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Multimodal Sensor Integration For Comprehensive Data Collection In Ruminant Digestive Health Monitoring

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Abstract. This paperexplains the approach to design and development of a sensor-based device tailored for real-time data collection to monitor and analyze ruminant health and digestive processes using Machine Learning. The designed device uses a different nodes of sensors, which include pH, temperature, gas composition, and moisture sensors, along with optical and imaging sensors such as thermal cameras and cameras, to capture multimodal data for ruminant digestive health. Each sensor is selected based on its sensitivity to parameters capable of reading digestive parameters, with a reliable and well calibrated data acquisition system designed in such a way that ensures continuous monitoring in field conditions. The device's modular design facilitates easy deployment and maintenance, along with the low-power consumption and supports prolonged use in remote environments. Data collected from this setup are processed and transmitted through an IoT-based platform, enabling remote access and real-time monitoring. This Innovative device offers a scalable and easy to use non-invasive approach to ruminant health monitoring, providing crucial data that can lead to early diagnosis of digestive tract disorders, optimization of feed, and improved livestock management practices. Current work discussed in the paper lays foundation for future sensor-based diagnostic tools in precision agriculture, contributing to a more data-driven approach to livestock health.

INTRODUCTION

Health Monitoring of different ruminant animals is crucial for maximum output or productivity and ensuring animal stays healthy most of time. Several digestive issues which are observed in cattle, sheep, and other ruminants can result in theirpoor nutrient absorption capabilitywhich will increase their risk to metabolic diseases causing adverse affects in farm profitability. The conventional methods of inspection of the ruminant health currently involve the periodic physical examinations and clinical analysis by collection of laboratory samples. Usually these traditional approaches followed are often time consuming , invasive, and expensive for farmers. Considering these challenges, recentlydifferent IOT backed sensor based technologies are coming up in market for preclinical analysis of ruminant health.

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This paper introduces a portable system designed to develop a sensor-based device for collecting multimodal data which is essential for analyzing ruminant digestive health. The device consists of different sensors which can measure pH, temperature, moisture, gas composition, and also use image processing techniques to collect an extensive dataset which gives insights of disorders in ruminants digestive tract. By analyzing the data from the sensor nodes we can perform early detection of potential health problems such as acidosis or imbalances in digestive flora which is generally indicated through shifts in pH levels, temperature changes or other values collected through the portable data collection unit designed. The system is IOT connected , which enables it to transmit realtime data collected through the device to IOT cloud server accessible through the application hosted on the cloud.

The primary motive behind the design of this sensor setup is to develop a non-invasive solution for real-time monitoring of digestive disorders in ruminants. By interfacing multiple types of sensors, the device can capture a wide range of health parameters of the ruminants, thereby providing the data for pre clinical analysis of the digestive tract disorders in the ruminants. This multimodal approach allows the system to overcome the disadvantages associated with single-sensor devices and provides a detailed dataset for analysis of the ruminant digestive health. Field testing of this device enables livestock management practices to be future ready with data-driven health analytics, facilitating timely interventions and more effective disease prevention strategies. This study aims to contribute in precision livestock farming by demonstrating how sensor-based technologies can support sustainable solutions and root cause detection for bovine diseases.

CURRENT WORK

The systematic literature review research work performed by research scholars on sensor-based monitoring technologies in the industrial sector, with specific focus on their application in livestock management and ruminant health monitoring system. With recent proliferation in the sensor based monitoring and deep learning and AIOT related research for inference on the edge, various non-invasive health assessment tools that can help towards precision farming and effective livestock management. Current literature study done studies numerous applications, from traditional image processing and manual observation methods to advanced deep learning models, each contributing towards advanced research in ruminant health monitoring techniques with the aid of technology. This review systematically addresses the latest technologies employed across diverse applications focused on the ruminant health monitoring and wearable AIOT technology.

In their 2024 study, Hernández et.al carried their research work ondeployment of wearable sensors to track the cattle activities.Different sensors like accelerometers, GNSS, and temperature sensors were interfaced and the data was analyzed for different cattle activities like grazing, ruminating, and walking. Different ML Techniques were used on the collected data and the resultswere obtained by combining support vector classifiers with time-series data from these sensors. The results showed high accuracy for predicting cattle behaviors, there by making a foundation for further studies on cattle health monitoring.

