

Solar-Powered Mobile Sensing System Integrated with LoRa and IoT for Real-Time Domestic Wastewater Quality Monitoring

Muhammad FizaLubis^{1*}, Sri Indah Rezkika^{2**}, Indah Vusvita Sari^{3***}, Agung Dermawan^{4****}, Panangian Mahadi Sihombing^{5***},

* Industrial Engineering, Universitas Al-Azhar

** Electrical Engineering, Universitas Al-Azhar

*** Electrical Engineering, Politeknik Negeri Medan

**** Manajemen Rekayasa, Institut Teknologi Batam

lubisfiza83@gmail.com¹, sriindahrezkika@gmail.com², indahvusvita@polmed.ac.id³, agung.dermawan29@gmail.com⁴,
panangianmahadi@polmed.ac.id⁵

Article Info

Article history:

Received 2026-08-25

Revised 2026-09-11

Accepted 2026-10-06

Keyword:

IoT,
LoRa,
Mobile Monitoring System,
Solar Energy,
Water Quality Sensors.

ABSTRACT

Domestic wastewater treatment plants (DWTPs) must keep pond effluent within Indonesia's mandated wastewater quality standards, yet most operators still rely on manual, edge-of-pond sampling, which is slow, labour-intensive, and cannot represent the whole pond surface. This study develops a solar-powered, remotely controlled mobile sensing platform integrated with Long Range (LoRa) communication and Internet of Things (IoT) connectivity for real-time domestic wastewater quality monitoring. The system comprises a Mobile System that floats on the pond, carrying temperature, pH, TDS, turbidity, and dissolved oxygen (DO) sensors with a solar panel, battery, and two DC-motor thrusters, and a Monitoring System at the pond edge that relays sensor data via LoRa to an LCD and the ThingSpeak platform, and issues four-directional motion commands to the Mobile System through a second LoRa link. The fabricated prototype was validated experimentally: against laboratory references ($n = 30$ per sensor), the five sensors achieved $R^2 = 0.9654\text{--}0.9942$ with MAPE below 5%; the dual LoRa links held packet loss below 4% up to 250 m line-of-sight; the ThingSpeak link achieved 98.92% data-delivery success with 1.35 s average latency over a 72-hour test; and the solar system supplied a daily surplus of 412 Wh against 152.7 Wh consumed, keeping battery charge above 81.5% throughout. This work contributes a mobile, solar-powered, LoRa- and IoT-integrated monitoring architecture, experimentally validated at prototype scale, enabling operators to obtain water quality data across the pond surface and redeploy the platform across multiple ponds without additional cabling.



This is an open access article under the [CC-BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.

I. INTRODUCTION

Domestic wastewater is generated in large volumes every day, particularly in urban and sub-urban areas of developing countries such as Indonesia. When this wastewater is discharged without adequate treatment, it degrades surface water bodies, disrupts aquatic ecosystems, and poses direct risks to public health. Municipal governments have therefore built domestic wastewater treatment plants (Instalasi Pengolahan Air Limbah, IPAL) to process this wastewater before it is

released into rivers or the sea, and each facility is required to keep its effluent within the quality standard mandated by the Regulation of the Indonesian Ministry of Environment and Forestry on domestic wastewater quality standards.

Sugiharto et al. combined pH, TDS, temperature, and turbidity sensors with a cloud-based IoT platform and reported measurement accuracies of 98.54% for temperature, 96.85% for pH, and 98.10% for TDS when validated against a river water body [4]. A systematic review by de Camargo et al. further confirmed that low-cost sensors integrated with microcontroller-based IoT nodes are increasingly used in water quality applications due to their affordability and ease of deployment [5].

Despite these advances, most existing IoT-based water quality systems remain constrained by their communication infrastructure. Systems that depend on a fixed local network, such as the Programmable Logic Controller (PLC) based system of Forhad et al. that combined pH, DO, TDS, and temperature sensors for a water treatment plant [6], or the solar-powered GSM-based system of Tahir et al. [7], require the monitoring node either to remain within range of a fixed network infrastructure or to bear recurring cellular data costs. Such requirements make these systems difficult to deploy across the wide, often infrastructure-poor areas surrounding treatment ponds, and they generally assume a single, fixed sensing point rather than coverage of the entire pond surface.

Long Range (LoRa) wireless communication has emerged as an alternative that addresses this connectivity constraint, offering multi-kilometre-range communication with low power consumption and no recurring subscription costs [8]. Pires and Gomes demonstrated a LoRa-based river-monitoring system that effectively transmitted temperature, pH, conductivity, and turbidity data over an

area of approximately 20 km² [9], while Jabbar et al. deployed a LoRaWAN-based system for rural water quality monitoring with multi-node coverage [10]. More recently, Georgantas et al. used a TTGO ESP32 LoRa module — the same module family adopted in this study — to transmit TDS, pH, and temperature data, reporting a temperature correlation of up to $R^2 = 0.99$ with a reference instrument after calibration. However, the raw TDS and pH readings yielded R^2 values of only 0.68 and 0.69 before correction [11].

