

Internet of Things (IoT) Applications for Estrus Detection and Management in Precision Livestock Farming: A Review

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ABSTRACT

The livestock industry represents a vital sector of the global economy, where reproductive management plays a key role in sustaining productivity and profitability. Estrus detection, a critical component of reproductive efficiency, directly influences breeding success and overall herd performance. Recent advancements in the Internet of Things (IoT) have introduced new opportunities to enhance estrus detection through the integration of sensors, data analytics, and machine learning algorithms. This review explores the potential of IoT-based technologies in livestock estrus detection, focusing on a wide range of approaches including wearable and non-wearable sensors, data collection frameworks, and advanced analytical methods. Commercial IoT-based estrus detection systems are also examined, alongside comparative evaluations of detection performance, advantages, and limitations. Key challenges such as battery life, connectivity, network coverage, data security, privacy, and cost scalability are discussed in detail. Furthermore, the paper highlights future directions, including the integration of IoT with precision livestock farming and the role of emerging technologies in improving animal welfare and production efficiency. Overall, this review provides a comprehensive overview of IoT-based estrus detection, outlining current progress, practical implications, and recommendations for future research and implementation.

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1. INTRODUCTION

The global livestock industry has expanded rapidly in recent years, driven by the rising demand for animal products including milk, meat, and wool. Sustaining this growth requires maintaining high reproductive efficiency, which is a key determinant of profitability and long-term sustainability in livestock production systems [1]. One of the most critical components of reproductive efficiency is the accurate detection of estrus. Estrus, commonly referred to as heat, is the reproductive phase during which female animals are receptive to mating and conception. Timely and precise estrus detection plays a decisive role in improving breeding success, optimizing reproductive performance, and shortening the calving interval, all of which directly influence farm profitability [2].

Traditionally, estrus detection has relied on visual observation of behavioral and physical changes such as increased activity, restlessness, vocalization, and mounting behavior. While these methods have been widely practiced, they are often labor-intensive, subjective, and prone to human error, resulting in low detection

accuracy and missed breeding opportunities. To address these shortcomings, technological advancements have introduced automated detection methods, including hormone assays, pedometers, and video-based monitoring systems [3]. Among these, Internet of Things (IoT) technologies have emerged as a highly promising approach. By integrating sensors, connected devices, and real-time analytics, IoT enables continuous, non-invasive monitoring of physiological and behavioral parameters associated with estrus. Such systems not only enhance detection accuracy but also reduce labor requirements and contribute to improved reproductive outcomes and profitability.

This paper reviews the current state of IoT-based estrus detection technologies in livestock, focusing on cattle, sheep, and goats. Specifically, the following research questions are addressed:

1. What IoT-based technologies are currently applied for estrus detection in livestock, and how do they function?
2. What advantages and drawbacks do IoT-based systems present compared with conventional methods?
3. What challenges and opportunities exist for practical adoption, and how might these solutions influence livestock management and productivity in the future?

Recent studies have highlighted the growing relevance of IoT in dairy farming. Estrus detection is particularly important in dairy herds, where reproductive efficiency strongly influences milk production. For instance, [4] proposed an IoT-based framework incorporating sensors, gateways, and communication networks to monitor animal health, behavior, and productivity. Collected data are transmitted and analyzed using data analytics methods, enabling farmers to make informed decisions and improving efficiency through real-time monitoring, resource management, and cost reduction. Building on this, Lee [5] developed a smart monitoring system that integrated IoT devices with machine learning algorithms. Using a 3-axis accelerometer node connected to an IoT server, the system continuously tracked cow movements, applied classification algorithms to detect estrus, and alerted farmers in real-time. This approach provided a reliable, non-invasive solution for improving breeding management and animal welfare while enhancing profitability.

Similarly, [6] introduced a cow estrus monitoring system utilizing NB-IoT (narrowband IoT) communication. The system measured cows' activity levels and body temperature, transmitting data to a centralized server accessible to users in real-time. By employing dynamic threshold algorithms on three-axis acceleration data, the system adapted to breed variations, individual differences, and environmental factors. In addition, image recognition was used as a complementary tool, further increasing detection accuracy. This combination allowed for early health issue identification, minimized missed estrus events, and ultimately improved herd productivity. Although cattle dominate the current literature and commercial implementations, the technologies and methodologies reviewed are extensible to other livestock species with appropriate behavioral and physiological adaptations.

The remainder of this paper is organized as follows. Section 2 introduces IoT technologies applicable to estrus detection, including NB-IoT, LoRaWAN, RFID, accelerometers, pedometers, and inclinometers. Section 3 explores wearable and non-wearable sensors such as infrared thermography, pressure-sensitive mats, acoustic systems, and video-based monitoring. Section 4 discusses data collection, transmission, and analytics approaches. Section 5 reviews existing IoT-based estrus detection implementations, followed by Section 6, which evaluates their performance using key metrics and comparative analyses. Challenges, limitations, and adoption barriers are also discussed. Finally, Section 7 presents the conclusion and highlights directions for future research.

2. REVIEW METHODOLOGY

This review adopts a structured and domain focused literature analysis to examine the evolution, current state, and practical implications of Internet of Things (IoT) applications for estrus detection and management in precision livestock farming. The review period was intentionally limited to 2015–2024, as this decade marks the rapid maturation of IoT architectures, low power communication protocols, wearable sensing technologies, and data driven analytics relevant to livestock monitoring. Literature was collected from well established scientific databases, including IEEE Xplore, Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar, ensuring balanced coverage of engineering, agricultural, and interdisciplinary research. Search queries were formulated using combinations of keywords such as *“IoT estrus detection,”* *“precision livestock farming,”* *“automated heat detection,”* *“wearable livestock sensors,”* *“animal reproductive monitoring,”* and *“smart dairy farming.”* To ensure completeness, backward citation tracking was also applied to influential review and survey articles.

Following retrieval, the studies were screened using predefined inclusion and exclusion criteria to maintain technical relevance and analytical depth. Only peer-reviewed journal articles, conference papers, and selected commercial or system oriented studies that explicitly incorporated IoT components such as sensors, communication networks, edge/cloud platforms, or data analytics for estrus detection or reproductive management were included. Studies relying solely on manual observation or conventional reproductive

diagnostics without technological integration were excluded. The selected literature was then systematically classified according to sensor modality, communication technology, data analysis approach, and application context (experimental prototypes versus deployed commercial systems). Rather than performing a statistical meta-analysis, this review emphasizes comparative synthesis, identifying technological trends, performance trade-offs, adoption barriers, and research gaps. This approach is well suited to the heterogeneous nature of IoT-based estrus detection systems and allows meaningful comparison across diverse methodologies. The details related to review methodology are presented in Table 1.

Table 1. Temporal and technological classification of IoT-based estrus detection research (2015–2024)

Period	Dominant Technologies	Sensor Focus	Communication Methods	Data Analysis Approach	Key Research Trends
2015–2016	Early IoT adoption	Accelerometers, pedometers	Wi-Fi, Bluetooth	Threshold-based analysis	Initial automation of activity-based estrus detection; transition from manual observation
2017–2018	Wearable sensor systems	Activity, temperature, RFID	Wi-Fi, ZigBee	Statistical analysis, rule-based models	Increased use of wearable devices and basic data fusion
2019–2020	LPWAN-enabled IoT	Accelerometers, temperature, GPS	NB-IoT, LoRaWAN	Machine learning (SVM, decision trees)	Long-range connectivity for large farms; energy efficiency gains
2021–2022	Smart livestock platforms	Multi-sensor systems	NB-IoT, LoRaWAN, cellular	Neural networks, pattern recognition	Integration of AI with IoT; improved detection accuracy
2023–2024	Intelligent IoT ecosystems	Multi-modal sensing (activity, vision, acoustics)	Hybrid LPWAN–cloud architectures	Deep learning, sensor fusion	Shift toward precision livestock farming, commercial scalability, and decision-support systems

3. IOT TECHNOLOGIES FOR ESTRUS DETECTION IN LIVESTOCK

The Internet of Things (IoT) refers to a network of interconnected physical devices such as sensors, vehicles, and electronic systems that can collect, exchange, and analyze data through embedded software and communication technologies. By leveraging real-time data, IoT enables improved decision-making, enhances efficiency, and reduces operational costs across diverse industries, including agriculture. A general block diagram of an IoT system is presented in Figure 1. The central component is the IoT board, which can be programmed to process data and manage connected devices. Depending on the application, this board may be an Arduino, Raspberry Pi, or a similar platform. Sensor modules measure physical parameters and convert them into electrical signals, which are fed into the microcontroller. For wireless communication, RF modules are employed to transmit and receive signals. Network configuration plays a critical role in IoT deployment, and Virtual Private Servers (VPS) are often set up through software defined methods. Most IoT cloud services, such as those offered by Amazon and Microsoft, provide user-friendly web interfaces for system management [7]. The collected data is transmitted through the gateway and securely stored for analysis in Big Data environments [8].

