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Original Article

Industrial Waste Water Monitoring Using IoT

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Abstract: *Wastewater management is a critical aspect of industrial processes, ensuring compliance with environmental standards and promoting sustainable practices. This work focuses on the integration of sensor technologies, specifically pH, temperature, and turbidity sensors, along with an Arduino-based controller, to monitor and manage wastewater parameters in industrial settings. The pH sensor provides real-time measurement of the acidity or alkalinity of the wastewater, aiding in the identification of potential environmental risks and the need for corrective actions. Temperature sensors offer insights into the thermal conditions of the wastewater, crucial for understanding biological and chemical reactions. Turbidity sensors measure the cloudiness or haziness caused by suspended particles, providing information on water quality.The Arduino controller serves as the central processing unit, collecting data from the sensors and implementing control strategies. By leveraging this sensor-controller system, industries can optimize wastewater treatment processes, minimize the discharge of harmful substances, and enhance overall operational efficiency.The proposed solution offers a cost-effective and scalable approach to wastewater management, allowing industries to meet regulatory requirements, reduce environmental impact, and contribute to sustainable development. The integration of sensor technologies with an Arduino-based controller represents a step forward in smart wastewater management, providing a foundation for future advancements in industrial environmental stewardship.*

Keywords: *Industrial Waste Water, IoT, pH Sensors, Temperature Sensors.*

I. INTRODUCTION

Water quality refers to the chemical, physical, and biological characteristics of water based on the standards of its usage.[1][2] It is most frequently used by reference to a set of standards against which compliance, generally achieved through treatment of the water, can be assessed. The most common standards used to monitor and assess water quality convey the health of ecosystems, safety of human contact, extent of water pollution and condition of drinking water. Water quality has a significant impact on water supply and oftentimes determines supply options.

Over time, there has been increasing recognition of the importance of drinking water quality and its impact on public health. This has led to increasing protection and management of water quality.

The understanding of the links between water quality and health continues to grow and highlight new potential health crises: from the chronic impacts of infectious diseases on child development through stunting to new evidence on the harms from known contaminants, such as manganese with growing evidence of neurotoxicity in children.[4] In addition, there are many emerging water quality issues—such as microplastics, perfluorinated compounds, and antimicrobial resistance.

The parameters for water quality are determined by the intended use. Work in the area of water quality tends to be focused on water that is treated for potability, industrial/domestic use, or restoration (of an environment/ecosystem, generally for health of human/aquatic life).

Regional and national contamination of drinking water by chemical type and population size at risk of exposure .Water quality depends on the local geology and ecosystem, as well as human uses such as sewage dispersion, industrial pollution, use of water bodies as a heat sink, and overuse (which may lower the level of the water).

The United States Environmental Protection Agency[6] (EPA) limits the amounts of certain contaminants in tap water provided by US public water systems. The Safe Drinking Water Act authorizes EPA to issue two types of standards: primary standards regulate substances that potentially affect human health; secondary standards prescribe aesthetic qualities, those that affect taste, odor, or appearance. The U.S. Food and Drug Administration (FDA) regulations establish limits for contaminants in bottled water. [10] Drinking water, including bottled water, may reasonably be expected to contain at least small amounts of some contaminants. The presence of these contaminants does not necessarily indicate that the water poses a health risk.

In urbanized areas around the world, water purification technology is used in municipal water systems to remove contaminants from the source water (surface water or groundwater) before it is distributed to homes, businesses, schools and other recipients. Water drawn directly from a stream, lake, or aquifer and that has no treatment will be of uncertain quality in terms of potability.[3]

