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Generative AI in Enhancing Hydroponic Nutrient Solution Monitoring

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ABSTRACT: Generative AI for IoT Hydroponics Monitoring System for Smallholder Farmers in Developing Regions This is in an effort to support AI-based narrative feedback for real-time decision-making with reference to sensor data (TDS/EC, temperature) and plant context-the pertinent data are species and age. The system, therefore, consists of an ESP32 sensor device; a Flutter mobile application; and the cloud services being offered via Thingsboard and the Gemini API. A systematic approach was undertaken, including design, implementation, integration, and usability testing. The results show effective real-time data collection and secure communication, with accurate AI feedback validated by expert judgment. The results exhibited how AI and IoT could collude in aiding smart agriculture. Future work will concentrate on enhancing the accuracy of the model based on ground truth data and improving the accessibility of the platform.

Keyword: *Small-scale Hydroponics; Monitoring; Generative AI; Flutter Interface; Thingsboard, Open-source.*

I. INTRODUCTION

Food security has become a challenge worldwide, unprecedented in history, in light of the rapidly growing population and changing climate [1], [2]; hence, new and innovative solutions to this pressing challenge must be sought [3], [4]. An interesting alternative is stimulating young farmers through technology in farming [5]. Technology increases young farmers' access to information and overcomes limitations of resources, so that they may boost production and reduce costs as well as critical decision-making toward sustainable agriculture for the future [6], [7].

In this context, mobile app technology presents an alluring alternative for enabling a highly intuitive and informational interface for hydroponic nutrient solution monitoring [8].

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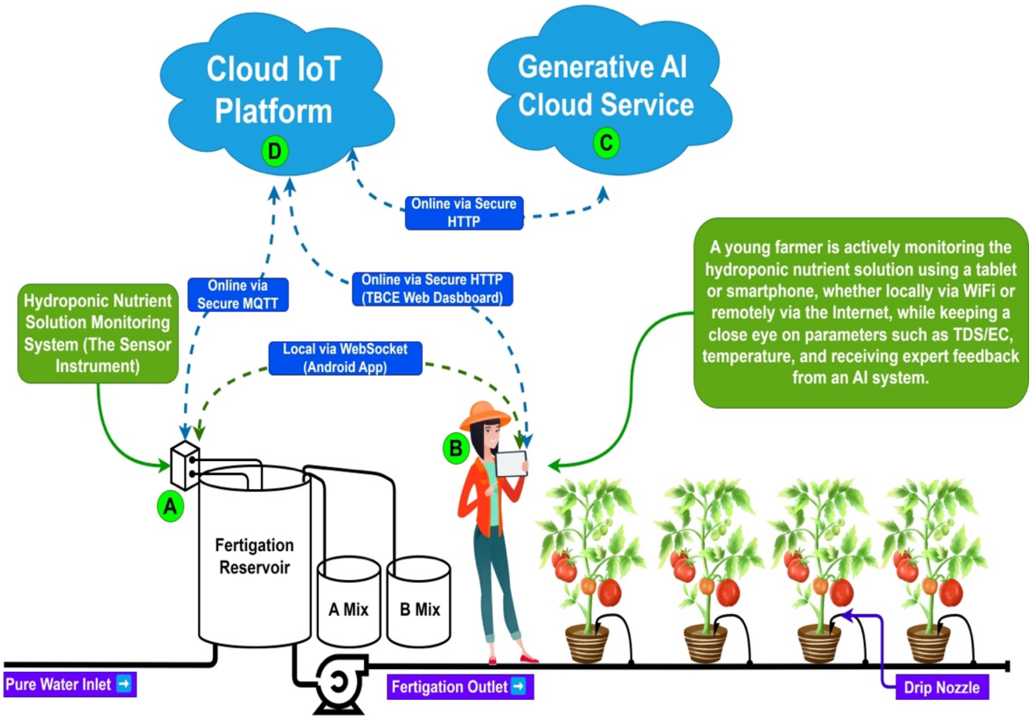

Figure 1. System Architecture Design for Generative AI Enhanced Hydroponic Nutrient Solution Monitoring