Yu et al. in 2024used machine learning to identify and predict milk urea nitrogen (MUN) levels in dairy cows by analysis of the gut microbiome. The study focused on microbial markers associated with nitrogen utilization, they havesuccessfully demonstrated how machine learning models could categorize individuals based on MUN concentrations, thus making it a valuable health biomarker. The researchers utilized Random Forest and SHAP visualizations for predictions, providing a reference framework for managing livestock using microbiome data .

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In 2023, Yan et.alprovided a study of environmental factors on the gastrointestinal microbiomes of ruminants. Their research demonstrated that microbial networks remain resilient even when subjected to environmental stressors. By using network analysis and machine learning techniques, they suggested how microbes adapt to different environmental conditions, stressing the importance of their role in maintaining ruminant health. This resilience in microbial networks turns out advantageous for the sensor-based diagnostics by integrating with environmental data for a more thorough health assessment .

In a 2023 study, Peng et.al carried out research work on microbial biomarkers linked to methane emissions in ruminants by implementing different machine learning techniques to forecast these emissions from microbial compositions. Their research suggested on how precision feed strategies can be informed through microbiome management as a means of reducing methane output, thereby achieving profitable livestock farming practices. The study of these biomarkers by combining mems gas-sensing technologies with microbial analysis can help monitor methane levels in ruminants effectively.

Baldwin et.al in 1977 proposed a dynamic model of ruminant digestion. They suggested a simulation model to examine nutrient breakdown and digestive processes. This model accounts for microbial growth and digestion dynamics, providing potential areas of improvising the techniques accuracy by AIOT sensor integration.During this research different versions of these models were combined with real-time sensors, therbyoffering the possibility for more precise evaluations of ruminant digestive efficiency.

The literature review outlines the latest and prominent research work that had been done in the field of the sensorbased data collection technologies and machine learning applications for monitoring ruminant health and behavior. The literature review provides us a better insights of using different tools and techniques as well as gap in them , including wearable sensors, microbiome analysis, and environmental monitoring, all of them contributing significantly to Precision Livestock Farming (PLF). As suggested by Hernández et al. (2024), wearable devices equipped with accelerometers and GNSS sensors facilitate precise tracking of cattle activities such as grazing and ruminating, thus offering valuable insights into behavioral health. Additionally, research conducted by Yu et al. (2024) and Yan et al. (2023) demonstrates how different machine learning tools and techniques can be utilized to identify microbial biomarkers for detecting health indicators; these investigations reveal existance of strong correlations between gut microbiota dynamics with factors like nitrogen utilization efficiency and adaptation to the environment.

Further, Peng et al. (2023) stressed the the ability of machine learning regression models to forecast methane emissions in ruminants by highlighting microbial biomarkers in their research, thereby facilitating the development of eco-friendly feeding strategies. Baldwin et al. (1977) led a key basework for further researchers with their dynamic model simulating ruminant digestion, which serves as a foundation for incorporating modern sensors capable of real-time nutrient absorption monitoring. To summarize in short the literature review carried and as per the review, these studies highlight the transformative potential of multimodal sensor data which uses environmental, behavioral, and microbial information to enhance comprehensive and real-time health surveillance in livestock management systems. Such integration can prove vital for fostering sustainable and data-driven practices within livestock management.

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WORKING PRINCIPLE

The proposed consists of interfacing different sensors to collect the data on the physiological condition of ruminants, allowing for real-time monitoring and further predictions of their digestive health. It consists of a multisensory array for the measurement temperature, pH levels, gas composition, and moisture detection to collect data regarding the ruminant health. These sensors are calibrated prior to collection of the data which can be used further for health analysis and abnormality prediction of ruminant.

The collected data is from the sensors nodes is preprocessed, cleaned andthen fed into machine learning models to recognize patterns that signify both healthy and unhealthy digestive states. This allows the system to identify abnormalities by spotting deviations from standard norms. By combining and analyzing this varied data, the system is expected to provide an effective non invasive technique for early detection of digestive disorders, supporting proactive management of ruminant health.

SYSTEM DESIGN

The proposed system design for the sensor based data acquisition unit is divided into three major modules.: Data Collection, Data Processing and Integration, and Analysis and Decision-Making. These three modules are responsible for detection of abnormalities in ruminant health in realtime.

In the Data Collection Layer, sensors are used to directly collect live data from cow dung samples to assess digestive health parameters. An NPK Sensor analyzes levels of nitrogen, phosphorus, and potassium to provide view of the nutrient absorption efficiency. The odor sensor interfaced identifies gases such as ammonia and methane that reveal microbial activity and fermentation within the digestive system. A pH Sensor evaluates dung acidity to detect any imbalances like acidosis. Furthermore, a Thermal Camera records temperature profiles which might indicate microbial processes or infections; while an RGB Camera captures color and texture changes potentially related to health issues. When the devices is exposed to sample the data is collected by the device and is sent to a data acquisition module controlled by ESP32 microcontrollerwhich and organizes everything for further processing steps.