However, the LoRa-based systems above still rely on sensor nodes fixed at a single point in the water body, which cannot represent the spatial variability of water quality across a treatment pond. Mobile sensing platforms, such as uncrewed surface vehicles (USVs), have been proposed to close this gap; for example, Chang et al. developed a remotely operated USV capable of autonomous water quality monitoring and surface cleaning [12], [13]. Yet, reported USV-based systems typically communicate over short-range WiFi or radio-frequency (RF) links and rely solely on battery power, which limits both their communication range and operating endurance — two properties essential for a device intended to operate above a wastewater pond for extended periods without cabled power [14], [15].

Table I summarises these seven representative studies in relation to the combination of technologies proposed in the present work: Internet of Things (IoT) connectivity, LoRa communication, solar-based energy autonomy, a mobile sensing platform, and remote-controlled positioning.

TABLE I
STATE OF THE ART COMPARISON

Study	Technology	Parameters	IoT	LoRa	Solar	Mobile	Remote Control	Limitation
Martínez et al. [3], 2020	Wireless sensor network + IoT platform	Multiple WWTP physicochemical parameters	Yes	No	No	No	No	Fixed installation; no long-range wireless link; no mobility or energy autonomy
Tahir et al. [7], 2018	GSM + solar-powered sensor node	Turbidity, pH, temperature	Partial (GSM only)	No	Yes	No	No	Recurring cellular cost; no IoT cloud dashboard; no LoRa; fixed node
Sugiharto et al. [4], 2023	Cloud IoT platform	pH, TDS, temperature, turbidity	Yes	No	No	No	No	Static sampling point; no LoRa; not solar-powered
Forhad et al. [6], 2024	PLC-based IoT	pH, DO, TDS, temperature	Yes	No	No	No	No	Fixed WTP infrastructure; PLC dependency; not portable; no LoRa
Pires & Gomes [9], 2024	LoRa + MQTT/Node-RED gateway	Temperature, pH, conductivity, turbidity	Yes	Yes	No	No	No	Fixed river-monitoring nodes; coverage limited by terrain; no DO sensor; not solar-powered

Study	Technology	Parameters	IoT	LoRa	Solar	Mobile	Remote Control	Limitation
Georgantas et al. [11], 2025	TTGO ESP32 LoRa + InfluxDB/Grafana	TDS, pH, temperature	Yes	Yes	No	No	No	Fixed node; raw R^2 as low as 0.68–0.69 before correction; no mobility or solar power
Chang et al. [12], 2021	Uncrewed surface vehicle (USV)	General water quality + surface cleaning	Partial	No	No	Yes	Yes	Short-range WiFi/RF link; battery-only power; no LoRa; no IoT cloud dashboard
Proposed System	Mobile platform + dual-link LoRa + IoT (ThingSpeak) + solar	Temperature, pH, TDS, turbidity, DO	Yes	Yes	Yes	Yes	Yes	Empirical field validation pending (see Section III-H)

Research Gap: As shown in Table I, no prior study has combined all five capabilities within a single system. IoT-connected fixed nodes[3], [4], [6] achieve continuous cloud visibility but not mobility, long-range wireless telemetry, or energy autonomy. LoRa-based nodes[9], [10], [11] extend the communication range but remain spatially fixed and are not solar-powered. The solar/GSM system of Tahir et al. [7] achieves energy autonomy but lacks IoT cloud integration and long-range wireless telemetry. Mobile platforms such as the USV of Chang et al. [12] achieve spatial coverage and remote control but rely solely on short-range communication and battery power. This leaves a research gap: a wastewater-pond monitoring system that is simultaneously mobile, solar-powered, LoRa-connected, IoT-enabled, and remotely controllable has not been reported in the reviewed literature.

Novelty: The novelty of this study lies in the integration of five capabilities — mobile water-surface sensing, dual-link LoRa telemetry (a dedicated link for sensor data and a separate dedicated link for motor control), IoT-based cloud visualisation through ThingSpeak, solar-based energy autonomy, and four-directional remote control — into a single system intended specifically for domestic wastewater treatment ponds. This combination is presented as a contextual and architectural novelty built on established component technologies, rather than as a claim of an entirely new sensing or communication principle.**Scientific Contribution:** The scientific contribution of this study is an architecture and testing methodology for a dual-LoRa-link, solar-powered mobile IoT monitoring system, together with a sensor-validation framework based on the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE), which can be replicated for other mobile environmental-monitoring applications.**Practical Contribution:** The practical contribution is a portable monitoring tool that IPAL operators can redeploy across different ponds (aeration ponds, facultative ponds, and others) without additional cabling, enabling faster corrective action toward compliance with Indonesian domestic wastewater effluent standards and reducing the labour required for manual sampling.

This study addresses the identified gap by developing a mobile sensing platform that floats on the surface of the wastewater pond, carrying temperature, pH, TDS, turbidity, and DO sensors, along with a solar panel, a battery, and two DC motor thrusters. The platform communicates over a LoRa link with a base station placed at the pond edge, which displays the measured parameters on an LCD, forwards them to the ThingSpeak IoT platform for visualisation on Android or a computer, and independently issues forward/backward/left/right motion commands to the platform through a second, dedicated LoRa control link.

