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Smart Microcontroller-Controlled Hydroponic System for Optimized Environmental Monitoring in Small-Scale Farming

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Abstract

Smart farming is increasingly popular and serves as a support tool for renewable agricultural cultivation systems. However, hydroponic control tools remain expensive and are primarily limited to large-scale agrarian industries. The novelty of this research lies in addressing the lack of hydroponic control tools specifically designed for small-scale and affordable cultivation systems. This study aims to design and develop a simple operational hydroponic control system suitable for small-scale cultivation. The method involves adopting a programming system using microcontroller devices and utilizing Nutrient Film Technique (NFT) hydroponic installation components as the working mechanism. The results of this study indicate that the simple hydroponic control tool effectively responds to several testing parameters, including air temperature, water temperature, nutrient concentration, and humidity, with optimal data readings over 24 hours. This work provides a recommendation for developing cheaper and more affordable tools with mechanism that can be further improved.

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I. INTRODUCTION

Hydroponic systems have become one of the leading technologies in modern agriculture, gaining popularity and undergoing continuous development. These systems support agricultural production without using soil, relying solely on nutrient solutions and water [1]. Hydroponic systems are a key component of vertical farming, designed and utilized to improve efficiency, increase yield quantity, and enhance the quality of produce [2][3].

The development of hydroponic systems varies greatly depending on specific needs. Hydroponics is a flexible vertical farming method that can be implemented in limited spaces [4]. Another advantage of hydroponic systems is their environmental friendliness. The resulting plant commodities are minimally contaminated by dirt or similar substances [5]. Hydroponic systems are increasingly used in organic agricultural production, as they leave no residues of harmful substances such as chemicals from pests, diseases, or weed management.

A significant issue is that hydroponic system technology remains relatively expensive and is primarily suited for large-scale industries, requiring substantial investment. The advanced technology involved often incorporates smart farming techniques with precise automation systems, making these tools costly.

In recent years, agricultural technology has seen increased adoption, with smart farming being extensively developed to enhance efficiency, effectiveness, and productivity [6]. Modern hydroponic systems require designs that maintain the quality of inorganic substances according to needs, which are accurately and automatically measured [7].

However, challenges persist, as existing tools are limited to a few measurement parameters. For instance, research [8] discusses hydroponics systems using the Atmega 2560 microcontroller with pH and nutrient measurements in lettuce cultivation. Similarly, research [9] focuses on hydroponic systems incorporating microcontrollers with sensors measuring temperature, total dissolved solids (TDS), and water pH. Previous studies face limitations and have not been widely utilized in small- to medium-scale agricultural sectors or small industries with limited space availability. This is primarily due to the lack of suitable and affordable technology for rural areas. Therefore, precision agriculture approaches such as the Internet of Things and Industry 4.0, are needed on small scale to control critical variables such as pH, electrical conductivity, temperature, and light, among others. These approaches can lead to higher production efficiency and resource savings [10]. This study aims to provide a solution for more affordable and user-friendly hydroponic cultivation systems on a small scale.

The goal of this study is to create a simple hydroponic control tool tailored for small-scale industries using microcontroller devices. It also aims to implement a programming command system as a basic environmental control system. This tool serves as a reference for optimizing plant conditions in hydroponic cultivation systems. Information and Communication Technology (ICT) is used to sense, monitor, and control the agricultural environment, machinery, and equipment used by farmers. ICT connects heterogeneous technological devices and sensors employed within the system [11][12].

II. METHODOLOGY

The materials and tools used in the development of the hydroponic control tool consist of a combination of components as shown in Figure 1, including:

1. Hydroponic installation components, adopting the Nutrient Film Technique (NFT) [13]. These include PVC pipes (2 inches), L-shaped knee pipes (2 inches), PVC pipes (1 inch), Tee pipes (1 inch), Dopp pipes (1 inch), PVC pipes (½ inch), Tee pipes (½ inch), L-shaped knee pipes (½ inch), Dopp pipes (½ inch), a box/container, Styrofoam, and net pots.

2. Microcontroller components, which include an Arduino Uno, a PCB Board, a nutrient sensor (TDS Probe), an air temperature and humidity sensor (DHT11), a water temperature sensor (DS18B20), a light Intensity sensor (BH1750), an ultrasonic sensor (HC-SR04), electrical wires, an LCD display (Nokia 5110), a peristaltic pump, a power adapter, relays, and a panel box.