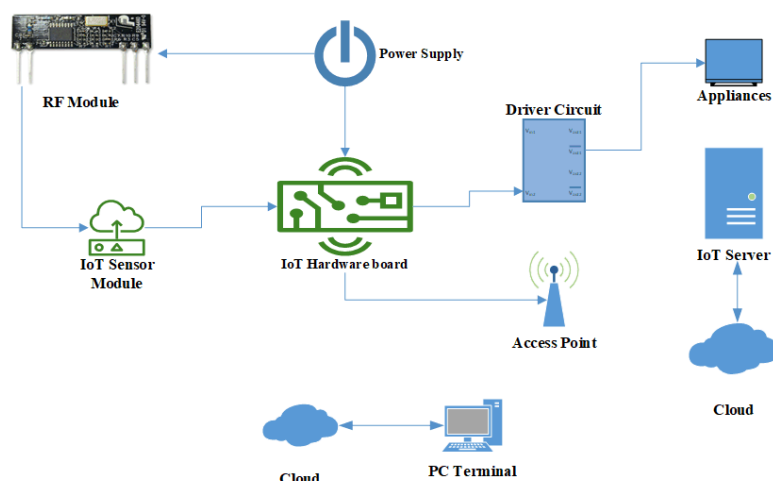


Figure 1. Block diagram of an Internet of Things (IoT) system

In agriculture, IoT has transformed data-driven decision-making. Sensors now allow farmers to continuously monitor parameters such as soil moisture, temperature, and humidity, leading to optimized irrigation and fertilizer usage. This results in higher yields and reduced input costs. A similar transformation is taking place in livestock farming, where IoT devices enable the monitoring of animal health, behavior, and reproductive cycles. Early detection of anomalies improves animal welfare, while timely estrus detection enhances breeding efficiency and productivity. Estrus the period when a female animal is receptive to mating is a crucial determinant of reproductive success, and accurate detection is vital for effective herd management.

IoT-based estrus detection systems typically utilize wearable or non-wearable sensors to capture physiological and behavioral indicators such as body temperature, movement patterns, and activity levels. The collected data is wirelessly transmitted to centralized servers or cloud platforms, where it is analyzed using advanced algorithms to determine estrus events. An example is SMARTernak, an IoT solution developed by DycodeX and illustrated in Figure 2. This system integrates RFID-based ear tags, smart cameras, and multiple sensors with AI-driven analytics to monitor cattle location, health, and reproductive status, providing actionable insights to farmers.

To ensure reliable connectivity, estrus detection systems rely on communication technologies optimized for IoT. Narrowband IoT (NB-IoT) is a Low Power Wide Area Network (LPWAN) technology that provides long distance coverage with low energy consumption, making it well-suited for farm environments with limited connectivity. Another widely used LPWAN technology is Long Range Wide Area Network (LoRaWAN), which supports long-range data transmission at minimal power cost, making it a practical choice for livestock monitoring applications.

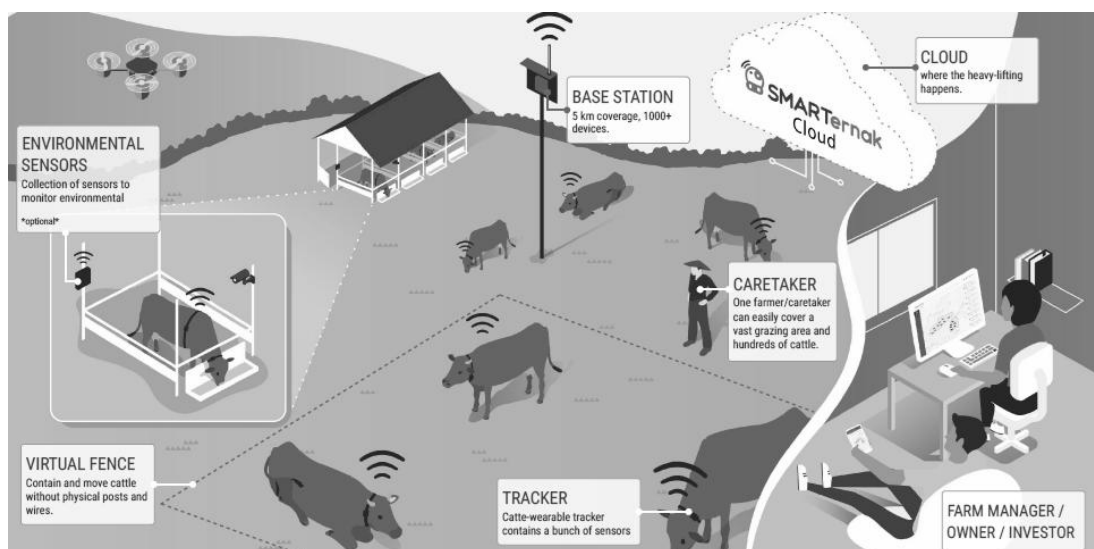


Figure 2. SMARTernak IoT-based livestock monitoring system by DycodeX.

3.1. NB-IoT

Narrowband Internet of Things (NB-IoT) is a Low Power Wide Area Network (LPWAN) technology specifically developed for IoT applications that demand low energy consumption, long battery life, and cost-effective connectivity [9]. It is optimized for devices such as sensors and meters that transmit small amounts of data at periodic intervals. Operating within the licensed spectrum, NB-IoT ensures secure and reliable communication with wide-area coverage, while also being capable of penetrating indoor and underground environments. This feature makes it particularly useful in agricultural contexts where devices may need to function in remote or obstructed locations. The NB-IoT architecture follows the LTE (Long Term Evolution) framework, consisting of three primary components: User Equipment (UE), which represents the IoT device; the Radio Access Network (RAN), which includes evolved NodeBs and NB-IoT base stations; and the Core Network (CN), responsible for packet data management, routing, and user authentication (Figure 3).

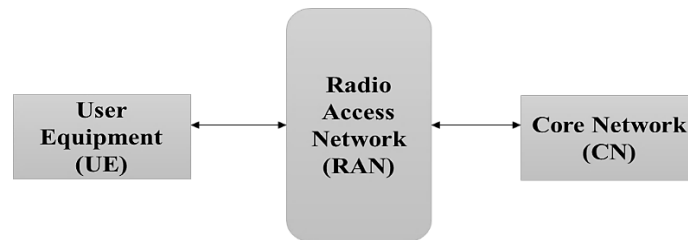


Figure 3. Basic architecture of NB-IoT

NB-IoT can be deployed in three operational modes: Standalone, where the network operates independently; Guard band, where it utilizes unused spectrum within LTE carriers; and In-band, where it shares spectrum with LTE signals. Its adaptability and low operational costs make it suitable for a wide variety of applications, ranging from smart cities and metering systems to healthcare, agriculture, and livestock management (Figure 4).

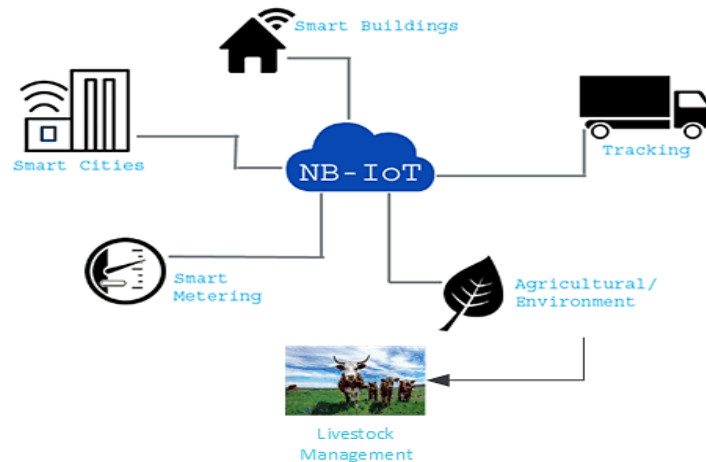


Figure 4. Key deployments of NB-IoT

Recent studies have demonstrated the effectiveness of NB-IoT in estrus detection for livestock. The work reported in [10] introduced a learning-assisted data analysis framework that leverages NB-IoT's robust connectivity for both confined and free-range breeding environments. In this system, sensors placed on the cow's neck capture behavioral data, which is transformed locally into multivariate time-series information. The data is then transmitted in real time to a cloud-based platform where deep learning models, including Long Short-Term Memory (LSTM) and Convolutional Neural Networks (CNN), are applied to identify temporal patterns and improve detection accuracy. Simulation results confirmed that this approach outperformed conventional methods in both accuracy and efficiency. Beyond estrus detection, the framework showed potential for monitoring animal health, detecting diseases, and identifying miscarriage risks.

Similarly, [6] presented a comprehensive design for a cow estrus monitoring system utilizing NB-IoT communication. The system integrates hardware, server platforms, algorithms, and software to create a reliable solution for estrus monitoring. Key design considerations include minimizing power consumption in the microprocessor, sensors, and algorithms. The system also introduces an enhanced detection mechanism by combining body temperature monitoring with image recognition techniques to analyze animal behavior, thereby reducing false detections and increasing reliability. Compared with other commercial products, the

NB-IoT-based design provided broader coverage, lower power usage, and reduced overall deployment costs, making it highly suitable for precision livestock farming.

3.2. LoRaWAN

Long Range Wide Area Network (LoRaWAN) is a low-power, long-distance wireless communication protocol widely adopted in Internet of Things (IoT) applications [11]. It operates in unlicensed radio spectrum bands and supports connectivity over several kilometers in open environments. The protocol has become popular in IoT deployments due to its combination of wide coverage, low energy consumption, and cost-effectiveness, making it particularly suitable for agricultural and livestock applications. The LoRaWAN architecture consists of three primary components: end devices, also referred to as nodes or sensors; gateways, which collect signals from multiple end devices; and the network server, which manages communication, encryption, and data routing between gateways and devices [12]. A schematic of the LoRaWAN network structure is shown in Figure 5.

