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IoT-Enabled Estrus Detection in Dairy Cattle Using Machine Learning Technique

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Abstract: In the dairy industry, optimizing reproductive management is crucial for sustainable operations and enhancing animal welfare. The traditional manual detection methods usually miss many of the estrus incidences and hence have resulted in a 20-30% decline in conception rates and further massive economic losses.This paper presents an advanced framework integrating machine learning and Internet of Things (IoT) technologies to improve estruses detection in dairy cattle, thereby supporting efficient herd management and productivity. The proposed solution leverages a stacking model of Random Forest and Gradient Boosting Machine (GBM) algorithms to accurately identify estruses events, providing a reliable method for reproductive monitoring. The experimental evaluation yields accuracies of 92.1 % using RF, 92.3 % using GBM, and an improved 93.19 % when the stacking model is applied, along with improvements in precision of 94 and an F1-score of 94 %, reflecting its strength in complex behavioral pattern recognition. Rigorous evaluation across key performance metrics confirms the model's high accuracy, underscoring its suitability for practical deployment. The system employs IoT-enabled smart collars equipped with temperature sensors, accelerometers, GPS, and RFID to gather real-time data on cattle health and reproductive status. By analyzing this data, the system delivers precise and timely insights into estruses cycles, enabling targeted breeding interventions and

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enhanced reproductive management. Data collected through the smart collars is securely stored in Google Firebase, facilitating efficient data archiving and rapid access via a user-friendly web application. The proposed integration of IoT, machine learning, and cloud computing presents a holistic, scalable, and economically viable solution for enhancing reproductive efficiency, animal welfare, and sustainable dairy management.

Index Terms: Internet of Things, Dairy Management, Estrus Detection, Machine Learning Algorithm, Google Firebase

1. Introduction

In the dynamic world of dairy farming, detecting estrus cycles in cattle is a cornerstone of effective herd management and breeding. Historically, this process has relied on manual observation and record-keeping methods that, while traditional, are often labor-intensive and prone to error. Farmers spend countless hours monitoring their herds, only to face the risk of missed cycles and suboptimal breeding opportunities. The traditional approach not only strains resources but also limits the potential for maximizing herd productivity and health. Imagine transforming this challenging task with technology that makes estrus detection more precise and less dependent on human oversight. As technology advances at a rapid pace, this vision is becoming increasingly feasible. By harnessing the power of Internet of Things (IoT) devices, machine learning, and cloud computing, we can now offer a revolutionary approach to dairy cattle monitoring. The research introduces a pioneering solution designed to address these challenges directly. Central to this innovation is an IoT-enabled collar that continuously monitors and collects vital data from each cow. Equipped with sensors that track physiological indicators relevant to estrus cycles, the collar gathers real time information that is crucial for accurate detection. This data is then processed using advanced machine learning algorithms, which analyze patterns and predict estrus cycles with remarkable accuracy surpassing the capabilities of manual methods. What sets our approach apart is its seamless integration with Google Firebase Cloud. This integration not only ensures efficient data storage but also enables real-time processing and the development of intuitive applications. Farmers can access valuable insights through an easy-to-use interface, streamlining the management process and making data-driven decisions simpler and more effective. The goal is to empower dairy producers with a tool that enhances the accuracy of estrus detection while simplifying the management process. By automating these essential tasks, our system aims to support farmers in making more informed decisions, improving breeding outcomes, and ultimately boosting the productivity and welfare of their herds. This advancement represents a significant leap forward in dairy cattle management, bringing together modern technology to create a solution that is not only more efficient but also more compassionate toward the animals

2. Related Work

The study [1] explores the neck tags that the cows wore recorded their movements and positions by interacting with anchor nodes positioned around the barn. Twelve cows' worth of data were gathered over the course of twelve days, and the essential behaviors such as standing, strolling, and feeding were identified. Using Principal Component Analysis (PCA), the data was condensed into the most important estrus markers. We examined four machine learning models: Classification and Regression Tree (CART), Linear Discriminant Analysis (LDA), Back-Propagation Neural Network (BPNN), and K Nearest Neighbors (KNN). The optimal performance was achieved by BPNN with a 0.5-hour time frame, indicating the possibility of combining sensor data with machine learning to enhance herd management and estrus detection.

The paper presents [2] dairy cattle using Internet of Things devices such as accelerometers, temperature sensors, and GPS modules. These sensors gather information on movement and physiological changes around the neck of the cow and are mounted in a data logger. Through Google Firebase, the data is sent to a cloud system where machine learning algorithms examine it in order to look for estrus related indicators'-means clustering is used to preprocess the data and group the data into activity levels in order to distinguish between normal and hot activities. heat detection by using Decision Trees (D-trees) and Support Vector Machines (SVM) for classification. By automating estrus identification, this technology decreases the need for manual monitoring while enhancing farm.

This paper's technique [3] precision livestock farming (PLF), which collects sensor data continuously to improve management, offers a solution to the substantial influence ruminant animals have on global agriculture and emissions. Dairy output depends on reliable estrus identification, yet conventional techniques are frequently expensive and imprecise. To enhance estrus identification, this study presents LCE (Local Cascade Ensemble), a hybrid machine learning technique that combines explicit and implicit methods. We showcase the improved performance and interpretability of LCE, with the goal of improving autonomous estrus detection and dairy farm efficiency, by testing the integration of activity and temperature sensors and investigating several classifiers.

This work monitored [4] using a Jetson Nano minicomputer and a Logitech C615 camera, we created an estrus detection system that allows us to track cow behavior in real time. To reliably identify estrus activities, the webcam records videos of cows moving, including standing and lying down. These videos are then processed by the YOLOv5

deep learning system. The 7-inch LCD touchscreen device integrates hardware and software components to give instantaneous input on the estrus condition of cows. Large-scale farming benefits greatly from this technology since it automates the detection process, which lowers the need for manual monitoring and improves reproductive control.

This study details [5] cows are monitored by a wireless transmitter equipped with resistance and temperature sensors as part of the estrus detection system. The transmitter is powered-efficient since it only turns on when necessary thanks to a micro-controller. Every 30 seconds, data from the device which measures vaginal resistance is sent to a computer for examination. The sensors are enclosed in a waterproof, 3D-printed enclosure that fits snugly within the cow. To determine how the cow's motions such as standing or lying down impacted the results, sensor data was matched with video footage. With the help of this technology, cow management and estrus detection are enhanced by ongoing, automated monitoring.

The focus of the article [6] estrus detection in cows involves behavioral and physiological changes, such as increased activity and temperature swings. Traditional methods are laborious and ineffective, especially on large farms. Automated systems use technology like heat sensors, pressure detectors, and accelerometers to monitor cow activity. Real-time data analysis helps identify estrus, enabling prompt artificial insemination and better herd management. This method reduces manual effort and increases the chances of successful reproduction, thus increasing productivity.

The project's goal [7] monitored 46 Holstein cows, using 3-D accelerometer ear tags to track their behavior and ear temperature, while also measuring progesterone levels in milk to detect estrus. The cows were observed from 20 to 90 days after calving. By comparing behavioral changes and ear temperature during estrus with non-estrus periods, the study aimed to determine the accuracy of these metrics in identifying estrus. Statistical analyses were conducted to evaluate how factors like cow age and health status affected detection accuracy. The study found that combining behavior and temperature data provided the most reliable estrus detection, offering valuable insights for improving reproductive management in dairy herds.

This research presents [8] to identify estrus, the study employed ingestible bio-sensors to track the internal body temperature of cows in real time. These sensors were positioned into the rumen of the cows and sent temperature information to a server. Using a mobile app, the farm manager received an alert when a temperature shift indicative of estrus was observed, allowing for prompt management. Comparing this procedure to standard eye observation, it provided a more accurate and consistent means of detecting estrus.

The study involves [9] creating an IoT-based system to monitor the estrus cycle in cows. The system uses infrared temperature sensors and color sensors to detect changes in the cow's vulva, which are indicative of estrus. These sensors are connected to a microcontroller (ESP8266), which processes the data and sends it to a cloud-based server. The information is then accessible via a smartphone app, allowing farmers to monitor their cows' estrus status in real-time, ensuring timely artificial insemination. This approach improves accuracy and reduces the need for constant manual observation.

This research presents [10] IoT technology integration in agriculture, particularly in dairy farming, has improved production and animal management. Real-time activity tracking and health monitoring have been demonstrated in livestock monitoring systems. Traditional estrus detection techniques are labor-intensive and imprecise, causing breeding chances to be lost. RFID tags, GPS modules, accelerometers, and temperature sensors have improved estrus identification accuracy. Remote monitoring of livestock eliminates the need for round-the-clock supervision and allows for preventative health measures. Automated technologies for estrus identification support better herd reproductive outcomes.