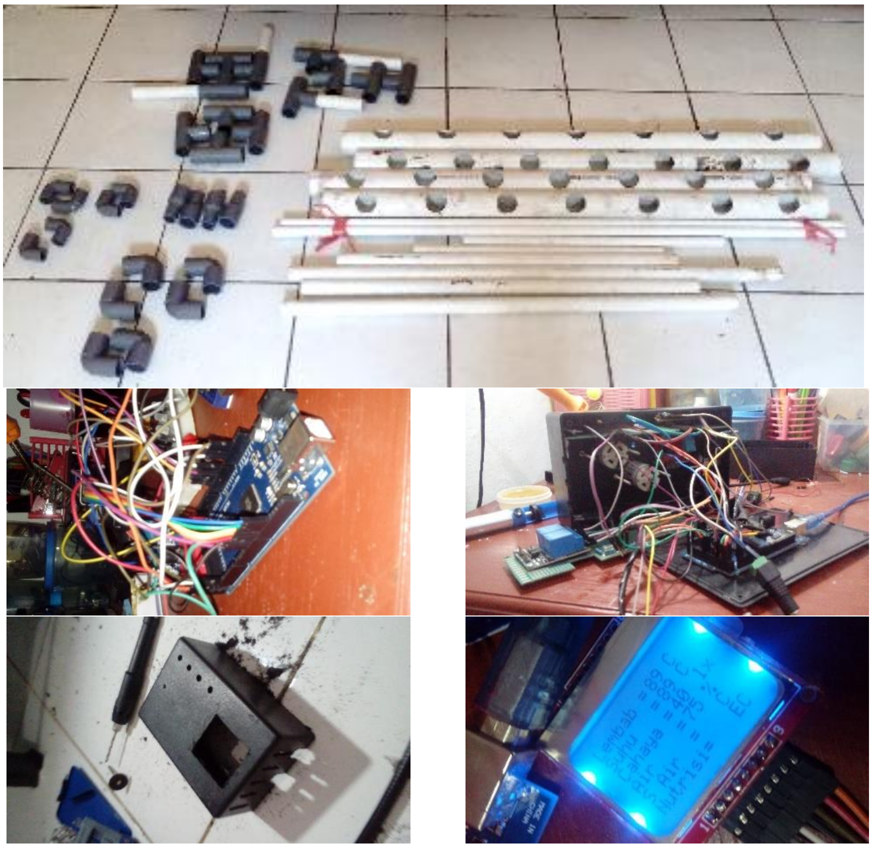

Figure 1. Assembly of microcontroller components

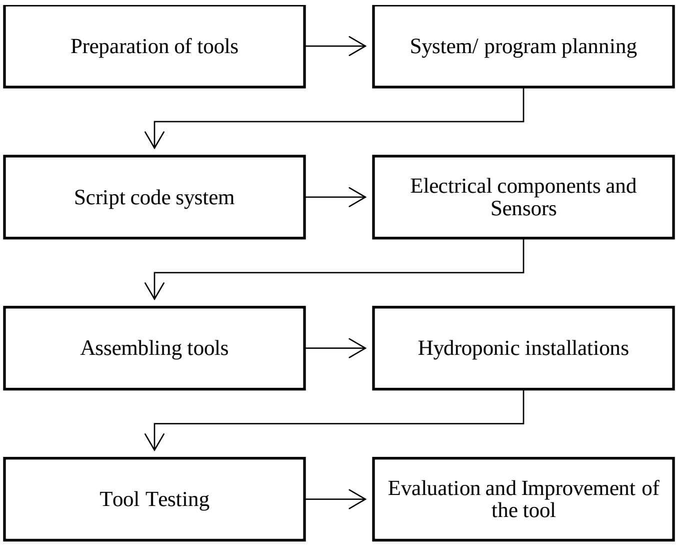

Figure 2. Flow chart of the manufacturing process

Programming using the Arduino IDE system involves an application designed to write, compile, and upload programs to the Arduino board. The Arduino development environment consists of a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions, and a series of menus. The system creation mechanism is illustrated in the flowchart, as shown in Figure 2.

III. RESULTS AND DISCUSSION

The development of the agricultural sector impacts the availability of fertile land, which significantly affects the decline in agricultural production. To address the issue of land limitations, adopting sustainable and environmentally friendly farming systems, such as hydroponic cultivation systems integrated with automation technology is essential. [14] [15]. Hydroponics is a method of planting that only requires minimal agricultural space [16]. It does not require large land areas, is easy to maintain, and has a high market value [17].

The hydroponic system method, crucial for plant growth, focuses on the continuous supply of water, oxygen, and nutrients while efficiently utilizing these resources [18]. Environmental factors such as air temperature, water temperature, humidity, and light intensity play important roles in the growth and development of plants within this system [19]. Therefore, implement measurement technology to monitor these parameters and integrating technology to provide operational information to users are necessary steps. Automatic parameter measurement can be achieved through the application of microcontroller technology [13].