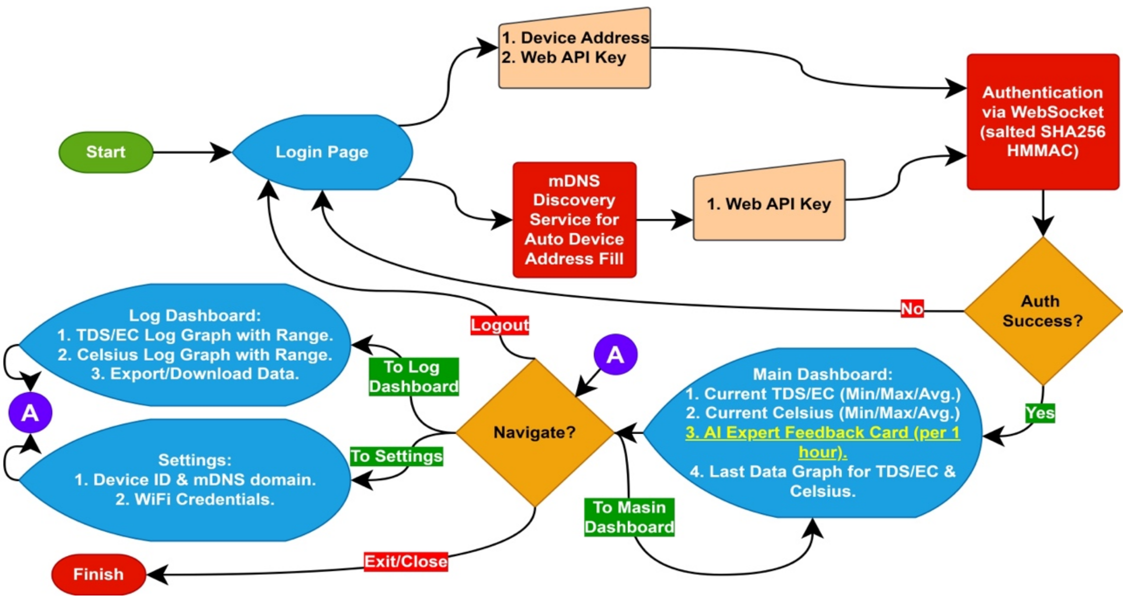

Figure 2. Flutter based mobile app interface flow for small-scale hydroponic nutrient monitoring.

Hydroponic systems need strict control and monitoring for nutrient levels for plant growth [8], [9], [10], [11], [12]. Mobile apps will give a simple and easily available interface platform to the farmers to check and modify nutrient levels, view past records, and receive reminders when a change in nutrient levels is to be done. With the integration of real-time sensor data and providing personalized recommendations, the app can empower farmers to make educated decisions and optimize their hydroponic systems for maximum performance and yield [13].

Furthermore, recent advances in technology have opened up possibilities for the use of mobile applications with greater capabilities. A single codebase UI SDK allows developers to build beautiful, consistent user interfaces on multiple platforms, saving on development time and efforts [14], [15]. Offering generative AI in the cloud makes it a convenient way to provide feedback for young farmers. This generative AI exploits machine learning to read the sensor data and parameters of a plant, such as type and age, to dispense personalized recommendations for the optimization of hydroponic nutrient solutions [16]. The advanced mobile app integrates an advanced user interface, real-time data monitoring, and personalized feedback, enabling novice farmers to make informed decisions and realize success in their hydroponic farming efforts [17].

In this work, we aim to develop a mobile app interface both with Flutter and the Gemini API [18] The mobile app will set up a local websocket connection to the hydroponic nutrient solution monitoring device (which we made previously), with the device acting as a websocket server. [19]. For trial purposes, we will prototype the application for testing and feedback. Using the Gemini AI, this application would sense and later process feedback and advice to young farmers based on sensor data. Such cutting-edge technology will demonstrate the viability of developing a tool that can improve the efficiency and productivity of hydroponic farming through real-time recommendations.

