A Prototype of IoT-Based Indoor Hydroponics Using MQTT for Sustainable Urban Housing

[1]Andre Kurniawan Pamudji, [2]Cindy Fiolita Graciela, [3]Stephani Inggrit Swastini Dewi, [4]Marcella Adelia Putri, [5]Vincenzhea Chrissa Siwi, [6]Nesia Rani Wijaya

[13456]Information Systems, Faculty of Computer Science,
[2]Architecture, Faculty of Architecture and Design
[123456]Soegijapranata Catholic University, Semarang, Indonesia

[1]andre.kurniawan@unika.ac.id, [2]cindy@unika.ac.id, [3]stephaniinggrit@unika.ac.id, [4]24n10004@student.unika.ac.id, [5]24n10033@student.unika.ac.id, [6]24n10032@student.unika.ac.id

Abstract— Urban population growth significantly reduces the availability of open land for household farming, thus threatening urban food security. Indoor hydroponics offers a space-efficient solution, but manual maintenance often lags behind in addressing water quality fluctuations. Although IoT solutions have been widely developed, they generally still rely on rigid local servers or hardcoded Wi-Fi configurations, thus limiting multi-device scalability. This research aims to develop an indoor hydroponic automation and monitoring system using a hybrid communication architecture to support remote deployment without complex configuration. Adopting the Prototyping Software Development Life Cycle (SDLC) model, this research integrates Information Systems with green architecture. The hardware side is based on a WeMos D1 R32 microcontroller connected to an analog pH sensor, a water level sensor, and a 4-channel active-low relay module to control LED growlights and three mini submersible pumps in separate water and nutrient tanks. The HiveMQ Cloud Broker infrastructure was used to facilitate asynchronous telemetry over TCP port 1883 and data delivery to the browser via WebSockets port 8000 using the Eclipse Paho JavaScript library. Results: A physical prototype was successfully realized in the form of a compact vertical rack. The Trimmed Mean Filter algorithm in the firmware indicated reliable performance under the tested scenario in stabilizing the noise of analog pH readings. The web dashboard successfully processed JSON and updated the telemetry graph responsively during functional testing. The automatic extraction of the device's MAC Address successfully isolated MQTT topics to prevent data collisions between devices. Conclusion: This system effectively addresses the limitations of urban residential space through a biophilic design approach while providing an adaptive smart living solution for urban communities.

Keywords— Biophilic Design, HiveMQ Cloud Broker, Indoor Hydroponics, MQTT WebSockets, Wemos D1 R32

I. INTRODUCTION

Urban population growth increases residential density and limits open land for household agriculture. [1], which is the main challenge for independent food security in urban environments [2]. This limited space encourages people to look for plant cultivation methods that are efficient, practical, and can be applied in narrow areas such as indoors.[3]. Within the smart city concept, the smart living aspect emphasizes the use of technology to create a better and more sustainable quality of life. One implementation is technology-based urban farming in modern residences as part of sustainable living and green architecture, integrating vegetation elements into building designs to improve environmental quality and space efficiency. [4], [5].

Indoor hydroponics is the most suitable urban farming method because it saves land and water compared to conventional farming, making it very relevant for homes, apartments, and modern buildings. [6]. In addition, the indoor system protects plants from extreme weather and external disturbances so that plant growth is more stable. [7]. This application also has strong relevance in architecture and built environment design. Modern residences today encourage the integration of natural elements to improve environmental quality and occupant comfort, in line with green architecture and biophilic design approaches. [8]. Through this method, unproductive areas such as corners of rooms, closed balconies, service areas, or communal spaces can be utilized as aesthetically pleasing household-scale food production spaces, improving visual quality, and supporting the health of residents through air circulation and a more natural atmosphere. [9][10].

In the context of sustainable architecture, indoor hydroponics supports resource efficiency, space optimization, and a reduced building footprint. This aligns with the Indonesian government's strategic focus on improving urban food security through the use of digital technology and modern agriculture toward smart cities. [11]. This concept is able to support food independence as well as the efficiency of modern residential space. [12]. The use of Internet of Things (IoT) technology in hydroponic systems further strengthens the concept of smart buildings that integrate digital technology for operational efficiency and the quality of life of its users. [13].

