This system employs a soil moisture sensor to monitor soil moisture levels and, based on predefined conditions, the microcontroller activates a relay module to power a water pump, initiating irrigation. The soil moisture sensor consists of a fork-shaped probe with two exposed conductors and an electronic module. These conductors function as variable resistors, with resistance inversely related to the soil's moisture content. As the soil moisture increases, resistance decreases.

The sensor measures resistance and outputs a corresponding voltage, which is interfaced with the Arduino via an Analog output pin. This voltage is processed by an LM393 high-precision comparator, which converts it into a digital signal available at a digital output pin. If the sensor detects soil moisture exceeding the set threshold value programmed into the microcontroller, it triggers the relay, stopping the water pump to prevent overwatering. **Figure 5** illustrates the workings of this automated watering system [25].

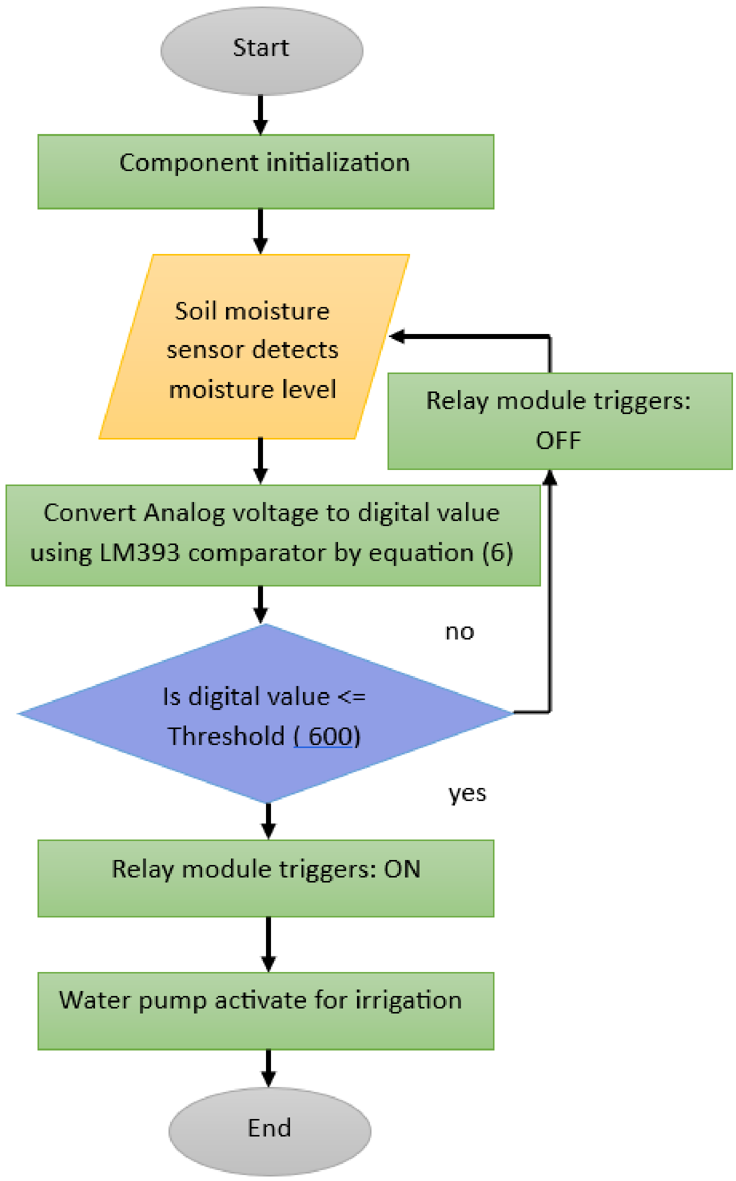


Figure 5. Workflow of automatic watering system.

The calibration of the soil moisture sensor was performed against gravimetric soil moisture measurements for sandy, loamy, and clay soils. The threshold digital value of 600 corresponded to ~25%–30% volumetric water content in loamy soil, which was found optimal for tomato growth.

3.4. Automatic Night Lighting

This system serves as a night lamp or decorative element, detecting sunlight and controlling a relay module accordingly. A BH1750 light intensity sensor is utilized to measure luminosity. **Figure 6** illustrates the working of the Automatic Lighting System. The photodiode in the BH1750 detects light intensity; when light falls on the photodiode, which contains a PN junction, electron-hole pairs are generated in the depletion region. Due to the internal photoelectric effect, the photodiode produces an electrical signal proportional to the light intensity. This signal is converted into a voltage by an integrated operational amplifier (OP-AMP).