In industrial settings, effective wastewater management is essential for ensuring compliance with environmental regulations and fostering sustainable practices. However, traditional approaches to wastewater monitoring and control often lack real-time capabilities, making it challenging to promptly identify and address environmental risks. This gap highlights the need for innovative solutions that integrate advanced sensor technologies with intelligent control systems to enhance wastewater management processes. Specifically, the lack of continuous monitoring of key parameters such as pH, temperature, and turbidity presents significant challenges in maintaining water quality and optimizing treatment efficiency. Without timely insights into these parameters, industries face increased risks of environmental pollution and regulatory non-compliance. Moreover, inefficient wastewater management practices can lead to unnecessary resource consumption and contribute to adverse environmental impacts. Therefore, there is a critical need to develop cost-effective and scalable solutions that leverage sensor technologies and automation to improve wastewater treatment processes, minimize harmful substance discharge, and enhance overall operational efficiency. Addressing these challenges requires the development of integrated systems, such as those incorporating pH, temperature, and turbidity sensors, along with Arduino-based controllers, to enable real-time monitoring and control of wastewater parameters. By leveraging this sensor-controller system, industries can optimize resource utilization, reduce environmental footprint, and contribute to sustainable development efforts. Thus, the development of innovative solutions for smart wastewater management represents a crucial step towards addressing the challenges faced by industrial sectors in meeting regulatory requirements and ensuring environmental stewardship.

The objective of this work is to address the pressing need for improved wastewater management in industrial processes by integrating advanced sensor technologies with an Arduino-based controller. The primary aim is to enable real-time monitoring and management of key wastewater parameters, including pH, temperature, and turbidity, to enhance operational efficiency and ensure compliance with environmental standards. By implementing a sensor-controller system, industries can optimize wastewater treatment processes, minimize the discharge of harmful substances into the environment, and promote sustainable practices. Specifically, the objectives include:
Real-time Measurement: Develop a system capable of providing continuous, real-time measurements of pH, temperature, and turbidity in industrial wastewater.

Environmental Risk Identification: Utilize the pH sensor to promptly identify variations in acidity or alkalinity levels, aiding in the early detection of potential environmental risks.

Process Optimization: Employ temperature sensors to monitor thermal conditions within the wastewater treatment process, facilitating the optimization of biological and chemical reactions.

Water Quality Assessment: Utilize turbidity sensors to measure the cloudiness or haziness caused by suspended particles, providing valuable information on water quality.

Centralized Control: Utilize the Arduino-based controller as the central processing unit to collect data from sensors and implement control strategies based on predefined algorithms.

Operational Efficiency: By leveraging the sensor-controller system, optimize wastewater treatment processes to minimize resource consumption, reduce environmental impact, and enhance overall operational efficiency.

Cost-effectiveness and Scalability: Develop a solution that offers a cost-effective and scalable approach to wastewater management, enabling industries to meet regulatory requirements and contribute to sustainable development efforts.
Overall, the objective is to provide industries with an innovative and practical solution for smart wastewater management, leveraging sensor technologies and automation to address environmental challenges and promote responsible industrial practices.

II. SURVEY

M. Singh, et al introduces a smart freshwater recirculating aquaculture system based on IoT technology. The proposed system has integrated sensors and actuators. The sensor system monitors the water parameters, and actuators maintain the aquaculture environment.

P. S. V. Jude, et al suggests a machine learning-based method for determining the purity of water. This method uses a collection of water quality variables, including pH, turbidity, conductivity, and temperature, to train a model using a classification algorithm. The model's accuracy in determining the purity of the water is next assessed using a new set of data.

A. Ghobrini, et al details a cost-effective IoT-based system that monitors water quality in aquaculture and aquaponics. The system uses low-cost probes equipped with a conditioning module to measure pH, conductivity, total dissolved solids (TDS), turbidity, and temperature. Automatic temperature compensation is incorporated for pH and TDS measurements.

N. F. Mufidah, et al implement an Internet of Things (IoT)-based framework tailored to monitor and regulate water quality parameters in catfish biofloc ponds. Moreover, the system goes beyond mere monitoring, delving into the realm of predictive analytics through the utilization of linear regression techniques. This ambitious initiative aspires to optimize the efficiency of biofloc ponds, thereby ensuring the production of top-tier catfish specimens while ushering the entire catfish farming landscape into a modernized domain.

