Smart Hydroponic Farming Using IoT Technologies: A Socio-Technical Approach to Urban Sustainability

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ABSTRACT

This paper presents that urban populations are increasingly facing challenges related to limited space, lifestyle constraints, and a rising interest in self-sustained food production. Smart farming systems integrating the Internet of Things (IoT) offer promising solutions to support sustainable, space-efficient agriculture. This paper presents the development of an innovative hydroponic gardening system using an ESP8266 microcontroller, ultrasonic water-level monitoring, LED indicators, and mobile-based control via the Blynk application. Beyond the technical contribution, this study emphasises the social significance of IoT-based farming in improving food awareness, reducing labour dependency, and supporting behavioural change towards sustainable urban living. Findings show that the system reliably automates water management, enhancing accessibility for individuals with limited gardening experience or time constraints. The project demonstrates how low-cost IoT hydroponics can support community resilience, environmental awareness, and adaptability to a modern lifestyle.

Keywords– Urban Farming; IoT-based Hydroponics, Smart Irrigation Automation; Water-Level Monitoring;

INTRODUCTION

Urbanisation and modern lifestyle transformations have significantly influenced how individuals engage with food production, gardening, and sustainable living. As residential areas become increasingly compact—especially with the rise of high-density housing such as apartments and condominiums—the availability of land for traditional soil-based farming has diminished drastically. According to UN-Habitat [1], modern cities continue to shift toward smaller living units, thereby reducing opportunities for home gardening and agriculture. At the same time, increasing global concerns about food security, health consciousness, and environmental degradation have encouraged society to re-evaluate the importance of home-based agriculture. The Food and Agriculture Organisation (FAO) notes that households worldwide are increasingly exploring alternative food sources and adopting self-sustaining practices to mitigate food insecurity [2]. Hydroponic systems, which allow plants to grow without soil and require minimal space, have emerged as a practical solution for urban environments. When enhanced with Internet of Things (IoT) technologies, these systems become even more accessible and manageable, making them suitable for modern lifestyle constraints, as noted by Sarkar [3].

Despite rising public interest in home gardening, many individuals struggle to adopt and maintain such practices due to limited time and demanding work schedules. Traditional gardening requires consistent monitoring and manual watering, tasks that may not be feasible for individuals juggling professional roles and personal responsibilities. Kim and Park [4] found that time constraints and a lack of routine compatibility are significant barriers preventing urban dwellers from engaging in gardening activities. In addition, beginners often lack gardening knowledge and may fear the risk of plant failure or wasted resources. Rahman et al. [5] reported that urban communities frequently avoid home farming due to a lack of technical understanding and uncertainty about maintaining plant health. These realities reflect broader social issues related to integrating sustainable behaviours into fast-paced lifestyles and highlight the need for automated agriculture systems that reduce manual labour and increase reliability.

From a social science perspective, enabling individuals to grow food at home contributes to personal well-being, environmental responsibility, and household autonomy. Smart farming systems can empower residents who previously felt excluded from gardening due to space or time limitations. Researchers in [6] concluded that IoT-based farming tools significantly increase accessibility for urban communities by simplifying complex agricultural tasks. Automation further benefits working adults, elderly residents, and students by reducing the physical and cognitive burden typically associated with plant care. Ghazali et al. [7] emphasise that technological assistance increases public interest and acceptance of home farming by reducing perceived effort. Additionally, widespread adoption of IoT, which enables home farming, can influence food-related attitudes, encouraging healthier diets and strengthening community resilience. The World Bank [8] notes that household-level food production is playing an increasingly important role during crises, such as pandemics, supply interruptions, or inflation-driven food insecurity.

In response to these needs, this project introduces a smart hydroponic gardening system designed to monitor water levels, automate pump control, and provide real-time updates through a mobile interface. The system integrates an ultrasonic sensor for precise water-level detection, LED indicators for intuitive visual feedback, and a relay-controlled water pump that can be activated manually or remotely via the Blynk IoT application. The ESP8266 microcontroller functions as the system's core, supporting seamless integration between sensors, actuators, and cloud-based communication. The Blynk platform and ESP8266 are commonly used to support beginner-friendly IoT systems due to their flexibility and low cost. Through these features, the project aims to create an accessible, efficient, and user-friendly farming solution adaptable to individuals with varying skill levels and living conditions.