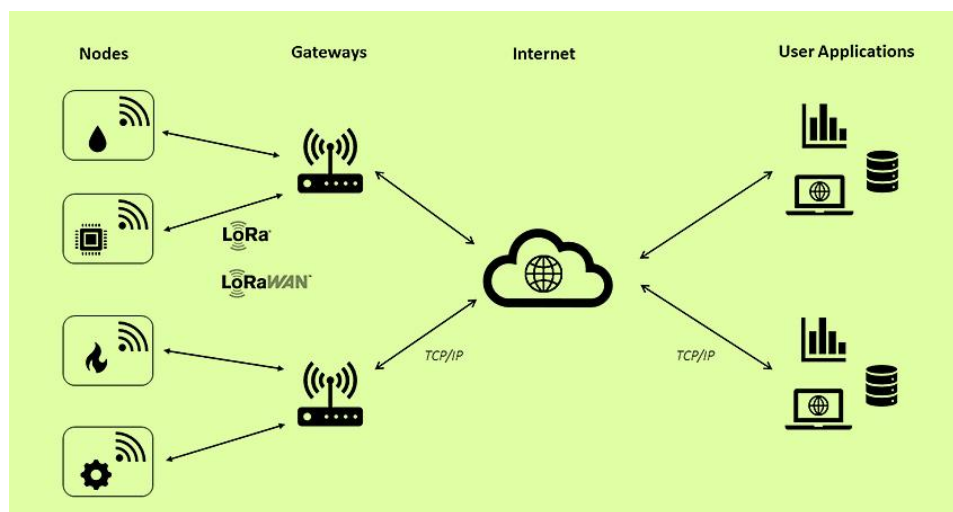


Figure 5. Basic network architecture of LoRaWAN

In livestock production, LoRaWAN can be applied to estrus detection by enabling wireless transmission of sensor data, such as body temperature, activity levels, or movement patterns, from animals to a central server. Small, low-power sensors attached to cattle collect behavioral or physiological data and relay it through gateways to a network server, where the information is analyzed to determine estrus status. LoRaWAN's long-range communication is particularly advantageous in large grazing areas, while its low energy requirements allow sensors to operate for extended periods without frequent battery replacement. Additionally, the low infrastructure cost associated with LoRaWAN makes it an affordable option for farmers seeking scalable IoT-based reproductive management solutions.

Several research efforts have demonstrated the utility of LoRaWAN in livestock estrus detection. In [13], an ultra-low-power platform was developed that integrates a micro-power accelerometer, FRAM-based microcontroller, and LoRa transceiver for activity monitoring. The system consumed only 2 μA during data collection and used the LoRaWAN protocol with a star topology, achieving communication distances exceeding 10 km in rural environments. This design significantly reduces maintenance costs by minimizing battery replacements, which are often a limitation in conventional systems.

Another study [14] introduced a smart livestock monitoring solution using orally ingested bio-capsules to capture physiological data such as temperature and body activity. The system operated on a custom long-range network (430 MHz) deployed in the United Arab Emirates. Data were transmitted to mobile and web applications, providing farmers with real-time insights into animal health and reproductive status. The system demonstrated a 100% detection rate for estrus, along with 61.29% accuracy for calving alerts and reliable disease prediction capabilities in unhealthy animals. Notably, the solution maintained robust performance even under extreme climatic conditions, underscoring the practicality of LoRaWAN-based livestock monitoring in diverse environments.

3.3. Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a widely adopted wireless technology that enables object identification and tracking using radio waves. In livestock management, RFID is commonly employed to

monitor and track individual animals within a herd. A typical RFID system is composed of three main components: an RFID reader, an RFID tag, and a database management system [15]. The reader emits radio signals and retrieves information stored on the tag, while the tag usually attached to the animal's ear or collar contains a unique identifier. The database management system then stores and processes this information for analysis. The basic architecture of an RFID system is presented in Figure 6.

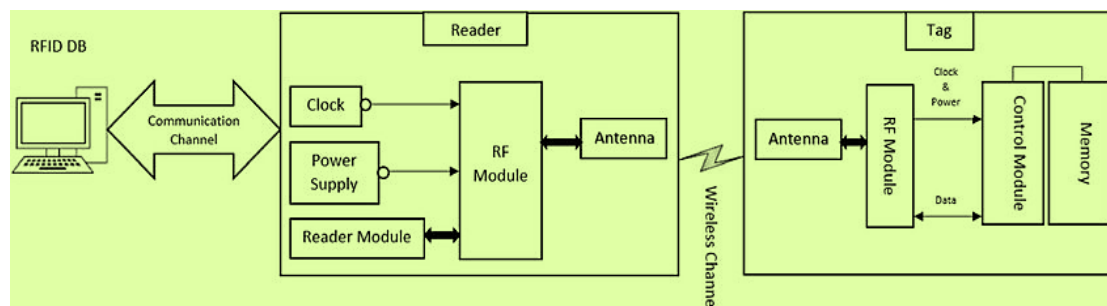


Figure 6. Basic architecture of an RFID system

For estrus detection, RFID can be applied to monitor the activity patterns of individual animals. Tags can be programmed to capture behavioral data, such as movement frequency and activity levels, which often change during the onset of estrus. The collected information is transmitted via RFID readers to a central database, where it is analyzed to identify estrus-related behaviors. This approach provides farmers with real-time, animal-specific reproductive insights, enabling timely interventions to maximize breeding success. Beyond reproduction, RFID also contributes to livestock health monitoring by identifying deviations in feeding, drinking, or resting patterns, which may indicate illness or injury. Such early detection helps farmers mitigate health risks, reduce the spread of disease, and prevent productivity losses.

In [16], a real-time RFID-based estrus detection system was proposed in which tags recorded the frequency of cows approaching a bull. Once this frequency surpassed a set threshold, the system triggered an alarm to notify the farmer. This method allowed timely fertilization following estrus detection, improving both reproductive efficiency and farm profitability. Similarly, RFID has been effectively used to track feeding, drinking, and mineral supplement intake by detecting animal proximity to feed bunks, water troughs, and supplement stations [17]. Such applications highlight the versatility of RFID as a tool for both estrus detection and overall livestock management.

3.4. Accelerometers, Pedometers, and Inclinometers

Wearable sensors such as accelerometers, pedometers [18], and inclinometers are increasingly used for monitoring livestock activity and have proven valuable in estrus detection. These devices capture different aspects of animal movement and posture, providing reliable indicators of reproductive status. Accelerometers measure acceleration through microelectromechanical sensors, and the resulting data can be processed to estimate overall activity levels. Pedometers utilize piezoelectric sensors to detect vibrations from footsteps, which allows for accurate step counting and assessment of mobility. Inclinometers determine the angle of the body relative to the ground, enabling the recognition of posture changes and rest-to-activity transitions.

In estrus detection, these sensors are commonly embedded in collars, ear tags, or leg-mounted devices. The data they capture is transmitted wirelessly to a central monitoring system where it is analyzed to identify behavioral patterns. Cows in estrus often exhibit elevated activity levels, reflected in higher acceleration values, increased step counts, and changes in body inclination. Using multiple sensors together can improve detection accuracy by providing complementary behavioral information.

A systematic review conducted by [19] examined the technologies available for estrus and calving detection in dairy cattle, with a particular emphasis on automated activity monitoring. The review was carried out through searches on the Google Scholar database using terms such as reproduction, dairy cows, estrus detection, parturition, and electronic devices. The findings showed that a wide range of commercial devices employ accelerometers, pedometers, and inclinometers to provide automated detection. These systems not only improve estrus detection rates but also generate calving alerts, thereby supporting better herd management practices. When integrated into precision livestock farming frameworks, such devices help farmers make informed decisions, improve productivity, and reduce reliance on manual observation.

Overall, the use of accelerometers, pedometers, and inclinometers provides a practical and non-invasive method for reproductive monitoring in dairy herds. By offering early and reliable detection of estrus and calving, these technologies allow farmers to enhance breeding efficiency, improve herd productivity, and reduce labor requirements.

4. SENSORS AND DATA COLLECTION METHODS

Sensors and automated data collection methods have become essential components of modern estrus detection in livestock. By integrating these technologies into livestock management systems, farmers can continuously monitor physiological and behavioral parameters of animals, enabling informed decisions that enhance reproductive efficiency, optimize productivity, and improve overall herd management. This section reviews the current state of research on IoT-based estrus detection, emphasizing the types of sensors and data collection strategies currently in use.

4.1. Wearable Sensors

Wearable sensors have emerged as one of the most effective technologies for estrus detection in livestock. These devices are designed to track parameters such as physical activity, body temperature, and other vital signs that are indicative of reproductive status. They can be attached to different parts of the animal’s body, including the ear, collar, or leg, in a non-invasive manner. Wearable sensors enable continuous monitoring, providing real-time data streams that can be transmitted wirelessly to a central server or cloud-based platform for processing and analysis. The adoption of wearable sensors offers significant advantages compared to conventional estrus detection methods like visual observation or hormonal assays. Automated monitoring reduces the labor burden, minimizes subjectivity, and decreases the likelihood of missed detections. In addition, the availability of real-time data allows farmers to make timely and evidence-based decisions regarding breeding, health management, and productivity optimization.