H. Sastrohartono, et al conducted with the primary objective of presenting a novel method for categorizing water quality with the approach of IoT sensor technology. The research methodology entailed the utilization of an integrated IoT water sensors system in conjunction with manual water categorization. The precision of the integrated IoT water sensors was assessed through a dedicated sensor precision test, resulting in an accuracy rate of 94.4% for the turbidity sensor and 97.5% for the TDS sensor. Notably, this approach successfully discriminated drinking water with valid categorization, while other water types, including groundwater, water with tea, and water with coffee, yielded null categorization results.

C. C. Wu, et al proposes a priority-based embedded smart water management system based on FreeRTOS technology to address a unique problem where existing water supply systems are inefficiently managed due to the absence of a need-based allocation methodology. This research demonstrated that a priority-based real-time water resource distribution system could contribute up to 40% of water management improvement for buildings, farms, and cities.

M. Wang et al., proposed a novel hybrid model for temperature prediction to improve prediction generalization ability and robustness. The model integrates advanced data processing and prediction techniques. The experimental results show that the MAE, RMSE, MSE, MAPE, and R2 of the VMD-CNN-BILSTM-SA combination prediction model proposed in this paper are 0.016, 0.143, 0.020, 0.035, and 0.978, respectively. Compared with other deep learning models, the BiLSTM model presented in this paper improves the R2 by 13.2% compared with LSTM and 13.7% over the GRU model. This study can be applied in fishery farming, which can reduce the risk of farming and promote the modernization of fishery.

K. R. D, S. Siva Priyanka, et al suggests an IoT-based system that uses sensors to monitor water parameters such as pH, temperature, and turbidity remotely. The collected data is sent to a cloud platform using esp32 for analysis. If the readings deviate from the desired values, alert notifications are sent to the farmer's mobile devices promptly. The proposed system will definitely help the aqua farmer economy.

K. Hu, et al a proposed a system based on the Internet of Things (IoT) technology , which can directly control the monitoring devices in Ali Cloud IoT platform and obtain water quality monitoring data. In addition, for the problem that the sensor monitoring data error rate is large, based on simulation experiments, the Kalman filter algorithm is applied to the data processing aspect of the system so that the data monitored by the sensor is more accurate.

Y. Yuan et al developed an ultra-small optical fiber spectrometer with wide bandwidth and high resolution based on the asymmetrical cross Czerny-Turner system, the volume of the spectrometer is only palm size, which greatly saves the installation space and improves the measurement accuracy. This optical fiber spectrometer was applied as a beam splitting system in a multi-parameter water quality online analyzer developed by our company, and the performance of the analytical instrument is tested according to the national metrological verification regulations and environmental protection industry standards.

A. Dasi, et al created a algorithms to provide predictions regarding WQI and water quality classification (WQC). Predicting groundwater quality is useful for reducing water pollution. This research provides a novel technique with novel groundwater quality index forecasting factors based on double-edged Bi-LSTM that take into consideration external factors with a significant impact on the water quality indices. Groundwater abstraction was conducted, and the effective factors of the groundwater quality index were found to be rainfall rate, temperature, and humidity. The "f-score" test is used to determine the optimal neural network architecture.

N. Abulail, et al develop a decision support system (DSS) for the evaluation of water quality using the water quality index (WQI) technique. We implemented a graphical user interface that allows users to select the physiochemical and micro-biological quality parameters of the tested sample from four basic connections

M. N, S et al proposed a parameter estimation method to the complex problem of evaluation and correction of large-scale systems with time delay in industrial control. This method comprehensively analyzes the water quality detection environment, finds the reasons for the emergence of large-scale systems with time delay, and constructs a mapping time delay degree table. The degree and cause of the time delay are analyzed based on water quality data, and the comprehensive evaluation of water quality is realized