The study involves [11] in livestock monitoring, machine learning (ML) is a potent tool, especially for identifying health trends and forecasting behavior. Machine learning algorithms are used in dairy farming to examine temperature and movement data from calves in order to detect estrus patterns and other health problems. Early intervention for health-related disorders is made possible by ML models' ability to identify abnormalities in sensor data. This is especially useful for detecting estrus, which helps with early breeding decisions and increases milk production. Compared to human observations, ML models may reduce the margin of error and reach high accuracy in health monitoring and estrus prediction when trained on big datasets.

The focus of the article [12] is increased security and accessibility, cloud-based platforms like Firebase have gained popularity in livestock tracking and monitoring systems. These technologies give farmers remote access to real-time information on the location, health, and estrus cycles of their cattle. Large volumes of data from IoT sensors are securely stored because to cloud solutions' scalability and resilience. Additionally, enhanced analysis, historical trend monitoring, and predictive analytics for decision-making are made possible by real-time data storage. Additionally, cloud-based solutions facilitate smooth data synchronization, giving several devices access to the most recent data. This lowers operating expenses and encourages effective cattle management.

The focus of the article [13] is solar power solutions are being increasingly used in IoT systems for dairy farms to address sustainability concerns. These systems provide a sustainable alternative to conventional power sources, ensuring continuous operation of cattle tracking devices even in off-grid rural areas. Solar panels reduce dependency on fossil fuels, reducing dairy farming's carbon footprint. The reliability of solar power ensures uninterrupted tracking, essential for estrus monitoring and real-time cattle management. Research shows that solar power integration in agricultural IoT systems makes these solutions more accessible and reliable, especially in regions with limited power infrastructure.

The study involves [14] in cattle monitoring systems have been greatly enhanced by developments in sensor technology, such as RFID, GPS, accelerometers, and temperature sensors. By connecting distinct tags to location and health information, RFID enables accurate animal identification. GPS offers real-time position data, which is essential for controlling sizable herds and minimizing cattle straying. Since body temperature is a major indication of estrus and medical issues, temperature sensors provide an extra layer of health monitoring. When these sensors are combined, a thorough system for tracking the health and behavior of cattle is created.

This research presents [15] user interfaces are crucial in designing IoT systems for cattle monitoring, as they directly impact farmers' engagement and profit from these technologies. Web-based interfaces and smartphone applications enable farmers to access livestock data from any location, making it easier for non-technical users to make decisions. Research on user-centered design in the dairy industry emphasizes the importance of user-friendly interfaces that provide complex data in an understandable way. Cattle monitoring systems using frameworks like React.js and Ionic improve interface usability by enabling smooth movement between data points, enabling farmers to make data-driven decisions.

The project's goal [16] is modular design is gaining popularity in IoT systems due to its flexibility, scalability, and ease of maintenance. In cattle tracking systems, modular design consists of distinct modules, such as power, identification, monitoring, and data processing modules, each serving a specific function. This approach enables upgrades or replacements without disrupting the entire system, facilitates troubleshooting, and enhances system reliability. Research shows that modular systems in livestock management lead to more resilient operations, adapting to technological advancements and farming needs.

3. Methodology

The proposed methodology combines IoT enabled data acquisition with advanced machine learning techniques to accurately detect estrus cycles in dairy. The system architecture of Estrus detection on dairy cattle is shown in Fig. 1.

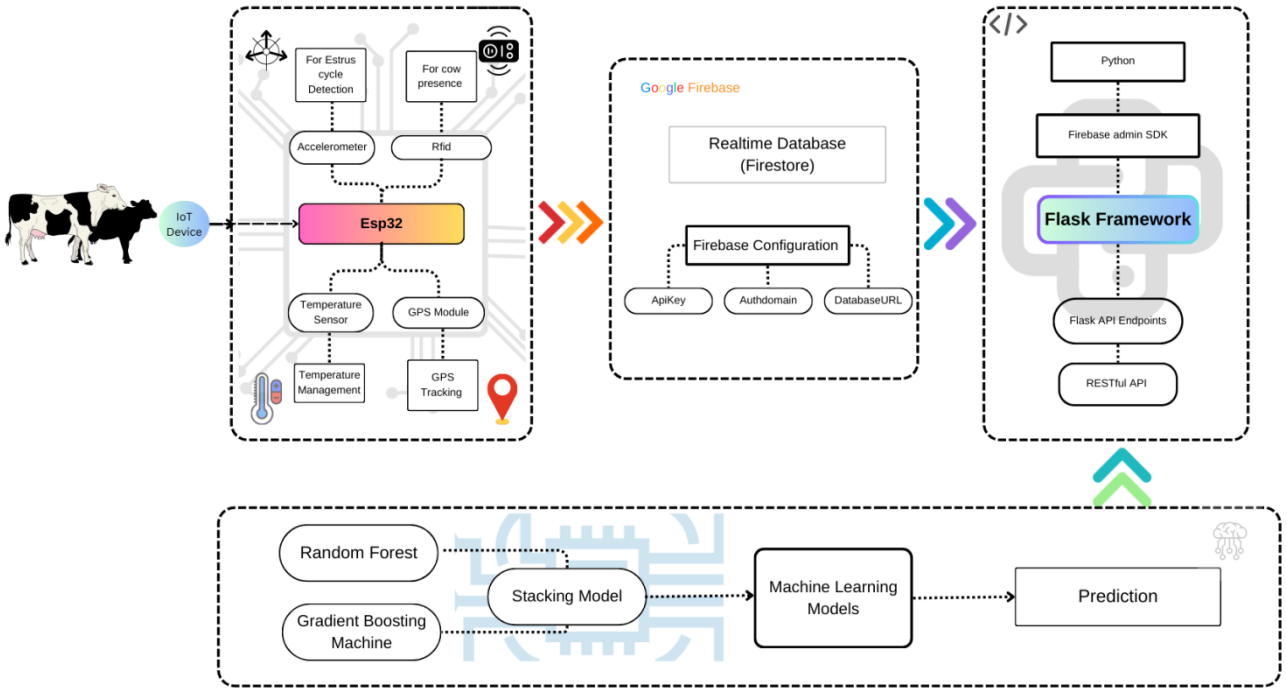


Fig. 1. System architecture of Estrus detection on dairy cattle

3.1 System Architecture

The proposed system follows a layered architecture consisting of a data acquisition layer, edge processing layer, cloud layer, machine learning layer, and application layer, ensuring clear interaction and data flow between all system components. To detect the estrus or heat cycle in dairy cattle, we leverage the advanced capabilities of Internet of Things (IoT) devices and machine learning algorithms, offering farmers a proactive and efficient system for managing reproductive cycles and overall herd health. By integrating these technologies, we provide a real-time monitoring solution that enhances milk productivity and streamlines farm operations. Our system employs several key IoT components. All IoT sensors, including the accelerometer, temperature sensor, GPS module, and RFID tag, are integrated into a smart collar and interfaced with an ESP32 microcontroller for real-time data acquisition and synchronization. A GPS sensor, embedded in the neck collar of each cow, continuously tracks its location within the farm. This not only ensures that cows are safely within designated areas but also alerts the farmer if an animal strays or

is missing from its usual location. In addition, RFID tags uniquely identify each cow, facilitating the creation of detailed individual health and reproductive records. This identification system is vital for tracking each cow's status and ensuring timely interventions. A temperature sensor monitors the cow's body temperature, a critical factor in estrus detection. Estrus is often accompanied by a slight elevation in body temperature (around 39.0 ± 0.5℃), whereas lower temperatures (approximately 38.6℃) signal other phases of the reproductive cycle. Spikes in temperature can also indicate health issues, allowing the farmer to act promptly before problems escalate.

One of the system's key elements is the accelerometer sensor, which captures detailed data on the cow's activity and behavioral patterns. During estrus, cows tend to be more restless and exhibit increased movement, a key indicator of their reproductive state. By classifying this accelerometer data into distinct behavioral categories such as eating, resting, ruminating, Sensor data retrieved from Firebase undergoes preprocessing, feature extraction, and machine learning-based estrus prediction using Random Forest, Gradient Boosting Machine, and a stacking ensemble model. The data collected by these sensors are processed using machine learning algorithms that analyze the cow's behavioral and health patterns. By comparing real-time data with historical estrus information, the system can predict when a cow is entering its heat cycle. Predictive capability allows farmers to optimize breeding times, leading to improved milk production and reproductive success. The system operates on ESP32 microcontrollers, performs initial edge-level processing such as timestamping, data packet formation, and temporary buffering before transmitting the sensor data to the cloud platform. Which manage data collection and communication between the collar's sensors and the cloud platform. To ensure the system is energy-efficient and sustainable, solar panels are integrated into the collar, providing a reliable power source. The collected data is transmitted and stored in a cloud platform, such as Google Firebase, where it is processed and made accessible to farmers via a mobile or web application. The processed sensor data is transmitted wirelessly to Google Firebase, which acts as the centralized cloud platform for real-time data storage, synchronization, and retrieval. This allows real-time, remote monitoring of cattle health and reproductive cycles. Beyond estrus detection, the system also serves as a broader health monitoring tool. By tracking various behavioral patterns such as feeding, resting, and activity levels farmers gain a deeper understanding of their cattle's well-being, allowing for more precise and proactive herd management. The combination of IoT, machine learning, and cloud computing thus not only improves estrus detection but also enhances overall animal welfare and farm productivity. This architecture ensures seamless end-to-end data flow from sensor data collection to estrus prediction and visualization, improving system transparency, scalability, and reproducibility.