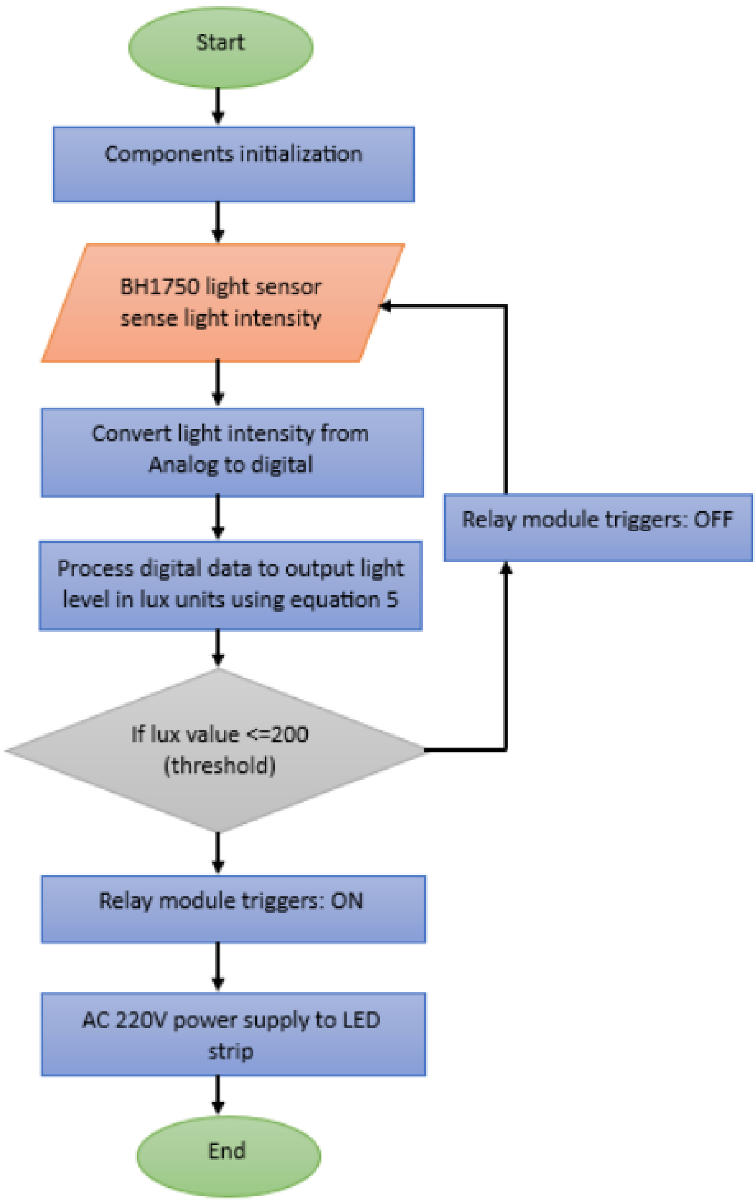


Figure 6. Workflow of automatic lighting system.