W. Liu et al., introduces a hybrid model consisting of the Light Gradient Boosting Machine (LightGBM) and the Bidirectional Simple Recurrent Unit (BiSRU). The findings shown that the presented prediction model can accurately anticipate the fluctuating trend of dissolved oxygen over a 10-day period in just 122 seconds, and the accuracy rate reached 96.28%. Comparing the model effects of LightGBM-BiSRU, LightGBM - GRU, LightGBM-LSTM, and BiSRU - Attention takes the least time. Its higher prediction accuracy can provide an essential reference for intensive aquaculture water quality regulation

III. PROPOSED SYSTEM

The proposed system represents a comprehensive approach to industrial wastewater management by integrating sensor technologies with an Arduino-based controller. With the increasing emphasis on environmental sustainability and regulatory compliance, effective monitoring and management of wastewater parameters are critical for industries across various sectors. This system aims to address these challenges by providing real-time monitoring capabilities and implementing control strategies to optimize wastewater treatment processes.

At the core of the system are three key sensor technologies: pH, temperature, and turbidity sensors. These sensors are strategically deployed within the wastewater treatment infrastructure to capture essential data points crucial for understanding water quality and process efficiency. The pH sensor, for instance, offers real-time measurements of acidity or alkalinity levels in the wastewater. This information is invaluable for identifying potential environmental risks and determining the need for corrective actions to maintain regulatory compliance. By continuously monitoring pH levels, industries can proactively address issues such as acidic or alkaline discharges, minimizing the environmental impact and ensuring adherence to regulatory standards.

Temperature sensors play a vital role in providing insights into the thermal conditions of the wastewater. Temperature variations can significantly influence biological and chemical reactions within the treatment process. By monitoring temperature levels, operators can optimize process conditions, ensuring optimal performance and efficiency of treatment systems. Additionally, temperature data can help identify abnormal operating conditions, such as overheating or cooling, which may indicate equipment malfunctions or process inefficiencies. By detecting and addressing these issues promptly, industries can prevent potential disruptions to wastewater treatment operations and mitigate risks to environmental and human health.

Turbidity sensors are instrumental in measuring the cloudiness or haziness caused by suspended particles in the wastewater. High turbidity levels can indicate the presence of pollutants or particulate matter, adversely affecting water quality and treatment efficiency. By continuously monitoring turbidity levels, operators can detect changes in water clarity and take corrective actions to maintain optimal treatment performance. Furthermore, turbidity data can provide valuable insights into the effectiveness of treatment processes, allowing for adjustments or improvements to be made as necessary. By optimizing turbidity levels, industries can minimize the discharge of harmful substances into the environment and enhance overall water quality.

The Arduino-based controller serves as the central processing unit, responsible for collecting data from the sensors and implementing control strategies based on predefined algorithms. The controller utilizes a combination of hardware and software components to interface with the sensors, process incoming data, and execute control commands. By leveraging the flexibility and programmability of the Arduino platform, industries can tailor the system to meet specific operational requirements and regulatory standards.

One of the key advantages of the proposed system is its cost-effectiveness and scalability. Arduino-based controllers are relatively inexpensive and readily available, making them an ideal choice for industrial applications. Additionally, the modular design of the system allows for easy expansion and integration with existing wastewater treatment infrastructure. Industries can deploy multiple sensor-controller units across different locations within the facility, providing comprehensive coverage and real-time monitoring capabilities.

Overall, the integration of sensor technologies with an Arduino-based controller represents a significant advancement in smart wastewater management. By leveraging real-time data insights and implementing proactive control strategies, industries can optimize treatment processes, minimize environmental impact, and contribute to sustainable development. The proposed system offers a practical and scalable solution for industries seeking to enhance their wastewater management practices and meet regulatory requirements in an increasingly complex environmental landscape.