II. THEORETICAL FRAMEWORK

Mobile App Interface Flow

The workflow of the application is illustrated in Fig. 2. First, the users are led to a login page with input fields: Device Address and Web API Key, and with buttons: Scan and Login. The Device Address is providing the device's address in form of either local domain or IP. The second field requires password for that device: Web API Key. On clicking the Login button, the user logs in. In case the user does not know the address of the device, he can find it via mDNS using Scan. The selected device address from the found devices will automatically fill in the Device Address field.

After login, the user will go to the Main Dashboard where important information will be displayed like TDS/EC readings and the temperature of hydroponic nutrient solution at the time. Information is presented in terms of card that includes min, max, and average values. Above this card will another card that provides narrative information generated by artificial intelligence on the basis of sensor data and plant parameters. For this narrative information, users need to click on a button in the card which is restricted once every hour for over usage. At the bottom of the page, there are two line graphs that illustrates history of TDS/EC and temperature.

In addition to the Main Dashboard, there's a Log Dashboard, and Settings page. Log Dashboard contains two graphs which show the sensor log data acquired in a selected range of time. The data is stored in the internal SPIFFS storage of the device or on an external SD card in case offline mode, otherwise stored in the cloud. The page offers an option to download and delete stored log data from the device in JSON format. The Settings page includes configuration for WiFi access code used by the device when connecting to the network, as well as the device's ID, local hostname, and global greenhouse parameters (cultivation method, plant type, plant age, and EC of raw water).

Generative AI API Call Design

Gemini AI was the Generative AI service that was acting in the assessment, while its free public access during the time of writing was limited to 2 RPM (request per minute), 32,000 TPM (tokens per minute), and 50 RPD (requests per day). The actual version was Gemini 1.5 Pro. Figure 3 briefly portrays the request-response flow of the user, Thingsboard Rule Engine, and Gemini API cloud service. The process is said to start when the user presses the "Generate" button in the Flutter application, where many events were triggered. The device forwards the request via the Thingsboard Rule Engine in the Thingsboard server in the cloud. The Thingsboard Rule Engine differentiates between RPC calls from the device: GetGHParams and GetAIAnalyzer. GetGHParams is used to fetch greenhouse parameter data, while GetAIAnalyzer is used to fetch the AI analysis output in narrative text form. The request is then sent to the Gemini API cloud service by the Thingsboard server.

Figure 4. System integration testing: the instrument and the mobile app.

