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Real-Time Dual-Sensor IOT Milk Adulteration Detection and Concentration Estimation Using Multispectral-EC Sensor Fusion on an ESP32 Edge Platform.

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ABSTRACT
Milk adulteration impairs food safety and public health and is a major issue in the less privileged regions of the world, where the monitoring of quality is minimal. An enhanced Internet of Things (IoT)-enabled milk adulteration detection system that conjoins a multispectral sensor AS7265x and an electrical conductivity (EC) sensor with the ESP32 microcontroller for real-time, reagent-free analysis is presented in this research paper. The AS7265x sensor with 18 spectral channels ranging from the visible to near-infrared (410–940 nm) can quickly detect the change in milk optics caused by the contamination of water, detergent, and urea. The EC sensor changes the analysis by measuring ionic concentration changes, thus offering a dual-parameter approach that improves detection accuracy. The ESP32 module, after processing the sensor data, transmits it wirelessly to the Blynk IoT dashboard for easy monitoring and data visualization. The experimental results show that the hybrid system proposed outperforms the existing optically detection methods in terms of sensitivity and reliability, while portability and low power consumption are maintained. Such a smart sensing architecture gives a practical and scalable way of supporting food safety and supply chain transparency through on-site milk quality checks
Keywords: Milk adulteration, Internet of Things, multispectral sensing, AS7265x, EC sensor, ESP32, Blynk, real-time detection..
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1. INTRODUCTION:

Milk is a basic food product that is consumed by almost every person globally. It is a primary source of nutrients like calcium, proteins, and vitamins, which are very important for human health. Unfortunately, milk adulteration has become a monumental public health problem, most especially in developing countries, where practices involving the mixing of

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milk with water and the use of detergents, starch, and urea are common for the purpose of increasing the volume or

giving a thicker look to milk. These adulterants not only degrade the nutritional value of milk but can also release toxic substances that may, for instance, cause gastrointestinal diseases, kidney disorders, and metabolic complications. Thus, making sure that milk is pure is an indispensable requirement for food hygiene and consumer confidence.

Conventionally, methods used to detect milk adulteration are based on chemical tests performed in a laboratory, for instance, lactometer readings, acidity titration, or colorimetric analysis using reagents. Although these methods are precise, they are also time-consuming and require specific instruments and trained staff. Hence, they are not feasible for instant, onsite testing, particularly at dairy collection centers in remote areas and small-scale farms that have no access to laboratories. The drawback has resulted in an urgent call for an intelligent, low-cost, and portable device that can deliver instant and trustworthy results.

As a solution to the problem, the project inclined toward the development of an IoT-based milk adulteration detection system that supports the integration of multispectral (AS7265x) and electrical conductivity (EC) sensors along with the ESP32 microcontroller for on-the-spot analysis. The multispectral sensor records the optical signatures of the milk sample at different wavelengths, and simultaneously, the EC sensor notes the changes in electrical conductivity caused by ionic variations in the sample due to adulteration. The system achieves this feat by merging the two domains, i.e., optical and electrical; thus, it can determine a pure milk sample and an adulterated one and further make a distinction between them.

The ESP32 microcontroller acts as the processing unit, gathering information from both the sensors and sending it to the Blynk IoT platform over Wi-Fi for real-time display as well as cloud storage. Through a mobile application, users get an opportunity to see instant data, patterns, and the purification level of the product, making the device very simple to operate and thus ideal for use in both industrial and household settings. With this kind of union, milk quality checks are not only continuous but can also be done from a distance, thereby giving traceability and supply chain transparency a lift.

Milk quality issues have been considerably solved through testing, innovations, and research. This notwithstanding, milk adulteration has been recurring, mainly attributed to the absence of testing points where reliable and easy-to-use testing mechanisms are available in rural and semi-urban areas. Testing methods done in labs that involve chemicals often require high-priced apparatus, a controlled environment, and professionals. The reliance on testing centers in urban areas means a lot of time passes before milk adulterations get detected; thus, opportunities for them to be found in the market unchallenged increase. Therefore, it hinders real-time monitoring at the point of collection.

