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Design and Development of Low-Cost AI-Enabled Biosensors for Real-Time Detection of Milk Adulteration using IoT Framework

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Abstract: *Milk adulteration has emerged as a critical issue affecting food safety, public health, and consumer trust across both developed and developing nations. The intentional addition of harmful substances such as urea, starch, detergents, hydrogen peroxide, and synthetic milk compounds compromises nutritional quality and can lead to severe health risks. Traditional detection techniques, including chemical testing and laboratory-based analysis, are often expensive, time-consuming, and inaccessible in rural or decentralized supply chains. Therefore, there is a pressing need for innovative, cost-effective, and real-time detection systems.*

This research paper presents the design and development of a low-cost biosensor integrated with Artificial Intelligence (AI) and an Internet of Things (IoT) framework for real-time detection of milk adulteration. The system employs electrochemical sensing techniques combined with machine learning models such as Support Vector Machine (SVM) and Random Forest for classification and prediction. Data collected from sensors is transmitted via IoT modules to a cloud platform for remote monitoring and analysis. The study uses 250 milk samples, including both pure and adulterated samples, to validate system accuracy. Results indicate that the proposed system achieves over 90% accuracy, demonstrating its reliability and efficiency. This approach not only reduces dependency on laboratory testing but also enhances real-time decision-making, ensuring safer dairy consumption and improved regulatory monitoring.

Keywords: Milk Adulteration, Biosensors, Artificial Intelligence, IoT, Food Safety, Machine Learning

I. INTRODUCTION

Milk is one of the most essential and widely consumed food products globally due to its high nutritional value, including proteins, calcium, vitamins, and essential fats. However, the increasing demand for milk and dairy products has led to widespread adulteration practices aimed at maximizing profits. Common adulterants include water, starch, urea, detergents, and synthetic compounds, which degrade the quality of milk and pose significant health risks. Conventional methods for detecting adulteration rely on laboratory-based chemical analysis, which requires skilled personnel, sophisticated equipment, and considerable time. These limitations make such methods unsuitable for on-site or real-time detection, especially in rural areas and decentralized supply chains.

With advancements in technology, the integration of Artificial Intelligence (AI) and the Internet of Things (IoT) has opened new avenues for developing smart detection systems. AI enables pattern recognition and predictive analysis, while IoT facilitates real-time data transmission and remote monitoring. Biosensors, particularly electrochemical and optical sensors, have gained attention for their ability to detect chemical changes in milk quickly and accurately.

This research focuses on designing a low-cost, portable biosensor system that leverages AI and IoT to provide real-time detection of milk adulteration. The system aims to bridge the gap between traditional laboratory methods and modern technological solutions, ensuring affordability, scalability, and accessibility. By enabling rapid and accurate detection, the proposed system contributes to improved food safety standards and consumer protection.

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LITERATURE REVIEW

The issue of milk adulteration has been widely studied, and several detection methods have been proposed in the literature. Traditional approaches, such as chemical titration and chromatography, have proven effective but are limited by their complexity and cost. Recent advancements in biosensor technology have provided alternative solutions for rapid detection. Electrochemical biosensors, for instance, have demonstrated high sensitivity in detecting substances like urea and hydrogen peroxide in milk samples (Singh & Verma, 2020). These sensors operate by measuring electrical changes resulting from chemical reactions, making them suitable for real-time applications.

In addition to biosensors, Artificial Intelligence has been increasingly used to enhance detection accuracy. Machine learning algorithms such as Support Vector Machine (SVM), Random Forest, and Neural Networks can analyze complex datasets and identify patterns associated with adulteration (Kumar & Patel, 2021). These models improve classification accuracy and reduce false positives, making them highly valuable in food quality assessment.

IoT-based systems have also been explored for monitoring food quality. Sharma. (2022) developed a smart dairy monitoring system that integrates sensors with cloud computing platforms for real-time analysis. However, many existing systems are expensive and require advanced infrastructure, limiting their applicability in resource-constrained environments.

This study builds upon previous research by combining low-cost biosensors, AI algorithms, and IoT connectivity into a single integrated system. The focus on affordability and portability addresses the limitations of existing solutions, making the proposed system more accessible and practical for widespread use.

OBJECTIVES OF THE STUDY

The primary objective of this research is to develop an efficient, low-cost system for detecting milk adulteration in real time using advanced technologies such as Artificial Intelligence and IoT. The study aims to design a biosensor capable of identifying common adulterants like urea, starch, and detergents by detecting changes in chemical properties such as pH, conductivity, and viscosity. Another key objective is to integrate machine learning algorithms that can accurately classify milk samples as pure or adulterated based on sensor data.

Additionally, the research seeks to develop an IoT-based framework that enables real-time data transmission and remote monitoring. This feature is particularly important for ensuring continuous quality assessment in dairy supply chains. The system is designed to be portable and user-friendly, allowing farmers, vendors, and regulatory authorities to perform on-site testing without requiring specialized training.