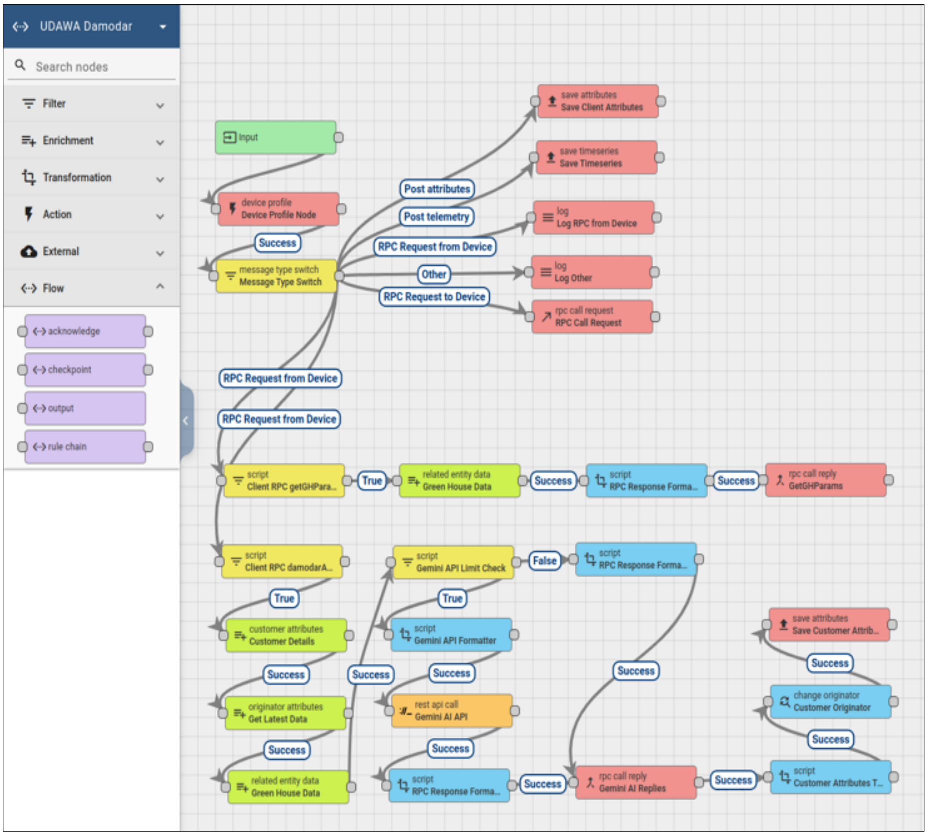

Figure 5. Thingsboard Rule Engine Implementation

The Gemini API cloud service processes the request and returns a response in JSON format. The response includes the AI-generated text narrative, which is subsequently sent back to the Thingsboard server. The Thingsboard server then forwards the response to the device, where it is displayed to the user.

III. METHODS

System Architecture Design

This research aims to develop an architectural design for a farmer-centric hydroponic using nutrient conditions around monitoring systems specifically developed for small-scale farmers [20], [21], [22], [23]. Very little cost and resource-based operation are also expected, with the system working in local and remote modes. In local mode, peer-to-peer connectivity with WiFi allows for direct communication between the sensor device and the user's gadget. On the remote mode, the system connects to the Cloud IoT Platform over the Internet. The instruments and cloud infrastructure had already been developed and tested [19]. In this research, we focus on a local system interface that would fit [24].

The sensor instrument (Fig. 1) (A) is located in the nutrient reservoir as shown in Figure 1. Two probes measure TDS/EC and nutrient solution temperature. The variables mentioned earlier are very critical in determining the quantity of fertigation liquid (fertilizer and irrigation) to be supplied to the plants by means of a dripper or any other type of hydroponic system. Another key parameter is pH; however, the expense incurred in purchasing a probe is considerable, its life is low, requires much maintenance, and, thus, often dissuades small-scale farmers from regularly checking pH conditions [25]. In practice, assuming that the raw water source does not vary, and this is what water pH conditions will hold?? In such instances, farmers can determine the safe acidity limits by utilizing manual pH measuring devices such as litmus paper.

This low-cost hydroponic nutrient monitoring system has been developed that supports offline as well as online access [19]. This particular system supported cloud access through a web-based dashboard interface. In this study, a mobile app-based interface was developed for better accessibility. The interface provides farmers with the opportunity to interact with devices on the local network and access the system using this friendly mobile platform even when there is no Internet connectivity. The mobile app integrates a generative AI service running in the cloud, generating valuable feedback based on hydroponic nutrient solution conditions and general data such as plant type and age. This feature empowers young farmers to gain insights into hydroponics and utilize resources more efficiently, leading to increased agricultural yields and data-driven decision-making.