In indoor systems, room temperature tends to be stable, so temperature control was outside the scope of this prototype because the system was designed for relatively stable indoor environments. Unlike outdoor systems, indoor hydroponics focuses primarily on water pH stability, nutrient tank level, and solution circulation. [14], Because an imbalance in these parameters can cause cultivation to fail. However, the main problem with home hydroponics is the manual monitoring process. [15]. Busy urban communities often delay addressing changes in water conditions, resulting in plants not growing optimally.

IoT technology is present as a solution through a smart agriculture system that is capable of carrying out automatic monitoring and control in real-time. [16]. Integration of sensors, microcontrollers, and web-based information systems helps users monitor conditions remotely [17][18], and perform automatic actions such as activating pumps and nutrient mixers when the pH is outside the ideal limits.

Previous hydroponic IoT research has been widely developed [15][18], One of these studies discusses monitoring using microcontrollers and conventional web-based systems. However, these studies generally haven't implemented the cloud-broker-based MQTT communication protocol for real-time data exchange [19]. In fact, MQTT is considered lighter and more efficient for IoT data communication because it uses a publish-subscribe mechanism with a low latency level [20]. Additionally, utilizing a cloud broker such as HiveMQ provides an absolute advantage as it does not require the installation and management of a standalone local broker server [19], so that the connection between the microcontroller and web applications becomes more flexible, stable, and easy to develop on a multi-device scale (automatic topic generation to reduce manual MQTT topic configuration).

Based on these conditions, this study develops the implementation of MQTT communication using HiveMQ Cloud Broker on an automated indoor hydroponic system based on Wemos D1 R32 integrated with a real-time web-based monitoring application. This study aims to design and build the system so that pH conditions, nutrient volume, and pump control can be monitored and controlled precisely through the user's device. Thus, the development of this automated indoor hydroponic system is not only a solution for urban agricultural technology, but also an architectural design innovation that is adaptive to the challenges of urbanization and land limitations, and supports the realization of the concepts of smart living, green architecture, and independent food security.

II. METHOD

This research applies the Prototype methc within the Software Development Life Cyc (SDLC) framework. This method was chose because of its adaptive characteristic allowing for gradual iteration and refineme of hardware and software components based on iterative prototype observation and functional validation. The research implementation flow is integrated in a multidisciplinary manner between information technology engineering and architectural spatial analysis, which is systematically divided into five stages as shown in Figure 1.

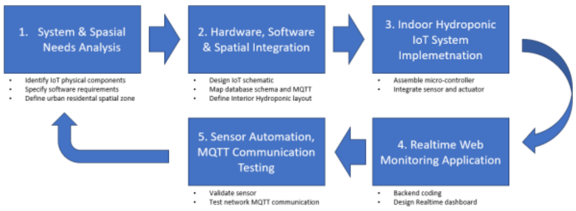

Figure 1. Software Development Life Cycle

A. Space Requirements Analysis and Architectural Integration

A space requirements analysis was conducted to determine the physical parameters of an indoor hydroponic installation in a modern, high-density residential environment. This study identified potential unproductive areas within buildings, such as corners, service areas, enclosed balconies, and communal spaces, for conversion into independent food production spaces. The spatial aspects analyzed in detail are summarized in Table 1.

Table 1. Interior Space Requirements Parameters

Spatial Aspects	Analysis Parameters	Implementation Target
Artificial Lighting	Absence of direct solar radiation in indoor areas	Full substitution using LED Growlight
Accessibility & Ergonomics	Ease of resident interaction in routine maintenance	Placement at active hand reach height (80-120 cm)
Spatial Dimension	Optimizing the limited floor area of the residence	Vertical/compact design integrated furniture elements
Utility System	Leakage risks and power supply requirements	Close access to main power outlets and waterproof material

B. Hardware Requirements Analysis

Hardware components are selected based on power consumption efficiency, analog signal reading accuracy, and fail-safe connection reliability. Component specifications are detailed in Table 2.