In the Data Processing and Integration Layer, raw data collected from sensors is preprocessed to remove noise, outlier detection, normalization and also to standardize measurements across different types. Then, a data integration platform merges these sensor readings into a comprehensive dataset that indicates digestive health status based on dung samples. The system is connected to IOT using the WIFI,so that data transmission unit sends this processed information to a central cloud server for real-time monitoring with minimal delay.

In the Analysis and Decision-Making Layer, a cloud-hosted pre-trained machine learning model processes integrated data to detect patterns associated with both normal and abnormal digestive conditions. When anomalies such as unusual pH or nutrient levels are found, an alert is activated. Notifications are immediately sent to farm staff or veterinarians through a mobile app or dashboard for swift response. Additionally, there is a storage and logging module that records raw and processed data in a cloud-based database, ensuring long-term accessibility for trend analysis while supporting continuous retraining of the model to improve its accuracy over time. This refined architecture provides a comprehensive system enabling real-time health monitoring via dung analysis, facilitating early detection of digestive issues and promoting proactive

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livestock health management. Below is the diagram illustrating this proposed system's architecture.

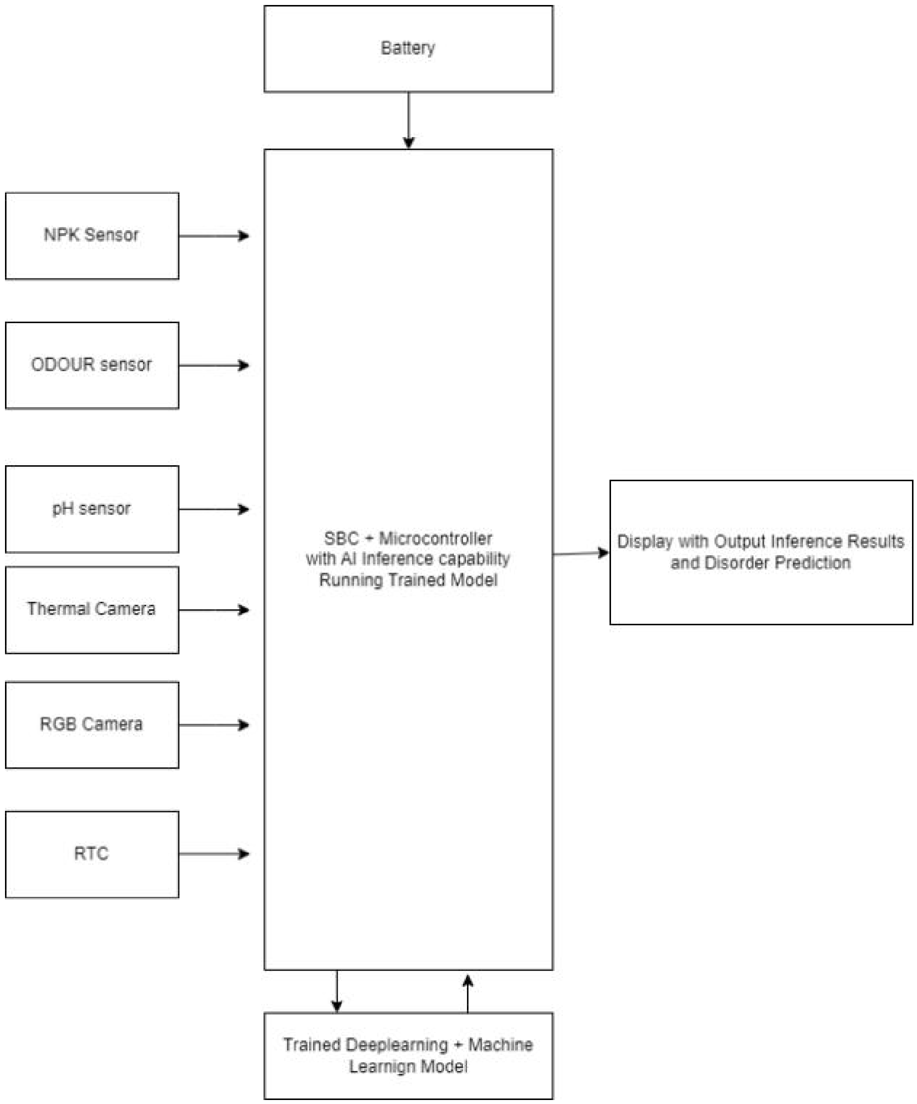

FIGURE 1. Architecture Diagram of the System

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The use case diagram of the system is shown below:

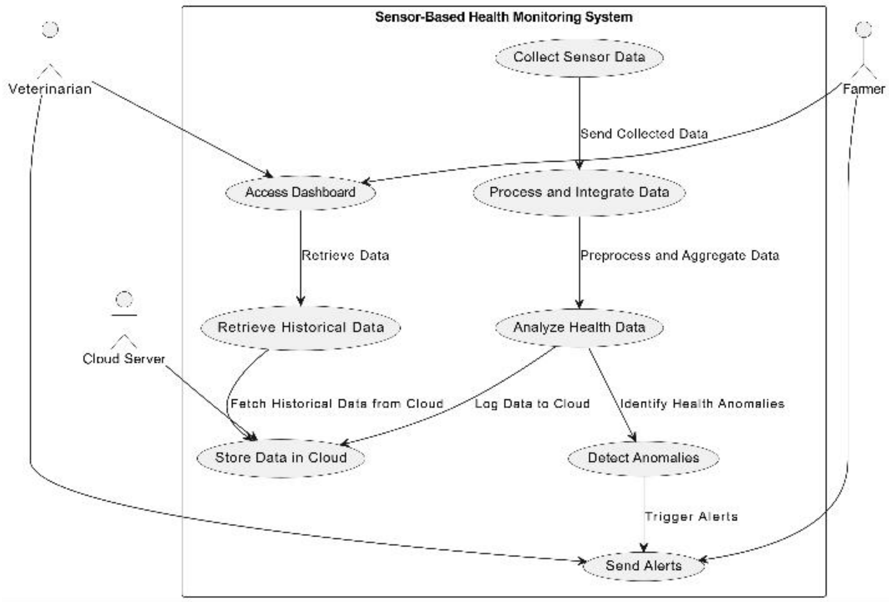

FIGURE 2. Use Case Diagram of the System

As shown in the usecase diagram the system is designed to gather real-time physiological and environmental data using various sensors (including NPK, pH, odor detectors, thermal units, and RGB cameras) that are attached or positioned near the animal. This collected data is transmitted to a single-board computer or microcontroller equipped with AI inference capabilities. There, an advanced deep learning model analyzes the information to identify patterns related to digestive health and detect potential disorders. Different factors responsible for the health disorders such as nutrient levels, acidity balance, and temperature changes are recorded and these sensors inputs for assessment of the animals condition. If any abnormalities are found within this monitored environment, the system can alert farm staff or veterinarians immediately there by helping in immediate detection, resulting in automated monitoring of the cattle health with timely intervention, which supports proactive health management practices for optimized results.

The schematic diagram is created using Easy EDA software, and PCB layouts are created. Below is the circuit diagram for the implemented sensor setup.

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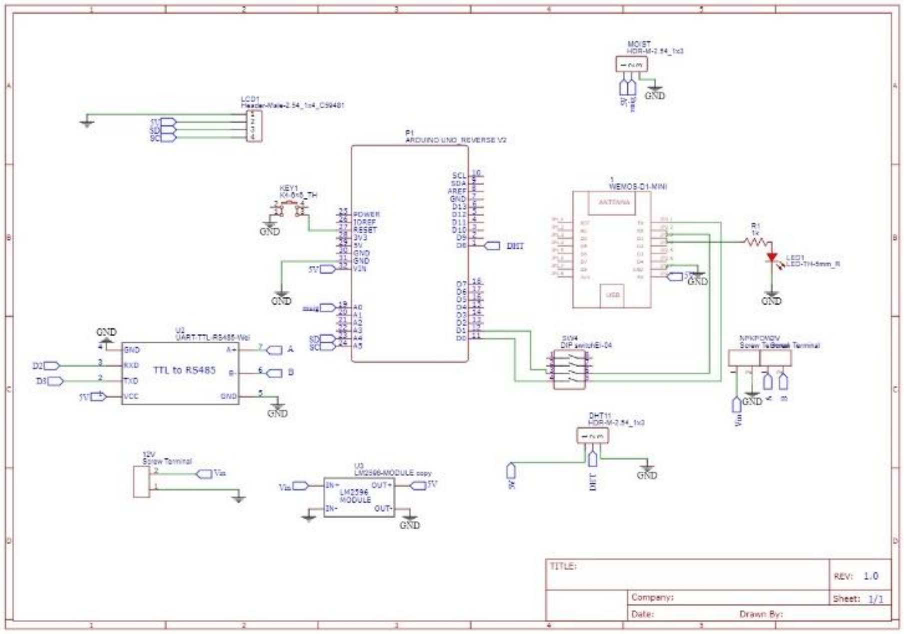

