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Design, Build and Test the Performance of an IoT-Integrated Zeolite–RO Hybrid Filtration System

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***Abstract*—Groundwater in densely populated urban areas such as DKI Jakarta is frequently contaminated, both chemically and physically, making it unfit for direct consumption. This research aims to design, build, and test the performance of a Hybrid Zeolite–Reverse Osmosis (RO) filtration system integrated with the Internet of Things (IoT) to treat groundwater into drinking-ready water. The system consists of an ESP32 as the main controller, a flow meter sensor, a feeder pump, a booster pump, and a solenoid valve connected to a Firebase Realtime Database and the Kodular application. Testing covered three aspects: device control, water discharge monitoring, and filtered water quality. Results show that all devices could be controlled according to commands without communication errors, with an average flow sensor reading error of 1.884% (98.12% accuracy) against a 5-liter filling target. The filtered water quality showed a decrease in TDS from 153 ppm to 19 ppm (87.6% efficiency), EC from 201 µS/cm to 38 µS/cm (81.1% efficiency), salinity from 50 ppm to 0 ppm (100% efficiency), and an increase in ORP from 150 mV to 228 mV, with all parameters meeting WHO standards and comparable to branded bottled water. This research proves that integrating a hybrid filtration system with IoT supports the automatic and monitored optimization of groundwater utilization.**

***Index Terms*—groundwater, hybrid filtration, zeolite, reverse osmosis, Internet of Things**

I. Introduction

Clean water is a vital basic need for human life, both for consumption, sanitation, and worship activities. Based on global data, around 2 billion people in the world still do not have access to safe and decent drinking water, so the problem of clean water remains an urgent issue that is in line with the sixth goal of the Sustainable Development Goals (SDGs).

In densely populated urban areas such as DKI Jakarta, groundwater remains the main source of clean water for residents, but around 65–75% of groundwater wells in urban areas of DKI Jakarta are chemically polluted (TDS >500 mg/L) and microbiologically, while some other urban points experience heavy metal pollution due to industrial waste, as well as seawater intrusion due to land subsidence that exacerbates contamination (Mustafa, 2024; Iskandar et al., 2025). This condition demands the availability of efficient and reliable water treatment technology.

Hybrid filtration systems combine multiple water treatment techniques in one integrated circuit to achieve maximum performance. Porous aluminosilicate zeolite media has been shown to be effective in adsorbing heavy metals, ammonia, and suspended particles while preventing fouling on the membrane when combined with Reverse Osmosis (RO) (Nizam et al., 2021). Previous studies on the application of hybrid zeolite–RO filtration systems show that this technology is able to reduce the value of Total Dissolved Solids (TDS) from 1500 mg/L to 45 mg/L with an elimination efficiency of about 97%, as well as remove up to 99% of pathogenic bacteria in contaminated groundwater (Syam et al., t.t.). However, the main challenge of RO technology is membrane fouling, which inhibits water flux and increases maintenance costs due to high operational pressure (Ahmed et al., 2023), so an automated control system is needed to maintain membrane operational stability.

Previous studies have generally focused on the filtration aspect itself (Nizam et al., 2021; Nur et al., 2025; Widiastuti et al., 2021) or on a separate IoT-based pump control system (Kusumastuti et al., 2025), so there is still a research gap in the integration between the existing hybrid filtration system and a comprehensive IoT-based remote monitoring and control system, including real-time water discharge monitoring as well as remote actuator control.

Based on this description, this study aims to design, build and test the performance of an Internet of Things (IoT)-based monitoring and control system on the available Hybrid Zeolite–Reverse Osmosis (RO) filtration system, so that contaminated groundwater can be treated into ready-to-drink water while allowing users to monitor water discharge and operate pumps and valves remotely. The novelty of this research lies in the integration between: (1) hybrid zeolite–RO filtration technology for groundwater treatment, (2) IoT-based pump and valve control systems using ESP32, Firebase Realtime Database, and Kodular applications, and (3) measurable system performance testing in the aspects of device control, water discharge monitoring, and filtration water quality.

II. Methods

A. Place and Time of Research

The research was carried out in Building L, 4th Floor, Jakarta State University. The research lasted for three months, including the stages of problem identification and literature study, system design, preparation of tools and materials, assembly and integration of hardware and software, testing and calibration, data collection, to data analysis and report preparation.

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B. System Block Diagram

The raw water is flowed using a feeder pump to a filtration system consisting of three media tubes, namely Tube 1 containing Sand Filter and Zeolite, Tube 2 containing Manganese Greensand (MGS), and Tube 3 containing Activated Carbon. After passing through all three stages, water is flowed to the booster pump to increase pressure before entering the Reverse Osmosis (RO) membrane as the final purification stage.