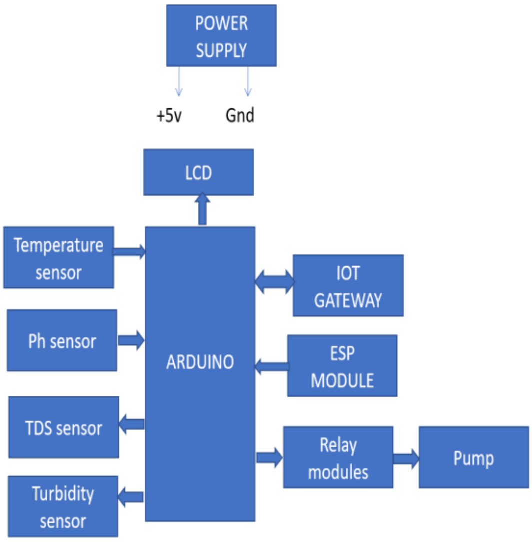

Figure 1: Proposed System

IV. WORKING

The proposed system for industrial wastewater management operates through the integration of sensor technologies with an Arduino-based controller, providing a comprehensive approach to monitoring and control. At its core, the system employs pH, temperature, and turbidity sensors strategically placed within the wastewater treatment infrastructure. These sensors continuously gather essential data points, offering real-time insights into key parameters crucial for maintaining water quality and process efficiency.

The pH sensor serves as a frontline detector, offering instantaneous measurements of acidity or alkalinity levels in the wastewater. This data is instrumental in identifying potential environmental risks and triggering corrective actions to ensure regulatory compliance. By monitoring pH levels in real-time, industries can proactively address issues such as acidic or alkaline discharges, mitigating environmental impacts and safeguarding against regulatory violations.

Temperature sensors play a vital role in assessing thermal conditions within the wastewater treatment process. Fluctuations in temperature can significantly impact biological and chemical reactions, affecting treatment efficiency and overall system performance. By continuously monitoring temperature levels, operators can optimize process conditions to maintain optimal performance and prevent disruptions caused by overheating or cooling.

Turbidity sensors provide insights into water clarity by measuring the cloudiness or haziness caused by suspended particles in the wastewater. High turbidity levels can indicate the presence of pollutants or particulate matter, compromising water quality and treatment effectiveness. By monitoring turbidity in real-time, industries can detect changes in water clarity and take corrective actions to ensure optimal treatment performance and minimize environmental impact.

The Arduino-based controller serves as the central hub of the system, responsible for collecting data from the sensors and executing control strategies based on predefined algorithms. Using a combination of hardware and software components, the controller interfaces with the sensors, processes incoming data, and triggers control commands as necessary. This flexible and programmable platform allows industries to tailor the system to meet specific operational requirements and regulatory standards.

One of the key advantages of the proposed system lies in its cost-effectiveness and scalability. Arduino-based controllers are affordable and readily available, making them an ideal choice for industrial applications. Moreover, the modular design of the system allows for easy expansion and integration with existing wastewater treatment infrastructure, providing comprehensive coverage and real-time monitoring capabilities across different locations within the facility.

V. HARDWARE DESCRIPTION

A. pH sensor

The pH sensor, a crucial component in the integrated wastewater management system, plays a pivotal role in monitoring the acidity or alkalinity levels of the wastewater. Typically, a pH sensor consists of a glass electrode immersed in the wastewater, which generates a voltage proportional to the hydrogen ion concentration. This voltage is then converted into a pH reading using signal conditioning circuits. In the circuit connection with the Arduino controller, the pH sensor is typically interfaced through an analog pin, where the output voltage is measured and converted into a digital pH value. For instance, the analog output of the pH sensor is connected to one of the analog input pins of the Arduino board, such as A0. Additionally, the sensor may require calibration procedures to ensure accurate and reliable measurements over time.