Overall, this project contributes not only to the technical development of IoT-based hydroponic automation but also to the broader social objective of promoting sustainable, inclusive, and modern farming practices. By lowering barriers to participation, the system encourages behavioural transformation toward greener lifestyles, supports urban food self-sufficiency, and demonstrates how digital innovation can translate environmental awareness into practical everyday action. Graham and Smith [9] argue that digital tools play a crucial role in shifting societal habits toward sustainability, making solutions like this smart hydroponic system valuable for long-term community resilience and environmental awareness. As such, this project serves as a model for how low-cost IoT innovations can strengthen urban communities and contribute meaningfully to sustainable development goals.

LITERATURE REVIEW

Technical Foundations

Smart farming technologies combine embedded systems, electronics, and automation to support efficient plant cultivation in environments with limited space or resources. The Internet of Things (IoT) plays a central role by enabling the interconnection of sensors, microcontrollers, and cloud platforms to automate tasks such as irrigation, nutrient circulation, and environmental monitoring. Microcontroller platforms, such as the ESP8266 and ESP32, are widely used due to their built-in Wi-Fi connectivity, low cost, and suitability for real-time data processing in agricultural applications [10]. In hydroponic systems, ultrasonic sensors such as the HC-SR04 are commonly used to measure water levels due to their high accuracy, non-contact operation, and minimal maintenance requirements [11]. Relay modules serve as safe switching mechanisms, enabling low-voltage microcontrollers to control high-voltage devices, such as water pumps, thereby ensuring stable automation and electrical isolation [12]. Additionally, LED indicators provide intuitive visual feedback to support user interaction, while mobile IoT platforms, such as Blynk, offer remote access to sensor data and device controls, enhancing user convenience and overall system usability [13].

Hydroponic farming forms another core technical foundation for this project. Hydroponic systems replace soil with nutrient-rich water solutions, delivering essential minerals directly to plant roots and enabling faster growth, reduced water usage, and lower risk of soil-borne diseases. Research indicates that hydroponic systems can

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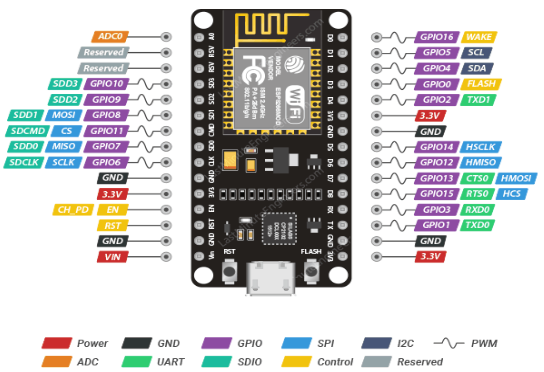
reduce water consumption by up to 90% compared to traditional soil-based farming and are highly adaptable for vertical or compact designs, making them suitable for urban homes [14]. Vertical hydroponic towers maximise plant yield per unit area, making them ideal for apartments or homes without access to traditional garden plots. Because hydroponics requires continuous water circulation, automated monitoring systems become crucial for maintaining a nutrient balance, regulating water levels, and ensuring the proper operation of pumps. The integration of IoT into hydroponic systems, therefore, enhances system efficiency while reducing human error, supporting a more accessible and sustainable approach to modern agriculture.

Comparative Projects and Technologies

Many previous studies and DIY projects have explored the integration of IoT technologies into smart gardening systems, forming a rich comparative landscape for this project. Sarkar's early work on IoT-based smart gardening demonstrated how microcontrollers and basic sensors could automate irrigation and report soil moisture levels through cloud platforms [3]. More recent projects have shown the effectiveness of using the ESP8266 with the Blynk platform in creating user-friendly automated watering systems. These comparative studies consistently highlight that low-cost IoT components, when properly integrated, can achieve surprisingly efficient and reliable automation for small-scale agricultural setups.