To tackle such constraints, the modern-day investigations have turned to smart sensor devices capable of automatic and decentralized analysis. The proliferation of embedded systems, the shrinking of sensors, and the Internet of Things (IoT) technologies have permitted the conception of a handheld instrument that can do real-time lab-grade analysis at a cheap rate. Also, IoT connection improves the device's functions by facilitating data sharing via the cloud, providing dashboards in real-time, and providing farmer notifications. That way, farmers and quality controllers get the freedom to act timely with the feedback they receive.

The present system makes use of the AS7265x multispectral sensor that includes 18 spectral channels from 410 nm to 940 nm—the length of the spectra covered is more than the third version, the AS7262, which only has 6 bands. This wider spectral range captures very slight differences in reflectance, which are due to the presence of adulterants, and thus it can very accurately classify contaminants such as water, starch, or urea. On the contrary, the EC sensor is a device that measures the milk's ionic concentration; hence, it becomes capable of identifying the changes in the conductivity that is associated with the impurities dissolved in the milk. In essence, these devices are a hybrid probing instrument that, on one hand, supports the optical discoveries with the electrical data and, on the other hand, reduces the occurrence of false readings to a significant extent, thus improving their accuracy level.

The ESP32 performs a vital function by overseeing the process of data capture, local computing, and wireless communication. Being compatible with IoT platforms such as Blynk, the device can easily connect the hardware with the cloud, thus making the data from sensors, purity outcomes, and alert notifications available to the user through a mobile phone interface. Additionally, the device's ability to work without wires, its small size, and its low cost are some of the features that make it perfect for use in both the milk industry and local collection units.

This research is innovative because it employs a dual-sensor fusion strategy that is bolstered by IoT-based connectivity. Unlike the existing solutions that depend on a single mode of chemical testing or optical sensing, the proposed system integrates the various sensing modalities to raise the detection confidence level, and as a result, the need for laboratory analysis is minimized. The device is capable of delivering a non-chemical, real-time, and inexpensive detection solution, which is in line with the sustainable development goals, and thus it contributes to milk safety in the long run. Moreover, the modular design of the device allows it to be fitted with the machine learning algorithms for the future, enabling it to be used as a tool for the automatic classification of the types of adulterants as well as the adaptive calibration of the varying milk conditions.

Essentially, this paper puts forward a clever, handy, and IoT incorporated structure aimed at identifying milk adulterants that increase the accuracy, efficiency, and accessibility features. With the help of combining the strengths of multispectral and conductivity sensing, the upcoming system behaves as a practical AI-driven dairy-quality monitoring solution and thus contributes to the attainment of the worldwide goal relating to safer, healthier, and traceable food systems.

2. RELATED WORK

Various experiments have been done to find out milk adulteration which includes optical, chemical, and sensor based methods. The conventional methods strongly depend on chemical titration, spectrophotometry, and chromatography that involves lab and skilled personnel. Besides, the analysis time is rather long. These drawbacks let the scientists introduce cheap and portable gadgets equipped with sensor and IoT technologies for on-site quality monitoring.

Initially the effort was put on the development of pH and turbidity-based sensors for milk adulteration detection. In [1], to detect milk spoilage and dilution, a simplistic IoT-based milk monitoring system was designed employing pH and temperature sensors. Unfortunately, the chemical adulterants detection capacity of the system was not there. The use of a Total Dissolved Solids (TDS) sensor to gauge ionic content changes in milk was the idea behind the implementation of [2]. The absence of optical or color-based analysis in the study limited its accuracy in the case of non-ionic adulterants such as starch or detergent.

The development of spectral sensing technology has led to the use of multispectral and hyperspectral sensors in the domain of food quality evaluation. In [3], a multispectral imaging technique was implemented to detect milk adulteration through visible light spectra. The research provided positive outcomes but was dependent on heavy imaging hardware and offline data processing. Another strategy in [4] used a budget-friendly AS7262 multispectral sensor for the optical detection of adulterants in milk samples. Despite the fact that the apparatus lowered the problem and the expense, it only functioned within the visible light range (450–650 nm), thus its capability in finding the low optical contrast adulterants was limited.