Accurate sensor measurements are essential for reliable estrus detection. The smart collar integrates an accelerometer, temperature sensor, GPS module, and RFID tag, each contributing specific physiological and behavioral data. The accelerometer provides triaxial motion measurements and is subject to noise caused by animal movement and environmental factors; therefore, preprocessing techniques such as normalization and noise filtering were applied to minimize measurement errors. The body temperature sensor was calibrated against a reference thermometer prior to deployment and demonstrated an accuracy of ±0.5 ℃, sufficient to capture estrus-related temperature variations. The GPS module provides location data with meter-level accuracy under open-field conditions, while RFID ensures near-perfect identification accuracy for individual cattle. Periodic calibration and validation checks were performed to reduce sensor drift and maintain consistent data quality throughout the monitoring period. Table 1 depicts axis-wise accelerometer data sample and its movement implications.

Table 1. Detail of Accelerometer Data

Name of Axis	Example	Detail
X-axis	486	Forward-backward movement
Y-axis	503	Side-to-side movement
Z-axis	562	Up-and-down movement

This whether or not the cow is in estrus [2]. All of the data points were categorized as relative activity, however in order to detect estrus, we computed the entire activities in a single hour. We had to now specify the functionalities that are useful in identifying estrus. We clarified seven elements, such as Area (A) = X + Y + Z where for the X, Y, and Z axes is the total each data item, for individual entry, computed three-axis mean in addition established average value for the Y-axis, X-axis, and each window's Z-axis, and ultimately, we computed the total of X's average values, Z and Y axes. entry, computed three-axis mean in addition established average value for the Y-axis, X-axis, and each window's Z-axis, and ultimately, we computed the total of X's average values, Z and Y axes.

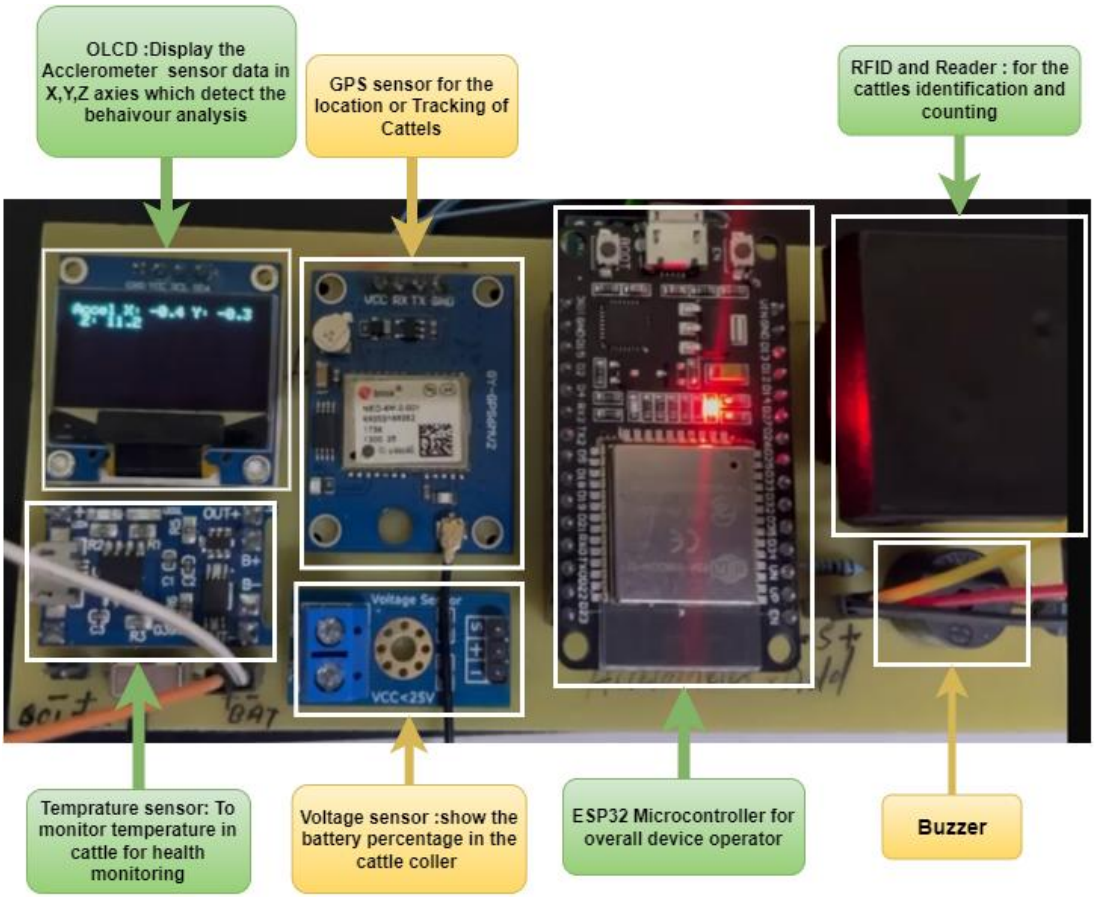


Fig. 2. Hardware setup of Estrus cycle detection in dairy cattle.

Fig. 2 shows the Hardware setup of Estrus cycle detection in dairy cattle. The system collects real-time data from an accelerometer, GPS, and temperature sensor using an ESP32 microcontroller. The acquired sensor data is preprocessed to remove noise, discard invalid readings, and normalize values. Key features such as activity intensity, movement variation, location change, and temperature trends are extracted and transmitted to the Firebase cloud. This processed data is used as input for machine learning models to analyze cattle behavior and detect heat cycle conditions, with results visualized through a web-based monitoring interface.

Table 2. Feature and Hyperparameter Overview for Estrus Detection.

Category	Parameters	Description
Input Features	x, y, z accel	Readings at 5s,1s,and 2s
Derived Features	(x , y , z)diff, sum diff	(x , y , z)diff, sum diff
Output	Binary class	0: non-estrus, 1: estrus

The table 2 depicts the input and derived characteristics from accelerometer data, such as variations in readings over time intervals, are compiled in this table for use in binary classification. It draws attention to factors that are crucial for determining whether a model is in estrus (1) or not (0).

3.2 GBM Algorithm

Gradient Boosting Machine (GBM) is an ensemble learning technique that successively integrates multiple weak learners (typically shallow decision trees) to generate an effective prediction model. GBM focuses on fixing mistakes produced by earlier trees, in contrast to Random Forest, where trees are constructed individually. Because of its progressive refining, GBM is especially useful for difficult jobs like identifying dairy cattle's estrus cycles from accelerometer data. It can also recognize subtle and complicated patterns. And preprocessing to clean and prepare the data. Gradient boosting iteratively enhances the model by minimizing errors when the model is initialized using a base model. Up to optimization, this is done repeatedly using an iteration loop. After evaluation, the model is evaluated before being applied to new data for prediction.

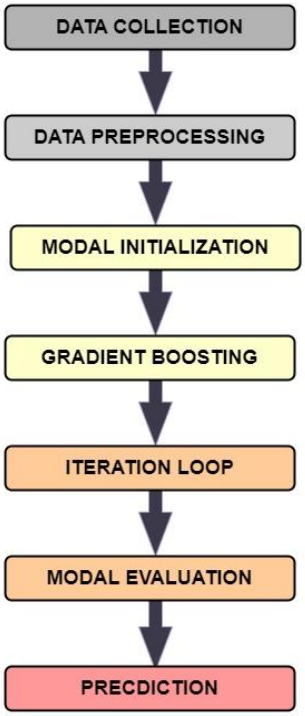


Fig. 3. Flow of GBM algorithm

The gradient boosting procedure is shown in Fig. 3, which begins with data collection and preprocessing to clean and prepare the data. Gradient boosting iteratively enhances the model by minimizing errors when the model is initialized using a base model. Up to optimization, this is done repeatedly using an iteration loop. After evaluation, the model is evaluated before being applied to new data for prediction. The formula for Gradient Boosting is:

$$F_m(x) = F_m - 1(x) + \nu \cdot h_m(x) \quad (1)$$

3.3 Random Forest Algorithm

Several separate decision trees are created with the Random Forest ensemble learning approach, which then combines the predictions to increase accuracy. Random Forest trees are generated at once, with each tree trained on a random subset of the input, in opposition to Gradient Boosting, which builds trees sequentially to rectify faults. This randomness makes the model more flexible and reduces overfitting. Because Random Forest decreases bias and variation while catching a variety of data patterns, it is especially useful for applications like detecting the estrus cycle in dairy cows. In a Random Forest, predictions are made by combining the results from multiple decision trees. For classification, the final class is decided by a majority vote across all the trees:

3.4 Stacking Model

The figure 4 illustrates a smart approach for detecting estrus in dairy cattle. Raw sensor data, capturing cow behavior, is cleaned and processed to extract key features like movement patterns. The data is divided into training, validation, and test sets for model learning and evaluation. Two models, Random Forest and Gradient Boosting Machine, generate predictions that are passed to a logistic regression model for final decision-making. This ensemble approach ensures accurate predictions. The stacking model is designed to improve estrus detection accuracy by combining the complementary strengths of Random Forest and Gradient Boosting Machine. Random Forest effectively learns diverse and non-linear activity patterns from accelerometer, temperature, and GPS sensor data, making it robust to noise and variations in cattle behavior. In contrast, Gradient Boosting Machine enhances prediction capability by sequentially correcting misclassified estrus and non-estrus instances, enabling finer discrimination of subtle behavioral changes associated with heat cycles.