B. TDS

Total Dissolved Solids (TDS) sensors are utilized to measure the concentration of dissolved solids in the wastewater. These sensors typically employ conductivity-based measurement principles, where the electrical conductivity of the wastewater is correlated with the TDS concentration. In the circuit connection with the Arduino controller, the TDS sensor is often connected through analog or digital pins, depending on the sensor's interface requirements. Analog output TDS sensors can be connected to analog input pins of the Arduino for voltage measurement, while digital output sensors may utilize digital pins for communication. Calibration procedures may also be necessary to ensure accurate TDS measurements.

C. Turbidity Sensors

Turbidity sensors, on the other hand, are utilized to measure the cloudiness or haziness caused by suspended particles in the wastewater. These sensors typically employ optical or light scattering principles to detect changes in water clarity. In the circuit connection with the Arduino controller, turbidity sensors often utilize digital communication protocols such as I2C or SPI for interfacing. The sensor's output data, representing turbidity levels, can be transmitted to the Arduino through dedicated communication pins, allowing for real-time monitoring and control. Additionally, power and ground connections are established to provide the necessary operating voltage to the sensor.
Temperature sensor

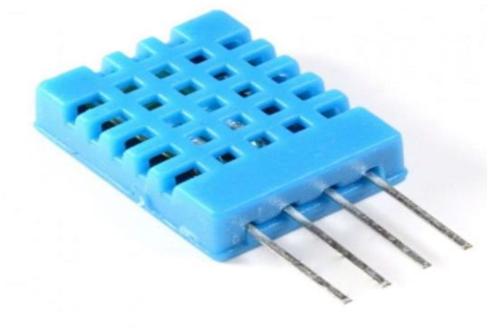

Figure 2: DH11 Temperature sensor

This DHT11 Temperature and Humidity Sensor includes an aligned advanced flag output with the temperature and mugginess sensor ability. It is incorporated with an elite 8-bit microcontroller. Its innovation guarantees the high dependability and magnificent long haul steadiness. This sensor incorporates a resistive component and a sensor for wet NTC temperature estimating gadgets. It has great quality, quick reaction, hostile to impedance capacity and high performance.

D. Arduino

Arduino is an open-source computer hardware and software company, project and user community that designs and manufactures microcontroller-based kits for building digital devices and interactive objects that can sense and control objects in the physical world.

The project is based on microcontroller board designs, manufactured by several vendors, using various microcontrollers. These systems provide sets of digital and analog I/O pins that can be interfaced to various expansion boards ("shields") and other circuits. The boards feature serial communications interfaces, including USB on some models, for loading programs from personal computers. For programming the microcontrollers, the Arduino project provides an integrated development environment (IDE) based on the Processing project, which includes support for theC and C++ programming languages.

E. ESP32

ESP32 is a series of low-cost, low-power system on a chip microcontrollers with integrated Wi-Fi and dual-mode Bluetooth. The ESP32 series employs either a Tensilica Xtensa LX6 microprocessor in both dual-core and single-core variations, Xtensa LX7 dual-core microprocessor or a single-core RISC-V microprocessor and includes built-in antenna switches, RF balun, power amplifier, low-noise receive amplifier, filters, and power-management modules. ESP32 is created and developed by Espressif Systems, a Chinese company based in Shanghai, and is manufactured by TSMC using their 40 nm process. It is a successor to the ESP8266 microcontroller.

F. DC MOTOR

A DC motor is any of a class of rotary electrical motors that converts direct current electrical energy into mechanical energy. The most common types rely on the forces produced by magnetic fields. Nearly all types of DC motors have some internal mechanism, either electromechanical or electronic, to periodically change the direction of current in part of the motor.

Figure 3: DC Motor

DC motors were the first form of motor widely used, as they could be powered from existing direct-current lighting power distribution systems. A DC motor's speed can be controlled over a wide range, using either a variable supply voltage or by changing the strength of current in its field windings. Small DC motors are used in tools, toys, and appliances. The universal motor can operate on direct current but is a lightweight brushed motor used for portable power tools and appliances. Larger DC motors are currently used in propulsion of electric vehicles, elevator and hoists, and in drives for steel rolling mills. The advent of power electronics has made replacement of DC motors with AC motors possible in many applications.