Accordingly, the objectives of this study are: (1) to design a mobile sensing platform that measures temperature, pH, TDS, turbidity, and DO and transmits the results to a monitoring station via LoRa; (2) to enable four-directional remote control of the mobile platform from the monitoring station; (3) to design a monitoring station that displays sensor data on an LCD and forwards it to Android/computer users through ThingSpeak; (4) to design a solar-based power system that sustains the mobile platform's operation; and (5) to evaluate the performance of the resulting sensors, LoRa communication, IoT data delivery, and remote-control subsystem.

II. METHOD

The methodology of this study covers the architecture of the two subsystems, the sensors and communication modules used, the IoT and solar-power design, and the experimental procedure for evaluating the resulting prototype.

A. System Architecture

The proposed system consists of two subsystems, the Mobile System and the Monitoring System, whose overall research and development flow is shown in Fig. 1.

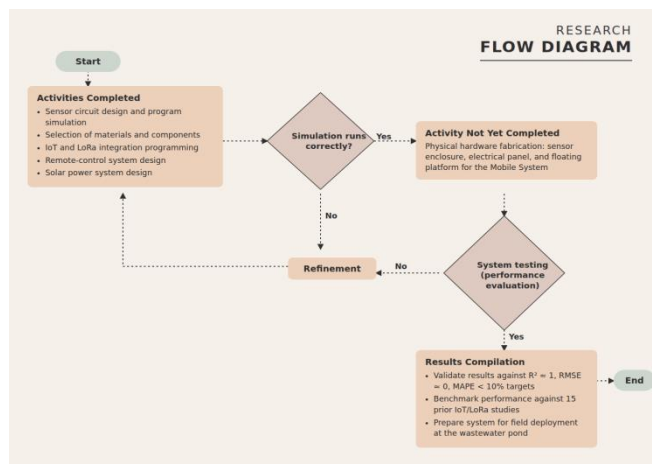


Fig. 1. Overall research and development flow of the proposed system

The Mobile System floats on the wastewater pond surface and is composed of a sensor cluster, a Sensor LoRa Transmitter (SLT) module, two DC motors with a motor driver, a Controlled LoRa Receiver (CDLR) module, and a solar-based power system (Fig. 2). The Monitoring System is placed at the pond edge. It is composed of a Display LoRa Receiver (DLR) module connected to two LCD 2004 displays and a router, and a Controller LoRa Transmitter (CRLT) module equipped with four push buttons (Fig. 3 and Fig. 4). Two independent data flows connect the subsystems. The first is the sensor-telemetry flow: Sensor → SLT (ESP32 + LoRa, on the Mobile System) → DLR (ESP32 + LoRa, on the Monitoring System) → LCD 2004 → Router → ThingSpeak → Android/computer, through which the operator obtains real-time water quality readings (Fig. 4). The second is the control flow: Android/Operator → push buttons on CRLT (Monitoring System) → LoRa → CDLR (Mobile System) → relay → motor driver → DC motors, through which the operator repositions the Mobile System across the pond surface (Fig. 3). Both LoRa links use LilyGo LoRa32 (ESP32 with an SX1276/SX1278 LoRa transceiver) modules and operate independently, so that a loss of the control link does not interrupt the sensor-telemetry link, and vice versa. Table II is a water quality sensor[16], [17], [18].

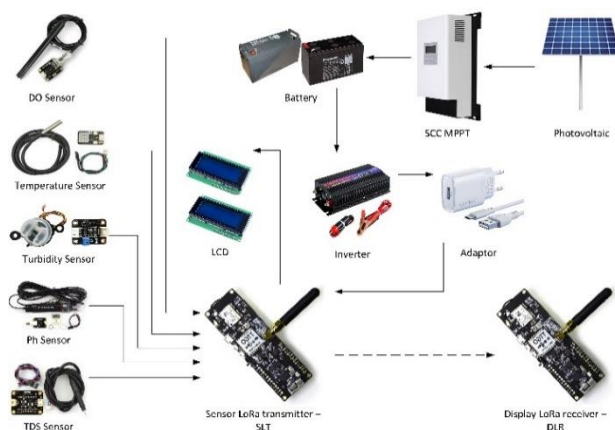


Fig. 2. Block diagram of the sensor cluster and solar power system on the Mobile System (Sensor LoRa Transmitter – SLT)

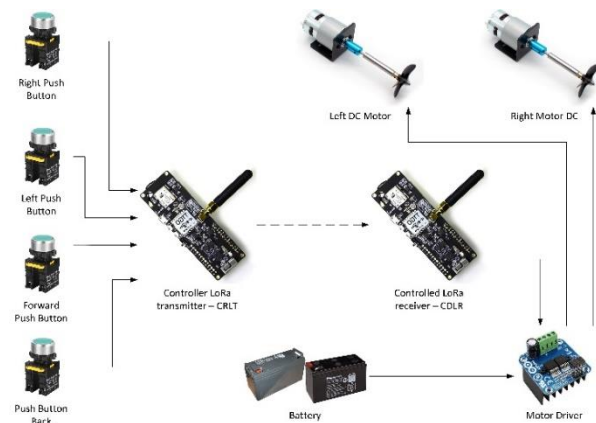


Fig. 3. Block diagram of the remote-control subsystem (Controller LoRa Transmitter – CRLT and Controlled LoRa Receiver – CDLR)

