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Design of an IoT-Integrated Lab-Scale Sequencing Batch Reactor with Real-Time Water Quality Monitoring

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Abstract - Decentralized wastewater treatment is increasingly important for urban sustainability, and the Sequencing Batch Reactor (SBR) is a compact and flexible option. However, SBRs are usually operated on fixed timers and checked by manual sampling, which leaves operators blind to rapid changes inside the tank. This paper presents the design, fabrication and monitoring system of a 25 liter lab-scale SBR for domestic wastewater, built with low-cost Internet of Things (IoT) hardware. The reactor is sized from laboratory characterization of raw sewage collected from a campus sewage treatment plant (BOD 125 mg/L, TSS 136 mg/L, pH 7.59). It runs a five-phase cycle of fill, react, settle, decant and idle. Sensors for pH, total dissolved solids, turbidity, temperature and water level are connected to an Arduino Uno, which passes the data to an ESP32 microcontroller for transfer to a web dashboard. The sensors were calibrated against laboratory instruments and agreed with the manual readings to about 98 percent for pH and total dissolved solids. The dashboard provides live values, trend graphs, batch phase display, alarms, maintenance records and report export. The work shows a cost-effective path to adding digital oversight to decentralized biological treatment.

Keywords - Sequencing batch reactor; wastewater treatment; Internet of Things; ESP32; real-time monitoring; sensor calibration; dashboard

I. INTRODUCTION

Rapid urbanization and industrialization have sharply increased the generation of domestic wastewater, while freshwater resources are becoming scarcer. Treating and reclaiming wastewater is now a core part of sustainable urban infrastructure. Biological treatment depends on microbial communities that break down organic pollutants, and its performance is sensitive to operating conditions and available land [1].

The Conventional Activated Sludge Process (ASP) uses separate tanks for aeration, settling and sludge return. This raises land and construction costs, makes it hard to install in space-constrained urban areas, and gives limited resilience to organic shock loads. Manual monitoring of dissolved oxygen, pH and suspended solids also causes long response delays [1].

The Sequencing Batch Reactor (SBR) addresses these problems by carrying out equalization, aeration and clarification in a single tank, one phase after another [2]. Its efficiency, however, depends on precise phase timing. If the aeration or settling period is wrong, the biological floc may not settle or the effluent may miss discharge standards. Manual sampling cannot follow parameter changes that happen within minutes in each batch phase, and the delay between sampling, analysis and adjustment lowers treatment quality.

This work develops an IoT-integrated lab-scale SBR to close that gap. The objectives are: (i) to design and fabricate a lab-scale SBR, (ii) to treat real domestic wastewater, (iii) to continuously acquire pH, total dissolved solids (TDS), turbidity, temperature and water level data, (iv) to transmit the data to a cloud-ready dashboard, and (v) to validate the sensors against laboratory methods. The study is limited to domestic wastewater and to monitoring, batch timing and visualization. Automatic actuator control is left for later work.

II. LITERATURE REVIEW

Model-based optimization of SBR design and operation has been shown to reduce long-term operating cost, but the multi-variable formulations are computationally heavy and slow to solve on the fly [3]. Reviews of industrial applications show that composition varies so much between effluents that fixed operating timers are hard to standardize, which argues for adaptive control [4]. A full-scale audit of SBR plants reported pollutant removal above 91 percent and showed that batch configurations can have good energy economics [5].

Several studies support IoT-based monitoring. Low-cost ESP32-based systems using MQTT dashboards have replaced expensive SCADA systems for decentralized SBRs, and an optical turbidity sensor can serve as a proxy for total suspended solids [6]. Low-cost microcontrollers can handle high-frequency logging of pH, dissolved oxygen and temperature, with good agreement against laboratory tests early in operation [7]. Turbidity correlates linearly with suspended solids in domestic wastewater, but it needs periodic recalibration because floc size and colour change [8].

Sensor fouling is the main limitation. Biofilm growth on submerged electrodes caused measurable drift within about one week, and the authors recommended physical cleaning every 7

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to 10 days [9]. Machine learning applied to sensor data has predicted influent BOD in real time and adjusted aeration automatically [10]. Finite state machine models have been used to drive SBR phase transitions from events instead of fixed times [11]. Onboard control logic is also advised so that a Wi-Fi outage does not stop the cycle [12]. Real-time dissolved oxygen control has cut aeration energy per kilogram of BOD removed by about 35 percent [13].

Together, these studies show that low-cost sensing is feasible, that calibration and maintenance are essential, and that continuous data open the way to smarter control. The present work builds this sensing and visualization layer on a lab-scale reactor treating real campus sewage.