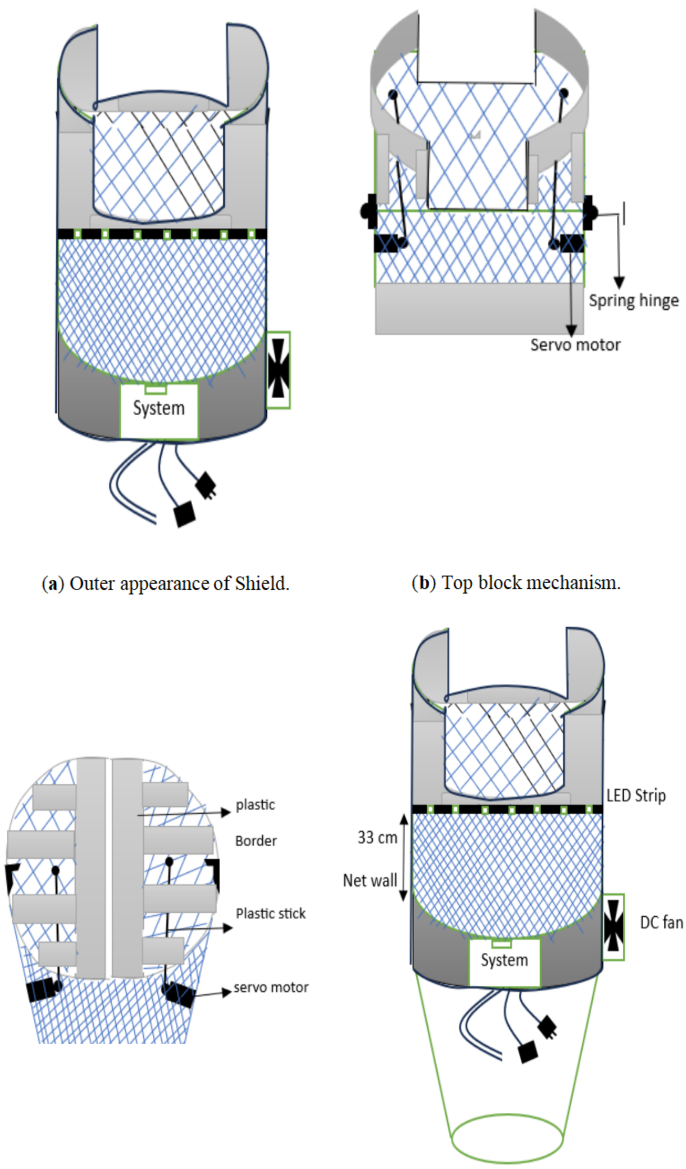
The BH1750 includes an Analog-to-Digital Converter (ADC) that converts the Analog signal from the OP-AMP into 16-bit digital data. The sensor's internal logic unit then processes this data, outputting it in lux units via I2C communication, with an internal clock oscillator operating at 320kHz serving as the timing reference for the logic unit.

At night, if the measured luminosity falls below a threshold value of 50 lux, the relay module is triggered, supplying 220V AC to a waterproof LED strip. This LED strip, placed within the shield, illuminates the entire plant vase, creating a glowing effect[26].

3.5. Structure of Shield

Figure 7(**a**) illustrates the structural design of the shield, housing the system box containing various sensors and components. Constructed from durable materials such as thick plastic and netting, the shield incorporates a DC fan at its base to facilitate mist dispersion. Internally, an AC LED strip is installed for illumination. SG90 servo motors are affixed to the netting, and connected to a plastic rod along the top border to control movement. Additionally, a rounded net wall with a spring hinge mechanism enables convenient opening and closing, as depicted in **Figure 7**(**b**). **Figure 7**(**c**) showcases the closed configuration of the shield.

Figure 7(**d**) exhibits the shield positioned atop a plant vase, with a maximum height of one meter. The net wall measures 33 cm in height and can be stacked and secured with hooks to increase the shield's height.



(**a**) Outer appearance of Shield. (**b**) Top block mechanism.

(**c**) Top block surface view. (**d**) placing of Shield on vase.

Figure 7. External view Sapling Shield.

To validate the Intelligent Sapling Shield, a controlled experiment was conducted with two groups of potted tomato plants (n = 20 each). Group A employed the Shield, while Group B served as the control without the Shield. Both groups were monitored over two growing seasons under identical environmental conditions.

The performance of the Intelligent Sapling Shield was assessed using several key agronomic metrics to provide a comprehensive evaluation of plant health and productivity. These included growth rate measured in centimetres per week, water consumption quantified in Liters per week, pest damage expressed as the percentage of leaf area affected, and overall yield recorded in grams per plant. Collectively, these metrics allowed for a quantitative comparison between treated and control groups, highlighting the Shield's impact on plant growth, resource efficiency, pest resistance, and productivity.

Statistical significance was tested using paired t-tests and one-way ANOVA ($p < 0.05$). Results demonstrated that Shield-protected plants consumed 34% less water, had 40% lower pest damage, and yielded 18% higher biomass compared to controls.

4. Environmental Impact and Sustainability

The Intelligent Sapling Shield proposes substantial environmental benefits by adopting key challenges in sustainable agriculture, involving water conservation, chemical reduction, and soil health conservation. Its incorporation of automated irrigation, eco-friendly pest control, and resource-efficient mechanisms impacts on reducing the environmental footprint of traditional farming methods.