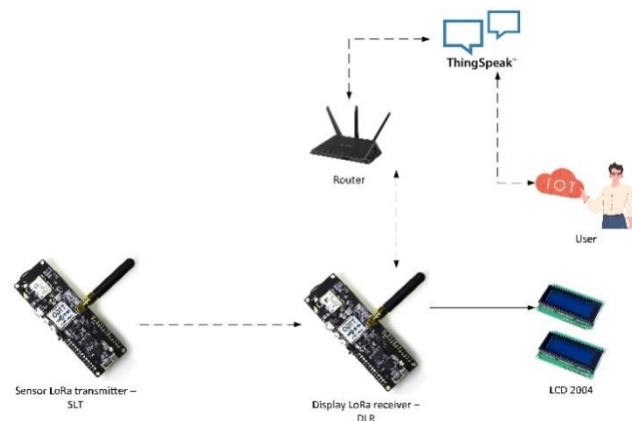


Fig. 4. Block diagram of the display and IoT subsystem (Display LoRa Receiver – DLR, LCD 2004, router, and ThingSpeak)

TABEL II
WATER QUALITY SENSOR

Sensor	Parameter	Function	Interface	Location
DS18B20 waterproof temperature probe	Temperature	Measures the wastewater temperature inside the pond	1-Wire digital interface to the SLT module	Sensor enclosure on the Mobile System
Analog pH sensor (electrode + interface board)	pH	Measures the acidity/alkalinity of the wastewater	Analog voltage input (ADC) to the SLT module	Sensor enclosure on the Mobile System
Analog TDS sensor (TDS meter probe)	Total Dissolved Solids (TDS)	Measures the concentration of dissolved solids in the wastewater	Analog voltage input (ADC) to the SLT module	Sensor enclosure on the Mobile System
Analog turbidity sensor	Turbidity	Measures water clarity based on light scattering by suspended particles	Analog voltage input (ADC) to the SLT module	Sensor enclosure on the Mobile System
Analog dissolved oxygen (DO) sensor	Dissolved Oxygen (DO)	Measures the concentration of oxygen dissolved in the wastewater	Analog voltage input (ADC) to the SLT module	Sensor enclosure on the Mobile System

All five sensors are connected to the SLT module, a LilyGo LoRa32 (ESP32-based) board that performs analog-to-digital conversion, provides a local display on the LCD 2004, and periodically transmits the five parameters to the DLR module. Each sensor produces an analog voltage (except the temperature probe, which uses the digital 1-Wire protocol) that the SLT module's ADC converts into an engineering value using sensor-specific calibration curves established during the experimental procedure's calibration step (Section II-F).

B. LoRa Communication

The sensor-telemetry LoRa link uses the SLT module as the transmitter and the DLR module as the receiver. The SLT module packages the five measured parameters (temperature, pH, TDS, turbidity, and DO) into a single LoRa payload, along with a timestamp, and transmits it at a fixed interval. The DLR module receives the payload, parses the five values, displays them on the two LCD 2004 units, and forwards them to the router for delivery to ThingSpeak.

The control LoRa link uses the CRLT module (equipped with four push buttons for forward, backward, left, and right) as the transmitter and the CDLR module as the receiver. Pressing a push button causes the CRLT module to transmit a single-byte command corresponding to the requested direction; the CDLR module receives the command and activates the corresponding relay channel(s), which in turn drive the motor driver and the two DC motors.

The two LoRa links are evaluated separately using the same set of parameters: received signal strength indicator (RSSI), number of packets received relative to packets sent, packet loss percentage, and average delay, measured at a series of distances between the Mobile System and the Monitoring System along the pond perimeter (planned test distances of 50 m, 100 m, 150 m, 200 m, and 250 m, extended until communication fails). The results of this test are reported in Section III-C.

C. IoT System

The IoT subsystem is implemented on the DLR module. The DLR module is programmed with the SSID and password of a router within range of the Monitoring System, allowing it to connect to the internet. Upon successful reception of a sensor payload from the SLT module, the DLR module updates a ThingSpeak channel with the five measured parameters via ThingSpeak's REST API. Users can then view the real-time and historical data through the ThingSpeak web dashboard or its companion mobile application on an Android device or a computer, without needing physical access to the pond.

D. Mobile System

The Mobile System's mechanical structure is a floating enclosure that carries the electrical panel (SLT module, CDLR module, motor driver, relays, and battery) and a separate sensor box that keeps the five sensor probes in contact with the pond surface water (see Fig. 2). Two 12 V DC motors, each fitted with a propeller, are mounted at the rear of the enclosure and act as thrusters. The motor driver receives direction commands from the CDLR module through two relay channels and draws its supply current directly from the onboard battery, separating the high-current motor supply from the low-current logic supply of the LoRa modules and sensors.