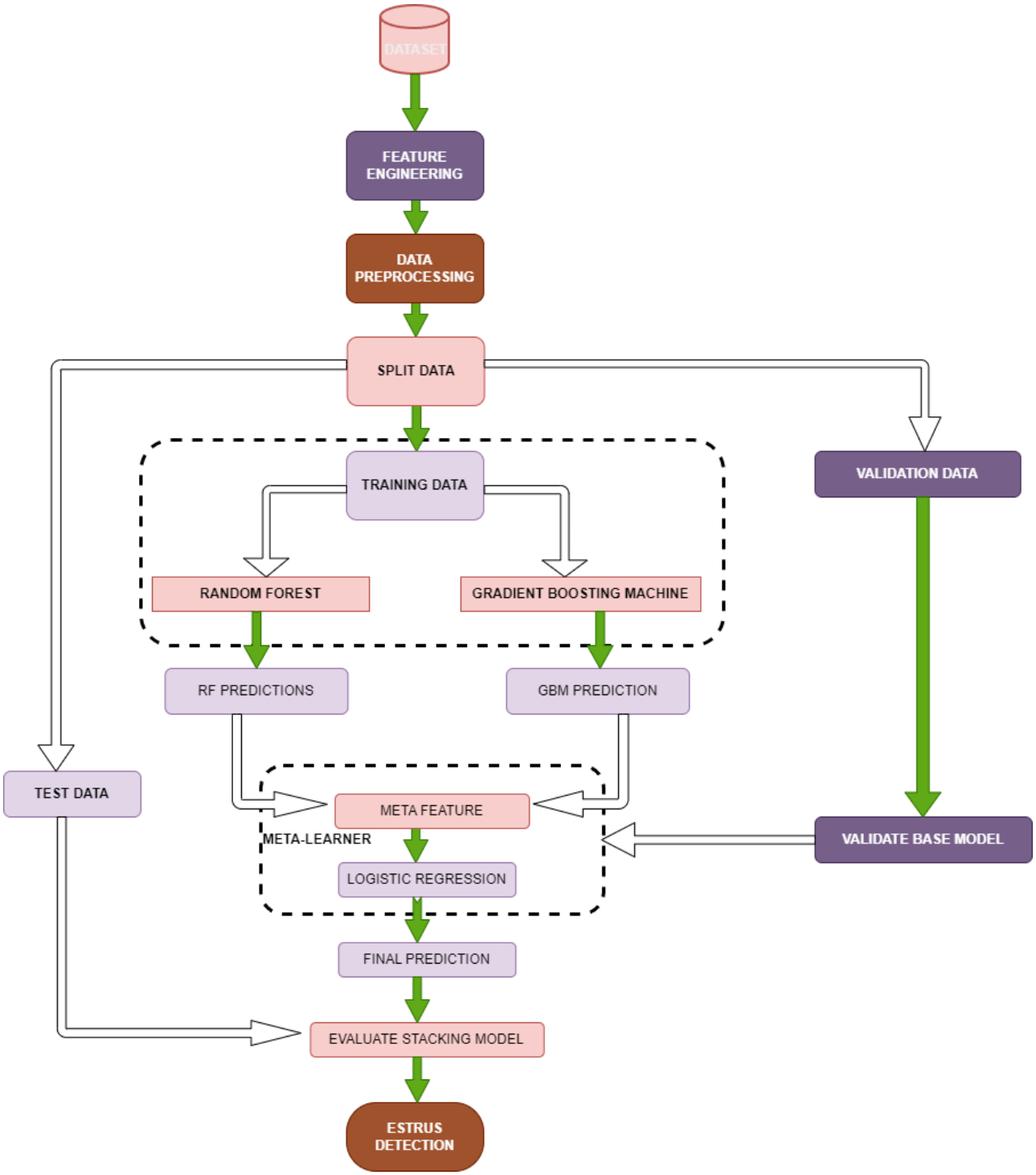


Fig. 4. Architecture of Stacking model.

The prediction outputs of both base models are then used as input features for a meta-learner, implemented using logistic regression. This meta-learner learns the optimal contribution of each base model and produces the final estrus prediction. By integrating multiple learning perspectives, the stacking approach reduces individual model bias and variance, leading to improved accuracy, reliability, and generalization in real-time cattle estrus monitoring The model is tested for effectiveness, providing farmers with valuable insights into estrus cycles for efficient herd management. To calculate a stacking model for estrus detection: Train Base Models Train multiple base models (e.g., Logistic Regression, Decision Tree, Random Forest) using features from your cattle monitoring system (e.g., accelerometer, temperature, GPS):

$$P_1(X), P_2(X), \ldots, P_n(X) \tag{2}$$

where $P_1(X)$ is the prediction from each base model. Create Meta-Model Input. Use the predictions from the base models as new input features:

$$Meta - Input = [P_1(X), P_2(X), \dots, P_n(X)] \quad (3)$$

Train Meta-Model Train a final meta-model (e.g., Logistic Regression) using these inputs:

$$Y_{meta} = \mathrm{f}_{meta}(P_1(X), P_2(X), \dots, P_n(X)) \quad (4)$$

This meta-model produces the final estrus detection prediction.

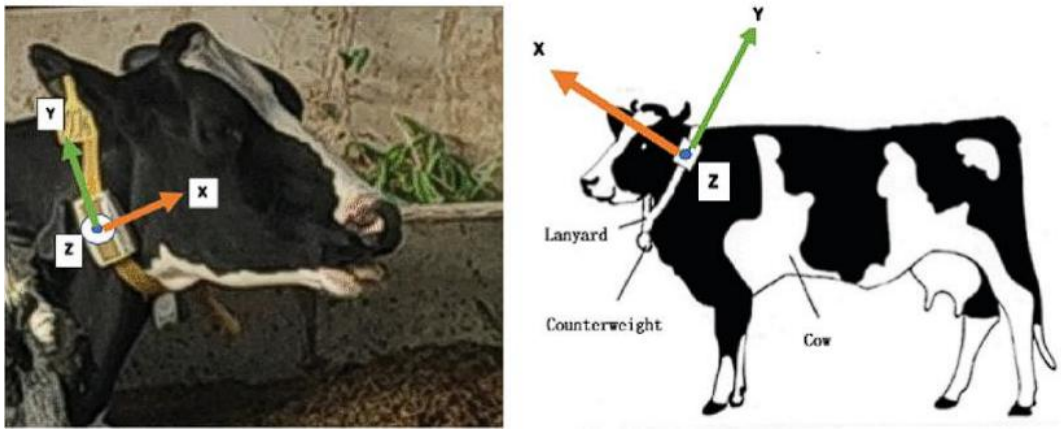


Fig. 5. Preview of Accelerometer sensor in smart collar.

The Figure 5 shows a cow with a collar that tracks its movements thanks to an accelerometer sensor. The sensor provides a comprehensive view of the cow's activities and movements by tracking motion in three directions: up and down (Z-axis), side to side (Y-axis), and forward and backward (X-axis).