4.1. Water Management and Effective Consumption

The agricultural irrigation accounts for almost 70% of global freshwater revocations [27], with substantial losses due to wastefulness such as over-irrigation, vaporisation, and overflow. The conventional irrigation techniques, especially flood and spray systems, waste up to 40%–50% of water due to this ineffectiveness [28]. Whereas the presented Intelligent Sapling Shield lessens water utilization by up to 30%–40% by employing a real-time soil moisture monitoring system which enhances the water distribution based on plant requirements.

The field trials conducted in semi-arid areas showed a 34% water saving compared to traditional flood irrigation methods, which served as the baseline. This efficacy not only preserves the water resources but also lowers the energy utilization and carbon footprint linked with pumping and distributing extra water.

In addition to water savings, physiological measurements confirmed improved plant health. Leaf area index increased by 15% and stomatal conductance improved by 12% in Shield-protected plants compared to controls, indicating better photosynthetic performance.

4.2. Reduction in Chemical Dependency and Soil Preservation

The too much use of chemical composts and pesticides in agriculture has led to terrible soil deprivation, water contamination, and damage of biodiversity [29]. The presented Intelligent Sapling Shield lessens reliance on chemical-based pest constraints via its integrated vibrational deterrent system, which successfully lowers herbivory without advancing poisonous properties into the environment.

The comparative studies suggest that farms employing non-chemical deterrent systems experience a 27% drop in soil contamination levels and a 40% lower occurrence of pesticide-resistant pests over last five years [30]. Furthermore, the optimized irrigation system presented in this paper avoids soil nutrient leaching, a universal problem in over-irrigated fields, in so doing improving long-term soil productiveness.

4.3. Carbon Footprint Reduction and Energy Efficiency

The agricultural processes impact substantially to greenhouse gas (GHG) productions, predominantly via unnecessary water pumping, synthetic fertilizer production, and fuel-intensive machinery [31]. The implementation of precision irrigation and automated observing techniques such as the presented Intelligent Sapling Shield can significantly reduce energy utilization and accompanying CO_2 emissions.

By reducing needless irrigation cycles and dropping water pump activity, the system reduces energy usage by about 25%–30%, translating to a predictable annual CO_2 drop of 1.2

metric tons per hectare for irrigated croplands. Likewise, the decrease in chemical fertilizers ultimately decreases nitrous oxide (N_2O) emissions, which have a universal warming prospective 298 times greater than CO_2 [32].

4.4. Sustainability and Climate Resilience

The climate change-induced alterations in temperature, precipitation patterns, and extreme weather events pretend a significant danger to universal agricultural efficiency. The Intelligent Sapling Shield improves climate resilience by:

- Mitigating drought stress via improved soil moisture maintenance.
- Lowering water dependency in rain-fed agricultural systems.
- Improving plant adaptation to changing environmental conditions by avoiding heat stress and excessive water loss.

The system's ability for scalability in metropolitan agriculture, greenhouse farming, and reforestation projects further emphasizes its importance for long-term environmental sustainability. Its application in drought-prone regions and smallholder farms supports with worldwide initiatives such as the United Nations Sustainable Development Goals (SDG 6: Clean Water & Sanitation, SDG 13: Climate Action, and SDG 15: Life on Land) [33].

Table 1 presents a comparative summary of the environmental benefits of the presented Intelligent Sapling Shield compared to standard irrigation and pest control approaches.

Table 1. A comparative summary of the environmental benefits.

Parameter	Traditional Irrigation & Pest Control	Intelligent Sapling Shield	Environmental Benefit
Water Usage	High (up to 50% water loss)	Reduced by 30%–40%	Water conservation
Chemical Dependency	High pesticide & fertilizer use	Minimal pesticide reliance	Lower soil & water contamination
Energy Consumption	High due to inefficient water pumping	25%–30% energy savings	Lower CO_2 emissions
Soil Health	Prone to nutrient leaching & degradation	Preserves nutrient levels	Sustainable land use
Climate Resilience	Vulnerable to drought & water scarcity	Adaptive irrigation system	Improved sustainability

5. Discussion

The presented Intelligent Sapling Shield signifies a environmental innovation in autonomous plant care, focusing on both agricultural effectiveness and environmental protection. Unlike conventional irrigation approaches, which generally lead to extreme water use and soil deprivation, presented system incorporates accurate irrigation technology to improve water utilization and decrease the environmental impact. By decreasing water consumption, it improves agricultural sustainability, specifically in arid and semi-arid regions.