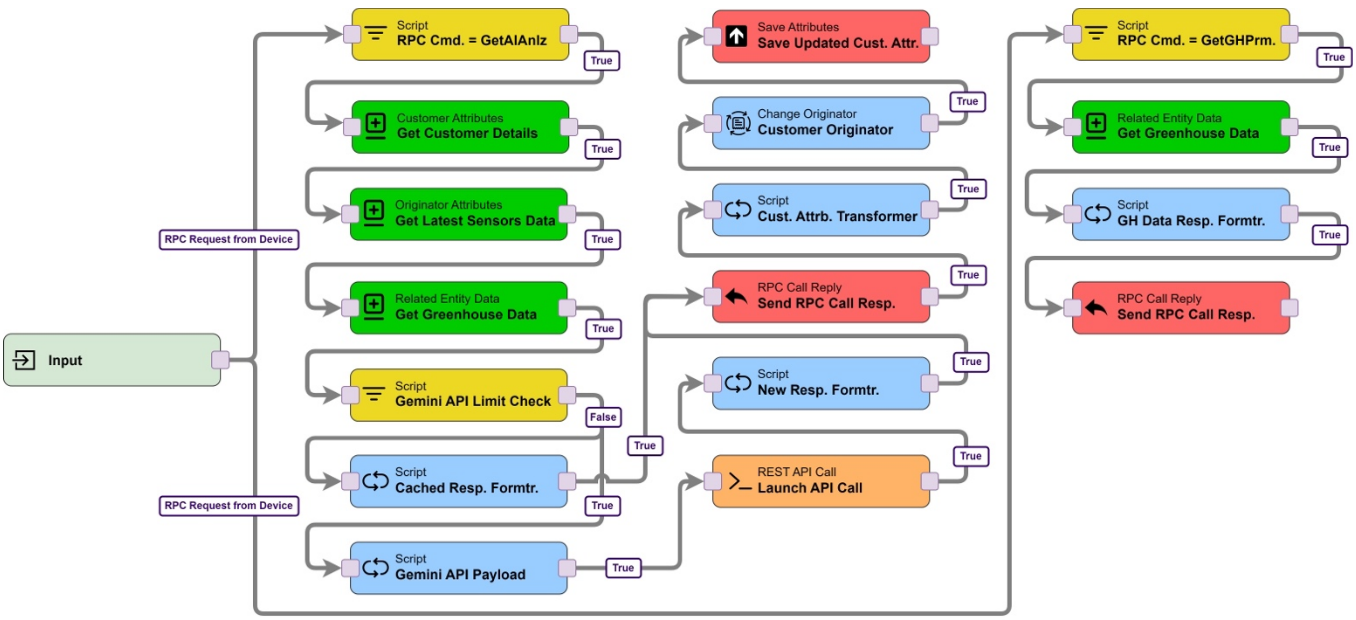

Fig. 3. Request and response flow between the user, the Things board Rule Engine, and the Gemini API cloud service.

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IV. DISCUSSION

System Integration Testing

The results of the system integration testing, as shown in Fig. 4, have demonstrated that the user interface application successfully connects to the sensor device. The application.

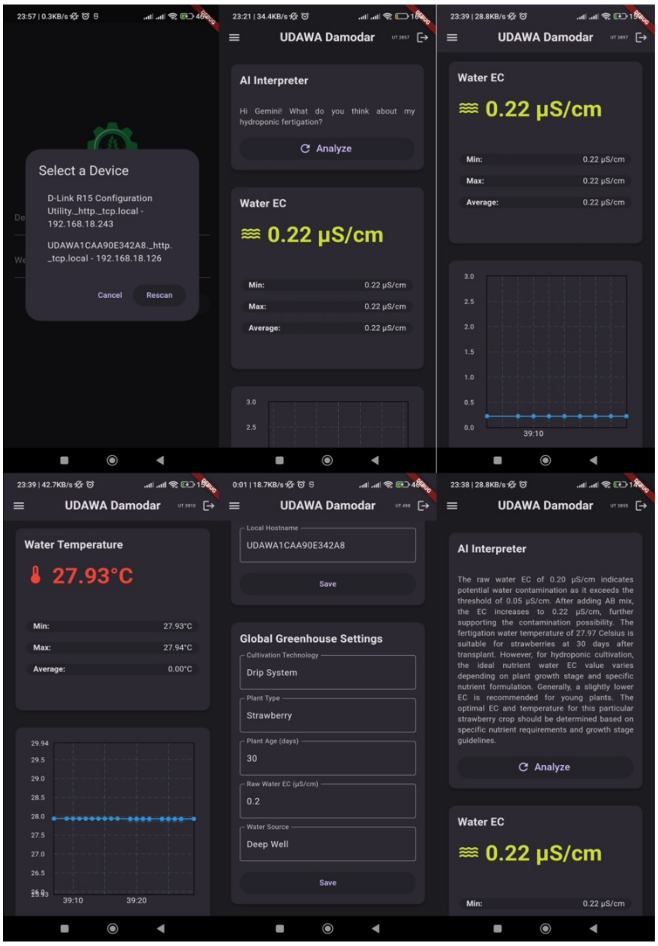

Figure 6. Flutter based mobile app implementation.