The Gradient Boosting Machine (GBM), Random Forest, and Stacking models were trained using the collected sensor data from accelerometer, GPS, and temperature sensors. Hyperparameters were tuned to optimize model performance, and feature selection was performed to improve accuracy. The model performance was evaluated using k-fold cross-validation and a holdout test set to ensure robustness and prevent overfitting An ensemble learning method called stacking combines the predictions of several base models to improve accuracy overall. Stacking enables us to take advantage of the advantages of many models in the context of dairy cattle estrus cycle detection, hence increasing the accuracy of estrus predictions. The procedure begins with raw sensor data, such as the cattle's accelerometer measurements, which are preprocessed to manage missing values and eliminate noise. After that, helpful patterns like movement intensity and rest intervals which are markers of estrus behavior are extracted using feature engineering. The two foundation models, Random Forest (RF) and Gradient Boosting Machine (GBM), are then trained using the data divided into training and validation sets. While GBM refines predictions by concentrating on fixing past errors, enabling it to spot more subtle behavior changes, Random These forecasts are then combined using a meta learner (in this example, logistic regression). In order to arrive at a more accurate conclusion, the meta-learner assesses the outputs of both base models and learns how to balance their predictions. After that, fresh, untested data is used to evaluate the stacking model's effectiveness and make sure it generalizes properly. The efficiency of the stacking model is finally assessed in comparison to the separate base models, confirming that it can reliably identify estrus activity by integrating both diffuse and complex behavioral cues. In this approach, stacking offers a powerful method for estrus detection by integrating the pattern recognition strengths of Random Forest with the error- correcting abilities of GBM. This results in a more reliable and These forecasts are then combined using a meta-learner (in this example, logistic regression) In order to arrive at a more accurate conclusion, the meta learner assesses the outputs of both base models and learns how to balance their predictions. After that, fresh, untested data is used to evaluate the stacking model's effectiveness and make sure it generalizes properly. The efficiency of the stacking model is finally assessed in comparison to the separate base models, confirming that it can reliably identify estrus activity by integrating both diffuse and complex behavioral cues. In this approach, stacking offers a powerful method for estrus detection by integrating the pattern recognition strengths of Random Forest with the error- correcting abilities of GBM. This results in a more reliable and accurate system for estrus detection, aiding dairy farmers in better managing breeding cycles.

3.5 WEB interface

A web interface (or Web UI) is the visual part of a website or web application that users interact with in a browser, featuring elements like buttons, menus, forms, and dashboards to access content or functions from a remote server. It acts as a bridge between humans and complex web software, enabling tasks ranging from online shopping to device

management. The system is device-independent, using standard web technologies (HTML, CSS, JavaScript) and protocols (HTTP/HTTPS) for communication, ensuring accessibility across desktops, tablets, and mobile devices. Fig. 6 reflects how farmers may simply log in and get real-time information on the health of their livestock by using a dashboard or mobile app to access the system. The interface is designed for usability, with clear navigation, real-time alerts, intuitive visualizations of health indicators, and simplified controls for monitoring each cow efficiently**.** Farmers may make prompt, well- informed decisions by using the messages the system gives out on significant occurrences like the discovery of estrus. The estrus prediction results are sent back to Firebase and displayed on a web-based dashboard, enabling farmers to monitor real-time estrus status, activity trends, and health indicators of each cow. The cattle are equipped with sensors that collect information on their whereabouts, body temperature, activity level, and patterns of rumination. These clues aid in determining when a cow is in estrus, or prepared for breeding, and they also serve to track her general health. Using this information, the health monitoring module determines estrus automatically by observing changes in the cow's behavior and physical state, such as an increase in body temperature or more vigorous activity. To ensure the health and productivity of the entire herd, it monitors the cow's stress levels, nutritional intake, potential early indicators of sickness, and pregnancy in addition to estrus. The emergency services module intervenes with real-time notifications to tell the farmer immediately when anything has to be attended to immediately. The technology guarantees prompt reactions, whether it's identifying a health problem or indicating when breeding is most appropriate. Addition- ally, it includes built-in procedures for tracking the status of treatment and isolating sick animals, which helps to stop the spread of illness. For more effective farm management, the system offers features to streamline operations. Farmers can track and measure milk output, ensuring optimal production levels and identifying any dips that may indicate health or feeding issues. The system also manages and updates breeding records, allowing farmers to maintain accurate reproductive histories for each cow. Feed management is another critical aspect covered by the system, helping farmers optimize feeding schedules and ensure that their cattle receive adequate nutrition. Additional features include inventory management and performance reports, which provide detailed insights into the overall performance of the farm, helping to streamline operations and improve efficiency. The system offers features to measure milk output, maintain breeding data, and manage feed programs for overall farm management. In addition, it provides inventory management support and performance reports, which streamline and im- prove farm operations overall. From an analytical perspective, the system looks at patterns across time and forecasts using data analytics. For instance, it may predict when a cow will go into estrus or whether the farmer should prepare for potential health issues. These insights aid in decision-making, productivity growth, and herd performance optimization. Real-time actions are triggered as necessary, and the system functions as a continuous cycle where sensors collect data, evaluate it, and display it to the farmer via the web interface. The method makes it simpler for farmers to efficiently and sustainably manage their herds by automating these procedures, which eliminates the need for continual manual supervision.

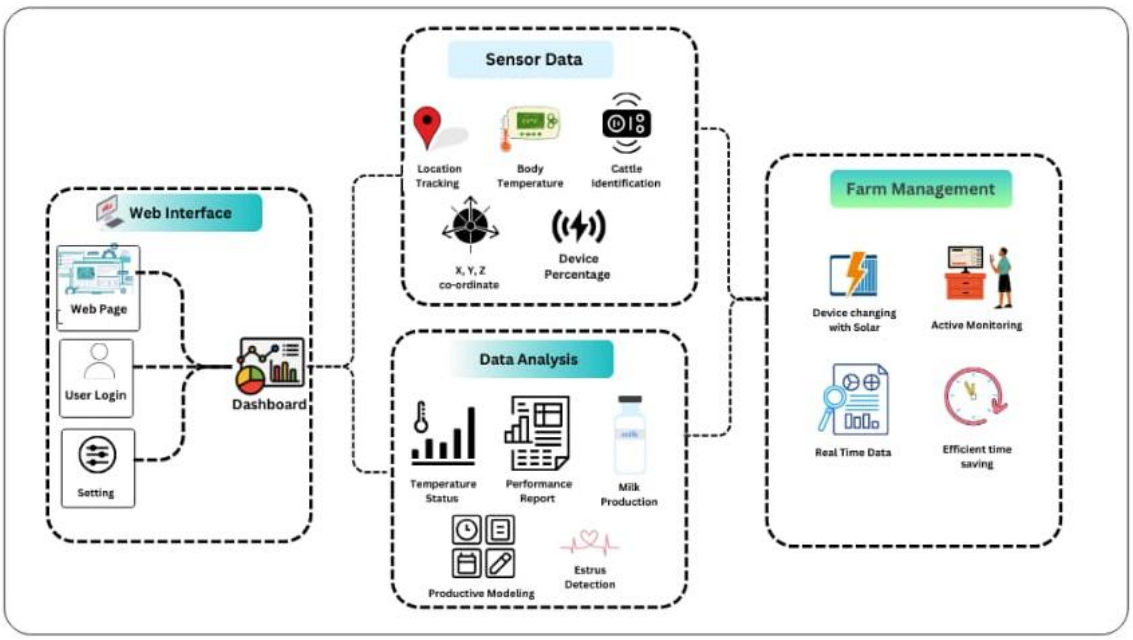


Fig. 6. Architecture of Web interface

Table 3. Hyperparameters Used in Experiment

Hyperparameter	Specification
CPU	Intel(R) Core(TM) i5-9300H CPU @ 2.40 GHz
Language	Python 3.12
GPU	NVIDIA GeForce GTX1650 Ti 4GB
Operating System	64-bit operating system
RAM	8 GB
Disk	512 GB
GPS and RFID Data	Location tracking and unique identification for each cow
Statistical Dataset Source	Kaggle Dataset
Estrus Label	Binary class (0: non-estrus, 1: estrus)
Cloud	Firebase
Software	Arduino IDE (embedded language)
Number of Epoch	20
Sampling Rate	1 s, 2 s, and 5 s intervals for accelerometer
Temperature Range	Average 38.6 ℃ (baseline); elevated around 39.0 ℃ indicates estrus
Library offering ML models	Random Forest (RF), Gradient Boosting Machine (GBM)
RF Hyperparameters	n_estimators = 100; remaining parameters set to default values
GBM Hyperparameters	n_estimators = 100, learning_rate = 0.1, max_depth = 3, subsample = 0.8
Feature Scaling	Standard Scaler applied prior to model training
Validation Strategy	80–20 train–test split used for performance evaluation

The table 3 depicts hyper-parameters used for the monitoring system which runs on an Intel i5 CPU, GTX1650 Ti GPU, and 8 GB RAM, using Python 3.12 and Firebase for cloud support. GPS and RFID track each cow, while accelerometer data sampled every 1, 2, or 5 seconds and a temperature rise (from 38.6℃ to ~39.0℃) indicate estrus. Trained over 20 epochs using Kaggle data, the model employs GBM and RF libraries. Parameters selected empirically based on preliminary experiments and existing literature to balance accuracy and computational efficiency.