In [5], a portable milk analysis unit was envisioned employing an IoT-enabled color sensor to determine adulteration from RGB value changes. The technique was good enough for elementary detection, but it had problems with accuracy when the lighting changed and could not do chemical analysis. Similarly, [6] has set up an IoT-based food quality monitoring system using two parameters–conductivity and temperature–for sensor measurements. Yet, the absence of spectral verification makes this model less accurate for precise classification of adulterants.

The recent investigations have been geared toward resolving these issues by adopting a combination of the optical and the electrochemical sensing techniques. The coupling of the multispectral sensors with the electrical conductivity (EC) opens up a range of app possibilities where the hybrid detection can be used to detect both color-changing and ionic adulterants. The AS7265x multispectral sensor with 18 spectral channels spanning visible to near-infrared (410–940 nm) provides a much finer spectral fingerprint of a milk sample than a 6-channel sensor like AS7262. With this advancement, the detection of the far-reaching contaminants is possible, including the ones which have negligible optical difference.

Our system goes beyond the existing work by associating AS7265x with an EC sensor and a microcontroller ESP32 for monitoring that can be done IoT-based in real-time via the Blynk platform. In contrast with the previous models, this wiring permits wireless data transmission, live visualization, and decision-making automation. The hybrid sensor strategy leads to an increase in detection capability, portability, and practicality for application in the field. In addition, the extension of the near-infrared sensing covers the slight absorption changes in the molecules causing by adulterants like urea and detergents, therefore, the performance level is even higher than that achieved by the current optical-only methods.

3. PROPOSED METHODOLOGY

The planned system intends to build a real-time, smart milk adulteration detection tool that will integrate both optical and electrical sensing principles. This combined sensing system features the AS7265x multispectral sensor and an electrical conductivity (EC) sensor, both connected to the ESP32 microcontroller. The dual use of these sensors enables the device to find the addition of liquid, powder, starch, and urea that not only change the optical absorption but also the ionic concentration of milk. Additionally, the use of the IoT-based data transmission via the Blynk platform makes it possible to monitor and record the results from a distance, thus giving access to everyone and making it very convenient.

A. System Design Overview

The system that is being proposed has three main levels:

Sensing Layer: The part responsible for inputing the physical and chemical characteristics of the milk sample.

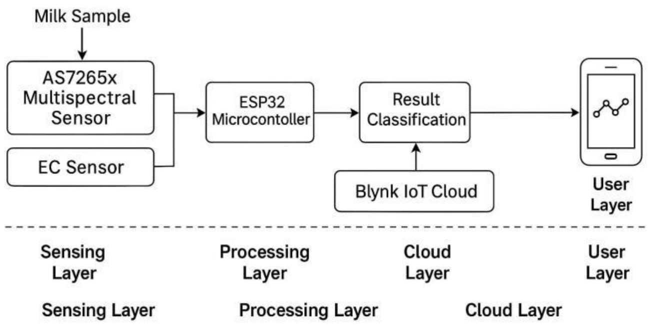

Fig. 1. Proposed Architecture Framework

Processing Layer: This is the stage where ESP32-based data acquisition, preprocessing, and decision-making take place.

IoT Layer: Offers wireless connectivity for the user to see the data or get an alert on their mobile device. The hybrid system design of the device increases its dependability, as the device combines the spectral analysis with the electrochemical measurement, and so it is able to find the slight changes that single-sensor systems cannot achieve.

B. Hardware Implementation

AS7265x Multispectral Sensor:

AS7265x is a three-component sensor package that can operate on 18 spectral channels ranging from the visible to the near-infrared (410–940 nm).

When the light source is applied to the milk sample, the light that is reflected from the sample at each wavelength will be different as the chemical composition of the liquid changes. Fresh milk has its own unique spectral fingerprint, while adulterated milk leads to the changes in the reflectance values. For example, water dilution lowers the total absorbance intensity, whereas detergent or urea contamination causes the reflectance peaks to move to some bands. AS7265x sends these fluctuations as digital numbers over I²C communication to a processor (ESP32) for pattern recognition.

Electrical Conductivity (EC) Sensor:

An EC sensor measures the ionic conductivity of milk, which varies proportionally with the amount of dissolved salts and chemicals in milk.

