Smart Water Treatment System for Landscaping Application

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ABSTRACT

Water scarcity and pollution are major worldwide issues, especially in arid regions like Oman, where inadequate wastewater treatment and ineffective management lead to significant water waste. This paper presents a smart algae-based water treatment system that utilizes algae-derived bio-adsorbent powder for efficient wastewater purification. Dried algae were calcined at high temperatures to produce a fine powder with strong adsorption capacity for removing heavy metals, organic pollutants, and excess nutrients such as nitrogen and phosphorus. The system integrates an ESP32 microcontroller with pH, turbidity, TDS, and temperature sensors to monitor water quality in real time and ensure optimal treatment conditions. Experimental tests using contaminated water samples over a 72-hour period demonstrated significant improvements in water clarity, toxin reduction, and pH balance after treatment, with turbidity falling from 1000 NTU to 85.3 NTU, total dissolved solids dropping from 1372 PPM to 612 PPM, and pH shifting from 6.83 to a near-neutral 7.97. The treated water showed potential for reuse in agriculture, landscaping, and industrial processes, reducing overall water waste. The proposed IoT-enabled algae powder filtration system offers a sustainable, low-cost, and scalable alternative to conventional wastewater treatment methods.

Keywords- Algae bio-adsorbent, IoT, wastewater purification, sustainability, real-time monitoring

INTRODUCTION

With growing water scarcity and pollution, efficient wastewater management has become a global necessity, especially in arid regions like Oman. Traditional water treatment methods are often costly, energy-intensive, and reliant on chemicals that can negatively impact the environment. As water demand escalates due to population growth and industrialization, sustainable and cost-effective alternatives are urgently needed.

This research presents a smart water treatment system that utilizes algae-derived powder as a natural bio-adsorbent to remove heavy metals, organic contaminants, and excess nutrients from wastewater. The system integrates IoT-based monitoring using an ESP32 microcontroller, pH, turbidity, TDS, and temperature sensors for real-time data collection and automated control. The proposed solution aims to provide a low-cost, sustainable, and scalable alternative to conventional wastewater treatment techniques, contributing directly to water conservation efforts in Oman and similar arid environments.

Related Work

The growing demand for sustainable and cost-effective water treatment technologies has led to extensive research into alternative purification methods. This section reviews four key studies that provide relevant insights and context for the development of the proposed algae-based smart water treatment system.

Asiwal et al. (2016) investigated wastewater treatment through effluent treatment plants (ETPs) with a focus on industrial applications, particularly within the steel sector. The study addressed water shortages caused by rapid industrialization and urbanization, emphasizing the use of physical, chemical, and biological treatment techniques to enhance recycling and reuse of industrial water and sludge. The work highlights the importance of advanced ETP design in sustainable industrial water management.

Batra et al. (2017) developed a portable antimicrobial water filter designed to be both affordable and user-friendly. Their prototype used layers of sand, cloth, activated charcoal, and cotton to remove turbidity, odor, and microbial content from contaminated lake water. Experimental analysis confirmed that the sand layer played a crucial role in antimicrobial activity and overall filtration performance, demonstrating the potential of natural materials in enhancing water quality.

Prabhu et al. (2020) proposed a smart wastewater treatment plant using IoT, emphasizing affordable recycling solutions for domestic and industrial applications. Their system integrates pH, turbidity, and ultrasonic sensors connected to an Arduino Nano and ESP8266 microcontroller. Real-time data were visualized using the Blynk application, while a solenoid valve controlled water flow between tanks. The study demonstrated that up to 90% of kitchen wastewater could be recycled efficiently for reuse in cleaning, gardening, and car washing.

Taloba (2022) introduced an artificial neural network (ANN)-based optimization model for water treatment and desalination. The system combines coagulation, flocculation, sedimentation, filtration, and reverse osmosis (RO) processes, supported by ANN analysis of parameters such as pH, turbidity, conductivity, and temperature. By optimizing operational conditions, the model reduces energy consumption and enhances desalination efficiency, demonstrating the potential of AI in improving water purification performance.