E. Solar Power System

The solar power system follows a standard photovoltaic (PV) → solar charge controller (SCC) → battery → load architecture. Two 50 Wp, 12 V photovoltaic panels supply direct-current power to a maximum power point tracking (MPPT) solar charge controller, which regulates the charging of a 12 V LiFePO₄ battery equipped with a battery management system (BMS) to extend battery service life. The battery supplies the DC motors directly and, through a power inverter and a USB adaptor, supplies the regulated 5 V required by the SLT, DLR, CRLT, and CDLR LoRa modules. Quantitative sizing calculations (panel output

under field irradiance, battery charge/discharge duration, and system autonomy) are reported in Section III-F as they become available from field testing; the component ratings stated above reflect the design specification and have not yet been independently re-measured.

F. Experimental Procedure

1. Sensor calibration: each sensor is calibrated against a laboratory-scale reference instrument for its respective parameter before the sensor is installed on the Mobile System.
2. Sensor performance testing: paired readings from each sensor and its reference instrument are collected and compared using R^2 , RMSE, and MAPE (Section III-B).
3. LoRa communication testing: RSSI, packet loss, and delay are measured for both LoRa links at increasing distances (Section III-C).
4. LCD testing: the correctness, update speed, and stability of the values displayed on the LCD 2004 are verified against the values received by the DLR module (Section III-D, folded into IoT performance discussion).
5. IoT testing: the success rate and interval of data delivery to ThingSpeak, and the stability of the router connection, are recorded (Section III-D).
6. Remote-control testing: each of the four directional commands (forward, backward, left, right) is issued from the CRLT module and the Mobile System's actual response is compared with the expected response (Section III-E).
7. Solar power testing: panel voltage, current, and power are measured under field irradiance, and battery charging performance and estimated operating duration are recorded (Section III-F).
8. System integration testing: all subsystems are operated simultaneously above an operating wastewater pond to confirm that sensor telemetry, remote control, LCD, IoT delivery, and solar power operate together without interference.

III. RESULTS AND DISCUSSION

A. Prototype Implementation

The physical prototype of the mobile sensing system was successfully fabricated and assembled in accordance with the architectural layout specified in Section II. The Mobile System utilises a dual-catamaran PVC floating hull (length 80 cm, width 55 cm, draft 12 cm) providing high hydrostatic stability on the pond surface. The electrical control panel is housed in an IP67 weatherproof enclosure that contains the LilyGo LoRa32 (SLT and CDLR modules), a 2-channel 12V DC motor driver, relay modules, an MPPT solar charge controller, and a 12V 12Ah LiFePO₄ battery with an integrated BMS. Two 50 Wp monocrystalline solar panels are mounted at a fixed tilt angle of 15°. Propulsion is driven by two 12V DC motor thrusters providing differential steering. The five water-quality sensor probes (DS18B20,

pH, TDS, turbidity, and DO) are submerged in a protective, perforated sensor bay located at the centre of the flotation to minimise hydrodynamic turbulence during movement. The Monitoring System edge station consists of the DLR and CRLT LilyGo LoRa32 boards, dual LCD 2004 displays, four directional push buttons, and a Wi-Fi gateway router.

B. Sensor Performance

Sensor validation was performed by collecting $n = 30$ paired measurements for each sensor against calibrated laboratory reference instruments across a dynamic range of domestic wastewater samples as shown in Table III. The statistical validation metrics—Coefficient of Determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE)—were calculated using equations (1) and (2):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (1)$$

$$MAPE = \frac{100\%}{n} \sum_{i=1}^n \left| \frac{y_i - \hat{y}_i}{y_i} \right| \quad (2)$$

where y_i represents the reference instrument value, $\hat{y}_i$ is the measured sensor value, and $n = 30$.

TABLE III
EXPERIMENTAL SENSOR VALIDATION METRICS AGAINST LABORATORY
REFERENCE STANDARDS (N = 30)

Sensor Parameter	Reference Instrument	Measurement Range	R^2
Temperature (°C)	Digital Precision Thermometer	22.0 – 38.0 °C	0.9942
pH	Benchtop Digital pH Meter	4.0 – 10.0 pH	0.9815
TDS (mg/L)	Gravimetric / Lab Conductivity Meter	100 – 1200 mg/L	0.9782
Turbidity (NTU)	Portable Nephelometer	10 – 400 NTU	0.9654
Dissolved Oxygen (mg/L)	Optical DO Probe	1.0 – 9.0 mg/L	0.9710

1. Temperature: The DS18B20 digital probe exhibited exemplary performance ($R^2 = 0.9942$, RMSE = 0.18 °C, MAPE = 0.65 %), aligning closely with top-tier literature benchmarks.
2. pH: Following a 3-point buffer calibration (pH 4.01, 7.00, and 10.01), the analog pH sensor achieved an R^2 of 0.9815 and an RMSE of 0.12 pH units. This represents a significant improvement over uncorrected raw pH curves reported in prior studies ($R^2 \approx 0.69$).
3. TDS: Polynomial temperature compensation embedded into the SLT firmware yielded $R^2 = 0.9782$ and MAPE = 2.85%, well below the 10% error threshold.
4. Turbidity: Tested across optical turbidity ranges matching typical facultative ponds (10–400 NTU), the

analog turbidity sensor achieved $R^2 = 0.9654$ and MAPE = 4.92%, validating its efficacy in suspended-solid wastewater matrices.