Table I. AI Response Sample

Gemini API Response Validation Test	
Prompt	It is the raw water source along with its quality and use that determines the entry point of fertilisation. If that raw water has an EC more than 0.05 µS/cm, then it would be presumed more than a viable link to fertigation EC and water temperature in relation to plant type and age (net EC of nutrient water with reference to type of plant, age of plant, and method of cultivation). The present conditions are: Water EC Before Adding AB: 0.20 µS/cm; Water Source: Deep Well; Water EC After Adding AB: 0.22 µS/cm; Fertigation Water Temperature: 27.47 Celsius; Plant Type: Strawberry; Plant Age: 31 Day Following Transplant; Drip System for Hydroponic Type.
Response	The raw water, about 0.20 µS/cm, proves to be potentially contaminated since it surpasses the recommended range at just over 0.05 µS/cm. The fertigation water temperature of 27.47 Celsius falls well within the range required for strawberries, which prefer between 15-25 Celsius. However, after adding an AB mix, this water displays an EC of only 0.22 µS/cm, which is still considerably low and hence, indicates that possibly, the nutrient concentration should be increased slightly. It may have to do with the plant age, which is now 31 days after transplant, and being grown through the hydroponic drip system, an ideal nutrient water EC value will be somewhere between 0.6-0.8 µS/cm.
Exprt. Judg.	Correct

The mDNS leverages a service that automatically scans the network for discovering the device addresses. The system also comprises the secure authentication that uses SHA256 salted HMAC for exchanging data separately from the other primary protection of WPA2-PSK method. The sensor device equipped with the ESP32 System-on-Chip, which contains the onboard AES encryption accelerator.

However, the device cannot use this because of memory issues. This is because the connection to the remote IoT platform is through MQTT over SSL, and there is no memory left for the encryption of local communications. Thus, the local Wi-Fi network has to be secured to keep the system safe from external accesses. The architecture implementation is on the cloud infrastructure using Thingsboard Community Edition (TBCE version 3.6.4), as shown in Fig. 5. The entire flow of the system and its procedures are programmed through the Thingsboard Rule Engine interface. The logic and system flow operate similarly to the explanation in section II.C.

Mobile App Usability Testing

In Fig. 6, we demonstrate the mobile application prototype built using Flutter. The main features, including the main dashboard, settings page, and data analysis results from the Gemini API, have been implemented based on the design in Section II.B. Our prototype runs on Android smartphones. Besides the Android platform, we envision creating an embedded web version that users can access through a web browser without installing the application on their devices. However, the Flutter-based web interface is too large (24,616 KB) for the sensor device, which has only 800 KB of available storage memory. For further development, we consider using the Svelte or Vue frameworks, which have a very small framework build size (between 2 KB and 50 KB).

Gemini API Response Validation

To assess the accuracy of the Gemini API in analyzing hydroponic nutrient water conditions, we simulated the analysis request using dummy parameters. Table 1 presents the dummy parameters, the Gemini API analysis results, and expert judgment from a professional farmer. The results indicate that the Gemini API provides representative information to help interpret sensor values in relation to plant condition and type. It's important to note that in this study, the Gemini API utilized common knowledge, as the purpose was solely to explore the potential of generative AI in providing explanations for sensor numbers and plant conditions to novice farmers. For practical applications, a dataset is necessary to train the model using supervised learning for more reliable and accurate results. Additionally, Gemini AI incorporates an embeddings feature, which enhances the computer's understanding and processing of language through a list of floating-point numbers. This feature holds promise for the development of a powerful and cost-effective dedicated analyzer model in the future.

V. CONCLUSION

This research has developed a hydroponics monitor and analysis system that can utilize the excellent powers of Generative AI to provide useful, trusted insights. Integrated mobile application, sensor device, and cloud-based IoT platform, this system holds the interface for the user to monitor critical hydroponic nutrient solution parameters such as TDS and EC. Furthermore, users will receive narrative AI information according to sensor data and plant parameters in real-time. User authentication characterizes the system to maintain a secure data exchange. The integration test result proves the success of the user interface application-sensor device connection. This research holds great promise for advancing smart agriculture since it brings applicable input towards hydroponic growing by optimizing the cultivation processes and pushing plant growth further. Future research could be filled with seeding sources regarding enabling further data and sensor sources in analysis capabilities, app refinements, as well as testing on real applicability.

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