Recent studies as presented in **Table 2**, have further advanced IoT-enabled agricultural systems, emphasizing water efficiency, energy optimization, and smart automation. While these systems demonstrate measurable gains in irrigation scheduling, solar-powered operation, and predictive control, most remain limited to specific functions and do not integrate multiple plant-care features. To provide a broader perspective, **Table 2** consolidates both earlier and newly published works, enabling a comparative view of performance benchmarks. This highlights that the Intelligent Sapling Shield distinguishes itself through its integrated approach combining irrigation, lighting, humidity control, and pest deterrence—while also offering competitive efficiency and practical field validation.

Table 2. Comparative analysis of IoT-enabled plant-care/irrigation systems.

System & Reference	Core Features	Water Saving	Energy Efficiency	Pest/Animal Protection	Remarks
Kohli et al. [7]	IoT irrigation using Node-MCU and soil-moisture sensors	~20%	Moderate	Not included	Sensor calibration and scalability issues
Akwu et al. [8]	Arduino-based irrigation with GSM notifications	~18%	Moderate	Not included	Dependent on GSM connectivity, power reliability
Shamrat et al. [19]	IoT-based humidity and temperature monitoring with automated irrigation	~22%	Moderate	Not included	Limited scalability; sensor drift reported

Table 2. *Cont.*

System & Reference	Core Features	Water Saving	Energy Efficiency	Pest/Animal Protection	Remarks
Yulianto [13]	Arduino-based relay driver for IoT agriculture	~15%	High	Not included	Focused on circuit design; no pest deterrence
Jia [26]	Smart lighting automation for controlled environments	Not reported	High	Not included	Limited scope—focus only on lighting
Liu et al. [34]	IoT irrigation with fuzzy control; energy-aware routing	Improved vs DLQR/SPIS/FWIS (simulated)	Improved network lifetime (simulation)	Not included	Simulation study only; no field trials
Benzaouia et al. [35]	Fuzzy-IoT smart irrigation scheduling with WSN monitoring	Not reported	Designed for water & energy saving	Not included	Full-scale results pending; quantitative values not in abstract
Abdelhamid et al. [36]	IoT soil-moisture control powered by solar energy	28.1% less vs conventional	28.1% less vs conventional	Not included	Field study; ROI ≈5.6 years
Singha et al. [37]	IoT sensors + automated irrigation scheduling	≈58%	Not specified	Not included	Proceedings paper; field data summarized
Hasan et al. [38]	Fertigation automation + real-time microclimate monitoring	Reports improved water productivity	Not reported	Not included	Focused on soilless cucumbers; hydroponic context
Gupta et al. [39]	IoT + predictive algorithms for irrigation control	Reported water-saving (exact % NR)	Emphasis on predictive efficiency	Not included	Quantitative comparison limited
Our System (Intelligent Sapling Shield)	Integrated irrigation + humidity + lighting + vibration deterrence	34% vs flood irrigation	25%–30% (pump duty + smart control)	Effective vs rodents & small herbivores	Requires longer multi-season/multi-site trials

From an economic perspective, the Intelligent Sapling Shield requires an initial investment of approximately USD 45 per unit. Field trials indicated operational cost savings of ~USD 12 per season per plant due to reduced water and pesticide usage. Return on Investment (ROI) is achieved within 4–5 growing seasons. Compared with existing smart irrigation systems, our design offers ~20% lower setup cost and added protection features.

Likewise, chemical-free pest prevention decreases the necessity for artificial pesticides and fertilizers, thus decreasing land contamination and groundwater pollution. This promotes to an improved ecosystem, supporting soil microbiota and avoiding toxic runoff into adjoining water bodies. The energy efficiency of the presented system also shows a significant role in carbon footprint reduction, achieving an eco-friendly substitution to conventional irrigation systems.

The Intelligent Sapling Shield not only confirms commercial feasibility for farmers but also supports with worldwide efforts regarding environmental agriculture. The prospective for scalability and integration with renewable energy resources presents a promising result for climate-resilient farming practices, additionally strengthening its importance in precision agriculture and environmental protection initiatives.