Table 2. IoT System Hardware Specifications

Components	Specifications	Special Functions
Micro controller	Wemos D1 R32 (ESP32-based)	Main computing, Wi-Fi handling, and ADC processing
pH Sensor	Analog pH Meter Kit Module	Reading the acidity level of the solution in the growing tray
Water Level Sensor	Analog Liquid Level Sensor	Measures the percentage of liquid volume (0-100%)
Mini Submersible Pump	DC 12V Pump	Distributing Plain Water, Nutrient A, and Nutrient B
Relay Module	4-Channel Relay (Active Low)	Digital actuator AC/DC circuit breaker/connector
Power Supply	12V DC Switching Adapter	Main power source for the electrical system
Storage Container	3 Separate Water Tank Units	Independent reservoir for Plain Water, Nutrient A, and Nutrient B
Vegetation Reactor	Growing Tray + PVC Pipe	The main growing medium for indoor hydroponic systems
Photosynthesis Lamp	LED Growlight Strip	Artificial light source for plant growth

C. Cross-Software Requirements Analysis

The software used includes integrated circuit development sub-systems to visual presentation on the client side (client-side interface), as shown in Table 3.

Table 3. Software Specifications

Software	Version	Implementation
Arduino IDE	Version 2.x / C++ Embedded	Firmware writing, serial debugging, and compilation
PHP	Version 8.x / Backend Engine	Server-side data logic processing and worker schema
Front-End Stack	HTML5, CSS3, JavaScript	Development of a responsive monitoring dashboard interface
Paho MQTT JS	Eclipse Paho CDN	WebSocket library for real-time data interaction in the browser
MySQL	Relational Database (RDBMS)	Storage of telemetry logs and tool configuration history
HiveMQ Cloud Broker	Managed MQTT Cloud Broker	Cloud infrastructure for IoT data publish-subscribe bridge

III. RESULTS AND DISCUSSION

A. Spatial Analysis

Based on the prototyping method stages that have been implemented, this IoT-based indoor hydroponic system has been successfully realized into a compact vertical rack with measured dimensions of 80 cm x 40 cm x 150 cm. This vertical configuration has been proven to meet the target of spatial efficiency of urban housing by only absorbing a floor area of 0.32 m2, far below the projection of the minimum requirement for conventional horizontal space which generally requires around 0.8 - 1.0 m2. The application of this prototype is integrated into underutilized residential interior areas, such as corners of rooms, service areas, closed balconies, and communal spaces. Artificial environment engineering is realized by embedding a full-spectrum LED Growlight Strip module directly above the growing tray. The presence of this artificial lighting eliminates the absolute dependence of plants on direct solar radiation, so that indoor vegetation cultivation can continue to run optimally independently.

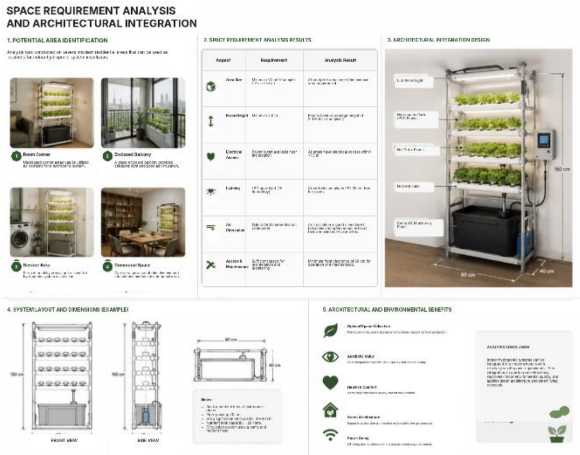

Figure 2. Spatial Analysis

The main control module based on the Wemos D1 R32 is housed in a protected panel on the outside of the cabinet. Three water tanks are placed at the base of the circuit independently, including the Plain Water, Nutrient A, and Nutrient B tanks. Each tank has been inserted with a mini submersible pump that is connected directly via utility pipes to the growing tray at the top, where the pH sensor and internal water level sensor are located.

B. Hardware and Sensor Implementation

The hardware realization stage is carried out by assembling all electronic components into a single integrated circuit using a custom PCB shield cross-section to minimize the risk of loose connections on the Wemos D1 R32 pins.