The water from the RO process then passes through the flow meter sensor to measure the water flow discharge. The data is read by an ESP32 microcontroller and sent over a Wi-Fi network to the Firebase Realtime Database, then displayed on the Kodular application so that users can monitor water discharge in real-time while remotely controlling feeder pumps, booster pumps, and solenoid valves. A diagram of the system blocks is shown in Fig. 1.

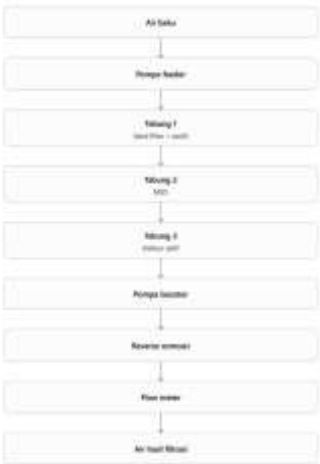

Fig. 1. Block diagram of IoT-integrated zeolite–RO hybrid filtration system.

C. Hardware and Software Designing

The hardware used consists of an ESP32 microcontroller, a YF-S201 flow meter sensor, a 4-channel relay module, a feeder pump, a booster pump, a solenoid valve, a power supply, and a water filtration system consisting of three filtration media tubes and an RO membrane. The ESP32 serves as a control center that reads sensor data, sends data to the Firebase Realtime Database over Wi-Fi, and receives commands from the application to control the relay. The configuration of the ESP32 pins used in this study is shown in Table I.

TABLE I. ESP32 PIN CONFIGURATION

Components	Pin ESP32	Function
Flow Meter	27	Water discharge reading input
Relay Pompa Feeder	22	Feeder pump control output
Relay Pompa Booster	21	Booster pump control output
Relay Solenoid Valve	23	Output control solenoid valve

The software is designed to allow the ESP32 to read the pulse from the flow meter sensor, convert it to the water discharge value (liters/minute), transmit the data to the Firebase Realtime Database, and read the control state (ON/OFF) stored on the Firebase to activate or deactivate the relay at the user's command. The two processes run in a looping manner without interfering with each other, so that the water discharge reading continues to run in real-time even though the user is sending control commands. The monitoring application was developed using Kodular, displaying real-time water discharge values as well as ON/OFF control buttons for feeder pumps, booster pumps, and solenoid valves.

D. System Testing

System testing is carried out on three main aspects, namely (1) testing the control of the device, by giving an ON/OFF command through the Kodular application on the feeder pump, booster pump, and solenoid valve, then comparing the command with the actual condition of the device; (2) water discharge monitoring testing, by draining water under several different discharge conditions and observing the suitability of the values displayed on the application, including accuracy testing using measuring cups as a comparison instrument on the 5-liter filling target for five attempts; and (3) water quality testing, by comparing the parameters of pH, TDS, EC (Electrical Conductivity), salinity, ORP (Oxidation Reduction Potential), and temperature before and after the filtration process against WHO standards and branded bottled water.

The average sensor measurement result and error percentage are calculated using the following equations (1) and (2).

$$\bar{V} = (\Sigma\, V\, sensor,i\,)\,/\,n\,,\ \ i = 1...n \quad (1)$$

$$Error\ (\%) = |\ (V\, sensor - V\, acuan)\,/\,V\, acuan\ | \times 100\% \quad (2)$$

where $\bar{V}$ is the average measurement result of the sensor (liters), V sensor is the volume read by the sensor in each experiment, V acuan is the reference volume on the measuring cup (5 liters), and n is the number of experiments.

III. RESULTS AND DISCUSSION

A. Device Control Test Results

Testing of the device control is carried out by repeatedly giving ON/OFF commands through the Kodular application on the feeder pump, booster pump, and solenoid valve. The test results are shown in Table II.

TABLE II. DEVICE CONTROL TEST RESULTS

Devices	Commands	Results
Pompa Feeder	ON	Pump on as commanded
Pompa Feeder	OFF	Pump off to order
Pompa Booster	ON	Pump on as commanded
Pompa Booster	OFF	Pump off to order
Solenoid Valve	ON	Valve opens to order
Solenoid Valve	OFF	Valve closed to order

Based on Table II, all devices respond to the commands given through the application without any communication errors or significant delays. The consistency of these results shows that the communication lines of the application →

Firebase → ESP32 → relay work reliably, so that the device control function is declared to have met the research objective, which is to produce a system that can be controlled remotely.

B. Water Discharge Monitoring and Accuracy Test Results

Water discharge monitoring testing shows that the flow meter sensor is able to read changes in water discharge responsively; when the flow rate changes, the sensor pulse value also changes and is instantly converted to a new discharge value, which is sent to the Firebase Realtime Database without significant delay and performs consistently in the Kodular application. The accuracy test of the 5-liter filling target using a measuring cup as a comparison, carried out five times, is presented in Table III.

