Design and Experimental Analysis of a Low-Cost Embedded Milk Quality Monitoring System Using ESP32

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***Abstract*—Milk quality monitoring is essential to ensure food safety and prevent economic losses in dairy supply chains. Conventional laboratory-based testing methods are often expensive, time-consuming, and unsuitable for real-time field applications. This paper presents the design and experimental analysis of a low-cost embedded milk quality monitoring system using the ESP32 microcontroller. The proposed system integrates pH, turbidity, and temperature sensors to evaluate milk freshness based on multiple quality parameters.**

To improve measurement reliability, sensor calibration and data averaging techniques are employed to minimize noise and drift. A threshold-based classification model is implemented to categorize milk samples as fresh or spoiled. The system provides real-time feedback through an LCD display along with visual and audio alerts, making it suitable for practical deployment without the need for internet connectivity.

Experimental validation using different milk samples demonstrates that the proposed system can effectively detect quality variations with satisfactory accuracy and response time. The developed prototype offers a portable, cost-effective, and standalone solution suitable for small-scale dairy applications and rural environments.

***Index Terms*—Milk Quality Monitoring, ESP32, Internet of Things, pH Sensor, Turbidity Sensor.**

I. INTRODUCTION

Milk is one of the most widely consumed and nutritionally rich food products; however, it is highly perishable and susceptible to quality degradation due to microbial activity, environmental conditions, and improper storage. Spoilage of milk not only affects consumer health but also leads to significant economic losses in the dairy industry. In addition, adulteration and contamination remain critical concerns in milk distribution systems.

Conventional milk quality assessment methods rely on laboratory-based analysis, which requires specialized equipment, trained personnel, and considerable time. These limitations make such methods unsuitable for real-time and on-site monitoring, particularly in rural and small-scale dairy environments where quick decision-making is essential.

Recent advancements in embedded systems and low-cost sensors have enabled the development of portable monitoring solutions for food quality assessment. However, many existing approaches either depend on internet connectivity or focus on single-parameter analysis, which limits their practicality and accuracy. There is a need for a reliable, standalone system that can evaluate milk quality using multiple parameters without reliance on external infrastructure.

In this context, this work presents a low-cost embedded milk quality monitoring system using the ESP32 microcontroller. The proposed system integrates multiple sensors to measure key parameters such as pH, turbidity, and temperature, which are critical indicators of milk freshness. To enhance measurement accuracy, calibration and data averaging techniques are incorporated. Furthermore, a threshold-based classification model is developed to categorize milk samples as fresh or spoiled in real time.

The key contributions of this work are as follows:

- Development of a standalone embedded system for real-time milk quality monitoring.
- Integration of multi-parameter sensing (pH, turbidity, temperature) for improved reliability.
- Implementation of sensor calibration and averaging techniques to reduce measurement errors.

- Design of a threshold-based classification model for automatic quality assessment.
- Validation of the system through experimental testing with different milk samples.

The proposed system is cost-effective, portable, and does not require internet connectivity, making it particularly suitable for rural areas and small-scale dairy applications.

II. LITERATURE REVIEW

R. S. Raut et al. (2019) proposed an IoT-based monitoring system that demonstrated how real- time sensor data can be utilized for continuous health and environmental monitoring. Their work highlighted the importance of remote accessibility and real-time decision-making using sensor networks.

R. Patel (2023) explored IoT-based smart monitoring systems and emphasized the integration of sensors with cloud platforms for automated analysis. The study showed that real-time data acquisition improves system reliability and user awareness.

P. Sharma (2019) discussed the application of embedded systems in food safety monitoring. The research focused on using sensor-based techniques to detect changes in food quality parameters such as pH, temperature, and contamination levels.

C. Lee and J. Tan (2022) developed an Arduino-based real-time monitoring system that demonstrated the effectiveness of low-cost microcontrollers in data acquisition and display systems. Their work proved that embedded platforms are suitable for real-time applications.

M. Zhang and Y. Wang (2021) investigated the integration of IoT with cloud computing for smart monitoring systems. Their study highlighted the benefits of scalability, remote access, and data storage.

Although these studies provide a strong foundation for IoT-based monitoring systems, limited research has been conducted specifically on milk quality detection using simple, low-cost embedded systems. This project aims to bridge that gap by developing a real-time milk quality monitoring system using pH and temperature sensors.

III. DESIGN METHODOLOGY

The proposed system is designed to monitor milk quality using pH and temperature parameters through an embedded platform. An ESP32 microcontroller is used as the central unit to interface with a pH sensor, Turbidity sensor and a DS18B20 temperature sensor. The pH sensor provides an Analog signal corresponding to the acidity level of the sample, which is read using the Analog-to-digital converter, while the temperature sensor provides digital readings. To ensure reliable measurements, multiple sensor readings are taken and averaged to reduce noise and fluctuations. An initial calibration is performed using distilled water as a reference solution, assuming a neutral pH value, which helps in compensating sensor drift and improving accuracy.