Several types of wearable IoT sensors are commonly used for estrus detection in livestock, and their applications are summarized in Table 2. These sensors represent an integral part of precision livestock farming, where technology is leveraged to improve efficiency and sustainability in animal production.

Table 2. Different wearable IOT based sensors for estrus detection in cattle.

Sensor	Details	Representational Image
GPS Trackers	GPS modules are used to track animal movements and grazing patterns, which provide insights into activity levels that indicate estrus. According to [20], Japanese dairy farming faced challenges in reproduction due to insufficient breeding management, leading researchers to design a system integrating GPS, accelerometers, wireless modules, and solar cells. The cattle sensor operated for two months without battery replacement and proved effective in detecting estrus in large, remote grazing areas.	 Figure 7. GPS Receiver Module
Pressure Sensors	Pressure sensors detect mounting behavior, a key indicator of estrus. As reported in [21], a commercially available estrus detection system incorporated pressure sensors to monitor mounting frequency and duration. Results showed a 96% detection rate, closely matching the 94% accuracy of visual observation methods, confirming its effectiveness as an automated alternative.	 Figure 8. Pressure Sensor
Temperature Sensors	Body temperature fluctuations are associated with estrus. According to [22], a wireless probe for monitoring vaginal conductivity and temperature was tested in cows for 48 hours. The study correlated data with animal activities and revealed systematic variations linked to estrus. This type of sensor provides automated estrus detection and is economically beneficial for farmers.	 Figure 9. Temperature Sensor

Sensor	Details	Representational Image
Electrocardiogram (ECG) Sensors	ECG sensors detect changes in heart rate and rhythm related to reproductive activity. In [23], researchers developed a non-invasive handheld device with ECG and acoustic sensors to determine pregnancy status and reproductive condition. Tested on over 2,000 cattle from 13 farms, the device provided real-time results and demonstrated potential for wider reproductive and health monitoring applications.	 Figure 10. Electrocardiogram (ECG) Sensor
Acoustic Sensors	Estrus in cattle is often accompanied by increased vocalization. According to [24], a collar-based cattle call monitor equipped with microphones and a post-processing algorithm was tested on group-housed cows. The system achieved 87% sensitivity and 94% specificity, successfully identifying vocalizations at the individual level. This demonstrated that estrus detection through vocal monitoring is feasible even in large groups.	 Figure 11. Acoustic Sensor
Blood Flow Sensors	Blood flow monitoring provides insights into reproductive health. In [25], researchers used ultrasonographic transducers to measure umbilical vessel blood flow during calving. Although primarily intended for parturition monitoring, this approach shows potential for estrus detection, as changes in reproductive blood flow can be linked to fertility status.	 Figure 12. Blood Flow Sensor
Accelerometers	Accelerometers measure changes in movement and activity levels. In [26], a study combined accelerometers mounted on the neck and leg with ultra-wideband localization to detect estrus and calving. Data on lying time, step counts, rumination, and travel distance confirmed that accelerometer-based monitoring is highly effective for automated estrus and calving detection.	 Figure 13. Accelerometer Sensor

4.2. Non-Wearable Sensors

Nonwearable sensors offer several advantages for estrus detection in livestock, such as reduced invasiveness and continuous monitoring. Infrared thermography, pressure-sensitive mats, acoustic sensors, and video-based monitoring systems each present unique benefits and challenges for identifying animals in heat. The integration of these technologies with IoT systems can improve the overall efficiency of livestock management and enhance animal welfare. As technology advances, we can expect further improvements in the accuracy and reliability of nonwearable sensors for estrus detection, which will contribute to more sustainable and productive livestock operations.

4.2.1. Video-based Monitoring Systems

Video-based monitoring systems have gained significant attention in recent years as a tool for estrus detection in livestock, largely due to advancements in computer vision and machine learning technologies. These systems track and analyze animal behavior, including restlessness, mounting events, and changes in social interactions, to identify animals in estrus [27]. Using cameras connected to analytical platforms, the systems can automatically detect and record behavioral changes without the need for direct human observation, offering a reliable and non-intrusive approach to reproductive monitoring. The general architecture of a video-based monitoring system is illustrated in Figure 14.

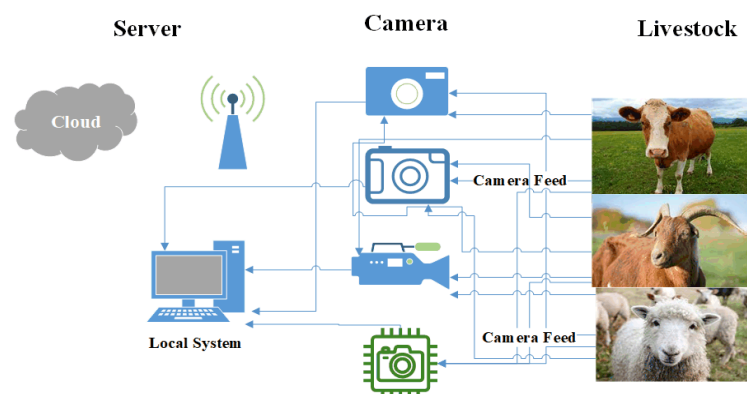


Figure 14. Architecture of video-based monitoring systems

A key strength of video-based monitoring is its ability to operate continuously, providing farmers with real-time information about the reproductive status of their animals. Beyond estrus detection, these systems can be integrated with other IoT-based devices, such as environmental sensors and automated feeding systems, to generate a more holistic overview of herd health, productivity, and welfare [28].

Despite these advantages, video-based monitoring systems face limitations in large-scale or outdoor operations. Variable lighting conditions, occlusions, and environmental complexities can reduce detection accuracy. Ongoing research is therefore focused on improving robustness through the development of advanced computer vision algorithms, higher-quality camera technologies, and more efficient data processing techniques. Such innovations are expected to enhance the reliability and scalability of video-based estrus detection systems, making them more practical for diverse livestock farming environments.

4.2.2. Infrared Thermography (IRT)

Infrared thermography (IRT) is a noninvasive imaging technique that measures the infrared radiation naturally emitted by objects to detect surface temperature variations. In livestock, studies have demonstrated that vulvar temperature rises during the estrus phase, making IRT a practical tool for reproductive monitoring [29]. By capturing and analyzing these temperature changes, IRT enables accurate detection of heat without the need for physical contact or invasive procedures. IRT can be effectively integrated with surveillance cameras to allow remote, continuous observation of livestock. Such systems provide farmers with the ability to identify animals in estrus without relying on wearable sensors, reducing both handling stress and equipment costs [30]. A typical configuration of an infrared thermography system for livestock estrus detection is illustrated in Figure 15.

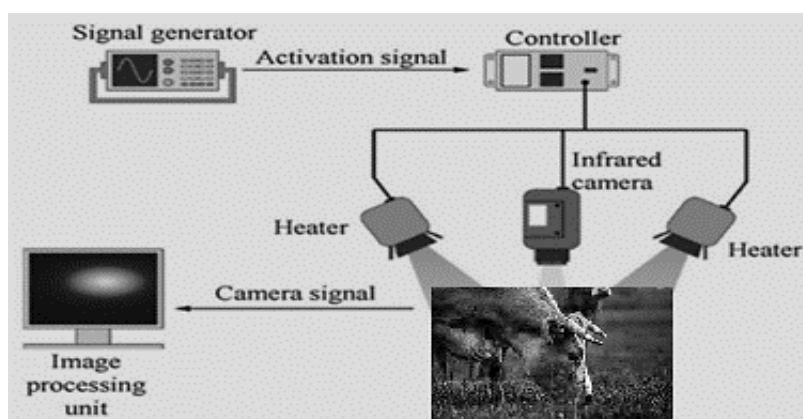


Figure 15. Infrared thermography setup

4.2.3. Pressure-sensitive Mats

Pressure-sensitive mats are non-wearable devices placed on the ground in specific areas where animals gather, as illustrated in Figure 16. These mats detect pressure variations produced during mounting behavior, which is one of the most reliable indicators of estrus. By recording the frequency and duration of these mounting events, the system enables farmers to determine the optimal time for insemination [31].

Pressure-sensitive mats provide a cost-effective and low-maintenance alternative to wearable sensors, making them particularly attractive for farms aiming to automate estrus detection with minimal intervention.

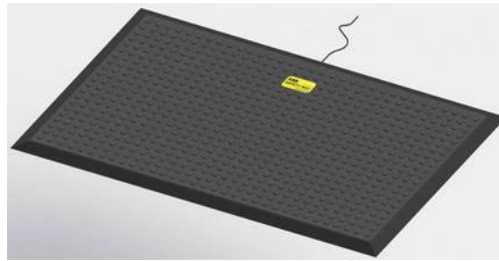


Figure 16. Pressure-sensing mat

4.2.4. Acoustic Sensors

Acoustic sensors have been widely used across various industries for decades, with significant progress in sound transmission, signal processing, and practical applications. An acoustic sensor converts sound wave energy into electrical signals, enabling the analysis of vocalization patterns. The general network architecture of an acoustic sensing system is shown in Figure 17.