Other researchers have expanded smart agriculture into more advanced domains, including multi-sensor integration, AI-driven plant health diagnostics, and predictive watering algorithms. For example, Zhao et al. developed a multi-sensor hydroponic monitoring system that combines temperature, humidity, and water-quality sensing to provide a holistic environmental profile [15]. Similarly, Chandra et al. demonstrated a solar-powered IoT irrigation system capable of operating in rural, off-grid locations, highlighting the potential of integrating renewable energy [16]. Compared to these advanced models, the hydroponic system developed in this study focuses on simplicity and accessibility, prioritising affordability, ease of assembly, and user-friendly operation. This aligns well with the needs of non-technical users, such as urban residents, students, and small households, who may not require complex analytics but benefit significantly from reliable automation and remote monitoring.



Socio-Technical Frameworks

Beyond technical considerations, smart hydroponic systems draw from socio-technical theories that emphasise how technology interacts with social behaviour, lifestyle patterns, and community adaptation. The adoption of smart farming technologies depends not only on engineering performance but also on user perception, accessibility, and alignment with everyday routines. According to B. Johnson and B. Reiss, socio-technical systems thrive when they reduce cognitive load, streamline user tasks, and create meaningful improvements in daily life [17]. In the context of urban agriculture, IoT-enabled farming systems support lifestyle integration by reducing the manual effort required for plant maintenance, making gardening more feasible for individuals with limited time or physical capability.

Research by Ghazali et al. [7] and Graham & Smith [10] emphasises that technology-supported sustainability initiatives are more likely to be adopted when users experience immediate benefits such as convenience, transparency, and control. Tools like the Blynk mobile application empower users by offering real-time access to their home farming environment, aligning with modern behavioural preferences for smartphone-based management of household tasks. From a community perspective, IoT hydroponics supports broader sustainability goals by promoting self-grown food, reducing dependence on commercial supply chains, and encouraging environmentally conscious habits. Studies by Alamu and Davis further demonstrate that smart urban agriculture enhances community resilience and promotes mental well-being by fostering engagement with nature, even in high-density environments [18]. Thus, the hydroponic IoT system developed in this project not only addresses technical challenges related to plant maintenance but also supports a positive social impact through behavioural empowerment, environmental awareness, and the integration of a sustainable lifestyle.

METHODOLOGY

The development was divided into three main parts: hardware setup, software programming, and system testing through real-world simulation. Each part played an essential role in ensuring the final system is practical, reliable, and user-friendly.

Hardware Design

The system's main component is an ESP8266 microcontroller (Figure 1), which was selected for its processing power, memory, and integrated wireless communication capabilities. It interfaces with signals from the ultrasonic sensor to measure the water level

Fig. 1 ESP8266 microcontroller [19]

Fig. 2 Ultrasonic sensor HC-SR04

For user feedback, three LEDs were used as visual indicators: a red LED (low level), a yellow LED (medium level), and a green LED (full level). The ultrasonic sensor HC-SR04 is employed in the project to measure distance by detecting the time it takes for sound waves to bounce back from an object. It helps detect the water level by measuring the distance between the sensor and the water surface.

Figure 3 illustrates the complete architecture of the Smart Hydroponic IoT Farming System. At the core of the design is the ESP8266 NodeMCU microcontroller, which acts as the central decision-making unit. It receives real-time water-level measurements from an ultrasonic sensor mounted inside the water reservoir. Based on these readings, the ESP8266 activates one of three LED indicators (red, yellow, or green) to inform the user visually of the tank's water status. The system also enables automated watering through a relay module, which serves as a safe electrical interface between the ESP8266 and the higher-voltage water pump. This pump delivers nutrient-rich water to the vertical hydroponic tower, ensuring the plants receive continuous circulation.