The study also aims to evaluate the performance of the proposed system using statistical methods such as mean, standard deviation, frequency distribution, and ANOVA. These analyses help determine the reliability and accuracy of the system under different conditions.

Another important objective is to ensure cost-effectiveness, making the technology accessible to small-scale dairy producers and rural communities. By addressing the limitations of existing methods, the proposed system aims to provide a scalable and practical solution for improving milk quality monitoring and ensuring public health safety.

METHODOLOGY

The methodology of this study involves the design, implementation, and evaluation of a low-cost AI-enabled biosensor system integrated with an IoT framework. The system architecture consists of three main components: the biosensor unit, the processing unit, and the IoT communication module. The biosensor unit includes electrochemical sensors that measure parameters such as pH, conductivity, and viscosity, which are indicative of milk quality. These sensors are connected to a microcontroller, which processes the raw data and prepares it for analysis.

A total of 250 milk samples were collected, including both pure and adulterated samples. Out of these, 20 samples were used for calibration and validation to ensure accuracy and reliability. The collected data was preprocessed to remove noise and normalize values before being fed into machine learning models. Support Vector Machine (SVM) and Random Forest algorithms were used for classification due to their high accuracy and robustness.

The IoT module enables real-time data transmission to a cloud platform, where the results are stored and analyzed. Users can access the data through a mobile or web interface, allowing remote monitoring of milk quality. Statistical analysis was performed using mean, standard deviation, and ANOVA to evaluate system performance.

This integrated approach ensures accurate detection, real-time monitoring, and efficient data management, making the system suitable for practical applications in dairy supply chains.

RESULTS AND DISCUSSION

The results of the present study demonstrate the effectiveness, reliability, and practical applicability of the proposed low-cost AI-enabled biosensor system integrated with an IoT framework for real-time detection of milk adulteration. A total of 250 milk samples were analyzed, including both pure and intentionally adulterated samples containing common contaminants such as urea, starch, detergent, and added water.

The biosensor unit successfully captured variations in key physicochemical parameters, including pH, electrical conductivity, and viscosity, which are widely recognized indicators of milk quality. The observed data revealed consistent and significant differences between pure and adulterated samples, thereby validating the sensitivity of the developed biosensor system. The mean pH value of pure milk was recorded around 6.6 to 6.8, whereas adulterated samples exhibited elevated pH values ranging from 7.5 to 8.2 due to the presence of alkaline adulterants like urea and detergents. Similarly, conductivity levels showed a noticeable increase in adulterated samples, indicating the presence of dissolved ionic substances. Viscosity measurements also varied, with diluted or adulterated milk showing lower consistency compared to pure samples.

The integration of Artificial Intelligence played a crucial role in enhancing the classification and prediction capabilities of the system. Machine learning models, specifically Support Vector Machine (SVM) and Random Forest algorithms, were trained using preprocessed sensor data. The models demonstrated high classification accuracy, with the Random Forest algorithm achieving an overall accuracy of approximately 94%, while SVM showed slightly lower but comparable performance. The confusion matrix analysis indicated a low rate of false positives and false negatives, which is essential for ensuring reliability in real-world applications.

The ability of AI models to identify complex patterns and correlations among multiple parameters significantly improved the detection efficiency compared to traditional threshold-based methods. Furthermore, feature importance analysis revealed that conductivity and pH were the most influential parameters in determining milk adulteration, followed by viscosity. This insight can be valuable for optimizing sensor design and reducing system complexity without compromising accuracy.

The IoT framework enabled seamless data transmission and real-time monitoring, which is a major advancement over conventional testing methods. Sensor data collected by the microcontroller was transmitted to a cloud-based platform, where it was stored, processed, and visualized. This allowed users to monitor milk quality remotely through mobile or web interfaces. The real-time nature of the system ensures immediate detection of adulteration, which is particularly beneficial in supply chain management and quality control processes.

The latency observed in data transmission was minimal, typically within a few seconds, indicating the efficiency of the IoT module. Additionally, the system demonstrated stable performance under varying environmental conditions, suggesting its suitability for field applications. The cloud integration also provides opportunities for large-scale data analysis, enabling the development of predictive models and trend analysis for dairy quality monitoring.

Statistical analysis further validated the effectiveness of the proposed system. Descriptive statistics, including mean and standard deviation, highlighted clear distinctions between pure and adulterated samples across all measured parameters. The standard deviation values were relatively low for pure samples, indicating consistency, whereas adulterated samples showed higher variability due to differences in the type and concentration of adulterants.

Analysis of Variance (ANOVA) was conducted to assess the statistical significance of the observed differences. The results indicated that the variations in pH, conductivity, and viscosity between pure and adulterated milk were statistically significant ($p < 0.05$), confirming that the biosensor system can reliably differentiate between the two categories. This statistical validation strengthens the credibility of the system and supports its practical implementation.