In livestock management, acoustic sensors are applied to monitor vocalizations, which often change during the estrus period. Research has shown that both cattle and swine produce distinct vocal behaviors during estrus, making sound-based monitoring a viable detection method [32], [33]. By deploying acoustic sensors in barns or grazing environments, farmers can remotely capture vocal data, which is then analyzed to identify estrus-related patterns. This noninvasive approach reduces the need for manual observation or wearable devices, while also providing continuous monitoring of animal behavior.

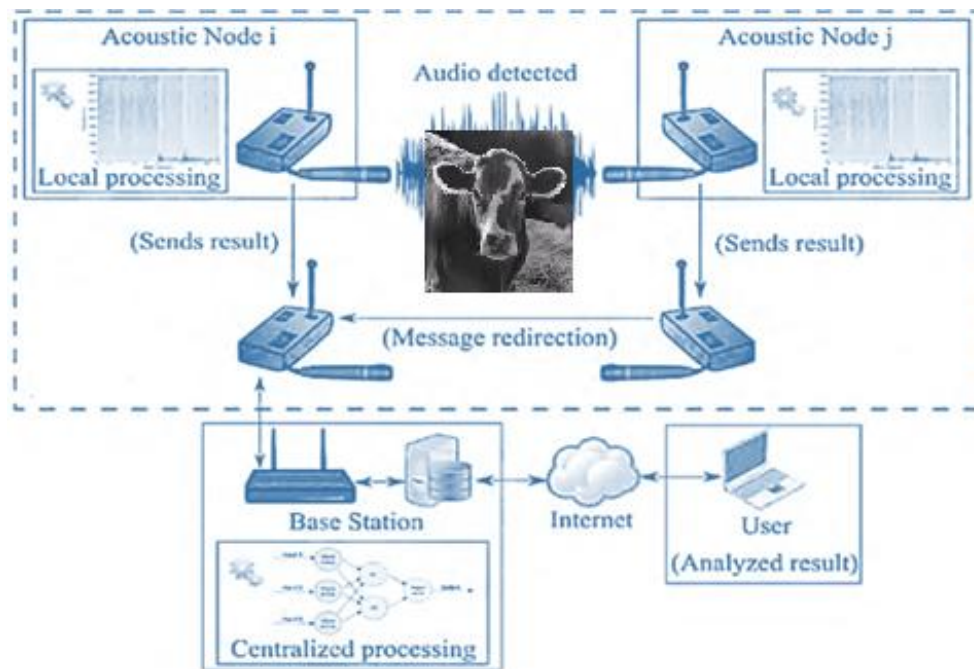


Figure 17. Acoustic sensor network

5. DATA COLLECTION, TRANSMISSION AND ANALYSIS

Data collection, transmission, and analysis are the core components of IoT-based estrus detection systems in livestock. Sensors are used to capture physiological, behavioral, and environmental information, which is then transmitted to a central server or cloud platform for processing, storage, and decision-making. The choice of sensor depends on the parameter being monitored. Physiological sensors record body temperature, heart rate, or hormone concentrations; behavioral sensors track activity and movement patterns; and environmental sensors capture external variables such as temperature, humidity, and lighting, which may influence animal physiology or behavior. Machine learning algorithms and artificial intelligence models are then applied to these datasets to identify patterns that signify the onset of estrus.

5.1. Data Collection Techniques

IoT-enabled data collection integrates distributed devices and sensors to gather real-time information from livestock. The interconnected nature of IoT allows seamless data monitoring, transmission, and storage, ensuring that information remains readily available for later analysis. The general framework of IoT-based data collection is illustrated in Figure 18.

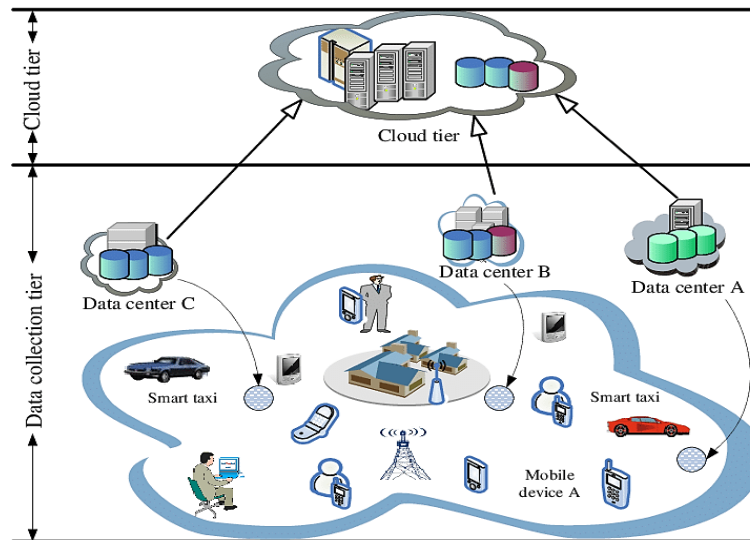


Figure 18. IoT-based data collection framework

Several key techniques are employed for estrus-related data collection:

a) Activity Monitoring

Increased activity levels are one of the earliest and most consistent signs of estrus. IoT devices such as accelerometers and pedometers are used to monitor animal movement [34]. These sensors, often attached to the neck or legs, record step counts, lying times, and activity intensities, which can then be processed to detect estrus-related changes [35].

b) Body Temperature Measurement

Body temperature fluctuations can serve as reliable estrus indicators. IoT-enabled sensors continuously measure temperature, providing valuable reproductive data. Infrared thermography (IRT) offers a noninvasive means of capturing body heat distribution [36], while temperature probes placed in the ear canal, subcutaneously, or vaginally can yield more precise readings [37].

c) Vocalization Analysis

Vocalization patterns often shift during estrus. IoT-based acoustic sensors can capture these changes in sound frequency, duration, and intensity, enabling the identification of reproductive status [38]. This method is particularly useful for species such as cattle and swine, which exhibit distinct vocal behaviors during estrus.

d) Hormone Detection

Hormonal fluctuations directly correlate with the reproductive cycle. IoT-integrated biosensors can detect key hormones such as progesterone or estradiol in biological fluids including blood, milk, or saliva [39]. These sensors provide real-time hormonal data, allowing highly accurate detection of estrus onset and improving breeding management decisions.

5.2. Data Transmission

After data has been collected by IoT devices, it must be transmitted to a central unit or cloud platform for storage, processing, and analysis. Both wired and wireless communication methods are used for this purpose. Wired communication relies on physical cabling, whereas wireless communication employs technologies such as Wi-Fi, Bluetooth, and cellular networks. Each mode differs in terms of transmission range, data rate, power consumption, and infrastructure requirements. These differences are summarized in Figure 19.

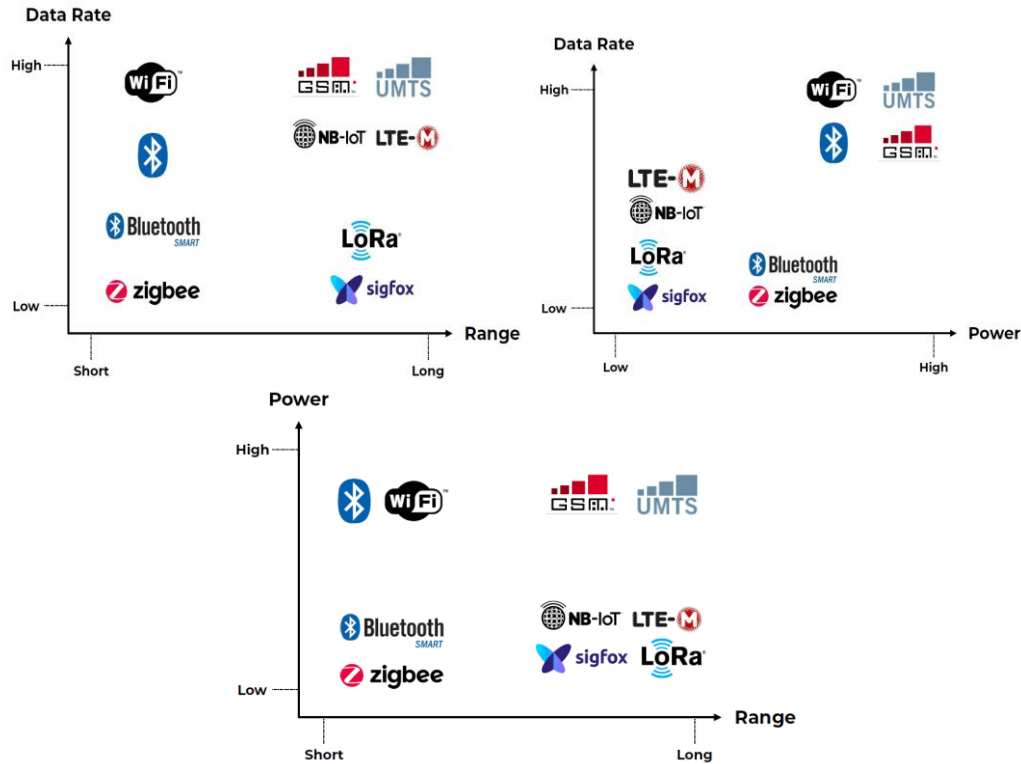


Figure 19. Comparison of data transmission modes with respect to range, data rate, and power consumption

a) Wireless Networks

Wireless connectivity, including Wi-Fi and cellular networks, is widely used in IoT systems to transmit data efficiently over large areas. This approach is particularly advantageous in extensive livestock farms where animals are dispersed across wide spaces [40]. However, wireless communication may suffer from interference, and a stable internet connection is necessary to ensure uninterrupted data flow.

b) Low-Power Wide-Area Networks (LPWAN)

LPWAN technologies such as LoRaWAN, Sigfox, and NB-IoT are designed specifically for IoT applications. They provide long-range communication with very low energy requirements, making them well suited for remote areas where network infrastructure is limited [41]. Despite their advantages, LPWANs often have lower data rates and restricted bandwidth compared to conventional wireless networks, which may limit their ability to support real-time, high-volume data transfer [41].

c) ZigBee and Bluetooth

Short-range communication technologies such as ZigBee and Bluetooth are also used in IoT-based estrus detection. These protocols consume less power than traditional wireless networks, extending the battery life of IoT devices [42]. Their limited range, however, restricts their use to smaller areas, and large-scale farms may require repeaters or additional infrastructure to achieve adequate coverage.

d) Wired Networks

In certain scenarios, wired networks such as Ethernet may be used for IoT data transmission. Wired connections offer high data rates and stable communication, reducing the likelihood of interference. However, their reliance on extensive cabling makes them impractical for large-scale livestock operations, where flexibility and scalability are essential.