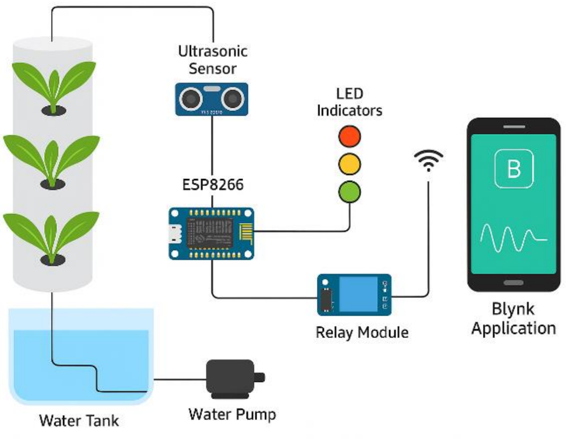


Fig. 3 System hardware block diagram

For user convenience, the system connects to the Blynk mobile application via Wi-Fi, allowing users to remotely monitor water levels and manually toggle the pump from their smartphones. Powering the system is a combination of a battery pack and a buck converter, which ensures all components receive the correct voltage. Overall, the diagram illustrates how sensors, IoT connectivity, automation hardware, and the hydroponic structure work together to create a compact, efficient, and user-friendly smart farming solution.

Sketching of Product

The idea behind the product originates from hydroponic techniques. The model consists of a tower for hydroponics, a water tank below, a spray for irrigation, and a control box. Before building the actual hardware, a rough sketch of the innovative gardening system was created to visualise the overall design and component placement, as shown in Figure 4. The sketch facilitated the planning of the wiring, layout, and structure of the system, particularly in ensuring that all components fit well within the prototype. It also served as a helpful reference during the assembly process, making it easier to explain the concept to others. The figure below shows the initial design of the product before physical construction.

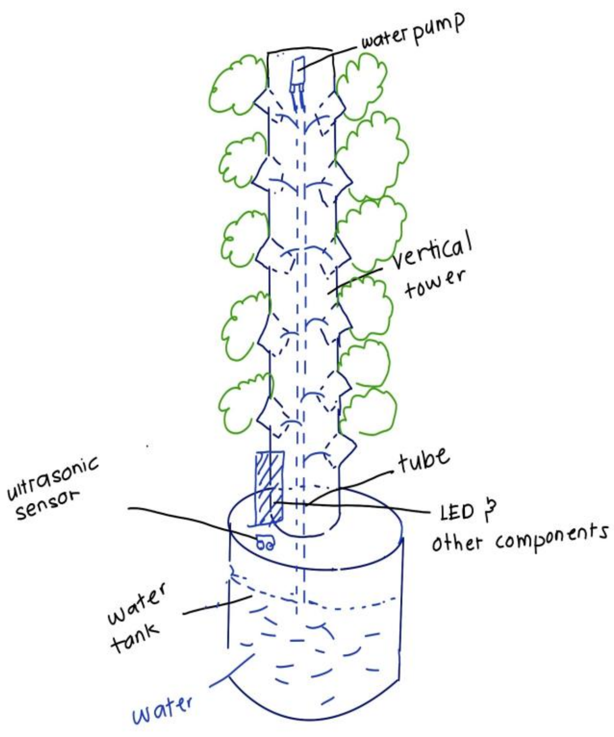


Fig. 4 Drawing of the prototype

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Software Development

Three software programs are used to complete the project: Proteus 8 Professional software for circuit design, Arduino IDE software for controlling the entire IoT system, and the Blynk IoT platform, which provides the cloud interface and mobile application.