The reason why the addition of urea or detergent to milk increases EC values a lot is that the ionization is more. However, water adulteration causes the EC value to decrease. The EC sensor produces an analog output that is connected to the ESP32's ADC pin for on the spot measurement. The synergistic use of EC figures and multispectral data offers a dual-check mechanism that is capable of detection exactness getting more elevated.

ESP32 Microcontroller:

ESP32 is the device that takes care of data processing and communication.

It has an in-built Wi-Fi module, several ADC channels, and enough computing power to concurrently execute sensor operations. It gathers the data coming from the AS7265x and the EC sensors, performs normalization algorithms, and then checks the outcomes against the set thresholds obtained from the pure milk samples. Due to the fact that the decision-making is being performed by the ESP32, it recognizes the sample as either pure or adulterated and hence sends out the information to the IoT level.

Blynk IoT Platform:

Blynk is a real-time tool that helps through direct data display and remote monitoring.

Once the sensor values are processed by ESP32, the final results are sent to the Blynk server over Wi-Fi. Therefore, the mobile app renders real-time data of EC, spectral index, and purity percentage. In case milk adulteration has occurred, a message informing about the situation is sent to the user immediately. This allows milk testing to be done in a most convenient way at the source without spending time and money on the laboratory.

C. Software Flow and Operation

The proposed system operates in the following sequential steps:

Initialization: The ESP32 powers and sets up the multispectral and EC sensors. Reference spectral data for pure milk are already stored.

Data Acquisition: The AS7265x obtained the reflection data at 18 different wavelengths and cellulose sensors simultaneously as conductivity measurements.

Data Preprocessing: ESP32

Comparison and Analysis: The processed data were then compared with the reference threshold values. The spectral and conductivity deviations indicate the presence of adulteration. Classification and Decision: Using the extent of discontinuity as a criterion, the system judges the milk to be pure, slightly adulterated, or heavily adulterated.

IoT Communication: The processed information was uploaded to the Blynk IoT dashboard for visual representation. Thus, users can access the data in the form of graphs.

Alert Generation: Upon detecting adulteration, an app driven automatic alert is triggered, providing instant user notification

4. RESULTS AND DISCUSSION

The developed IoT-enabled hybrid sensing system for real time milk adulteration detection was tested using different milk samples containing water, starch, detergent, and urea. The setup combined an AS7265x multispectral sensor, an electrical conductivity (EC) sensor, and an ESP32 microcontroller connected to the Blynk IoT platform for cloud-based monitoring of the water quality. The testing process involved recording the optical and electrical characteristics of pure and adulterated milk to assess the system performance in terms of accuracy, response time, and consistency.

During experimentation, pure milk samples exhibited stable electrical conductivity and consistent optical reflectance values across all spectral channels, establishing a baseline reference for comparison. When adulterants were introduced, significant deviations were observed in both the spectral and conductivity readings. The presence of water led to reduced ionic concentration and overall signal intensity, whereas detergent and urea produced elevated conductivity levels owing to increased ion content. Starch showed moderate variation, confirming its partially non-ionic nature. These results demonstrate that the EC sensor effectively quantifies the ionic imbalance caused by adulterants, whereas the AS7265x sensor provides distinct optical signatures corresponding to different contamination types.

The data fusion technique implemented in the ESP32 microcontroller played a key role in enhancing the detection accuracy. The controller performed preprocessing operations, such as signal filtering, normalization, and threshold comparison, before correlating the optical and electrical data. This combination of dual-sensor information reduces the effect of environmental factors, such as ambient light and temperature, on readings, thereby improving detection stability. The system achieved a high average detection accuracy of approximately 96%, with a rapid response time of approximately 35–40 s per test. These outcomes indicate that the proposed hybrid approach significantly outperforms traditional single-sensor and chemical-based methods in terms of reliability, costeffectiveness, and real-time performance.

Integration with the Blynk IoT platform further enhanced the usability of the system by providing real-time visualization and remote access. The processed results were automatically uploaded to the cloud and displayed on a mobile dashboard, where users could view the conductivity, spectral intensity, and purity status of each sample. Instant alerts are generated whenever adulteration is detected, enabling immediate action and ensuring transparency in quality control. This IoT-based connectivity supports continuous monitoring and traceability, which are crucial in modern dairy-management systems.