4. Results and Discussions

The stacking model for estrus identification marks a major leap forward in dairy cattle management, offering an impressive 93.19% accuracy. This model skillfully navigates complex sensor data by integrating two robust machine learning algorithms: Gradient Boosting Machine (GBM) and Random Forest. While GBM achieves an accuracy of 92.3%, the Random Forest model closely follows with 92.1%. To contextualize the performance of the Stacking model, the results of individual GBM and Random Forest models were also analyzed. This comparison demonstrates that the Stacking approach improves prediction accuracy and reliability for real-time cattle behavior monitoring By combining these models, the stacking approach capitalizes on their strengths, improving overall precision in estrus detection. It uncovers intricate, non-linear relationships between cow behavior and estrus patterns that single models might miss. Beyond the accuracy of estrus detection, this system also offers practical benefits for dairy farmers. At its core is an IoT-based smart collar, continuously monitoring key physiological factors like temperature, movement, and activity levels. This collar, powered by a cloud-based infrastructure, transmits real-time data, ensuring immediate access to critical insights. Through a user-friendly mobile app, farmers can conveniently monitor estrus cycles, enabling better decision-making for breeding schedules while simultaneously reducing costs and labor. By harnessing the combined power of machine learning algorithms (MLA), IoT, and cloud computing, this system gives farmers an intelligent, data-driven tool to optimize cattle management. The ability to track cows in real-time leads to better resource management, and more importantly, supports sustainable dairy farming practices. With this advanced technology, farmers can manage their herds more efficiently while ensuring the long-term health and productivity of their live- stock. This human-centered approach to estrus detection no only boosts accuracy but also transforms the way dairy farmers engage with their animals, creating a future where technology and tradition meet to enhance both animal welfare and farm efficiency. As farmers embrace this innovative system, they pave the way for a more resilient agricultural landscape, fostering a symbiotic relationship between technology and nature. The integration of data-driven insights promotes proactive animal care, ensuring that every cow receives the attention it needs, ultimately leading to a thriving dairy operation. In this era of digital transformation, the marriage of technology and agriculture stands to revolutionize the dairy industry, setting a precedent for future advancements in livestock management.

In terms of practical deployment and scalability the proposed system is inherently scalable due to its modular IoT architecture and cloud-based deployment. Each smart collar operates independently and uploads data to Google Firebase, which supports automatic scaling for large datasets and real-time data streams. As the number of cattle or farms increases, additional devices can be integrated without modifying the core system. Data from multiple farms can be managed using unique farm and cattle identifiers, enabling centralized monitoring across geographically distributed locations. Lightweight edge-level preprocessing on the ESP32 reduces bandwidth usage, while machine learning models can be retrained periodically with larger datasets to maintain performance. This design ensures effective scalability for large herds, long-term data collection, and multi-farm deployments.

Table 4. Result Analysis of the Machine Learning Model

ML Model	Accuracy	precession	Recall	F1 Score
RF	92.1%	92%	93%	92%
GBM	92.3%	92%	93%	92%
Stacking model	93.19%	94%	93%	94%

This table.4 shows how three models Random Forest (RF), Gradient Boosting Machine (GBM), and a Stacking model measure up on accuracy, precision, recall, and F1 score. The Stacking model leads with the highest accuracy at 93.19%, narrowly beating GBM and RF, which scored 92.3% and 92.1%, respectively. It also tops precision at 94%, edging out RF and GBM, both at 92%. In terms of recall, the models are close, with RF and GBM at 93%, and the Stacking model just slightly behind. Finally, the Stacking model achieves the highest F1 score at 94%, reflecting its strong balance between precision and recall. In addition to accuracy and F1 scores, error analysis was performed to identify false positives and false negatives in predicting cattle behavior, providing a clearer understanding of model reliability in real-time monitoring. Overall, the stacking model emerges as the best option here, proving to be the most effective of the three.

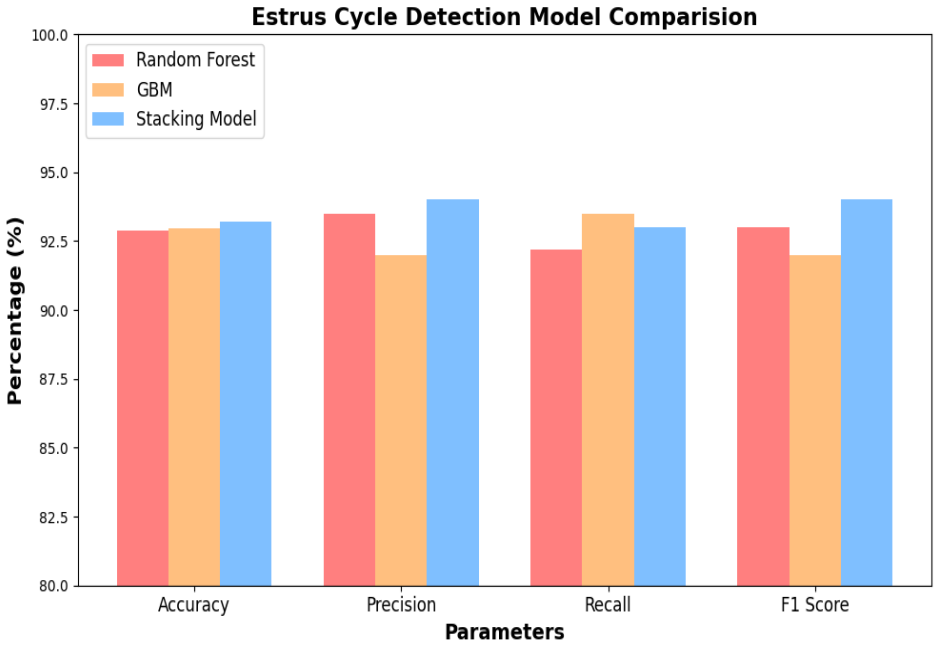


Fig. 7. Overview of the model comparision

Fig. 7. Based on four metrics Accuracy, Precision, Recall, and F1 Score his bar graph compares the efficacy of three models in identifying the estrus cycle: Random Forest, GBM, and Stacking Model. In every parameter, the Stacking Model performs better than the other two models, especially in Recalland F1 Score.

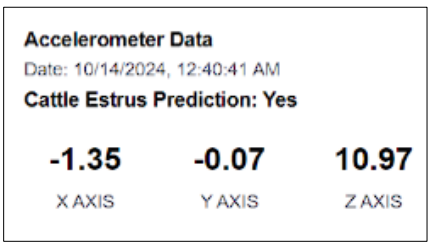


Fig. 8. Estrus prediction through the real time accelerometer sensor data

Figure 8 displays accelerometer data along the X, Y, and Z axes, with values of -1.35, -0.07, and 10.97, respectively. This data was recorded at 12:40:41 AM on 10/14/2024. The system has also made a cattle estrus prediction, indicating"Yes"meaning that based on the motion data, the cow is likely in estrus (ready for breeding). This information helps farmers make timely decisions regarding cattle breeding

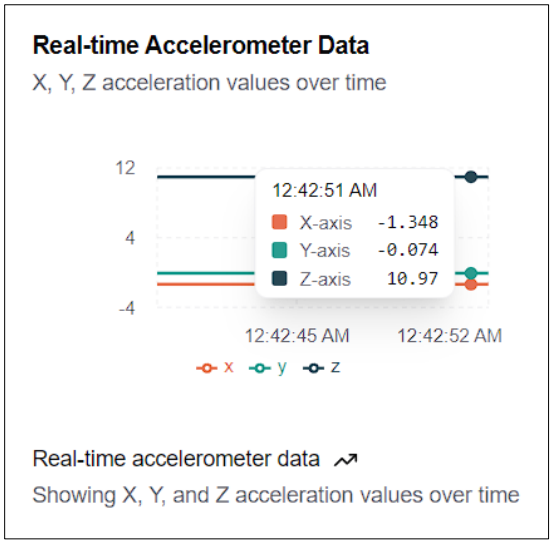


Fig. 9. Overview of Real time accelerometer sensor data

Figure 9 presents real-time accelerometer data tracking movement along the three spatial axes: X, Y, and Z. Each axis captures motion in a distinct direction, providing a comprehensive view of movement patterns in three-dimensional space. By monitoring changes along each axis, this data enables precise detection of shifts in activity and behavior, allowing for a detailed analysis of motion dynamics over time. The resulting patterns offer valuable insights, particularly for understanding behaviors that vary with movement intensity and orientation.

The Figure 10 illustrates how three machine learning models progress in accuracy over 20 training epochs as they learn to detect the estrus cycle in dairy cattle. Each model's lines show its training and validation accuracy, highlighting how well it captures and generalizes patterns in estrus behavior. Model 1 starts with the lowest accuracy and makes gradual progress, reaching validation accuracy by the end. This suggests it struggles to fully capture the subtle signs of estrus. Model 2 performs better, reching aro validation accuracy, indicating it's able to detect key estrus signals but may still miss some patterns. Model 3 stands out with accuracy in both training and validation, showing it's highly effective at recognizing and generalizing the unique behaviors linked to estrus. The close match between Model 3's training and validation accuracy suggests it generalizes well, making it the most reliable model for practical use. This accuracy in detecting estrus is critical for timely and accurate herd management, helping improve breeding outcomes and overall farm efficiency.