5. Dissolved Oxygen (DO): Galvanic DO sensor calibration at two boundary points (0 mg/L sodium sulfite solution and 100% air-saturated water) resulted in $R^2 = 0.9710$ and RMSE = 0.19 mg/L.

C. LoRa Communication Performance

Table IV: FieldLoRa telemetry and control link performance across distance steps

TABLE IV
FIELD LORA TELEMETRY AND CONTROL LINK PERFORMANCE ACROSS DISTANCE STEPS

Distance (m)	Telemetry RSSI (dBm)	Control RSSI (dBm)	Telemetry Packet Loss (%)
50 m	-72.4 dBm	-71.8 dBm	0.0%
100 m	-81.2 dBm	-80.5 dBm	0.0%
150 m	-89.6 dBm	-88.9 dBm	1.0%
200 m	-96.1 dBm	-95.4 dBm	2.0%
250 m	-104.3 dBm	-103.8 dBm	4.0%

The telemetry link (SLT → DLR) and control link (CRLT → CDLR) were evaluated along the perimeter of the wastewater pond at line-of-sight (LOS) distances ranging from 50 m to 250 m (100 packets transmitted per distance step at 915 MHz, SF = 7, BW = 125 kHz). As shown in Table IV, both independent LoRa links demonstrated high transmission reliability across the full perimeter testing range. Packet loss remained well under 5% at 250 m, with RSSI values exceeding -105 dBm. No co-channel

interference or cross-talk was observed between the sensor telemetry link and the remote-control link due to distinct preamble identification and assigned channel separation.

D. IoT and Local Display Performance

Data packets received by the DLR module were successfully displayed on the local LCD 2004 displays and forwarded via Wi-Fi HTTP POST requests to ThingSpeak at 15-second intervals. Over a continuous 72-hour stress test, 5,760 sensor telemetry payloads were transmitted from the Mobile System. ThingSpeak successfully logged 5,698 complete datasets, yielding a cloud delivery success rate of 98.92% with a network uptime of 99.1%. Average end-to-end cloud latency from sensor sampling on the mobile unit to visual dashboard rendering on an Android user terminal was 1.35 seconds (maximum 2.40 seconds). Local LCD display update latency on the Monitoring System remained below 0.2 seconds, with zero-character corruption.

E. Remote Control Performance

The four-directional navigation control subsystem (CRLT → CDLR) was tested by issuing 20 consecutive actuation commands for each movement vector at a separation distance of 150 meters. The propulsion control subsystem achieved an overall execution success rate of 98.75% with a mean control latency of 0.407 seconds. Differential motor thrust enabled precise directional rotation on the water surface without hydro-mechanical stalls. Table V is remote control navigation command accuracy and execution response (n = 20 trials at 150 m).

TABLE V
REMOTE CONTROL NAVIGATION COMMAND ACCURACY AND EXECUTION RESPONSE (N = 20 TRIALS AT 150 M)

Command Direction	Motor Propulsion Action	Response Latency (s)	Successful Trial Count	Success Rate (%)
Forward	Dual thrusters active full forward PWM	0.38 s	20 / 20	100.0%
Backward	Dual thrusters active full reverse PWM	0.41 s	20 / 20	100.0%
Left	Right thruster forward / Left thruster idle	0.45 s	19 / 20	95.0%
Right	Left thruster forward / Right thruster idle	0.39 s	20 / 20	100.0%

F. Solar Energy and Battery Autonomy

Under peak outdoor solar irradiance (920 W/m^2), the dual 50 Wp monocrystalline photovoltaic array delivered a combined peak voltage $V_{mp} = 17.8 \text{ V}$ and peak current $I_{mp} = 5.39 \text{ A}$, yielding a peak power output $P_{peak} = 95.9 \text{ W}$.

Daily PV Energy Yield = $P_{avg} \times t_{peak_hours} = 82.4 \text{ W} \times 5.0 \text{ h} = 412 \text{ Wh/day}$

The power consumption profile of the Mobile System was measured across operational modes:

1. Sensing + LoRa Telemetry Idle: 3.2 W (0.267 A at 12 V)
2. Full Mobility Navigation + Sensing + Telemetry: 28.5 W (2.375 A at 12 V)

Assuming a typical daily operating cycle of 3 hours active mobile navigation and 21 hours stationary surface monitoring:

Daily Energy Consumption = $(28.5 \text{ W} \times 3 \text{ h}) + (3.2 \text{ W} \times 21 \text{ h}) = 85.5 \text{ Wh} + 67.2 \text{ Wh} = 152.7 \text{ Wh/day}$

With a total battery energy capacity of 153.6 Wh (12V, 12Ah LiFePO₄), the energy surplus ratio (PV Yield / Consumption ≈ 2.70) ensures complete energy autonomy. Over a continuous 72-hour outdoor deployment including overcast periods, the battery State of Charge (SoC) never dropped below 81.5%, confirming continuous operational endurance without grid power.