III. METHODOLOGY

A. Influent Characterization

Raw wastewater was collected from the campus sewage treatment plant and analyzed using standard APHA methods [15]. The measured values were BOD 125 mg/L, total solids 1193 mg/L, TDS 1060 mg/L, TSS 136 mg/L and pH 7.59. Against the CPCB discharge limits of 30 mg/L for BOD and 100 mg/L for TSS [14], the minimum required removal efficiencies are 76 percent for BOD and 26.5 percent for TSS. The influent pH is within the 6.5 to 8.5 range suitable for biological treatment, so no pH correction is needed.

B. Reactor Design

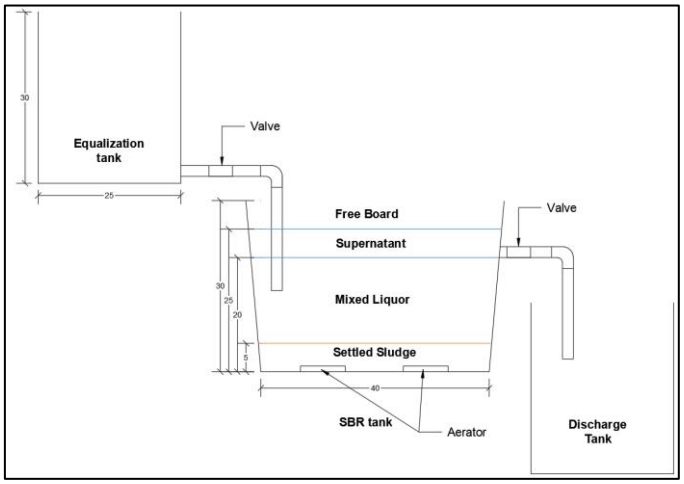


Figure 1: SBR schematic layout

The reactor is built in a 40 L transparent container, of which 30 L is used as the tank volume. The tank measures 40 cm × 25 cm × 30 cm (30 L). A 5 cm freeboard is left empty at the top, which gives a working volume of 25 L (25 cm working depth). The bottom 5 cm (5 L) holds the activated sludge. Each cycle exchanges 5 L, giving an exchange ratio of 0.20, so 15 L of treated water stays in the tank. The outlet is placed 20 cm above the base, so 5 L of supernatant is decanted per cycle. From bottom to top the tank has four zones: settled sludge (0 to 5 cm), mixed liquor (5 to 20 cm), supernatant (20 to 25 cm) and freeboard (25 to 30 cm). Fig. 1 shows the layout, with an equalization tank, the SBR tank and a discharge tank, plus two aerators at the base of the SBR tank.

C. Cycle Design

The cycle is divided into five phases as percentages of a 300 minute cycle (Table I).

TABLE I. SBR CYCLE TIME AND PHASE DISTRIBUTION

Phase	Share of cycle	Duration
Fill	5%	15 min
React	60%	180 min
Settle	20%	60 min
Decant	10%	30 min
Idle	5%	15 min
Total	100%	300 min

D. Fabrication

The reactor is built in a 40 L heavy-duty transparent acrylic/HDPE container, of which 30 L is used as the tank volume. The transparency lets flocculation and sludge settling be observed without opening the reactor. Bulkhead fittings for the influent, effluent and sensor cables were sealed with waterproof silicone. Two ceramic fine-bubble diffusers connected to a dual-outlet air pump supply oxygen to keep dissolved oxygen at or above 2 mg/L. Fine bubbles give more air-water contact area and better mixing. Wastewater transfer uses 12 V DC peristaltic pumps, which keep sludge away from the motor internals, and normally-closed solenoid valves that prevent backflow.

E. Sensing and Electronics

The sensor node uses an Arduino Uno. The analog pH, TDS and turbidity sensors are connected to pins A0, A1 and A2, a DS18B20 digital probe measures temperature, and an HC-SR04 ultrasonic sensor measures the water level. Analog readings are averaged over multiple samples to reduce noise, and the ultrasonic sensor averages five distance readings before calculating level and volume. The Arduino sends pH, TDS, turbidity, temperature and volume as one comma-separated line over serial communication (SoftwareSerial, 9600 baud) to an ESP32. A voltage divider matches the 5 V Arduino signal to the 3.3 V ESP32 logic. Sensors are mounted mid-depth on 3D-printed brackets, away from the diffusers to avoid bubble interference. A 12 V, 5 A power supply with a step-down converter separates the electronics from pump switching noise, and an opto-isolated relay module is provided for switching the 12 V equipment.