Another important aspect of the results is the cost-effectiveness and energy efficiency of the system. The use of low-cost sensors and microcontrollers significantly reduces the overall cost compared to traditional laboratory equipment. Despite the low cost, the system does not compromise on performance, achieving high accuracy and reliability. Power consumption was also found to be minimal, making the system suitable for battery-operated or portable applications. This is particularly important for deployment in rural and remote areas where access to electricity and laboratory facilities may be limited. The compact and portable design further enhances the usability of the system, allowing on-site testing without requiring specialized training or expertise.

The discussion of results also highlights some challenges and limitations observed during the study. While the system performed well for common adulterants, its ability to detect unknown or complex adulterants was limited. This is primarily due to the dependence on predefined patterns and training data used in the AI models. Expanding the dataset to include a wider range of adulterants and variations can improve the robustness of the system. Additionally, sensor calibration was identified as a critical factor affecting accuracy. Over time, sensors may drift or lose sensitivity, necessitating periodic calibration and maintenance. Environmental factors such as temperature and humidity were also found to have a minor impact on sensor readings, although these effects were not significant enough to affect overall system performance.

Despite these limitations, the overall findings indicate that the proposed AI-enabled biosensor system is a highly promising solution for real-time milk adulteration detection. The combination of biosensing technology, machine learning, and IoT integration provides a comprehensive approach that addresses the shortcomings of traditional methods. The high accuracy, rapid response time, and real-time monitoring capabilities make the system suitable for various applications, including dairy farms, milk collection centers, processing units, and regulatory agencies. Furthermore, the ability to store and analyze data on cloud platforms opens new possibilities for data-driven decision-making and policy development in the dairy industry.

The results and discussion clearly demonstrate that the developed system is capable of providing accurate, reliable, and real-time detection of milk adulteration at a low cost. The integration of AI and IoT enhances the functionality and scalability of the system, making it a viable solution for improving food safety and quality assurance. With further improvements in sensor technology and data analytics, the system has the potential to become a standard tool for milk quality monitoring in both developed and developing regions.

Table 1: Performance Analysis of AI-Enabled Biosensor System

Parameter	**Pure Milk (Mean ± SD)**	**Adulterated Milk (Mean ± SD)**	**Accuracy (%)**
pH Level	6.7 ± 0.2	7.8 ± 0.5	92%
Conductivity (mS/cm)	4.5 ± 0.3	6.2 ± 0.6	90%
Viscosity (cP)	1.6 ± 0.1	1.2 ± 0.2	88%
AI Classification Accuracy	-	-	94%

The results demonstrate that the proposed system effectively differentiates between pure and adulterated milk samples. Significant variations were observed in pH, conductivity, and viscosity values, which were accurately detected by the biosensors. The AI models achieved a classification accuracy of 94%, indicating high reliability.

ANOVA analysis revealed statistically significant differences between pure and adulterated samples ($p < 0.05$), confirming the effectiveness of the system. The integration of IoT allowed real-time monitoring and data visualization, enhancing usability and accessibility. Overall, the results highlight the potential of the proposed system as a practical and efficient solution for milk adulteration detection.

ADVANTAGES OF PROPOSED SYSTEM

The proposed system offers several advantages over traditional methods of milk adulteration detection. One of the most significant benefits is its low cost, which makes it accessible to a wide range of users, including small-scale farmers and vendors. The portability of the system allows on-site testing, eliminating the need for laboratory infrastructure.

Another key advantage is the integration of Artificial Intelligence, which enhances detection accuracy by analyzing complex patterns in sensor data. The use of machine learning algorithms reduces the likelihood of false positives and improves overall reliability.

The IoT framework enables real-time data transmission and remote monitoring, allowing users to track milk quality continuously. This feature is particularly useful for large-scale dairy operations and supply chain management.

Additionally, the system is user-friendly and does not require specialized training, making it suitable for widespread adoption. The combination of biosensors, AI, and IoT creates a powerful tool for ensuring food safety and quality.

LIMITATIONS

Despite its advantages, the proposed system has certain limitations that need to be addressed in future research. One of the primary limitations is the detection of unknown or complex adulterants that may not produce significant changes in the measured parameters. This can affect the accuracy of the system in certain cases.

Another limitation is the dependency on sensor calibration. Over time, sensors may lose sensitivity or accuracy, requiring regular maintenance and recalibration. Additionally, the system relies on internet connectivity for IoT functionality, which may not be available in remote areas.

The performance of the AI models is also dependent on the quality and quantity of training data. Limited datasets may result in reduced accuracy and generalization Capacity. Addressing these limitations will be crucial for improving the robustness and scalability of the system.

II. CONCLUSION

This research presents a comprehensive approach to detecting milk adulteration using a low-cost AI-enabled biosensor integrated with an IoT framework. The system demonstrates high accuracy, real-time detection capabilities, and cost-effectiveness, making it suitable for practical applications. The integration of advanced technologies enhances the efficiency and reliability of milk quality monitoring, contributing to improved food safety standards.

Future research can focus on expanding the range of detectable adulterants, improving sensor technology, and enhancing AI models for better accuracy. The proposed system has the potential to revolutionize dairy quality monitoring and ensure safer consumption of milk products.

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