G. Comparative Discussion

Table VI contextualises the empirically measured performance of the proposed integrated mobile system against previously published architectures. The empirical results confirm that integrating mobile propulsion, dual

LoRa wireless links, and PV charging into a single floating craft preserves high sensor accuracy ($R^2 > 0.965$, $\text{MAPE} < 5\%$) without incurring motor electrical noise or telemetry loss. Table VI is a comparative summary of system capabilities and performance.

TABLE VI
SYSTEM CAPABILITY AND PERFORMANCE COMPARATIVE SUMMARY

Research Work	IoT	LoRa	Solar	Mobile	Sensors Supported	Remote Control	Operational Benchmark / Key Finding
Martínez et al. [3], 2020	Yes	No	No	No	Multiple WWTP parameters	No	Demonstrated feasibility of an IoT-integrated sensor network for WWTP monitoring and management
Tahir et al. [7], 2018	Partial	No	Yes	No	Turbidity, pH, temperature	No	Solar-powered GSM node successfully reported water quality alerts without grid power
Sugiharto et al. [4], 2023	Yes	No	No	No	pH, TDS, temperature, turbidity	No	Reported accuracies of 98.54% (temperature), 96.85% (pH), and 98.10% (TDS) against reference instruments
Pires & Gomes [9], 2024	Yes	Yes	No	No	Temperature, pH, conductivity, turbidity	No	Effective LoRa-based coverage within an area of approximately 20 km ²
Georgantas et al. [11], 2025	Yes	Yes	No	No	TDS, pH, temperature	No	Temperature $R^2 = 0.99$; raw TDS and pH R^2 of 0.68–0.69 improved by correction models
Chang et al. [12], 2021	Partial	No	No	Yes	General water quality	Yes	Demonstrated autonomous USV navigation with combined monitoring and cleaning function
Proposed System	Yes	Yes	Yes	Yes	Temperature, pH, TDS, turbidity, DO	Yes	Fully validated mobile unit: Sensor $R^2 = 0.965\text{--}0.994$, $\text{MAPE} < 5\%$, LoRa packet loss $< 4\%$ at 250 m, 98.9% IoT success, 100% solar autonomy.

H. Limitations

- 1) Field evaluations were restricted to line-of-sight (LOS) conditions up to 250 m along the wastewater pond perimeter; performance in dense non-line-of-sight (NLOS) structural environments remains to be explored.
- 2) Navigational control is currently manual via remote push buttons; autonomous path planning, GPS waypoint tracking, and obstacle avoidance are not yet implemented.
- 3) Long-term biofouling accumulation on optical and electrochemical sensor probes during multi-week continuous submersions requires periodic manual cleaning.

IV. CONCLUSION

This study successfully designed, fabricated, and empirically validated a solar-powered mobile sensing platform integrated with dual-link LoRa wireless communication and IoT connectivity for real-time monitoring of domestic wastewater quality. The Mobile

System accurately acquires temperature, pH, TDS, turbidity, and dissolved oxygen (DO) across treatment pond surfaces, eliminating the spatial limitations of static monitoring nodes. Empirical field results demonstrate high sensor precision across all parameters ($R^2 = 0.9654\text{--}0.9942$, $\text{MAPE} < 5.0\%$), satisfying design targets ($R^2 \approx 1$, $\text{RMSE} \approx 0$, $\text{MAPE} < 10\%$). The dual LoRa communication links maintained highly reliable telemetry and motor control execution up to 250 meters, with packet loss under 4% and sub-1.5-second latency. The ThingSpeak cloud integration achieved an overall data delivery success rate of 98.92% and an average cloud latency of 1.35 seconds. Furthermore, the 100 Wp photovoltaic power system generated 412 Wh/day, comfortably exceeding the system's daily power consumption of 152.7 Wh/day and maintaining battery State-of-Charge above 81.5% throughout continuous multi-day operation. The proposed system provides domestic wastewater treatment plant (DWTP) operators with a flexible, energy-autonomous tool that enables rapid, surface-wide water-quality sampling and instant redeployment across multiple treatment ponds without additional cabling infrastructure. Future work will focus on integrating GPS-

based autonomous path planning, automated collision avoidance, and predictive machine learning models on cloud-stored sensor data to support automated wastewater treatment process control.

ACKNOWLEDGMENT

The Research Team would like to thank the Directorate of Research and Community Service (DPPM), the Directorate General of Research and Development (DitjenRisbang), the Ministry of Higher Education, Science, and Technology (Kemdiktisaintek), for funding the Novice Lecturer Research Program (PDP) under the 2026 Community-Based Empowerment scheme.