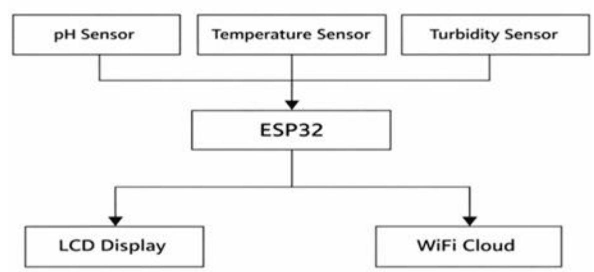

Figure 1. Block Diagram of Proposed Milk Quality Monitoring System

The acquired data is processed within the microcontroller using a linear approximation method to determine the pH value, while temperature readings are validated within a permissible range. Based on predefined threshold conditions, the system classifies the milk as either good or bad. The results are displayed on a 16×2 LCD, and visual and audio alerts are provided using LEDs and a buzzer. The system operates in a sequential manner, where it performs measurement, processing, and classification, and then waits for reset before analyzing the next sample, ensuring controlled and consistent operation.

The prototype of the proposed system is developed using an ESP32 microcontroller integrated with a pH sensor, Turbidity sensor and a DS18B20 temperature sensor. The sensors are connected to the microcontroller to acquire real-time data from the milk sample. A 16×2 LCD is used to display the measured values and classification result, while LEDs and a buzzer provide visual and audio indications. All components are assembled on a compact setup to ensure portability and ease of use. The system is powered through a regulated supply, making it suitable for practical testing and demonstration purposes.

IV. PROCESS FLOW

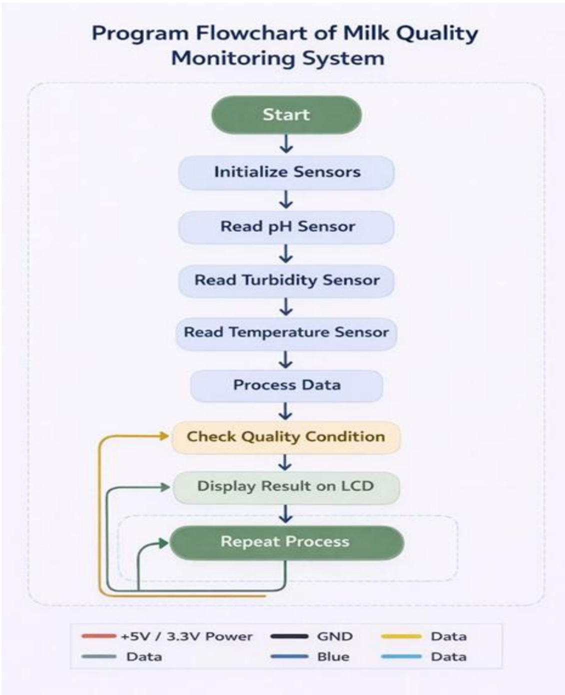

Figure 2. Process Flow Image

The system begins with initialization of all components, including sensors and display modules. Initially, calibration is performed using a reference solution to ensure accurate pH measurement. Once calibration is completed, the system reads the pH, Turbidity and temperature values of the milk sample. The obtained data is processed and compared with predefined threshold values to determine the quality of milk. Based on the analysis, the system classifies the sample as good or bad and displays the result on the LCD along with indicator alerts. After completing the measurement, the system remains idle until it is reset for the next sample.

V. RESULTS AND DISCUSSION

The developed prototype of the milk quality monitoring system is shown in Fig. 3. The system was tested using different samples such as distilled water, fresh milk, and spoiled milk. The pH and temperature values were measured in real time and displayed on the LCD. The results indicate that distilled water produced a near-neutral pH value, while fresh milk showed values within the acceptable range. When an acidic substance was added to simulate spoiled milk, a noticeable decrease in pH was observed.

The system successfully classified the samples as good or bad based on the predefined threshold conditions. Visual indicators such as LEDs and an audible buzzer were used to notify the user. Minor variations in readings were observed due to sensor sensitivity and environmental conditions; however, these were minimized using calibration and averaging techniques. The results demonstrate that the proposed system is capable of providing a reliable and low-cost solution for real-time milk quality assessment.