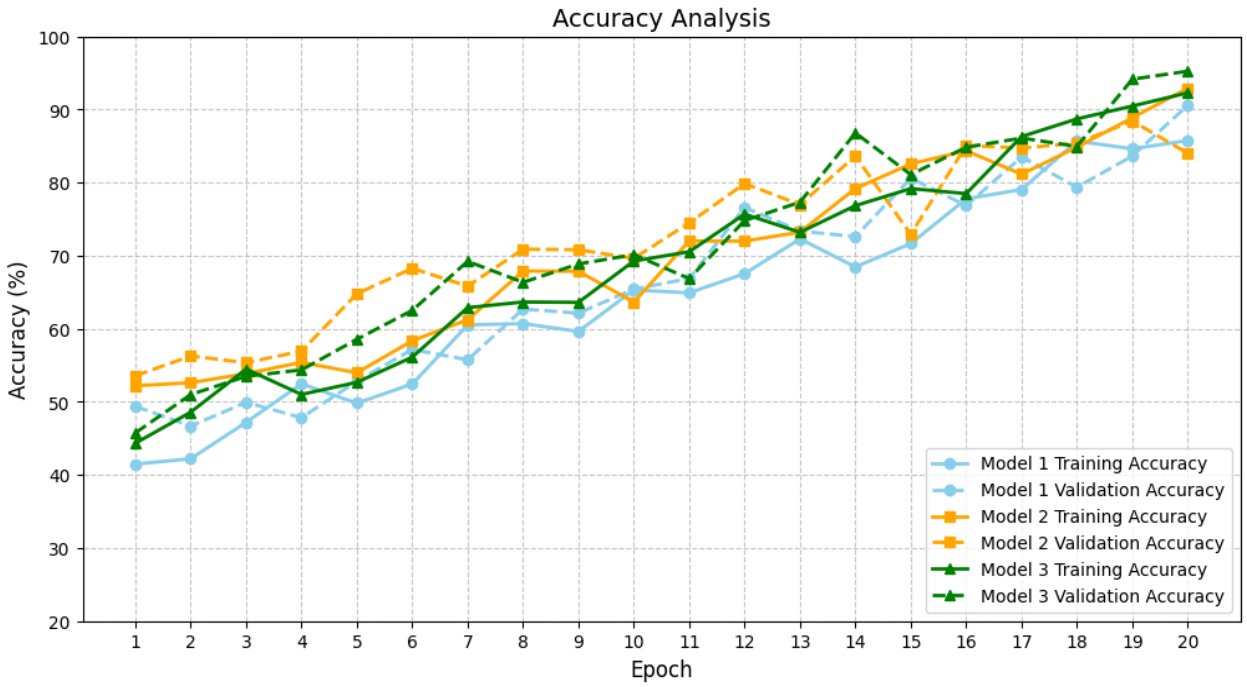


Fig. 10. Overview of model training and validation accuracy analysis

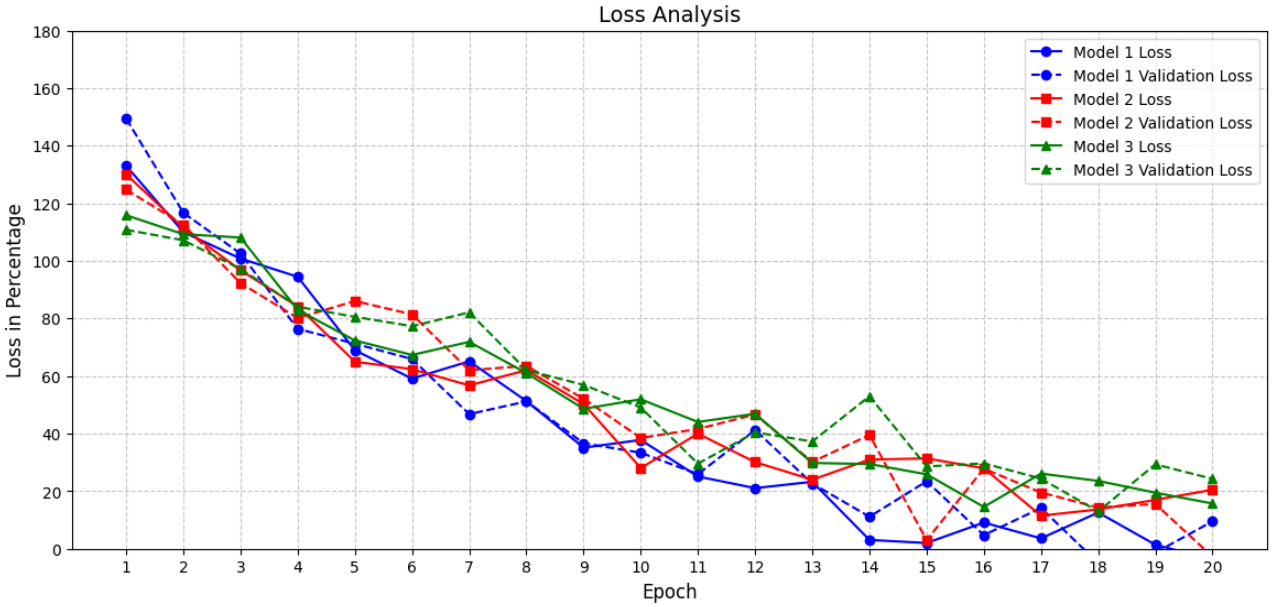


Fig. 11. Overview of training and validation loss analysis

The figure 11 illustrates the loss reduction over 20 training epochs for three machine learning models designed to detect estrus cycles in dairy cattle. Loss represents model error, with lower values indicating better performance. All three models show a steady decrease in loss, reflecting their improvement in detecting estrus-related patterns.

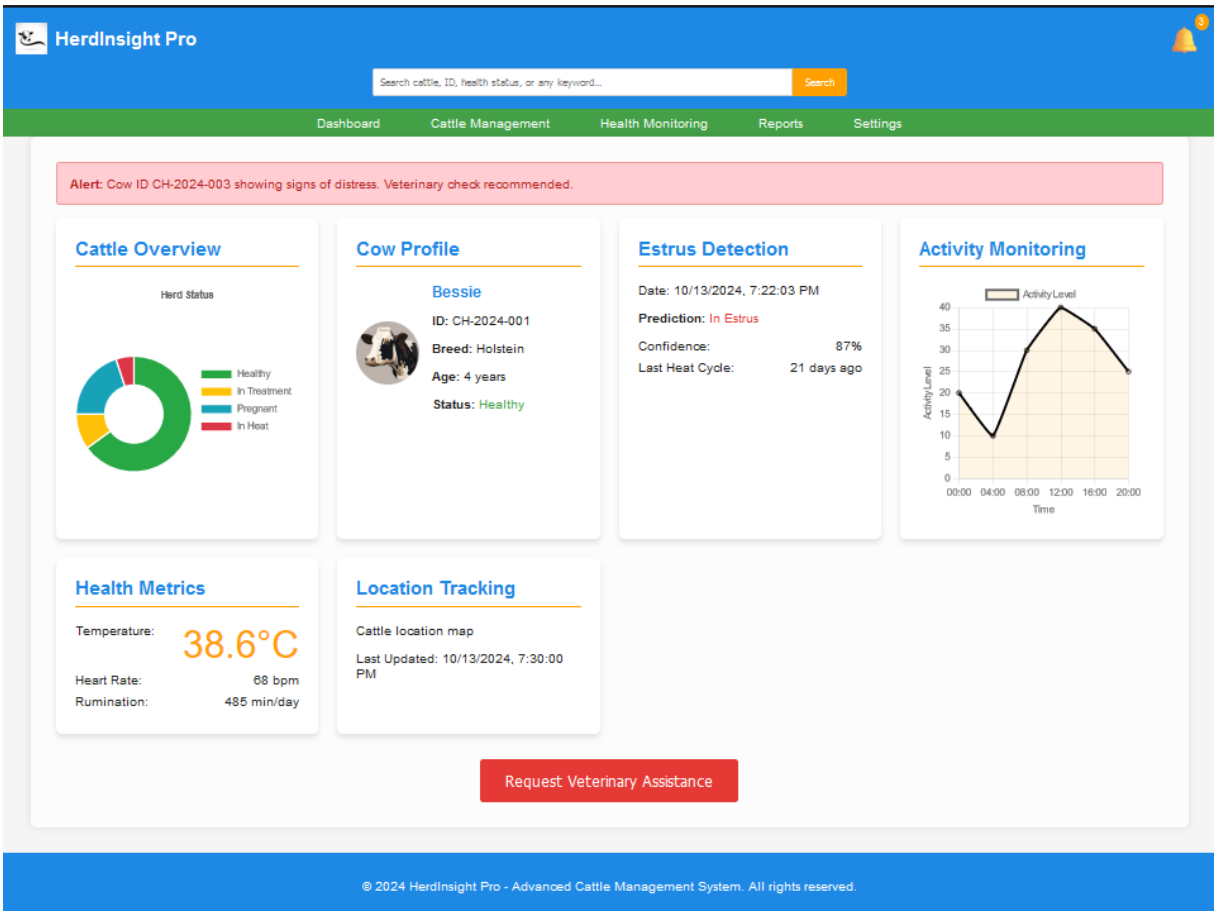


Fig. 12. Web application interface of dairy cattle estrus detection

Model 1 (blue) starts with the highest loss but gradually decreases, showing consistent improvement, though it takes longer to reduce error. Model 2 (red) begins with a slightly lower initial loss and declines similarly, eventually achieving a validation loss close to Model 1. Model 3 (green) consistently maintains the lowest loss across both training

and validation, suggesting it learns more effectively and faster than the others. The close alignment between training and validation loss for each model indicates minimal overfitting and good generalization. Model 3 stands out as the most effective, with the lowest loss values, making it the best candidate for accurate estrus cycle detection in dairy cattle.