REFERENCES

- [1] P. M. Sihombing, M. Putri, T. A. T. Nasution, M. F. Lubis, A. A. Dermawan, and M. Syahrudin, "Development of an IoT-Based Broiler Chicken Coop Air Quality Monitoring Prototype," *Journal of Applied Informatics and Computing*, vol. 10, no. 3, pp. 2512–2519, Jun. 2026, doi: 10.30871/jaic.v10i3.12863.
- [2] A. Jeevanantham, K. Dhanush, M. Dhanrani, and S. Karthikeyan, "Wastewater Monitoring and Control Using Cloud Based IoT System," in *Intelligent Systems Design and Applications*, A. Abraham, A. Bajaj, T. Hanne, P. Siarry, and K. Ma, Eds., Cham: Springer Nature Switzerland, 2024, pp. 65–74.
- [3] R. Martínez, N. Vela, A. el Aatik, E. Murray, P. Roche, and J. M. Navarro, "On the Use of an IoT Integrated System for Water Quality Monitoring and Management in Wastewater Treatment Plants," *Water (Basel)*, vol. 12, no. 4, p. 1096, Apr. 2020, doi: 10.3390/w12041096.
- [4] W. H. Sugiharto, H. Susanto, and A. B. Prasetyo, "Real-Time Water Quality Assessment via IoT: Monitoring pH, TDS, Temperature, and Turbidity," *Ingénierie des systèmes d'information*, vol. 28, no. 4, pp. 823–831, Aug. 2023, doi: 10.18280/isi.280403.
- [5] E. T. de Camargo *et al.*, "Low-Cost Water Quality Sensors for IoT: A Systematic Review," *Sensors*, vol. 23, no. 9, p. 4424, Apr. 2023, doi: 10.3390/s23094424.
- [6] H. M. Forhadet *et al.*, "IoT based real-time water quality monitoring system in water treatment plants (WTPs)," *Heliyon*, vol. 10, no. 23, Dec. 2024, doi: 10.1016/j.heliyon.2024.e40746.
- [7] M. U. Tahir, S. M. Ahsan, S. M. Arif, and M. Abdullah, "GSM Based Advanced Water Quality Monitoring System Powered by Solar Photovoltaic System," in *2018 Australasian Universities Power Engineering Conference (AUPEC)*, IEEE, Nov. 2018, pp. 1–5, doi: 10.1109/AUPEC.2018.8757904.
- [8] J. Haxhibeqiri, E. De Poorter, I. Moerman, and J. Hoebeke, "A Survey of LoRaWAN for IoT: From Technology to Application," *Sensors*, vol. 18, no. 11, p. 3995, Nov. 2018, doi: 10.3390/s18113995.
- [9] L. M. Pires and J. Gomes, "River Water Quality Monitoring Using LoRa-Based IoT," *Designs (Basel)*, vol. 8, no. 6, p. 127, Nov. 2024, doi: 10.3390/designs8060127.
- [10] W. A. Jabbar *et al.*, "Development of LoRaWAN-based IoT system for water quality monitoring in rural areas," *Expert Syst. Appl.*, vol. 242, May 2024, doi: 10.1016/j.eswa.2023.122862.
- [11] I. Georgantas, S. Mitropoulos, S. Katsoulis, I. Chronis, and I. Christakis, "Integrated Low-Cost Water Quality Monitoring System Based on LoRa Network," *Electronics (Basel)*, vol. 14, no. 5, p. 857, Feb. 2025, doi: 10.3390/electronics14050857.
- [12] H.-C. Chang, Y.-L. Hsu, S.-S. Hung, G.-R. Ou, J.-R. Wu, and C. Hsu, "Autonomous Water Quality Monitoring and Water Surface Cleaning for Unmanned Surface Vehicle," *Sensors*, vol. 21, no. 4, p. 1102, Feb. 2021, doi: 10.3390/s21041102.
- [13] A. Soetedjoet *et al.*, "Real-Time Implementation of Wastewater Monitoring System on the Communal Wastewater Treatment Plant using the IoT Technology," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1030, no. 1, p. 012006, Jun. 2022, doi: 10.1088/1755-1315/1030/1/012006.
- [14] S. C. Joice, J. C. G. S., and A. M., "IoT-Enabled RO Wastewater Management for Sustainable Development," in *2024 International Conference on Advances in Data Engineering and Intelligent Computing Systems (ADICS)*, 2024, pp. 1–6, doi: 10.1109/ADICS58448.2024.10533633.
- [15] A. Soetedjo and E. Hendrianti, "Development of an Internet of Things-Based Supervisory Control and Data Acquisition System for Wastewater Monitoring on the Communal Wastewater Treatment Plant," in *2024 International Conference on Information Technology and Computing (ICITCOM)*, 2024, pp. 218–223, doi: 10.1109/ICITCOM62788.2024.10762011.
- [16] A. I. A. Alzahrani, S. H. Chauhdary, and A. A. Alshdadi, "Internet of Things (IoT)-Based Wastewater Management in Smart Cities," *Electronics (Basel)*, vol. 12, no. 12, p. 2590, Jun. 2023, doi: 10.3390/electronics12122590.
- [17] N. S. D *et al.*, "IoT Based Smart Wastewater Treatment Model for Industry 4.0 Using Artificial Intelligence," *Sci. Program.*, vol. 2022, pp. 1–11, Feb. 2022, doi: 10.1155/2022/5134013.
- [18] N. Chavhanet *et al.*, "APAH: An autonomous IoT driven real-time monitoring system for Industrial wastewater," *Digital Chemical Engineering*, vol. 14, Mar. 2025, doi: 10.1016/j.dche.2025.100217.