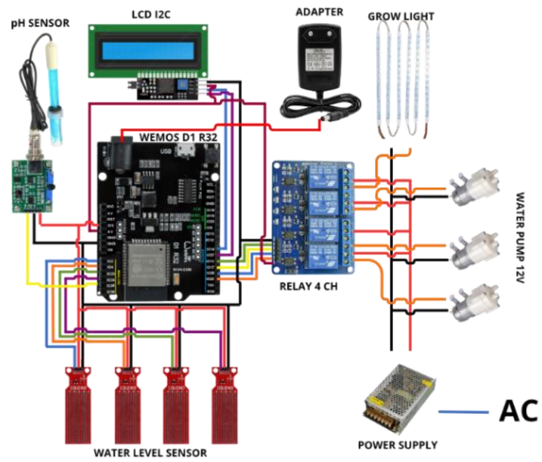

Figure 3. Schematic drawing

Based on the physical implementation and schematic drawing above in Figure 3, the mapping of the actuator's pinout interconnection and electrical system is described in detail into the following three engineering aspects:

1. I2C Data Bus and Analog ADC Interconnection: The 16x2 LCD display is connected to the ESP32 hardware I2C bus lines, namely GPIO pins 21 (SDA) and GPIO 22 (SCL) for local parameter data visualization. Meanwhile, the analog pins are strictly configured on the Analog-to-Digital Converter (ADC1) block to avoid internal Wi-Fi wave interference, with the following divisions: GPIO Pin 36 (VP) for the pH sensor, GPIO Pin 39 (VN) for the Water Level of the Planting Tank, GPIO Pin 34 for the Plain Water Tank, GPIO Pin 35 for the Nutrient Tank A, and GPIO Pin 32 for the Nutrient Tank B.
2. Relay Drive Logic (Active Low): The 4-channel relay module is controlled via digital pins GPIO 25 (Plain Water Relay), GPIO 26 (Pump A Relay), GPIO 27 (Pump B Relay), and GPIO 14 (Growlight Relay). Since the relay module used has Active Low Trigger properties, the circuit breaker instructions in the firmware are programmed in reverse using the digitalWrite(PIN, HIGH) command to turn off the coil, and digitalWrite(PIN, LOW) to bridge the COM-NO terminal so that the active actuator receives voltage from the 12V DC adapter.
3. Implementation of the Filter Algorithm and Inverse pH Calibration Equation: In initial hardware testing, the raw voltage readings of the analog pH sensor were highly susceptible to noise from pump current fluctuations. This issue was successfully resolved by implementing a Trimmed Mean Filter (5-sample Bubble Sort) in the Wemos firmware.

C. Dashboard Implementation Results

On the software side, the monitoring system is implemented through the main interface file index.php, which acts as a central control dashboard. This dashboard implements the Eclipse Paho MQTT JavaScript Client library via CDN to bridge direct data communication between the client browser and the broker cloud without going through repetitive PHP backend processing.

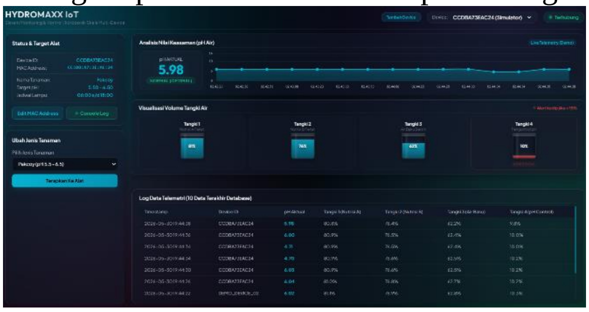

Figure 4. Real-time Dashboard Monitoring

The operational mechanism of cross-device data in the index.php file is described through the following six pillars of sub-system handling:

1. Asynchronous Handshake: The connection is initiated using the client.connect() function. The system dynamically generates a random string code as the Client ID (e.g., WebClient_x7f9a) to prevent connection drops due to instance conflicts in the HiveMQ broker.
2. Telemetry Subscription: Once the onConnectSuccess() callback function is triggered, the browser automatically subscribes to the topic hydroponics/CCDBA73EAC24/telemetry to capture the actual pH and volume data payload of the 4 water points in real-time.
3. Configuration Synchronization: The browser also subscribes to the topic hydroponics/CCDBA73EAC24/config to ensure that the lower and upper pH threshold values currently active in the microcontroller memory are perfectly synchronized on the user's screen.
4. Data Handling & Parsing: Whenever an asynchronous message arrives via

the onMessageArrived(message) callback, the JSON string is parsed using the JSON.parse() function to instantly update the Chart.js-powered historical graph and tank water level animation without triggering a web page reload.