5.3. Data Processing and Analysis

Following data collection and transmission, the next stage in IoT-based estrus detection is data processing and analysis. This step is critical for converting raw sensor data into actionable insights and typically involves the application of machine learning algorithms and artificial intelligence (AI) techniques. These computational approaches enable the identification of behavioral and physiological patterns that indicate estrus onset.

a) Machine Learning Algorithms

Machine learning models are widely applied to analyze livestock data, recognizing patterns that correlate with estrus. Techniques such as support vector machines (SVM), decision trees, and artificial neural networks have been used to process historical and real-time data collected by IoT devices. These algorithms can generate accurate predictions of estrus onset by detecting variations in activity, body temperature, or vocalizations [43]. Their adaptability allows integration across multiple sensor types, making them effective in diverse farm environments.

b) Artificial Intelligence Techniques

Artificial intelligence methods, particularly deep learning, provide enhanced capabilities for analyzing large and complex datasets. Deep learning models can extract subtle, non-linear patterns from high-dimensional data, improving estrus detection accuracy [44]. Unlike conventional algorithms, these models continuously learn and adapt as more data becomes available, refining predictions over time. Their ability to fuse multimodal inputs, such as sensor readings and video data, makes AI a promising tool for robust and automated estrus detection.

IoT-based systems that integrate advanced sensors, communication technologies, and intelligent data analysis approaches offer considerable improvements over traditional estrus detection techniques. These systems provide continuous monitoring, higher accuracy, and reduced labor requirements. However, several challenges remain, including high implementation costs, concerns over data security and privacy, and the requirement for technical expertise to manage and maintain IoT infrastructures. Addressing these limitations will be essential for widespread adoption.

By overcoming these barriers, livestock managers can fully leverage IoT technologies to optimize breeding programs, improve animal welfare, and enhance overall productivity in the livestock industry.

6. REVIEW OF IOT-BASED ESTRUS DETECTION IN LIVESTOCK

A wide range of researchers has explored IoT-based estrus detection in livestock with the goal of optimizing breeding efficiency and improving animal health [45]. These systems primarily employ sensors and connectivity technologies to monitor physiological and behavioral indicators of estrus, such as temperature, physical activity, and mounting behavior [46]. By integrating automated monitoring, farmers can anticipate the optimal time for insemination more accurately, thereby reducing costs and improving reproductive success. Figure 13 presents the amount of scholarly work in this field, illustrating the growing trend of research publications from 2016 to the present.

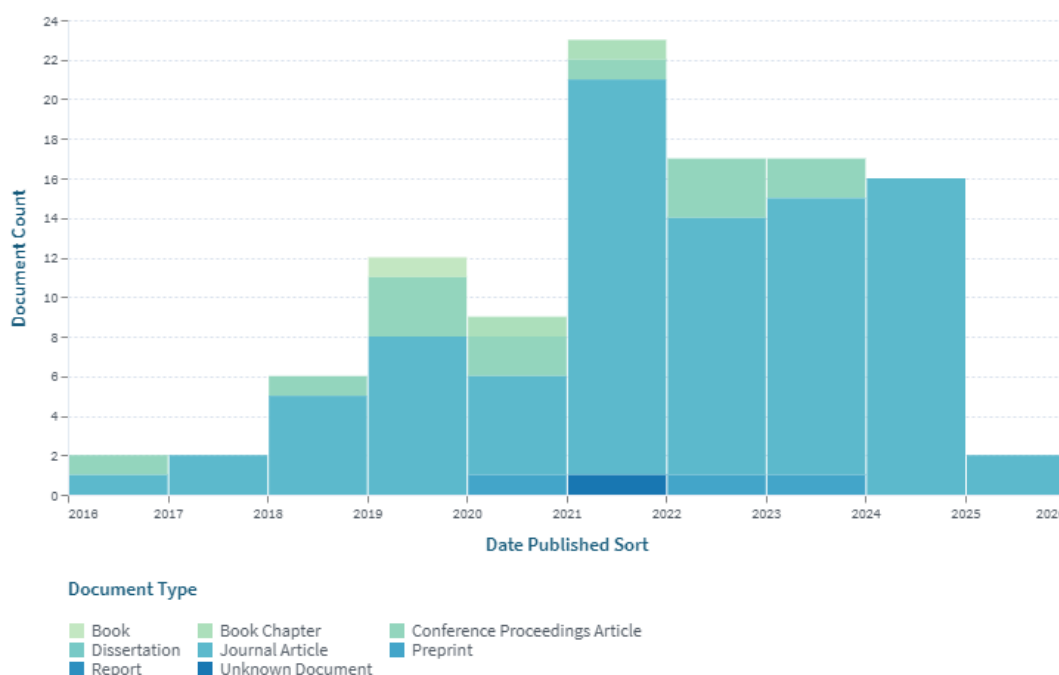


Figure 13. Stacked bar representation of scholarly works on estrus detection using IOT from 2016 to present [47].

Over the past two decades, there has been a marked surge in research interest, particularly from 2021 onwards. Between 2016 and 2020, publication output was relatively modest, but it began to increase steadily as the importance of accurate estrus detection became more widely recognized. This rise has been driven by several factors, including the demand for precision livestock farming, the need for disease prevention, efficiency in farm operations, and global demand for sustainable food production. The development of advanced sensors, wearable devices, and computer vision techniques has further fueled innovation, leading to more reliable and scalable methods of estrus detection. This momentum is expected to continue, with increasingly sophisticated technologies emerging to meet the needs of modern livestock management.

Among the physiological indicators studied, body temperature has proven to be a consistent predictor of estrus. For instance, [45] reported a study in which temperature sensors were used to track the core body temperature of cattle, showing a significant rise during estrus. Similarly, [49] demonstrated the value of biosensors in dairy cows, confirming a strong correlation between temperature fluctuations and estrus events. These findings underscore the reliability of temperature monitoring as a basis for automated estrus detection systems.

Behavioral changes have also been widely examined as indicators of estrus. A study by [50] established that increased physical activity is a reliable marker in dairy cattle. In line with this, [51] designed a wearable sensor-based system that tracked cow activity levels, successfully detecting estrus through increased movement. Likewise, [52] employed accelerometers to monitor mounting behavior and demonstrated high accuracy in estrus identification. Together, these studies validate behavioral monitoring as an effective and non-invasive approach to reproductive management.

In recent years, machine learning techniques have further enhanced the precision of IoT-based estrus detection. According to [53], acceleration and location data from 296 lactating cows over an eight-month period in a free-stall barn were analyzed using a backpropagation neural network (BPNN). The model achieved an accuracy of 95.46%, with sensitivity of 98.29% and specificity of 95.08%. Another investigation [54] evaluated four machine learning algorithms using data from 12 cows fitted with neck-mounted location and acceleration sensors. Among the tested approaches, the BPNN with a 0.5-hour time window achieved the best performance, with sensitivity, specificity, precision, and accuracy values ranging between 72.7% and 99.4%. These results highlight the effectiveness of combining behavioral metrics with artificial intelligence to refine estrus detection systems and demonstrate the potential of machine learning to transform livestock breeding practices.

Reliable data transmission is another essential aspect of IoT-based estrus detection. Various connectivity technologies have been tested to support real-time monitoring. LoRa has been one of the most widely adopted due to its long-range, low-power, and low-cost characteristics. In [55], researchers developed an ultra-low-power device that combined a micro-power accelerometer, FRAM microcontroller, and LoRa transceiver. The system successfully transmitted activity data over distances greater than 10 km using the LoRaWAN protocol in a star topology, making it highly suitable for rural farms with limited infrastructure. Other technologies such as ZigBee, Wi-Fi, and cellular networks have also been employed to ensure continuous and reliable communication in diverse farm environments.

Overall, IoT-based estrus detection has evolved from simple physiological monitoring toward integrated solutions that combine wearable devices, environmental sensing, and artificial intelligence. This evolution has significantly improved detection accuracy, reduced labor requirements, and enhanced animal welfare. The increasing number of scholarly contributions reflects the growing recognition of its importance. Table 3 provides a summary of selected studies, outlining their methodologies, findings, and limitations, offering an overview of the approaches taken and the challenges that remain in this field.