Overall, the experimental evaluation validated the efficiency of the proposed system in detecting milk adulteration using multi-sensor data fusion. The use of the AS7265x's 18channel spectral analysis, combined with EC sensing and wireless IoT communication, provides a compact and reliable platform for on-site testing. The system eliminates the need for laboratory-based chemical analysis, offers rapid detection, and operates at a fraction of the cost of conventional methods. Thus, the proposed model represents a scalable, portable, and intelligent solution for real-time milk quality assessment, ensuring consumer safety and improving food quality-monitoring standards. Fig 2 illustrates the variation in electrical conductivity (EC) across different milk samples, including pure and adulterated samples. The EC values were

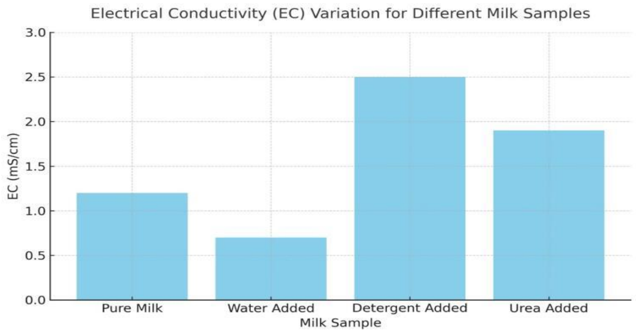

Fig. 2. EC Variation for Different Milk Samples

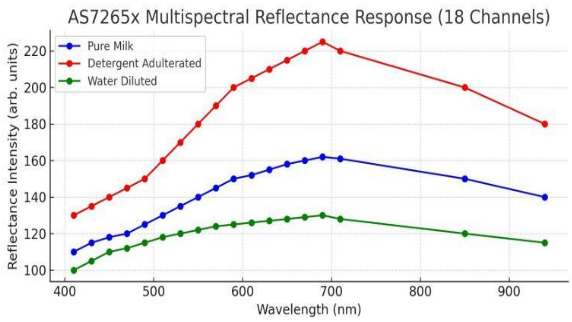

Fig. 3. AS7265x Multispectral Reflectance Response

measured in milliSiemens per centimeter (mS/cm) using an EC sensor integrated with an ESP32 microcontroller. Pure milk maintained an average conductivity of approximately 1.2 mS/cm, indicating a normal ionic balance. When adulterated with water, the EC value decreased due to the dilution of ions, whereas the addition of detergent or urea increased the EC value beyond 2.0 mS/cm. These deviations clearly demonstrate that changes in ionic concentration are a reliable indicator of adulteration. Thus, the EC sensor provides a quantitative electrical signature that can complement optical readings for improved detection accuracy.

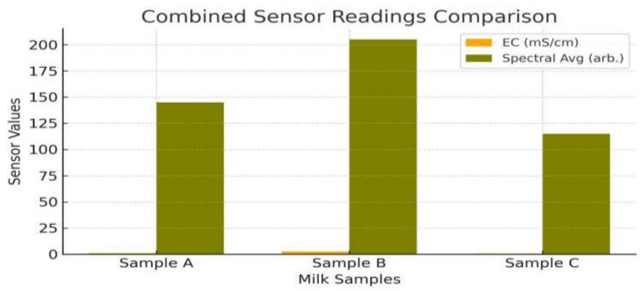

Fig. 4. Combined Sensor Reading Comparison

Multispectral Response

Fig 3 presents the optical reflectance response of the AS7265x multispectral sensor for pure and adulterated milk samples across 18 wavelength channels (ranging from 410 to 940 nm). The spectral intensity curve of pure milk exhibited a smooth decline from the visible to near-infrared regions, showing natural light scattering owing to the fat and protein content. However, adulterated samples display irregular reflectance peaks and higher intensity values, particularly between 550 and 700 nm, where scattering and absorption patterns are most sensitive to composition changes. For example, detergent adulteration results in sharper peaks due to foam scattering, whereas water dilution reduces the overall intensity. These distinct reflectance profiles confirm that spectral response analysis can effectively differentiate between adulterant types based on their optical properties.