FIGURE 3. Schematic Diagram

The NPK Sensor shown in the circuit diagram is responsible for determination of levels such as nitrogen, phosphorus, and potassium in cow dung to provide insights into the animal's digestive efficiency and nutrient absorption. The Odor Sensor monitors gases like ammonia released from the dung, offering valuable information on microbial activity and digestion status. The pH Sensor measures the acidity level of the cow dung,an essential parameter for evaluating gut health and identifying potential imbalances in digestion. A Thermal Camera records temperature variations within the sample, which can help In detecting microbial processes or possible infections. An RGB Camera supplies visual data regarding color and texture changes of the cowdung, further indicating health conditions. To ensure precise tracking of different health parameters, a Real-Time Clock (RTC) timestamps all collected data accurately. All these sensors are connected with an SBC (Single Board Computer) equipped with AI inference capabilities; this processor utilizes trained models to analyze assembled data for diagnosing probable digestive issues based upon recurring patterns. This is observed within cow dung samples which effectively demonstrated the efficiency of the system.

Requirements are used in the project:

Hardware Requirements

1. Multi Parameter NPK Sensor Monitoring Device
2. Neural Processing Unit
3. Thermal Camera 8x8 Grid
4. RGB Camera
5. pH Sensor
6. MEMS Gas Sensors.
7. Atmega328P Controller
8. Battery

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Software Requirements

1. Brackets IDE
2. VS Code
3. AWS EC2

RESULTS AND DISCUSSION

The Fabricated Device is as shown in the figure below.

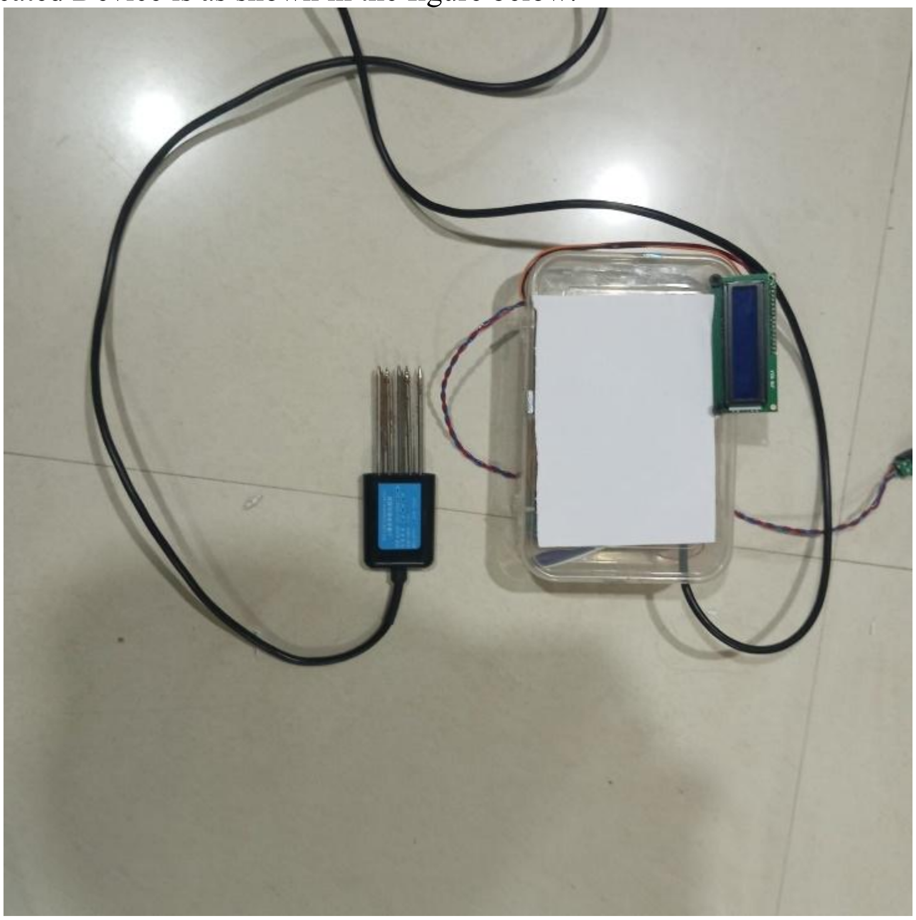

Figure 4. The Sensor Setup Developed

The IOT app designed for remote monitoring and collection is shown.