Hydroponic systems are generally managed independently by users, requiring significant time, effort, and attention for maintenance and other tasks. Therefore, there is a need for a system designed to provide a new, technology-based experience in the cultivation process and introduce an effective, automation-based approach [20]. Such a system should be easy to apply and accurate in plant cultivation, facilitating control, maintenance, and data collection as a basis for research information. One such application is the use of microcontroller systems [21].

The microcontroller system aims to optimize tasks through automatic control, enabling users to manage agricultural land effectively while assisting in monitoring and obtaining the necessary information [22]. The system offers an innovative approach to integrated plant cultivation with hydroponic control tools. This hydroponic system controls the flow of water and nutrient-rich media to maintain stability according to the nutritional requirements of each plant. The tool is designed to regulate parameters that measure water volume, air temperature, water temperature, light intensity, and nutrient levels in the water [23]. These parameters are essential for improving the accuracy of data collection.

The system we designed has the potential to create innovations that promote the effective use of agricultural land in diverse environments while enhancing and maintaining food security. With rapid technological advancements, the tools and systems we developed can be modified to meet the specific needs and demands of various environment. This tool has been tailored to address both general and industrial requirements. It is portable and easy to transport, providing a practical experience for individuals and groups through a robust and user-friendly tool.

Overall, the sensor network used to develop this simple hydroponic control tool operates effectively and optimally. This is demonstrated by the measurement results presented in Tables 6-9. The data in these tables indicate that the sensors installed in the hydroponic control tool show responsive fluctuations outside the standard value ranges based on physiological or agronomic aspects.

It can be assumed that the installed sensors are functioning correctly and producing the expected output, providing necessary information as a reference for data collection during cultivation.

Figure 3. Test of the working system on a hydroponic device

Figure 4. Devices that have been completed and tested on lettuce and pakcoy plants

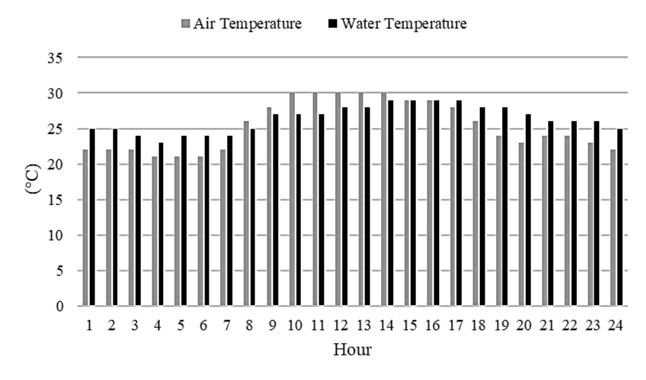

Figure 5. Results of air and water temperature sensor measurements over 24 hours

Figure 5 shows the response of the DS18B20 and DHT11 sensors for measuring air temperature and water temperature installed in the simple hydroponic control tool over 24 hours. The generated data distribution indicates that the water temperature ranged from 20-28 °C during the 24 hours, compared to the air temperature, which only increased for 7 hours to around 30 °C. This aligns with the findings of research [24], which reported measured temperature values in hydroponic systems with aeration averaging 30.24 ± 0.25 °C.

This indicates that the data captured by the sensors over the 24 hours had optimal recording accuracy, providing a reliable basis for obtaining temperature data during plant cultivation in the NFT hydroponic system. However, the generated data values may vary with environmental conditions. Water temperature is influenced by surrounding environmental conditions, depending on the location of the equipment [25]. Temperature changes significantly based on the environmental conditions affecting it [26].

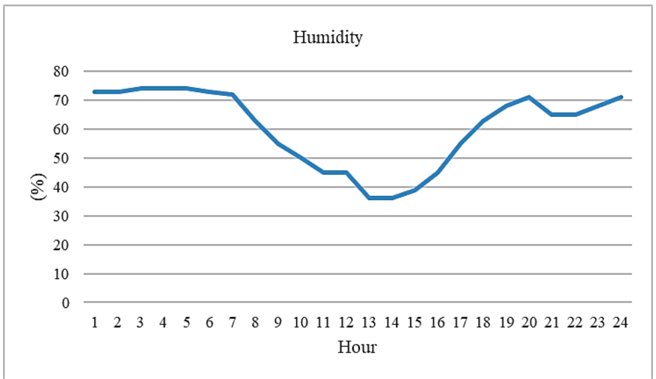

Figure 6. Results of humidity sensor measurements over 24 hours

Figure 6 displays the environmental humidity measurement data graph of the hydroponic system using the DHT11 sensor, which exhibited fluctuating values. The results show excellent performance in humidity measurement during the testing phase. Under various environmental conditions, humidity dynamically shifts between high- and low-resistance states [27]. The humidity sensor performed effectively in detecting humidity and showed linearity within the range of 30–90% relative humidity (RH) [28]. Based on the test results, it can be concluded that the sensors functioned effectively.