5. Downlink Command (Publish): The applyCropConfig(event) function is used to send a new instruction packet when the user changes the crop variety. The data packet is wrapped in the Paho.Message object format and then fired to the device control topic.
6. Retained Message Optimization: The configuration publishing process enables the retained = true attribute. This mechanism ensures that the last decision parameter (such as the pH limit for Pakcoy or Selada) will remain in the HiveMQ broker memory, so that if the Wemos is rebooted due to a power outage, it can immediately retrieve the last configuration instantly when it comes back on.

D. System Test and Data Communication

To test the reliability of the information system functionality and hardware integration, a series of structured tests were carried out using the Black-Box testing method as well as validation of the MQTT communication protocol data packets via HiveMQ Cloud Broker.

D.1 MQTT Network Test Results

This test aims to evaluate the accuracy of periodic data transmission every 10 seconds from the edge node to the dashboard interface. The results of the MQTT functionality matrix test are summarized in Table 4.

Table 4. Flow Validation Test Results MQTT

Network Parameters	Testing Indicators	Actual Results	Status
Publish Sensor Telemetry	Sending JSON string every 10 seconds by WeMos	Data sent intact to broker	Passed
Subscribe to Browser Data	WebSockets port 8000 payload capture	Text appears in the F12 console	Passed
RDBMS Synchronization	Automatic saving of MQTT data to MySQL via PHP	Data rows increase linearly	Passed
Dashboard UI Responsiveness	Chart.js chart visual updates without reloading	With sub-second latency	Passed
Retained Command Handover	Post-hardware reset config reading	Configuration successfully restored after reboot	Passed

D.2 Topic Routing Test Results

Routing testing was conducted to ensure no data leakage occurred when using the public broker. The results of the topic structure testing, observed using the MQTTX software, are shown in Table 5.

Table 5. MQTT Topic Structure Validation Results

Device Specific Topic Code	Data Operational Functions	Network Status
hydroponics/ CCDBA73EAC24/ telemetry	Data transmission from Wemos to Web Dashboard	Passed
hydroponics/ CCDBA73EAC24/ config	Transmission of plant parameters from the Web to Wemos	Passed

E. DISCUSSION

The system's physical implementation in the form of a vertical rack proved efficient in optimizing the limited land area of urban residential areas, occupying only 0.32 m² of floor area. Spatially, this system embodies the principles of Green Architecture and Biophilic Design by converting residual space into productive areas. The use of full-spectrum LED Growlight Strips provides high placement flexibility within the room, while psychologically enhancing the visual comfort of the interior and strengthening the occupant's connection with natural elements in the domestic space.

The analog pin mapping on the Wemos block proved crucial in maintaining stable sensor readings when the ESP32's internal Wi-Fi module was active. The use of a Trimmed Mean Filter (Bubble Sort 5 samples) helped reduce transient voltage noise caused by the pump motor's induced current. In terms of safety, the use of Normally Open (NO) terminals on the relay module acts as a double layer of security. If the system loses power or crashes, the NO circuit will automatically disconnect, autonomously preventing the risk of flooding the residential growing tray or mechanical damage due to the pump running dry.

The integration of the Eclipse Paho MQTT JavaScript library in the index.php file bypasses conventional HTTP POST or polling-based computational processes. Through a persistent WebSocket channel on port 8000, data flows from the HiveMQ Cloud Broker directly to the client browser with sub-second latency, without burdening the local server. Furthermore, the retained=true feature in the publish configuration function ensures that ideal plant parameters remain in the broker's memory, allowing WeMos to instantly restore the latest configuration data after a sudden reboot.

Black-box and topic routing testing results indicate that the proposed topic isolation mechanism has the potential to support future multi-device deployment. A topic isolation mechanism based on the automatic extraction of the device's original MAC address (CCDBA73EAC24) on the public cloud broker successfully addresses multi-device scalability challenges. This feature supports automatic MQTT topic generation, where lay users can directly install the device at home without the need for hardcoding. This convergence solidifies the system's position as an integral part of the adaptive Smart Building and Smart Living ecosystem for future food security.