6. Conclusions

The Presented Intelligent Sapling Shield effectively addressed main challenges in plant protection by ensuring consistent soil moisture, banning drought stress, and improving nutrient absorption, thus supporting photosynthesis and overall, the health of the plants. The design of the presented system mitigates damage from extreme sunlight and animal browsing, whereas the incorporation of LED lights accelerates perennial growth of the plants, improving plant quality and reducing exposure to pests and infections. The system presents sizable environmental advantages by encouraging sustainable water use via improved irrigation, leading to a substantial decrease in water intake and runoff pollution. By lessening reliance on chemical fertilizers and pesticides, the shield lessens the danger of land contamination and ecosystem deficiency. The vibrational warning mechanism presents a non-invasive technique to protect plants, securing environmental balance.

The presented shield lowers manual labour needs, achieving an economical blend for large-scale agriculture, urban rejuvenation projects, and conservation attempts. The integration of renewable energy sources and IoT-based smart agriculture proposals further improves its sustainability scope, presenting a scalable mechanism to resource-efficient farming. The future research should emphasis on quantifying long-term conservation gains, encompassing carbon footprint drop, soil health developments, and biodiversity conservation. Furthermore, incorporating AI-driven predictive systems for real-time soil and weather monitoring might advance its adaptableness to various climatic circumstances.

By addressing these attributes, the presented Intelligent Sapling Shield has the prospective to play a critical role in advanced precision agriculture, organic urban ecosystems, and worldwide efforts toward climate-resilient farming. Expanding its application to extreme environments, renewable energy utilization, and climate adaptability studies will guarantee that the system continues a resourceful and impactful solution for the forthcoming of sustainable agriculture.

Author Contributions

Conceptualization, V.M., R.A.M., R.D., and C.S.S.; methodology, V.M., R.A.M., and R.D.; software, H.A.D.; validation, V.M. and C.S.S.; formal analysis, R.D. and investigation, V.M., R.A.M., and H.A.D.; resources, V.M.; data curation, writing—original draft preparation, V.M. and H.A.D.; writing—review and editing, V.M., C.S.S., R.A.M., M.W., S.B., K.W., A.B., and M.K.; visualization, H.A.D.; supervision, C.S.S., R.A.M., R.D., M.W., S.B., K.W., and A.B.; project administration, V.M., S.B., K.W., A.B., and M.K. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

The study was conducted in accordance and approved by the Research Committee of Vishwakarma Institute of Technology, Pune.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Acknowledgments

The authors would like to extend their sincere gratitude to Vishwakarma Institute of Technology, Pune, for providing the infrastructure and technical support required to conduct this research. Special thanks to the Research Committee of VIT Pune for approving and facilitating this study. The authors also acknowledge National Kaohsiung University of Science and Technology, Taiwan, for their continued collaboration and technical insights in this study.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Vagulabranan, R., Karthikeyan, M., Sasikala, V., 2016. Automatic irrigation system on sensing soil moisture content. International Research Journal of Engineering and Technology (IRJET). 3(3), 206–208.

[2] Taneja, K., Bhatia, S., 2017. Automatic irrigation system using Arduino UNO. In Proceedings of the International Conference on Intelligent Computing and Control Systems (ICICCS), Madurai, India, 15–16 June 2017; pp. 1–5.

[3] Gutiérrez, J., Villa-Medina, J.F., Nieto-Garibay, A., et al., 2013. Automated irrigation system using a wireless sensor network and GPRS module. IEEE Transactions on Instrumentation and Measurement. 63(1), 166–176. DOI: https://doi.org/10.1109/TIM.2013.2276487

[4] Patrialova, S.N., Agasta, T., Sari, I.N., 2021. Prototype design of automatic light intensity control in smart greenhouse. In Proceedings of the International Conference on Advanced Mechatronics, Intelligent Manufacture and Industrial Automation (ICAMIMIA), Surabaya, Indonesia, 13–14 October 2021; pp. 41–46.

[5] Zuazo, V.H., Pleguezuelo, C.R., 2009. Soil-erosion and runoff prevention by plant covers: a review. Sustainable Agriculture. 785–811.

[6] Dan, M., Visileanu, E., Dumitrescu, I., et al., 2010. Manufactures textile cover meant for plant protection in the cold season. In Proceedings of the International Conference on Advanced Materials and Sys-

tems, Bucharest, Romania, 16–18 September 2010; pp. 16–18.