Overall, these studies demonstrate diverse approaches to improving water treatment-from natural filtration materials and IoT-based monitoring to AI-driven process optimization. However, few have explored the combined use of algae-derived powder with real-time IoT monitoring, as proposed in this work, to achieve sustainable and efficient wastewater purification.

METHODOLOGY

System Design

The proposed smart algae-based water treatment system integrates environmental sensing technology with IoT-based monitoring to provide an intelligent and sustainable approach to wastewater purification. The system combines multiple water quality sensors, an ESP32 microcontroller, and a cloud-based data platform to monitor and evaluate water conditions before and after treatment using algae-derived powder as a bio-adsorbent material.

At the core of the system is the ESP32 microcontroller, selected for its dual-core processing power, built-in Wi-Fi capability, and efficient energy management. It serves as the central controller, interfacing with all sensors, processing collected data, and transmitting information to the cloud for analysis and visualization. The sensing subsystem includes four primary components:

1. A pH sensor to measure the acidity or alkalinity of the water.

2. A turbidity sensor to assess water clarity by detecting suspended particles.

3. A TDS sensor to determine the concentration of total dissolved solids including salts and minerals and

4. A temperature sensor to monitor thermal conditions that affect the adsorption efficiency of the algae powder.

All sensors are connected to the ESP32 via designated GPIO pins: the pH sensor through GPIO35, the turbidity sensor through GPIO34, the TDS sensor through GPIO33, and the digital temperature sensor through GPIO4. Real-time data from these sensors are displayed on a 20×4 I2C LCD. The ESP32 also connects to ThingSpeak, a cloud-based IoT analytics platform, for remote data storage, visualization, and trend analysis. The system continuously collects readings from untreated water to establish baseline quality metrics. The water is then passed through a treatment unit containing calcined algae powder, which acts as a bio-adsorbent to remove heavy metals, organic pollutants, and excess nutrients. After treatment, the same sensors remeasure the pH, turbidity, TDS, and temperature values to evaluate purification effectiveness. Figure 1 presents the block diagram of the overall system architecture.

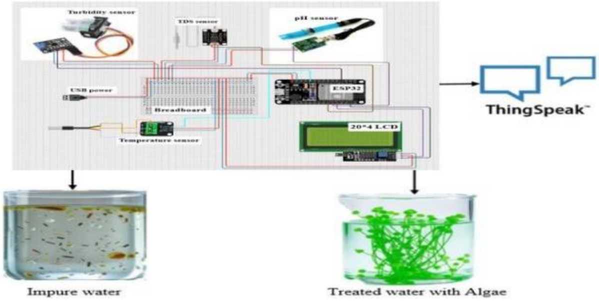

Figure 1. Block diagram of the smart algae-based water treatment system

Algal Biomass Processing

Algal biomass processing for filtration powder production followed a four-step procedure. Fresh algae biomass was first dried in a laboratory oven at 120°C for three days to remove moisture and stabilize the sample. The dried algae were then crushed and ground into smaller particles, and visible impurities were manually removed to obtain a clean material. The processed algae were placed into ceramic crucibles and heated in a muffle furnace at 300°C for two hours to carbonize the biomass and create a porous structure. This process yielded a black algae powder with enhanced surface area and adsorption capacity, suitable for eco-friendly water filtration applications (see Figure 2).

Figure 2. Algal biomass processing for filtration powder production

RESULTS AND DISCUSSION

System Performance

Systematic testing was carried out on the algae-based purification prototype to assess its functional performance. Prior to integrated testing, the sensing units, control module, and display interface were each independently verified for accuracy and reliability. A 20×4 I2C LCD display reliably presented real-time readings from all sensors simultaneously, confirming accurate monitoring of temperature, turbidity, TDS, and pH without delay or data loss.