Table 3. Summary of IoT-based research studies on estrus detection in livestock

S. No.	Method Used	Limitations	Citation
1	Monitoring system using AI with the Augmented Recognition Model (ARM) for estrous state prediction and behavior analysis in Hanwoo cattle.	Accuracy depends on continuous monitoring, which is difficult in large herds. Performance affected by environment, age, and health. High implementation and maintenance costs may hinder adoption.	[56]
2	Non-invasive detection of standing-heat behaviors using pan-tilt-zoom cameras, Python-based web application, and remote alerts.	Detection efficiency limited to 50%. Requires precise pre-calculation of camera field of view. May not be feasible in all farm settings.	[57]
3	Framework using multivariate behavioral time-series data from neck-mounted sensors transmitted via NB-IoT, analyzed with LSTM and CNN.	Neck-mounted sensors may be uncomfortable and require management. Relies on NB-IoT coverage, which is not available everywhere.	[58]

S. No.	Method Used	Limitations	Citation
4	IoT integrated with machine learning, using acceleration sensors to measure activity and predict estrus and calving dates.	Reliability depends on data quality and quantity, as well as the effectiveness of the algorithms used.	[59]
5	Multi-sensory livestock monitoring with edge-cloud storage and deterministic plus machine learning algorithms for health, production, and pregnancy monitoring.	Requires stable connectivity and suitable edge devices. Algorithm performance depends on data quality. High cost may limit use by small farms.	[60]
6	IoT-based automated monitoring system combining hardware, cloud infrastructure, and client applications to detect estrus and pathologies.	Algorithms limited to specific diseases. Needs improvement in cow location estimation and individualized modeling.	[61]
7	Low-cost monitoring using Raspberry Pi and accelerometer sensors adapted from human activity recognition methods.	Accuracy influenced by sensor placement and calibration. Hardware choices may not suit all farm environments.	[62]
8	IoT-based estrus detection with pan-tilt-zoom cameras, Python-driven cloud application, and cross-platform alerts.	Only 50% detection efficiency. Accuracy affected by lighting, behavior variability, and camera faults. High hardware and software costs.	[63]
9	Cloud IoT-based Livestock Management System (LMS) with wearable collars, smart tags, smart cards, and QR integration for monitoring physiological and environmental parameters.	High sensor costs may limit adoption. Accuracy influenced by calibration, animal behavior, and environmental factors.	[64]
10	IoT and analytics system for estrus detection using physiological data (respiration, pulse, sweat rate, skin and rectal temperature) and behavioral analysis.	Requires validation in real farm conditions. Accuracy depends on correct sensor placement and calibration.	[65]
11	IoT-based estrus detection for Korean native cattle using acceleration sensors to track activity and provide alarm services.	Variations in individual and breed-specific behavior may affect accuracy and require further system adaptation.	[66]

6.1. Commercial Implementation of IoT-Based Estrus Detection Systems

Commercial IoT-based estrus detection systems have gained widespread adoption in modern livestock farming due to their ability to improve reproductive efficiency and overall herd management. These systems integrate wearable sensors, gateways, and farm management software to provide farmers with real-time insights into animal health and reproductive status. Several commercial solutions are currently available, each employing unique hardware configurations, integration methods, and analytical software.

a) AfiAct II – Afimilk

The AfiAct II system, developed by Afimilk, utilizes leg-mounted tags that continuously record cow activity. Data from these tags is collected by the AfiAct II Gateway and processed by Afimilk's farm management software suite, including AfiFarm. By monitoring activity levels and restlessness, the system accurately identifies estrus periods while also offering health monitoring capabilities such as mastitis detection, lameness alerts, and calving notifications. Its integration with Afimilk's broader farm management solutions allows farmers to obtain a comprehensive overview of herd productivity and reproductive performance.

b) CowManager – Nedap

CowManager, a product of Nedap, employs ear-mounted tags that measure eating, rumination, and activity behaviors. Information from these sensors is transmitted to the CowManager Gateway, which then forwards it to the CowManager software platform. In addition to estrus detection, the system supports fertility management, feeding optimization, and health monitoring. By integrating with Nedap Livestock Management, CowManager enables farmers to manage operations holistically, ensuring that reproductive and nutritional strategies are aligned with herd welfare.

c) SCR Heatime® HR System – Allflex

The SCR Heatime® HR system by Allflex is based on neck collar tags equipped with sensors that capture activity, rumination, and resting patterns. These data are transmitted through the SCR DataFlow System to the SCR Heatime® software for analysis. The system not only detects estrus but also provides alerts for metabolic disorders and mastitis. Its compatibility with other farm management platforms allows seamless integration into broader herd monitoring programs, giving farmers a unified tool for managing reproduction and health.

d) MooMonitor+ – Dairymaster

Dairymaster's MooMonitor+ uses collar-mounted tags in combination with antenna receivers to track activity, rest, and feeding behaviors. The data are analyzed using Dairymaster's software, which can also be integrated with the company's milking and feeding systems. Apart from estrus detection, MooMonitor+ provides early alerts for mastitis, calving events, and respiratory distress. By combining reproductive and health monitoring functions, the system offers a holistic approach to dairy herd management.

e) E-Track – BouMatic

BouMatic's E-Track solution makes use of leg-mounted devices that monitor cow behavior, including activity, rest, and feeding. Data from these sensors are collected via the E-Track Gateway and analyzed using BouMatic's software platform. Integration with the BouMatic Herd Management System ensures that estrus detection, health alerts, and calving predictions can be viewed alongside other operational data. This combination enables efficient decision-making and enhances the productivity of dairy operations.

f) HerdInsights – HerdInsights

HerdInsights employs collar-mounted devices linked to a dedicated Gateway and cloud-based software platform. The system detects estrus by analyzing patterns in activity, rest, and feeding behavior. It also provides alerts for health concerns, including mastitis, lameness, and calving events. Farmers can integrate HerdInsights with other farm management software to centralize data from multiple sources, thereby improving efficiency and operational oversight.

g) SMARTernak – DycodeX

SMARTernak, developed by DycodeX, represents a more advanced IoT-based cattle management solution designed for both estrus detection and broader herd monitoring. The system uses durable wearable devices to collect data on cattle movement, body temperature, and other physiological parameters. Information is transmitted to a cloud-based platform, where it is analyzed to identify patterns related to reproduction, nutrition, and health. Farmers can access the data through a mobile app or web-based dashboard, enabling real-time monitoring and timely interventions. SMARTernak also generates automated alerts when abnormal behavior or physiological changes are detected, assisting farmers in identifying estrus events and health issues early. Integration with other farm management platforms further strengthens its role as a comprehensive livestock management tool.

7. PERFORMANCE EVALUATION

Performance evaluation is crucial in IoT-based estrus detection systems as it enables the assessment of the system's effectiveness in accurately detecting estrus in dairy cattle. IoT-based systems rely on various sensors and technologies to monitor animal behavior and physiological changes. These systems generate large volumes of data that require proper analysis to evaluate the accuracy and reliability of the detection methods used.

7.1. Metrics for IoT-based Estrus Detection

The performance of IoT-based estrus detection systems is typically assessed using a variety of metrics, including accuracy, sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and F1 score.

a) Accuracy

Accuracy is the proportion of true positive and true negative results among the total number of cases examined. It is expressed mathematically as shown in Eq. (1):

$$\text{Accuracy} = (TP + TN) / (TP + TN + FP + FN) \quad (1)$$

where TP represents true positives, TN represents true negatives, FP represents false positives, and FN represents false negatives.

b) Sensitivity

Sensitivity, also known as the true positive rate, measures the proportion of actual positive cases that are correctly identified by the system. It is expressed mathematically as shown in Eq. (2):

$$\text{Sensitivity} = TP / (TP + FN) \quad (2)$$

c) Specificity

Specificity, or the true negative rate, measures the proportion of actual negative cases that are correctly identified by the system. It is expressed mathematically as shown in Eq. (3):

$$\text{Specificity} = TN / (TN + FP) \quad (3)$$

d) Positive Predictive Value (PPV)

PPV, also known as precision, measures the proportion of true positive cases among the instances that the system classifies as positive. It is expressed mathematically as shown in Eq. (4):

$$PPV = TP / (TP + FP) \quad (4)$$

e) Negative Predictive Value (NPV)

NPV measures the proportion of true negative cases among the instances that the system classifies as negative. It is expressed mathematically as shown in Eq. (5):

$$NPV = TN / (TN + FN) \quad (5)$$

f) F1 Score

F1 score, also known as the harmonic mean of precision and recall, is a balanced measure of a system's performance that considers both PPV and sensitivity. It is expressed mathematically as shown in Eq. (6):

$$F1 \text{ Score} = 2 * (PPV * Sensitivity) / (PPV + Sensitivity) \quad (6)$$

When evaluating the performance of IoT-based estrus detection systems, it is essential to consider metrics that are relevant to the practical application of these systems in livestock management. While machine learning metrics like accuracy, recall, precision, specificity, and F1 score can provide insights into the system's algorithmic performance, there are additional metrics that need to be considered for IoT-based estrus detection systems:

- g) Detection rate: The percentage of true estrus events that the system is able to identify. A high detection rate is essential for effective breeding management. It is calculated using Eq. (7):

$$\text{Detection rate} = (\text{True Positives}) / (\text{True Positives} + \text{False Negatives}) \quad (7)$$

- h) False alarm rate: The percentage of false estrus alerts generated by the system. A low false alarm rate is important to minimize wasted resources and unnecessary interventions. It is calculated using Eq. (8):

$$\text{False alarm rate} = (\text{False Positives}) / (\text{False Positives} + \text{True Negatives}) \quad (8)$$

- i) Time-to-detection: The average time it takes for the system to detect estrus after the onset of estrus signs. A shorter time-to-detection allows for more timely breeding management decisions.