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F. Sensor Calibration

The pH sensor was calibrated with pH 4.0 and 7.0 buffers and verified against a laboratory benchtop meter. The TDS sensor used a two-point calibration (0.777 V for 280 ppm and 1.466 V for 476 ppm) taken against a laboratory TDS pen. The turbidity sensor was calibrated with clear water (2.65 V, index 4) and a murky sample (2.36 V, index 100), and compared with a laboratory nephelo-turbidity meter standardized with a 500 NTU solution. The turbidity sensor therefore reports a relative index, not a calibrated NTU value.

IV. RESULTS AND DISCUSSION

A. Sensor Performance

Table II compares the sensor and manual readings for the same wastewater sample.

TABLE II. COMPARISON OF SENSOR AND MANUAL READINGS

Sensor	Sensor Reading	Manual Reading	Accuracy
Ph	7.37	7.54	97.77%
TDS	455 PPM	464 PPM	98.0%
Turbidity	5 NTU	5 NTU	100%
Temperature	30°C	-	-

The pH and TDS sensors agreed with the laboratory instruments to about 98 percent, which is suitable for continuous monitoring. The turbidity match was exact for this sample. Because the sensor reports a relative index, a regression against laboratory turbidity or TSS over a range of samples is needed before it can serve as a TSS proxy. The temperature reading of 30 °C lies within the mesophilic range of 25 to 35 °C favorable for biological activity.

B. Monitoring Dashboard

A web dashboard, SBR-CORE Reactor Monitoring Console, presents the data from the ESP32 (Fig. 2). It has the following parts:

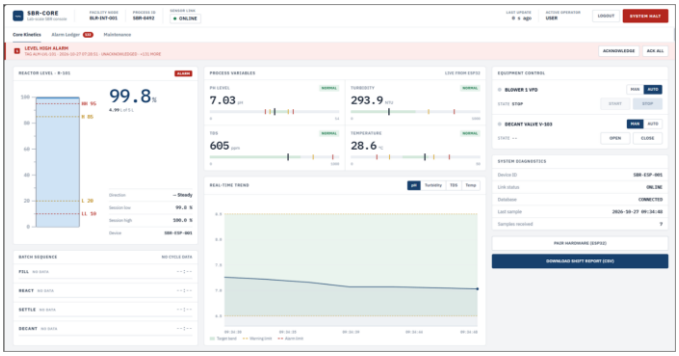


Figure 2: SBR-CORE monitoring dashboard

(i) reactor level as a percentage and volume, calculated from the ultrasonic distance and tank dimensions;
(ii) live pH, turbidity, TDS and temperature with colour-coded warning indicators;
(iii) a trend graph with a selectable parameter;
(iv) a batch sequence display of fill, react, settle and decant;
(v) an equipment control panel for the blower and decant valve;
(vi) an alarm ledger with priority, time and acknowledgement status;
(vii) maintenance records of equipment run hours and service limits; and
(viii) a shift report that can be downloaded in CSV format.

Together these let an operator see the state of the reactor from one screen, instead of reading each sensor on its own or waiting for laboratory results.

C. Discussion and Limitations

The dashboard screenshots presented here were produced in a simulated mode, so the alarm entries, trend graphs, run hours and report values show the functions of the interface and are not measured reactor results. Likewise, the equipment control and phase display do not by themselves show that the blower and valves are operated automatically. Full treatment performance, including measured BOD and TSS removal against the CPCB limits, needs to be verified in extended runs. Literature on sensor fouling [9] also indicates that regular cleaning and recalibration against laboratory tests is needed for long-term reliability

V. CONCLUSION AND FUTURE SCOPE

A 25 L lab-scale SBR was designed from measured campus wastewater characteristics and fitted with pH, TDS, turbidity, temperature and ultrasonic level sensors connected through an Arduino Uno and ESP32 to a monitoring dashboard. The calibrated pH and TDS sensors agreed with laboratory instruments to about 98 percent. The dashboard gives continuous visibility of reactor conditions, alarms, maintenance status and exportable reports. This shows that low-cost IoT monitoring can be added to decentralized SBR systems.

Future work includes: machine-learning models to estimate BOD and COD from the sensor data; automatic blower, valve and pump control from live readings; dissolved oxygen,

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ammonia and nitrate sensors for nutrient removal; SMS and e-mail alerts when CPCB limits are exceeded; automatic probe cleaning and drift detection; predictive maintenance using current and vibration sensors; long-term and pilot-scale testing; and solar power with a mobile application for remote use.

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