After individual component validation, all four sensors were tested in combination to assess integrated system performance. In all cases, the sensors provided consistent and precise measurements, confirming their reliability in real-time water quality monitoring. Figure 3 illustrates the system during testing with purified water and wastewater samples.

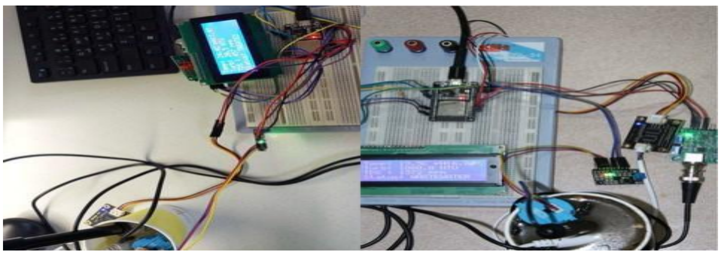

Figure 3. Testing purified water and wastewater samples

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Water Quality Results

A key innovation of this system-the algae-based water purification process, was evaluated over a 72-hour period to determine its effectiveness in reducing water pollutants. Table 1 summarizes the sensor readings recorded for pure water, polluted water, and treated water across all measured parameters.

Table 1. Summary of water quality sensor readings before and after algae-based treatment

Parameter	Pure Water	Polluted Water	After Treatment
Temperature (°C)	22.1	24.4	21.8
Turbidity (NTU)	20.5	1000	85.3
TDS (PPM)	457	1372	612
pH	7.12	6.83	7.97

The temperature sensor consistently provided stable readings between 19.5°C and 24.4°C, accurately monitoring water temperature and ensuring the environment remained suitable for algae activity. The turbidity sensor effectively distinguished between pure and polluted water, recording 20.5 NTU for clean water and 1000 NTU for turbid water. After treatment, turbidity was reduced significantly, demonstrating the adsorption efficiency of the calcined algae powder. The TDS sensor successfully measured dissolved solids, showing approximately 457 PPM for pure water and 1372 PPM for polluted water, with post-treatment values indicating meaningful reduction in dissolved contaminants. The pH sensor recorded values ranging between 6.83 and 7.97, with a slight increase in pH observed after the filtration process.

Figure 4 presents the IoT dashboard captured from the ThingSpeak platform, showing real-time sensor data trends during a representative monitoring session.

Figure 4. ThingSpeak IoT dashboard showing real-time sensor data

Overall, the integrated system proved stable, reliable, and effective over extended operational periods. The combination of sensors, microcontroller, and cloud platform worked in harmony to monitor water quality and validate the algae-based treatment process. Automation reduced reliance on manual observation while ensuring accurate water quality assessment. These outcomes support the system's potential scalability for application in sustainable water treatment solutions.

CONCLUSION

This paper presented a smart algae-based water treatment system that integrates bioremediation with real-time IoT monitoring, demonstrating the feasibility of a low-cost, sustainable approach to wastewater purification. Chlorella algae were thermally treated and processed into bio-adsorbent powder, which was applied as the primary filtration material. Experimental results showed a noticeable reduction in pollutants and significant improvement in water clarity, attributed to the adsorption capacity and surface functional groups of the calcined algae powder. The ESP32-based sensor network provided continuous, accurate monitoring of pH, turbidity, TDS, and temperature parameters, with data transmitted to the ThingSpeak cloud platform for visualization and trend analysis.

Looking ahead, several enhancements are proposed to further improve system performance and practical applicability. First, the integration of AI and predictive analytics could enable real-time optimization of algae activity and pollutant removal, providing automated control of the treatment process based on sensor inputs. Second, field-scale evaluation and sustainability assessments in diverse real-world environments would validate long-term reliability, adaptability, and ecological impact. Collectively, these improvements would transform the system into a fully autonomous, data-driven, and environmentally sustainable solution for water purification, capable of supporting broader applications in municipal and industrial wastewater management.

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