F. Research Limitations

This study is limited to the design and functional validation of a proof-of-concept prototype for an IoT-based indoor hydroponic system. The evaluation focuses on hardware-software integration, MQTT communication, dashboard functionality, and spatial suitability for limited urban residential areas. Extensive quantitative testing, including long-term uptime, sensor accuracy, latency measurement, power consumption, multi-device scalability, and full-cycle plant growth performance, was not conducted in this study. In addition, the prototype only monitors pH and water level, while parameters such as EC/TDS, water temperature, humidity, and ambient temperature remain outside the scope of this version. Future research should include quantitative performance evaluation, plant cultivation trials, broader environmental sensing, and user-centered testing in real residential settings.

IV. CONCLUSION

This study developed a proof-of-concept prototype of an IoT-based indoor hydroponic monitoring and automation system using a Wemos D1 R32 microcontroller and a hybrid MQTT-WebSockets communication architecture through HiveMQ Cloud Broker.

The prototype demonstrates the feasibility of integrating hydroponic hardware, pH and water level sensors, relay-based actuator control, and a web-based monitoring dashboard into a compact indoor farming system for limited urban residential spaces.

From the spatial and architectural perspective, the prototype shows potential for utilizing underused domestic areas through a compact vertical rack design measuring 80 cm × 40 cm × 150 cm. This configuration supports the concept of space-efficient indoor farming and provides an initial implementation of green architecture and biophilic design principles in urban housing environments.

From the information system perspective, the use of MQTT and WebSockets enables functional real-time communication between the microcontroller, cloud broker, and web dashboard. The automatic generation of device-specific MQTT topics based on the device MAC address also helps reduce manual topic configuration and supports clearer data separation between devices. In addition, the implementation of a Trimmed Mean Filter in the firmware helped reduce noise in analog pH sensor readings during prototype testing, while the use of Normally

Open relay wiring provided a basic fail-safe mechanism for actuator control.

Overall, the developed prototype indicates that IoT-based indoor hydroponics can be integrated with residential spatial design and web-based monitoring to support smart living and sustainable urban housing concepts. However, this study remains limited to functional prototype validation. Further research is required to conduct quantitative performance testing, including sensor accuracy, communication latency, power consumption, long-term system reliability, multi-device scalability, and full-cycle plant growth evaluation in real residential environments.

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REFERENCES

[1] S. R. Giyarsih *et al.*, "Interrelation Of Urban Farming and Urbanization: An Alternative Solution to Urban Food and Environmental Problems Due To Urbanization in Indonesia," *Front. Built Environ.*, vol. 9, Jan. 2024, doi: 10.3389/fbuil.2023.1192130.

[2] E. Rustiadi, A. E. Pravitasari, Y. Setiawan, S. P. Mulya, D. O. Pribadi, and N. Tsutsumida, "Impact Of Continuous Jakarta Megacity Urban Expansion on The Formation of The Jakarta-Bandung Conurbation Over the Rice Farm Regions," *Cities*, vol. 111, p. 103000, Apr. 2021, doi: 10.1016/j.cities.2020.103000.

[3] Ida Syamsu Roidah, "Pemanfaatan Lahan Dengan Menggunakan Sistem Hidroponik," *J. BONOROWO*, vol. 1, no. 2, 2014.

[4] S. T. . M. T. Bayu Widodo, S. P. . M. S. Uding Sastrawan, M. S. Ir. Wien Kuntari, and S. E. . M. S. Ayutyas Sayekti, "Penerapan Teknologi IoT dalam Urban Farming sebagai Solusi Ketahanan Pangan dan Pemberdayaan Pemuda," *Semhas PPM Pertan. dan Peternak.*, 2024.

[5] A. Armansyah *et al.*, "Urban Farming as an Alternative in Realizing Sustainable City Development in Indonesia," *J. Kawistara*, vol. 14, no. 1, p. 38, May 2024, doi: 10.22146/kawistara.84324.

[6] A. Lukmanul, "Urban Farming Metode Teknologi Dan Inovasi Baru Pada Pertanian Perkotaan (Urban Farming Technology and Methods New Innovations in Urban Agriculture)," *SSRN Electron. J.*, 2021, doi: 10.2139/ssrn.3782290.

[7] A. Ansar, G. M. D. Putra, and O. S. Ependi, "Analisis Variasi Jenis Dan Panjang Sumbu Terhadap Pertumbuhan Tanaman Pada Sistem Hidroponik," *J. Ilm. Rekayasa Pertan. dan Biosist.*, vol. 7, no. 2, pp. 166–173, Sep. 2019, doi: 10.29303/jrpb.v7i2.124.