TABLE III. 5 LITER VOLUME ACCURACY TEST RESULTS

Measuring Cup (L)	Sensor Yield (L)	Difference (L)	Error (%)
5.00	4.930	0.070	1.40
5.00	4.900	0.100	2.00
5.00	4.980	0.020	0.40
5.00	5.191	0.191	3.82
5.00	4.910	0.090	1.80
Average	**4.982**	**0.094**	**1.88**

Based on five tests, the sensor flow meter produced readings between 4.900 L to 5.191 L, with an average reading of 4.988 L and an average error of 1.884%, according to calculations using equation (2). The smallest error occurred on the third attempt (0.40%), while the largest error occurred on the fourth attempt (3.82%), which was likely caused by fluctuations in water flow during charging. With an average error of 1.884%, the accuracy level of the YF-S201 flow meter sensor against the 5-liter filling target reaches 98.12%, so the sensor can be categorized as accurate enough to support the real-time water discharge monitoring function.

C. Water Quality Testing Results

Water quality testing is carried out by comparing water parameters before and after the Hybrid Zeolite–Reverse Osmosis filtration process with branded bottled water and WHO standards. The test results are shown in Table IV.

TABLE IV. WATER QUALITY PARAMETER TEST RESULTS

Parameter	Before Filtration	After Filtration (RO)	Branded Bottled Water	WHO Standards
pH	7.18	7.18	7.34	6.5–8.5
TDS (ppm)	153	19	20	< 300
EC (µS/cm)	201	38	40	50–1500
Salinity (ppm)	50	0	0	< 600
ORP (mV)	150	228	231	+100 to +400
Temperature (°C)	±28	24.3	23.0	–

The pH value is relatively unchanged (remains 7.18) before and after filtration because filter sand media, zeolite, MGS, activated carbon, and RO essentially filter particles and solutes, rather than neutralize the acidity of the water; this value remains in the middle of the WHO standard range (6.5–8.5). The TDS value dropped drastically from 153 ppm to 19 ppm (87.6% efficiency), in line with the EC decrease from 201 µS/cm to 38 µS/cm (81.1% efficiency), as both parameters represent the amount of dissolved ions in water. The salinity dropped from 50 ppm to 0 ppm (100% efficiency), indicating that the dissolved salt content was almost completely removed by the RO membrane. The ORP value increased from 150 mV to 228 mV, close to the value of branded bottled water (231 mV), which indicates that the filtered water has a better ability to inhibit the growth of microorganisms. The temperature of the filtered water (24.3°C) is lower than before filtration (±28°C), likely influenced by the remaining time of the water in the piping system and filtration tubes. Overall, all parameters of filtered water are within the range of WHO standards and are comparable to branded bottled water.

D. Discussion

The test results in all three aspects — device control, water discharge monitoring, and water quality — show that the IoT system built successfully supports the remote and real-time operation of the Hybrid Zeolite–Reverse Osmosis filtration system. The successful data communication between ESP32, Firebase Realtime Database, and the Kodular application is the main key that allows all monitoring and control functions to run without significant problems. In terms of water quality, the filtration system that is the object of this study has been proven to be effective in reducing contaminant levels, especially TDS, EC, and salinity, while increasing the value of ORP.

This research still has limitations that need to be honestly disclosed, namely the measurement of water quality parameters (pH, TDS, EC, salinity, ORP, temperature) is still carried out manually using portable measuring instruments and has not been directly integrated into the built IoT system. The IoT system in this study only includes water discharge monitoring and device control, while water quality data is obtained from separate measurements. Further development can be focused on adding a water quality sensor that is directly connected to the ESP32, so that all parameters can be monitored automatically and in real-time through the Kodular application without the need for periodic manual measurements.

IV. CONCLUSIONS AND SUGGESTIONS

A. Conclusion

The IoT-based device control system was successfully implemented and functioned as designed; the feeder pump, booster pump, and solenoid valve can be controlled remotely through the Kodular app without any communication errors. The IoT-based water discharge monitoring system was successfully implemented in real-time with a flow meter sensor accuracy rate of 98.12% (average error of 1.884%) against the 5-liter filling target. The Hybrid Zeolite–Reverse Osmosis filtration system has been proven to be effective in reducing contaminants in groundwater, with a reduction in TDS of 87.6% and EC of 81.1%, a decrease in salinity of up to 100%, and an increase in ORP from 150 mV to 228 mV, and all parameters of filtered water are within the range of WHO standards and comparable to branded bottled water. The integration of filtration systems with IoT is proven to support the optimization of automatic and monitored groundwater utilization without requiring users to be physically present at the tool location.

B. Suggestions

Further research is suggested to integrate water quality sensors (pH, TDS, EC, or ORP) directly into the ESP32 so that all parameters can be monitored automatically and in real-time through the application without periodic manual measurements. The monitoring application can be expanded with automatic notification features, data history logging, and visualization of water discharge and quality trend graphs. In addition, periodic recalibration of the flow meter sensor or the application of signal filtering methods (e.g. moving average) can be considered to reduce errors due to fluctuations in water discharge.

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