The data in Figures 7 and 8 demonstrate good sensor readings, utilizing the Ultrasonic Sensor (HC-SR04) and the BH1750 Sensor for measuring nutrient concentration and lighting, respectively. The fluctuating values affirm that the sensors in the hydroponic system are functioned effectively. These values do not indicate sensor malfunctions but rather reflect the response of the cultivated plants.

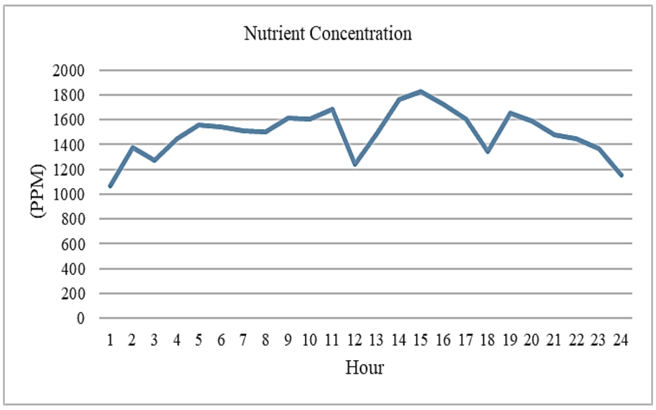

Figure 7. Results of nutrient concentration sensor measurements over 24 hours

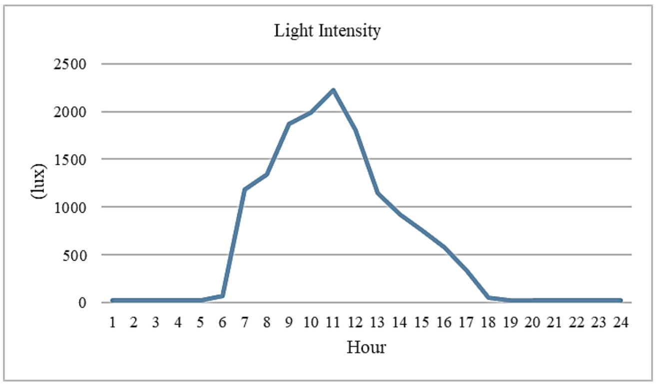

Figure 8. Results of light intensity sensor measurements over 24 hours

As noted in the research [29][30], changes in environment or climate affect plant biomass for bioenergy due to water scarcity and reduced nutrient mobility. Sensor systems are valuable for reading the environmental conditions surrounding the cultivation area. Sensor networks enable the monitoring of environmental variables indoors [31]. Lighting plays a crucial role in the physiology and behavior of living organisms. It enhances visual comfort and influences metabolic responses [32]. Factors such as the height of the light source, the distance between light sources, and dimensions significantly impact the lighting environment [33].

IV. CONCLUSION AND FUTURE PERSPECTIVE

The development of this microcontroller-based hydroponic control device demonstrates significant potential in advancing the agricultural sector, particularly for small-scale and home-based industries. By providing an affordable, portable, and user-friendly solution, this device addresses key challenges in hydroponic agriculture, such as efficient environmental monitoring and control of essential parameters like temperature, humidity, light, water, and nutrient concentration. Future enhancements could include the integration of more precise pH and nutrient concentration sensors, the implementation of Automatic Temperature Compensation (ATC) algorithms, and the incorporation of IoT functionalities for remote monitoring and data storage. Additionally, the inclusion of solar panels for energy sustainability would further support its use in diverse settings. This device offers a scalable solution that promotes sustainable farming practices, increases environmental awareness, and contributes to food security, making it a valuable asset for both urban and rural agricultural development.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the paper's publication.

AUTHOR CONTRIBUTION

The authors confirm their contribution to the paper as follows: Study conception and design: Enceng Sobari and Muhammad Aliyawan Aris; Data collection: Muhammad Aliyawan Aris; Analysis and interpretation of findings: Enceng Sobari; Draft manuscript preparation: Ridwan Baharta and Enceng Sobari. All authors have reviewed the findings and approved the final manuscript.

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