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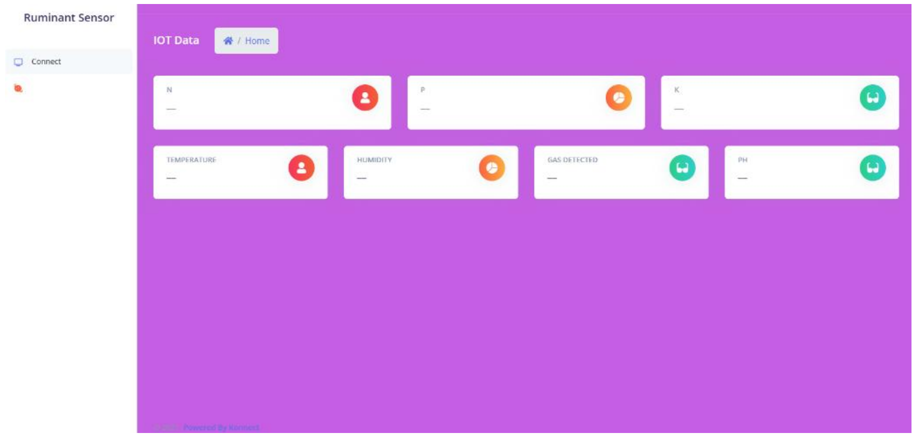

FIGURE 5. The IOT App Developed

The proposed system in this paper for detection of ruminant diseases combines multiple sensors such as NPK, pH, gas, thermal, and RGB which are used to monitor the digestive health of ruminants. This IoT-enabled setup facilitates real-time monitoring and data collection using MQTT to ensure efficient data transmission. The proposed design utilizes MQTT protocol, maintaining a low-latency, reliable connection between devices and the cloud is possible even in remote field conditions . Different sensors are used for monitoring of different parameters, The NPK sensor measures nitrogen, phosphorus, and potassium levels providing details about nutrient absorption; the pH sensor assesses digestive health by measuring acidity; gases such as ammonia are detected by the gas sensor indicating microbial fermentation activity. A thermal camera and RGB Camera is used to detect the temperature profiles related to microbial heat production are captured through a thermal camera; while an RGB camera documents sample color and texture changes.

Since MQTT protocol is used it is efficient and reliable remote monitoring, to feed the data for precision livestock farming. By enabling real-time data collection, transmission, and analysis, this setup represents a groundbreaking approach in ruminant health monitoring. It offers a scalable solution that can be deployed in the field to optimize animal health and welfare. Our further studies aim to improving the accuracy of the machine learning model further and expanding its capabilities to monitor additional health parameters.

Testing demonstrated that the MQTT protocol is perfect for this application, providing real-time updates with minimal delay and maintaining stable connections even when network conditions fluctuate. The device successfully captured a range of health metrics, as each sensor contributed complementary data to improve diagnostic accuracy. This multimodal approach overcomes the limitations of single-sensor systems by offering a comprehensive view of digestive health and enabling early detection of potential disorderan essential element for proactive livestock management.

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CONCLUSION

This paper outlines a multimodal sensor-based device designed for real-time monitoring of ruminant digestive health by analyzing cow dung by capturing various parameter such as NPK, pH, gas, and thermal sensors alongwithRGB cameras to provide aanalysis of digestive efficiency and health. The MQTT protocol is used for IOT cloud data transfer, to transfer it efficiently with low latency to a cloud platform where it undergoes analysis through a machine learning model aimed at detecting potential health issues. The IOT cloud panels help in keep a track of health remotely using IOT and Web application hosted on cloud that empowers farm personnel and veterinarians to intervene directly as they have access to all data form the animal for analysis along with predictions. This can result in efficient health management and profitable farming.

The results obtained after testing the device showed us the device's ability to effectively capture a diverse array of health parameters thereby providing non-invasive solution for precision livestock farming. The ability to continuously monitor health parameters and detect early signs of digestive disorders proves invaluable for enhancing animal welfare and farm productivity. Future advancements aim to boost the predictive accuracy of the machine learning model while expanding the device's features to monitor additional health metrics, thus further supporting data-driven, sustainable practices in livestock management.

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