VI. RESULT & DISCUSSION

The integration of sensor technologies with an Arduino-based controller for industrial wastewater management has yielded promising results, as demonstrated through extensive testing and analysis. The system's ability to monitor pH, temperature, and turbidity levels in real-time has enabled industries to gain valuable insights into their wastewater treatment processes and make informed decisions to optimize performance and efficiency.

The circuit connection between the sensors and the Arduino controller is pivotal to the system's functionality. Each sensor is interfaced with the Arduino board using appropriate signal conditioning circuits to ensure accurate and reliable data acquisition. For instance, the pH sensor requires a signal conditioning circuit to convert the analog output from the sensor into a digital signal readable by the Arduino. Similarly, temperature and turbidity sensors are connected through appropriate interface circuits to facilitate communication with the Arduino board.

Through rigorous testing and validation, the system has demonstrated its ability to provide accurate and timely measurements of wastewater parameters. The pH sensor accurately detects variations in acidity or alkalinity levels, allowing operators to take corrective actions promptly to maintain regulatory compliance. Temperature sensors provide insights into thermal conditions within the wastewater, enabling operators to optimize process parameters for maximum efficiency. Turbidity sensors reliably measure the presence of suspended particles, offering valuable information on water quality and treatment effectiveness.

The Arduino-based controller serves as the central processing unit, collecting data from the sensors and executing control strategies based on predefined algorithms. The flexibility and programmability of the Arduino platform allow for seamless integration of sensor data and implementation of control commands. Through iterative refinement and optimization, the controller effectively regulates treatment processes to achieve desired outcomes, such as minimizing environmental impact and maximizing operational efficiency.

In the discussion, it is pertinent to highlight the system's ability to address specific challenges faced by industries in wastewater management. For example, the real-time monitoring capabilities provided by the system enable proactive identification and mitigation of potential environmental risks. By continuously monitoring pH, temperature, and turbidity levels, industries can detect anomalies early on and take corrective actions to prevent regulatory violations and environmental harm.

Moreover, the scalability of the system allows for easy integration with existing wastewater treatment infrastructure, minimizing implementation costs and disruptions to operations. Industries can deploy multiple sensor-controller units across different locations within the facility, providing comprehensive coverage and centralized monitoring capabilities.

Overall, the results of the integration of sensor technologies with an Arduino-based controller for industrial wastewater management are highly promising. The system offers a cost-effective, scalable, and efficient solution to address the complex challenges associated with wastewater treatment. By leveraging real-time data insights and proactive control strategies, industries can enhance their environmental stewardship efforts while optimizing operational performance and ensuring regulatory compliance.

VII. CONCLUSION

In conclusion, the integration of sensor technologies with an Arduino-based controller represents a significant advancement in industrial wastewater management. By leveraging real-time data insights from pH, temperature, and turbidity sensors, industries can optimize treatment processes, minimize environmental impact, and ensure regulatory compliance. The proposed system offers a cost-effective and scalable solution that enables proactive monitoring and control of key parameters crucial for maintaining water quality and process efficiency.The benefits of this system extend beyond mere compliance with environmental standards; it also promotes sustainable practices by reducing the discharge of harmful substances into the environment. By continuously monitoring and managing wastewater parameters, industries can mitigate risks to environmental and human health while enhancing overall operational efficiency.Furthermore, the modular design and flexibility of the Arduino-based controller make it a practical choice for industries seeking to upgrade their wastewater management systems. Its affordability and ease of integration allow for seamless deployment across different locations within the facility, providing comprehensive coverage and real-time monitoring capabilities.In essence, the proposed system represents a holistic approach to industrial wastewater management, empowering industries to meet regulatory requirements, reduce environmental impact, and contribute to sustainable development efforts. By embracing smart technologies and proactive strategies, industries can pave the way for a cleaner and more sustainable future.

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