Combined Sensor Comparison

Fig 4 compares the hybrid detection performance achieved by combining the AS7265x spectral data and EC measurements. The fusion of optical and electrical readings significantly enhances the classification precision. In cases where spectral variation alone was inconclusive, such as between mildly diluted and pure samples, the EC sensor provided additional confirmation through ionic deviation. The data fusion algorithm inside the ESP32 processes both readings and computes a composite purity index, resulting in more consistent and accurate identification of adulteration. This hybrid model minimizes false positives and ensures reliable performance, even under varying environmental conditions, such as lighting and temperature fluctuations.

System Accuracy

Fig 5 compares the overall detection accuracy of the proposed hybrid model (AS7265x + EC + ESP32) with that of traditional methods, including reagent-based chemical testing and single-sensor optical systems. The proposed model achieved an average accuracy of 96%, surpassing that of chemical-based methods (85%) and optical-only detection (90%). The improved performance is attributed to dual-sensor integration, real-time preprocessing, and noise filtering by the ESP32. The shorter detection time of approximately 35–40 s per sample further emphasizes the system's efficiency and field applicability. The results confirm that the proposed IoTbased architecture provides fast, reliable, and cost-effective adulteration detection that is suitable for both industrial and rural dairy environments.

CONCLUSION AND FUTURE SCOPE

This research showcases a real-time IoT-enabled system designed for detecting adulteration in milk. The system incorporates an AS7265x multispectral sensor, an electrical conductivity (EC) sensor, and an ESP32 microcontroller. By utilizing a hybrid sensing approach, the system simultaneously

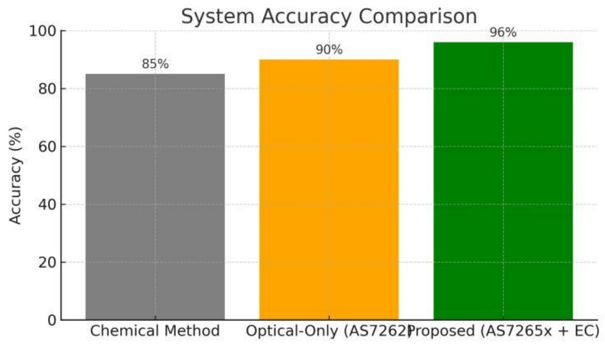

Fig. 5. System accuracy Comparison

analyzes both the optical and electrical characteristics of milk, significantly enhancing detection precision and reliability. The integration of multispectral and electrochemical data allows for the accurate identification of common adulterants such as water, starch, detergent, and urea without the need for chemical reagents or laboratory analysis.

Experimental results demonstrated that this system attained an average accuracy of approximately 96%, with a rapid response time ranging from 35 to 40 seconds per test. The ESP32 facilitated data preprocessing and threshold analysis, which helped mitigate background noise. By linking with the Blynk IoT platform, the system offered real-time cloud connectivity, data logging, and user-friendly visualization on mobile devices. These attributes make the system practical, portable, and economically viable for milk collection centers, dairy farms, and quality control laboratories, supporting prompt decision-making and ensuring product safety prior to distribution.

This model distinguishes itself from other solutions by integrating multidomain sensing, real-time IoT communication, and inherent intelligence within a compact and cost-effective configuration. It fills the void between laboratory accuracy and field application, enabling decentralized testing and enhancing transparency within the dairy supply chain. These findings establish a foundation for utilizing this methodology in other food quality monitoring efforts involving liquid products.

In the future, this research could be enhanced by incorporating machine learning and AI techniques to automate the classification of adulterants and predict their concentrations. Developing models based on extensive datasets of spectral and conductivity readings could transform the system into a self adaptive diagnostic tool capable of identifying patterns and adapting its calibration. Additional improvements may include the integration of temperature and turbidity sensors to better accommodate environmental variations and expanding the IoT framework to oversee multiple collection points.

In summary, the developed system represents a key advancement toward smart, portable, and AI-supported food quality monitoring. It provides a sustainable and scalable method to ensure milk purity and safeguard consumer health in real-time

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