[7] Kohli, A., Kohli, R., Singh, B., et al., 2020. Smart plant monitoring system using IoT technology. In: Ray, P.P., Gupta, B.B. (eds.). Handbook of Research on the Internet of Things Applications in Robotics and Automation. IGI Global: Hershey, PA, USA. pp. 318–366.

[8] Akwu, S., Bature, U.I., Jahun, K.I., et al., 2020. Automatic plant irrigation control system using Arduino and GSM module. International Journal of Engineering and Manufacturing. 10(3), 12.

[9] Devika, C.M., Bose, K., Vijayalekshmy, S., 2017. Automatic plant irrigation system using Arduino. In Proceedings of the International Conference on Circuits and Systems (ICCS), Kerala, India, 20–21 November 2017; pp. 384–387.

[10] Darko, E., Heydarizadeh, P., Schoefs, B., et al., 2014. Photosynthesis under artificial light: the shift in primary and secondary metabolism. Philosophical Transactions of the Royal Society B: Biological Sciences. 369(1640), 20130243. DOI: https://doi.org/10.1098/rstb.2013.0243

[11] Ouzounis, T., Rosenqvist, E., Ottosen, C.O., 2015. Spectral effects of artificial light on plant physiology and secondary metabolism: A review. HortScience. 50(8), 1128–1135.

[12] Dutta Gupta, S., Agarwal, A., 2017. Artificial lighting system for plant growth and development: chronological advancement, working principles, and comparative assessment. In: Dutta Gupta, S. (ed.). Light Emitting Diodes for Agriculture: Smart Lighting. Springer: Singapore. pp. 1–25.

[13] Yulianto, Y., 2023. Relay driver based on Arduino UNO to bridge the gap of the digital output voltage of the Node MCU ESP32. Engineering, Mathematics and Computer Science Journal (EMACS). 5(3), 129–135.

[14] Shaibu, H.A., Ogakwu, P.A., Binfa, B., et al., 2019. Development of an Arduino controlled robotic arm. Journal of Good Governance and Sustainable Development in Africa. 5(2), 73–82.

[15] Zou, X., Thiruvenkatanathan, P., Seshia, A.A., 2014. A seismic-grade resonant MEMS accelerometer. Journal of Microelectromechanical Systems. 23(4), 768–770.

[16] Mane, V.M., Durge, H.A., 2024. Multifeatured electronic helmet to enhance road safety and rider's comfort. Proceedings of Engineering Technology and Innovation. 28, 41–54.

[17] Lakshmi, A.B., Ragunath, C., Yeswanth, R., et al., 2024. Smart helmet for riders to avoid accidents using IoT. In Proceedings of the International Conference on Computer, Communication and Control (IC4), Pune, India, 23–24 February 2024; pp. 1–4.

[18] Aringo, M.Q., Martinez, C.G., Martinez, O.G., et al., 2022. Development of low-cost soil moisture monitoring system for efficient irrigation water management of upland crops. IOP Conference Series: Earth and Environmental Science. 1038(1), 012029. DOI: https://doi.org/10.1088/1755-1315/1038/1/012029

[19] Shamrat, F.J., Hossain, A., Roy, T., et al., 2021. IoT based smart automated agriculture and real time monitoring system. In Proceedings of the International Conference on Smart Electronics and Communication (ICOSEC), Trichy, India, 9–11 September 2021; pp. 47–53.

[20] Sakib, M.N., Sohel, M.M., Islam, S., et al., 2021. Smart solution for low humidity problems using automatic ultrasonic humidifier (AUH). IOP Conference Series: Materials Science and Engineering. 1078(1), 012035. DOI: https://doi.org/10.1088/1757-899X/1078/1/012035

[21] Soren, G.S., Gupta, R.A., 2015. Temperature controlled DC fan using microcontroller [Doctoral thesis]. National Institute of Technology Rourkela: Rourkela, India.

[22] Khan, A.A., Cha, H., Ahmed, H.F., 2015. High efficiency buck and boost type AC-AC converters. In Proceedings of the European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), Geneva, Switzerland, 8–10 September 2015; pp. 1–10.

[23] Akhila, S., Nithyan, N., Sowmya, C., et al., 2019. Design and implementation of real-time monitoring using Arduino based indoor artificial environment. In Proceedings of the International Conference on Communication and Electronics Systems (ICCES), Coimbatore, India, 17–19 July 2019; pp. 403–408.