[8] W. Zhong, T. Schroeder, and J. Bekkering, "Designing with nature: Advancing three-dimensional green spaces in architecture through frameworks for biophilic design and sustainability," *Front. Archit. Res.*, vol. 12, no. 4, pp. 732–753, Aug. 2023, doi: 10.1016/j.foar.2023.03.001.

[9] D. P. Caniago and M. A. Masril, "Transformasi Pertanian Dalam Ruangan: Hidroponik Cerdas Berbasis IoT," *Indones. J. Comput. Sci.*, vol. 12, no. 5, Oct. 2023, doi: 10.33022/ijcs.v12i5.3408.

[10] Z. Li, Y. Wang, H. Liu, and H. Liu, "Physiological and psychological effects of exposure to different types

and numbers of biophilic vegetable walls in small spaces," *Build. Environ.*, vol. 225, p. 109645, Nov. 2022, doi: 10.1016/j.buildenv.2022.109645.

[11] R. R. Rachmawati, "Smart Farming 4.0 Untuk Mewujudkan Pertanian Indonesia Maju, Mandiri, dan Modern," *Forum Penelit. Agro Ekon.*, vol. 38, no. 2, p. 137, Jun. 2021, doi: 10.21082/fae.v38n2.2020.137-154.

[12] A. Kamilaris, A. Kartakoullis, and F. X. Prenafeta-Boldú, "A Review on The Practice of Big Data Analysis in Agriculture," *Comput. Electron. Agric.*, vol. 143, pp. 23–37, Dec. 2017, doi: 10.1016/j.compag.2017.09.037.

[13] K. K. Y. Shin, T. P. Ping, M. G. B. Ling, C. Chee Jiun, and N. A. B. Bolhassan, "SMART GROW – Low-cost automated hydroponic system for urban farming," *HardwareX*, vol. 17, p. e00498, Mar. 2024, doi: 10.1016/j.ohx.2023.e00498.

[14] P. Y. Aisyah, I. Zarkasih, and M. Kurnia, "Smart And Sustainable Hydroponics: Fuzzy Logic-Based Environmental Control for Optimized Indoor Crop Growth," *Green Technol. Sustain.*, vol. 4, no. 2, p. 100311, Apr. 2026, doi: 10.1016/j.grets.2025.100311.

[15] Erlangga Adi Saputra, M. Ridhwan Sufandi, and Nurul Fadilah, "Sistem Monitoring Dan Kontrol Tanaman Hidroponik Berbasis Iot Mengunakan Microcontroller Arduino Dan Esp32 di Alwi Mini Farm," *Kohesi J. Multidisiplin Saintek*, vol. 10, no. 2, 2025.

[16] M. E. E. Alahi, N. Pereira-Ishak, S. C. Mukhopadhyay, and L. Burkitt, "An Internet-of-Things Enabled Smart Sensing System for Nitrate Monitoring," *IEEE Internet Things J.*, vol. 5, no. 6, pp. 4409–4417, Dec. 2018, doi: 10.1109/JIOT.2018.2809669.

[17] E. Sisinni, A. Saifullah, S. Han, U. Jennehag, and M. Gidlund, "Industrial Internet of Things: Challenges, Opportunities, and Directions," *IEEE Trans. Ind. Informatics*, vol. 14, no. 11, pp. 4724–4734, Nov. 2018, doi: 10.1109/TII.2018.2852491.

[18] Tjut Awaliyah Zuraiyah, Mohammad Iqbal Suriansyah, and Adan Pakhrizal Akbar, "Smart Urban Farming Berbasis Internet Of Things (IoT)," *Inf. Manag. Educ. Prof.*, vol. 3, no. 2, 2019.

[19] Rafael Praseli, "Implementasi MQTT Broker HiveMQ Cloud untuk Monitoring Multi-Sensor Berbasis ESP32," 2025.

[20] S. Stephanie, Jovin Kendrico, Vanesia Roselin, Winar Joko Alexander, Ziven Louis, and Okky Putra Barus, "Penerapan Smart Indoor Farming dan Clean Energy Technology untuk Peningkatan Kualitas Produksi Hidroponik," *PaKMas J. Pengabdi. Kpd. Masy.*, vol. 4, no. 2, pp. 304–312, Nov. 2024, doi: 10.54259/pakmas.v4i2.2953.