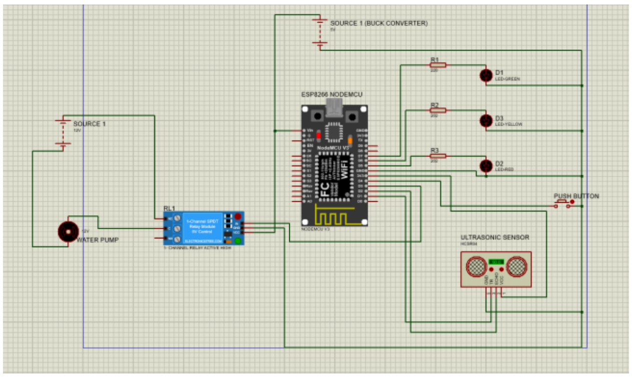

Fig. 5 Schematic Circuit

Proteus 8 Professional played a crucial role in the early development stage of the smart hydroponic system by enabling the virtual testing of the complete electronic circuit before physical construction. Using Proteus, all major components, including the ESP8266 NodeMCU, ultrasonic sensor, LED indicators, relay module, and push button, were assembled in a simulated environment, as shown in Figure 5. This allowed the researcher to verify the accuracy of the wiring layout as shown in Figure 5, ensure correct component behaviour, and detect potential issues such as incorrect pin assignments, voltage mismatches, or signal conflicts. Since Proteus allows real-time simulation of microcontroller code, it helped evaluate how the ESP8266 would respond to sensor inputs and control outputs, such as the relay and LEDs. Although some components, like relay modules or buck converters, required additional libraries or downloaded models, the simulation provided a safer and more efficient development workflow. By resolving hardware issues virtually, the researcher minimised trial-and-error during physical assembly, reducing time, cost, and wiring mistakes. Thus, Proteus served as a foundational stage that ensured the overall system's reliability before hardware implementation, as shown in Figure 6.

The Blynk IoT platform provided the cloud interface and mobile application needed for remote monitoring and control of the hydroponic system. The platform allowed the ESP8266 to send real-time water-level data to the user's smartphone and receive control commands for the water pump. Using the Blynk Console (web dashboard), virtual pins were configured to manage communication between the hardware and the application. The virtual buttons, value displays, and status indicators in the Blynk mobile app enabled users to instantly monitor tank water levels and toggle the pump on or off with a single tap. Blynk's built-in Wi-Fi and cloud features ensured that users could access the system from any location, which is particularly beneficial for individuals with busy schedules or limited time for plant maintenance. The integration of Blynk not only improved system usability but also added a modern smart-home feel to the hydroponic tower. Through this platform, the smart gardening system achieved full IoT capability, making plant care simple, efficient, and accessible.

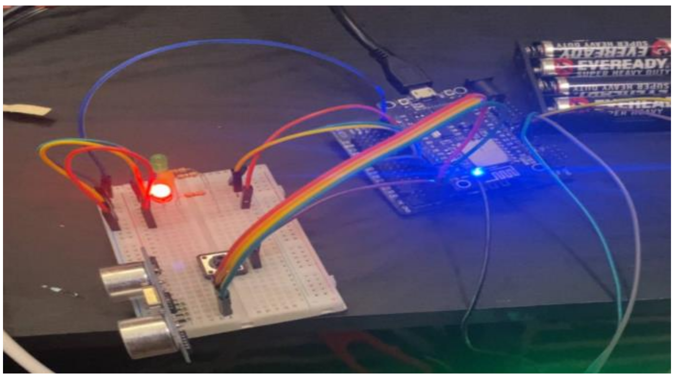

Fig. 6 Circuit wiring in a breadboard

RESULTS

System Functionality Test

After assembling the entire system on the prototype, several tests were conducted to ensure that all components functioned correctly together, as shown in Figure 7. The goal was to verify that the ESP8266 microcontroller could accurately read data from the ultrasonic sensor, control the LED indicators, switch the relay module to power the water pump, and respond to inputs from the push button and the Blynk app. During testing, the system accurately detected changes in water level and responded by lighting up the corresponding LED, which is red, yellow, or green depending on the measured distance. The relay and pump were also activated as expected, both manually and through the app. When the push button was pressed to turn on the water pump, the button in the Blynk application will also be updated to show that the button is in the on condition. This means the button system was fully functioning. These tests confirmed that the system was functioning as intended and that the integration between hardware and software was stable.

Fig. 7 All components of the hydroponic prototype

Water Level Detection Result

The ultrasonic sensor played a key role in monitoring the water level of the system. During testing, the sensor accurately measured the distance between itself and the water surface. Based on the distance readings simplified in Table 1, the system responded by lighting up the correct LED indicator. For example, the red LED turned on as a warning when the water level is below 8 cm. When the water level was approximately 9cm to 15 cm, the yellow LED lit up, indicating that the tank was halfway full. When the water level was between 16cm and 22 cm, the green LED turned on, indicating a full tank as tabulated in Table 1. This setup helped users easily understand the water level at a glance. The system responded quickly and consistently during the tests, showing that the ultrasonic sensor was reliable for this purpose. The water level was monitored through the Blynk application, indicating that the water level detection result was fully functional. The figure below shows that the water level was full, at 22cm, as displayed through the Blynk application on a smartphone.