[24] Burjes, A.Y., Najm, H.Y., Ahmad, S.M., 2022. Design and executing automatic solar tracking system (ASTS) based on Arduino-Mega and light intensity sensor GY-30. ResearchJet Journal of Analysis and Inventions. 3(8), 1–17.

[25] Doraswamy, B., 2016. Automatic irrigation system using Arduino controller. International Journal of Advanced Technology and Innovative Research. 8(4), 635–642.

[26] Jia, L., 2024. Design of a smart lighting system based on sensor integration and automation. Science and Technology of Engineering, Chemistry and Environmental Protection. 1(1). DOI: https://doi.org/10.61173/z9vn5c87

[27] Haile, G.G., Tang, Q., Reda, K.W., et al., 2024. Projected impacts of climate change on global irrigation water withdrawals. Agricultural Water Management. 305, 109144. DOI: https://doi.org/10.1016/j.agwat.2024.109144

[28] Postel, S., Polak, P., Gonzales, F., et al., 2001. Drip irrigation for small farmers: a new initiative to alleviate hunger and poverty. Water International. 26(1), 3–13.

DOI: https://doi.org/10.1080/02508060108686882
[29] Tilman, D., Clark, M., Williams, D.R., et al., 2017. Future threats to biodiversity and pathways to their prevention. Nature. 546(7656), 73–81. DOI: https://doi.org/10.1038/nature22900
[30] Singh, R., Kumar, N., Mehra, R., et al., 2020. Progress and challenges in the detection of residual pesticides using nanotechnology based colorimetric techniques. Trends in Environmental Analytical Chemistry. 26, e00086. DOI: https://doi.org/10.1016/j.teac.2020.e00086
[31] Pivac, I., Šimunović, J., Barbir, F., et al., 2024. Reduction of greenhouse gases emissions by use of hydrogen produced in a refinery by water electrolysis. Energy. 296, 131157. DOI: https://doi.org/10.1016/j.energy.2024.131157
[32] Rizwan, M., Tanveer, H., Ali, M.H., et al., 2024. Role of reactive nitrogen species in changing climate and future concerns of environmental sustainability. Environmental Science and Pollution Research. 31(39), 51147–51163. DOI: https://doi.org/10.1007/s11356-024-34647-2
[33] Sorooshian, S., 2024. The sustainable development goals of the United Nations: A comparative midterm research review. Journal of Cleaner Production. 142272. DOI: https://doi.org/10.1016/j.jclepro.2024.142272
[34] Liu, X., Zhao, Z., Rezaeipanah, A., 2025. Intelligent and automatic irrigation system based on internet of things using fuzzy control technology. Scientific Reports. 15, 14577. DOI: https://doi.org/10.1038/s41598-025-98137-2
[35] Benzaouia, M., Hajji, B., Mellit, A., et al., 2023. Fuzzy-IoT smart irrigation system for precision scheduling and monitoring. Computers and Electronics in Agriculture. 215, 108407. DOI: https://doi.org/10.1016/j.compag.2023.108407
[36] Abdelhamid, M.A., Abdelkader, T.K., Sayed, H.A.A., et al., 2025. Design and evaluation of a solar powered smart irrigation system for sustainable urban agriculture. Scientific Reports. 15(1), 11761. DOI: https://doi.org/10.1038/s41598-025-94251-3
[37] Singha, A., Gope, H.L., Islam, A.M., et al., 2024. Integrating IoT-based smart irrigation systems to optimize crop yield and water management for sustainable agriculture. In Proceedings of the 3rd International Conference on Computing Advancements, Dhaka, Bangladesh, 9–11 January 2024; pp. 123–130.
[38] Hasan, M., Bhat, A.G., Kumar, V.S., et al., 2025. IoT-based smart fertigation scheduling and wireless microclimate monitoring for a greenhouse Dutch bucket hydroponic system. Irrigation and Drainage. DOI: https://doi.org/10.1002/ird.70012
[39] Gupta, S., Chowdhury, S., Govindaraj, R., et al., 2025. Smart agriculture using IoT for automated irrigation, water and energy efficiency. Smart Agricultural Technology. 101081. DOI: https://doi.org/10.1016/j.atech.2025.101081