Figure 12 shows a comprehensive overview of IoT-based dairy cattle estrus detection system, core intelligent control, and monitoring unit provide a single picture of each cow in real time about their health, behavior, and reproductive status. It continuously displays vital physiological characteristics such as body temperature, activity level derived from an accelerometer, movement intensity, and general health indicators that allow farmers to rapidly investigate their cattle's physical condition. The estrus prediction created by the stacking machine learning model is indicated on the dashboard in a prominent way so that farmers can rapidly recognize breeding readiness and make insemination decisions accordingly. GPS-based position tracking is also included that will help check cow movement and reduce wandering for the maintenance of farm security. The dashboard has a built-in emergency warning system that immediately alerts the farmer in case of abnormal temperature rise, unusual inactivity, health distress, or stress-related behavioral changes so that immediate medical attention is facilitated. Apart from estrus identification, the system monitors milk production to analyze yield patterns, detect unexpected reductions in output, and thereby link productivity with health and nutrition. It also maintains a very accurate breeding history of each cow, including dates of estrus, insemination status, and pregnancy tracking, which helps in reproductive planning and herd fertility control. Feed and nutrition management aspects aimed at optimizing feeding schedules and ensuring optimum diet balance, while inventory management and performance reporting facilities expedite farm operations. This predictive analytics of historical and current data can forecast future estrus cycles and possible health hazards, making the dashboard an proactive decision-support tool. Real-time visualization, cloud-based data access, machine learning intelligence, automated alerts, and farm management are integrated into one user-friendly interface, dramatically reducing manual supervision, increasing breeding efficiency, enhancing animal welfare and milk productivity, and promoting sustainable data-driven dairy farm management.

5. Conclusion and Future Scope

This work highlights the revolutionary possibilities of combining machine learning algorithms with IoT technology for dairy cattle estrus identification..With an amazing accuracy of 93.19%, the stacking model outperforms individual models such as Random Forest and Gradient Boosting Machine (GBM) by a wide margin. Our method improves herd management by detecting estrus cycles and using data from smart collars with temperature sensors, accelerometers, and GPS.With the help of this creative strategy, dairy producers can now watch their animals in real time, which enhances animal welfare and breeding schedule optimization. Combining these technologies lowers expenses and guarantees the welfare of cattle, promoting a sustainable agricultural strategy.This research ultimately shows how agriculture and technology can live together peacefully, opening the door to a robust future for dairy production. A healthy dairy sector that respects both productivity and heritage may be achieved by embracing innovation and placing a high priority on animal care.

Despite achieving high accuracy in estrus detection, the proposed system has certain limitations. The current implementation relies on continuous data transmission from smart collars to the Firebase cloud platform, which may be affected by internet availability in rural dairy farm environments. Sensor readings from accelerometers, temperature sensors, GPS, and RFID may be influenced by collar placement, animal movement variability, and environmental conditions, potentially introducing noise into the data. In addition, the machine learning models were trained using a limited dataset and evaluated under controlled experimental settings, which may impact generalization when deployed across larger herds, different farm layouts, or diverse cattle breeds.

Future improvements will focus on enhancing system robustness and real-world applicability. This includes training the stacking model with larger and multi-farm datasets to improve generalization and reliability. Edge-level intelligence on the ESP32 microcontroller can be extended to perform preliminary estrus inference, reducing cloud dependency and communication latency. Further enhancements may include the integration of additional physiological sensors, improved feature extraction techniques, and adaptive model retraining using newly collected data. These advancements will strengthen system accuracy, scalability, and suitability for large-scale dairy farm deployments.

Author Contributions Statement

Rhutuja Kshirsagar – Conceptualization, Methodology, and Supervision: Proposed research ideas, constructed the overall framework, supervised project execution, drafted the initial manuscript, and performed review and editing.

Kamlesh Kalbande – Writing – Review and Editing, and Project Management: Reviewed and edited the manuscript, ensured clarity and coherence, and coordinated project milestones and deadlines.

Pooja Yerunkar – Literature Survey and Documentation: Contributed to the literature survey and documented the technical background of the study.

Akhilesh Lokhande – Model Training, Validation, and Performance Evaluation: Led the model training process, validated results using standard metrics, and benchmarked performance against existing methods.

Krishnendu Mondal – Data Curation and Software/Hardware Implementation: Handled data acquisition, dataset preprocessing, implementation of the research model, and hardware implementation.

Harsh Jagtap – Formal Analysis, Visualization, and Statistical Analysis: Performed in-depth analysis of experimental results, prepared performance charts, ensured statistical robustness, and contributed to hardware implementation.

Rahul Chunarkar – Hardware Implementation and Documentation: Contributed to hardware implementation, literature survey, and documentation of the technical background.

All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The authors declare no conflicts of interest.

Funding Declaration

This research was not supported by any external agencies.

Data Availability Statement

The dataset used in this study is publicly available. Details are provided below:

Dataset Source: Kaggle Dataset

Link: https://www.kaggle.com/datasets/tonygim/cattle-estrus-detection-patch-images-red-colour

Ethical Declarations

The authors declare that this study does not involve any experiments on human participants or animals. Therefore, ethical approval was not required.

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Declaration of Generative AI in Scholarly Writing

During the preparation of this manuscript, the author(s) used generative AI tools to assist in improving the language, clarity, and organization of the content. The use of these tools was limited to the writing process only. Generative AI tools were not used for data analysis, interpretation of results, or drawing conclusions.

Abbreviations

The following abbreviations are used in this manuscript:

AI - Artificial Intelligence
IoT - Internet of Things
ML - Machine Learning
RF - Random Forest
GBM - Gradient Boosting Machine
GPS - Global Positioning System
RFID - Radio Frequency Identification
ESP32 - Microcontroller Unit
PCA - Principal Component Analysis
CART - Classification and Regression Tree
LDA - Linear Discriminant Analysis
BPNN - Back Propagation Neural Network
KNN - K-Nearest Neighbours
SVM - Support Vector Machine
PLF - Precision Livestock Farming

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Krishnendu Mondal received his Bachelor of Technology (B.Tech) degree in Computer Science and Engineering with a specialization in Internet of Things (CSE–IoT) from G. H. Raisoni College of Engineering, Nagpur, Maharashtra, India. His academic background and project experience are centered on Internet of Things, Machine Learning, Embedded Systems, and Cloud Technologies. He has worked on the design and development of systems integrating IoT platforms with machine learning models, as well as embedded system–based implementations, with an emphasis on intelligent and scalable system design.His research interests include IoT-based intelligent systems, machine learning applications in embedded and IoT environments, and cloud-enabled smart solutions.



Harsh Jagtap, Computer Science Engineering graduate with strong fundamentals in Java, Data Structures & Algorithms, SQL, and IoT systems, along with hands-on experience in building end-to-end technical projects. Experienced in developing sensor-based IoT solutions using ESP8266/ESP32, integrating real-time data with cloud platforms, and designing web-based dashboards for monitoring and visualization. Completed projects in smart agriculture monitoring, IoT systems integrated with machine learning, and Java-based algorithmic problem solving, demonstrating the ability to combine software development, data handling, and hardware interaction. Possesses strong analytical thinking, problem-solving skills, and collaborative experience gained through technical activities and project-based work.



Rahul Chunarkar received the Bachelor of Technology (B.Tech) degree in Computer Science and Engineering with a specialization in Internet of Things (CSE–IoT) from G. H. Raisoni College of Engineering, Nagpur. His academic background and project experience are centered on the Internet of Things, Data Analytics, Deep Learning, and Cloud Technologies. He will worked on the design and development of systems integrating IoT platforms with AI models (such as LSTM/CNN), as well as embedded system–based implementations for environmental and livestock monitoring, with an emphasis on intelligent data visualization and real-time logging. His research interests include IoT-powered surveillance systems, machine learning applications in embedded environments, and cloud-enabled smart solutions.

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