Table 1 Water Level Detection Result

Water Level (cm)	LED Indicator Activated	Status Description
< 8 cm	Red LED	Low water level
9–15 cm	Yellow LED	Medium water level
16–22 cm	Green LED	Full water level

Safety and Reliability Assessment

Throughout testing, the prototype maintained electrical stability and safe isolation between the control (low-voltage) and actuation (high-voltage) sections via the relay module. No overheating, leakage, or signal interference was detected. The LED indicators provided redundant feedback in the event of a network failure, ensuring the system could still be operated manually.

DISCUSSION

The overall performance of the smart gardening system demonstrated that it successfully met the project's primary objectives. The combination of the ESP8266, ultrasonic sensor, relay module, LED indicators, water pump, and the Blynk IoT app worked together smoothly to provide a practical and user-friendly solution for monitoring and controlling plant watering. One of the system's strengths is its flexibility, which allows for manual control using a push button or remote control through the app, making it suitable for various user types. The use of visual indicators (LEDs) also made it easy to check water levels at a glance. However, some minor limitations were observed, such as the limited lifespan of the battery pack under continuous use and the water pump's capacity to draw water from the top of the hydroponic tower. The issues can be improved by using longer-lasting batteries and a high-powered water pump. Despite this, the system proved to be reliable during testing and demonstrated how IoT (Internet of Things) technology can make everyday tasks, such as gardening, more efficient and accessible. In the future, more sensors can be added to enhance the current system (such as soil moisture or temperature sensors) or by integrating solar power to make it even more sustainable.

Socio-technical aspects of using IoT in farming

Smart farming is never purely technical; it succeeds when people, practices, and infrastructure co-evolve. This prototype's socio-technical value starts with usability: clear tri-colour LEDs, a physical push-button override, and a familiar smartphone app reduce cognitive load and provide redundancy when connectivity is poor. These choices respect real-world contexts with busy schedules, intermittent Wi-Fi, and shared family use, and help cultivate trust that users can "see" the system state at a glance and still take manual control. At the same time, connectivity introduces dependencies (such as network availability, device provisioning, and app updates) and new responsibilities (including basic maintenance, sensor calibration, and pump replacement). Designing simple onboarding (Wi-Fi setup, labelled wiring, safe enclosure), fail-safe behaviour (timeouts, auto-off), and clear alerts is as important as electronics.

Equity and access also matter. Low-cost hardware and open tooling (Arduino IDE, Blynk) lower the digital divide for students and communities; documentation and local language guides can further widen participation. Electrical safety (including relay isolation, moisture ingress, and enclosure), as well as child-safe design, are essential in homes and classrooms. Interoperability, achieved by exposing sensor values via standard topics or HTTP, enables peer learning and shared troubleshooting, thereby strengthening the social network around the farm. Finally, sustainability is a socio-technical concept: choosing efficient pumps, exploring rechargeable or solar power, and designing for repair extend product life and reduce e-waste, while the tower itself encourages hyper-local food production and gardening literacy. In summary, the project exemplifies how thoughtful IoT design can align human routines, institutional goals (such as education and food security), and technical capabilities to make urban farming both practical and resilient.

CONCLUSION

This project successfully developed a smart gardening system utilising IoT technology by creating a hydroponic tower, specifically employing the ESP8266 microcontroller and the Blynk application to automate and simplify plant watering. The system was able to monitor water levels using an ultrasonic sensor, display the water status clearly through LED indicators and the Blynk application, and control a water pump both manually and with a push-button, as well as remotely through the Blynk mobile app. Throughout the testing process, the system proved to be reliable, responsive, and user-friendly. It helped demonstrate how technology can make gardening more accessible and convenient for people in urban environments, especially those with limited time or space. This project not only achieved its objectives but also demonstrated the potential of IoT in solving everyday problems in a practical and straightforward manner. This project can also attract more people to start planting in their residential areas with a modern gardening or farming style.

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