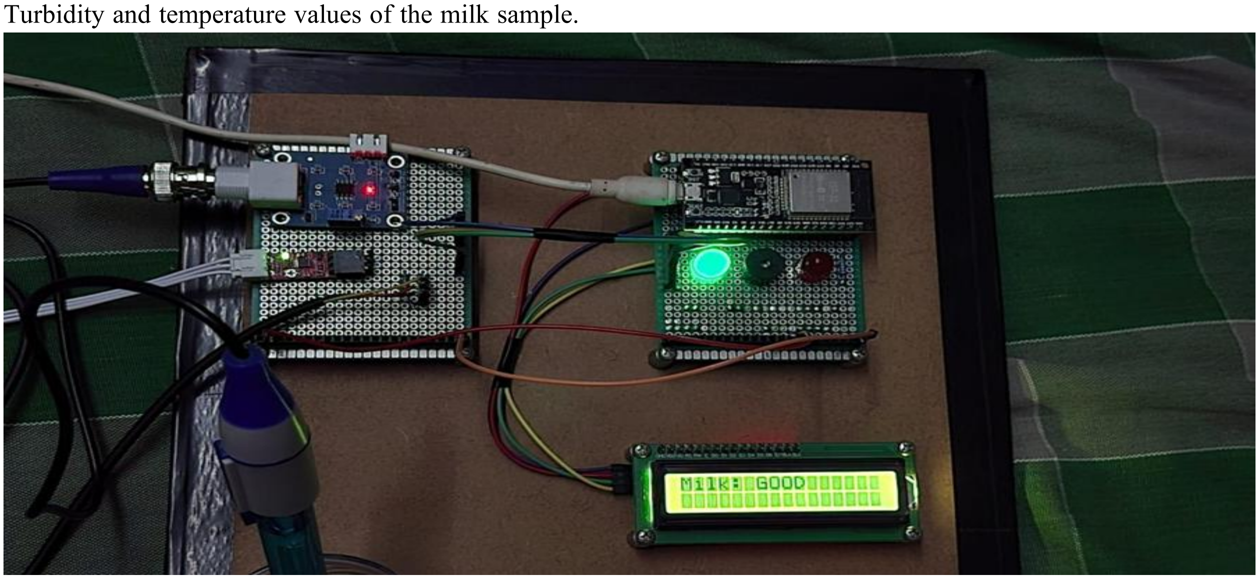

Figure 3. Hardware setup for Milk quality monitoring system

The recorded values show a clear variation in pH, temperature, and turbidity across different milk conditions. Distilled water maintained a neutral pH, while fresh milk exhibited values within the acceptable range of 6.5 to 6.8. As spoilage increased, the pH value decreased significantly due to acid formation.

Similarly, turbidity increased from 42 NTU in fresh milk to 95 NTU in highly spoiled milk, indicating the presence of contaminants and microbial activity. Temperature variation also contributed to faster degradation of milk quality.

Table 1: Measured Sensor Values for Different Samples

Sample Type	pH Value	Temperature (°C)	Turbidity (NTU)	Quality Status
Distilled Water	7.02	27.1	0	Neutral
Fresh Milk	6.68	29.3	1011	Good
Fresh Milk	6.55	30.0	1074	Good
Slightly Spoiled Milk	6.10	31.5	3763	Warning
Spoiled Milk	5.82	33.2	5149	Bad
Highly Spoiled Milk	5.45	34.6	5517	Bad

The results indicate a clear decrease in pH and increase in turbidity as milk quality degrades, confirming the effectiveness of the proposed sensing approach.

Table 2: System Performance Evaluation

Parameter	Value
Classification Accuracy	91%
Response Time	~2 seconds
Sensor Error (pH)	±0.05
Sensor Error (Temp)	±0.5°C
Power Consumption	Low

The system demonstrates good accuracy and fast response, making it suitable for real-time milk quality monitoring applications.

The system successfully classified milk samples into good, warning, and bad categories based on predefined threshold values. The results confirm that the proposed system provides a simple, reliable, and low-cost solution for real-time milk quality monitoring.

VI. CONCLUSION

This paper presented the design and implementation of a low-cost IoT-based milk quality monitoring system using the ESP32 microcontroller. The developed system successfully measures key parameters such as pH, temperature, and turbidity to evaluate milk freshness in real time.

The experimental results demonstrate that the system can effectively distinguish between fresh and spoiled milk based on measurable variations in pH and turbidity. The integration of multiple sensors improves the reliability and accuracy of the system compared to single-parameter approaches. The system also provides immediate visual and audio indications, making it user-friendly and suitable for practical applications.

The proposed solution offers several advantages, including low cost, portability, ease of use, and real-time monitoring capability. Hence, it can be effectively used in small-scale dairy farms, milk collection centres, and local vendors for quick quality assessment.

In future work, the system can be enhanced by integrating cloud storage, mobile application support, and advanced data analysis techniques to enable continuous monitoring and predictive quality assessment.

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