- j) System reliability: The overall reliability of the IoT devices and the data collection infrastructure. This can be assessed by metrics such as device uptime, data transmission success rate, and data completeness. This can be assessed using multiple metrics, as shown in Eq. (9), (10) and (11):

$$\text{Device uptime: Uptime (\%)} = (\text{Device operational time} / \text{Total time}) * 100 \quad (9)$$

*Data transmission success rate: Success rate (%) = (Number of successful transmissions / Total transmissions) * 100* (10)

*Data completeness: Data completeness (%) = (Amount of complete data received / Amount of expected data) * 100* (11)

- k) **Ease of use, scalability, and compatibility:** The simplicity of device installation, maintenance, and use of the software platform. This can be assessed through user feedback and the learning curve associated with adopting the system. Scalability is the ability of the system to accommodate increasing numbers of animals and additional IoT devices without affecting performance or requiring significant infrastructure changes. Compatibility is the ease of integrating the IoT-based estrus detection system with existing farm management software and other technologies used on the farm.
- l) **Cost-effectiveness:** The overall cost of the system, including initial investment, maintenance, and data processing, compared to the potential increase in productivity and profitability resulting from improved estrus detection. This can be calculated using metrics such as return on investment (ROI) or net present value (NPV) as in Eq. (12) and (13).

*Return on investment (ROI): ROI (%) = [(Net profit / Investment) * 100* (12)

Net present value (NPV): NPV = $\sum [(Cash\ inflow - Cash\ outflow) / (1 + Discount\ rate)^t] - Initial\ investment$ (13)
(Where $\sum$ denotes the sum over the time period 't').

7.2. Comparative Analysis of Different IoT-based Estrus Detection Methods

Over the past decade, several IoT-based estrus detection methods have been developed, each relying on different types of sensors and monitoring principles. These include accelerometers, pedometers, temperature sensors, RFID systems, video-based solutions, sound-based monitoring, pressure sensors, infrared thermography, vaginal impedance sensors, heart rate monitors, and urine analysis systems. Each method varies in terms of performance metrics such as accuracy, sensitivity, and specificity, depending on the technology employed, the conditions under which it is deployed, and the species or breed being monitored. Table 4 summarizes the reported performance of the main IoT-based estrus detection systems as documented in the literature.

Table 4. Reported Performance of IoT-Based Estrus Detection Systems

Type of System	Accuracy (%)	Sensitivity (%)	Specificity (%)	Citation
Accelerometers	90–95	85–95	90–95	[67], [68]
Pedometers	80–90	75–90	85–95	[69], [70], [71]
Temperature Sensors	75–85	70–85	80–90	[72], [73], [74]
RFID Systems	85–95	80–90	85–95	[74], [75], [76]
Video-Based Systems	80–85	75–80	80–85	[27]
Sound-Based Systems	85–90	80–90	85–90	[32], [33]
Pressure Sensors	80–90	75–85	80–90	[77]
Infrared Thermography	65–75	–	–	[78]
Vaginal Impedance Sensors	90–95	–	–	[79], [80]
Heart Rate Monitors	80–85	75–80	80–85	[81], [82]
Urine Analysis Systems	85–90	80–90	85–90	[83]

The comparative analysis highlights that accelerometer-based systems generally outperform other methods, achieving higher accuracy, sensitivity, and specificity. Pedometers and RFID systems also provide strong results, particularly when integrated into existing herd management platforms. Temperature sensors and video-based monitoring offer practical alternatives but may be more vulnerable to environmental influences, while sound-based and pressure-sensing technologies demonstrate good reliability in controlled environments.

Vaginal impedance sensors show very high accuracy but are invasive and may not be suitable for large-scale application.

Infrared thermography and heart rate monitoring present moderate performance levels and are often more effective when combined with other methods. Similarly, urine analysis systems show promise but require additional handling and may not be suitable for continuous monitoring.

Overall, no single approach can be considered universally optimal. The best system depends on farm-specific requirements, such as budget, infrastructure, herd size, and the level of technical expertise available. A hybrid approach, combining data from multiple sensors such as accelerometers, temperature monitors, and RFID systems, can provide a more comprehensive understanding of physiological and behavioral changes during estrus. Such integrated systems have been shown to enhance detection rates and reduce false positives, thereby improving breeding efficiency and overall herd management [84].

7.3. Challenges and Limitations

IoT-based estrus detection represents an emerging technological approach that integrates sensors and communication networks to monitor livestock physiology and behavior. While this technology has demonstrated significant potential for enhancing reproductive efficiency, milk yield, and economic returns, its adoption is accompanied by several challenges and limitations that must be addressed for large-scale implementation.

One of the key challenges is related to data quality and interpretation. The accuracy of IoT-based estrus detection systems depends heavily on the reliability of the data collected by sensors. Factors such as sensor placement, environmental conditions, and individual animal variability can influence the precision and consistency of readings. Furthermore, interpreting sensor-derived data can be difficult, as animals may exhibit different behavioral or physiological estrus patterns, complicating the development of universal detection models [34]. Another limitation lies in cost and implementation. The initial investment required for purchasing sensors, gateways, and integration software can be prohibitively high, particularly for small-scale farmers. In addition, ongoing maintenance, software updates, and calibration further increase operational costs. The complexity of the technology also demands technical expertise for installation and troubleshooting, creating a barrier for widespread adoption [85].

Privacy and security concerns are increasingly relevant as livestock data are collected and transmitted via wireless networks. The potential misuse or unauthorized access to sensitive data, such as reproductive performance or health status, poses risks to both farmers and industry stakeholders. Ensuring secure data transmission and storage is therefore critical to building trust in IoT-based solutions [86]. The issue of interference from other devices also affects system performance. IoT devices often operate in frequency bands that are shared with other wireless technologies. Interference can degrade signal quality, resulting in inaccurate readings or data loss, ultimately reducing system reliability [87]. Calibration and validation represent further challenges. For IoT-based estrus detection systems to function effectively, sensors must be regularly calibrated and validated. However, the absence of standardized protocols and the variability in animal behavior make calibration difficult. Without proper validation, the accuracy and reliability of the system may be compromised [88].

In addition, there are ethical considerations related to animal welfare. Continuous monitoring through wearable devices may alter natural behavior, cause discomfort, or raise concerns about over-reliance on technology for reproductive management. Ensuring that monitoring devices are minimally invasive and used responsibly is essential [89]. Another limitation arises from variability in animal behavior. Estrus expression can differ significantly across breeds, ages, and environments. Machine learning algorithms trained on one dataset may not generalize well to different herds or species, limiting the universal applicability of detection systems [50]. A related challenge is the potential for false alarms. Incorrectly identifying animals as being in estrus may lead to unnecessary interventions, such as premature insemination or veterinary procedures. These errors not only increase costs but may also negatively affect animal welfare [90].

Integration with existing farm management practices can also be difficult. Some farmers may continue to rely on traditional visual observation methods and may resist adopting complex IoT systems. Moreover, the requirement for technical expertise can discourage adoption among farmers with limited resources [91]. Wireless connectivity limitations present a further barrier, particularly in rural regions with poor network coverage. Since IoT systems depend on reliable data transmission, inadequate connectivity can delay detection, reduce system reliability, and undermine timely decision-making [92]. Another drawback is the limited accuracy in detecting early estrus signs. Certain physiological indicators, such as changes in vaginal mucus characteristics, are not effectively captured by current IoT sensors, which reduces their ability to detect estrus at the earliest stages [46]. Additionally, compatibility across breeds and species remains a challenge. Different livestock species and breeds express estrus differently, requiring tailored detection algorithms and customized hardware solutions. This limits the scalability of current IoT systems [93].

The need for regular maintenance and calibration is another factor that can burden farmers. Sensors must be frequently checked and recalibrated to ensure accuracy, a process that is often time-consuming and requires specialized knowledge [94]. Finally, there is a limited understanding of the long-term impact of IoT-based estrus detection systems on livestock performance and welfare. Although short-term benefits have been demonstrated, further research is needed to assess the potential effects on animal health, stress levels, and overall productivity over extended periods [95]. Silent heat represents a significant limitation for both conventional and IoT-based estrus detection systems. In such cases, animals exhibit minimal or no observable behavioral changes despite being physiologically in estrus, leading to missed detections and reduced reproductive efficiency. Behavior driven IoT approaches that rely primarily on activity or movement patterns may therefore underperform under silent heat conditions. Addressing this challenge requires the integration of continuous physiological sensing, such as body temperature, hormonal indicators, or internal biosensors, combined with multi-sensor data fusion and advanced analytics to identify subtle estrus related patterns that are not externally visible. Energy consumption and battery life also remain the primary failure points of wearable IoT devices used in livestock monitoring. Continuous sensing, frequent data transmission, and harsh farm environments significantly accelerate battery depletion, leading to data loss and increased maintenance burden.

While IoT-based estrus detection technologies hold considerable promise for improving livestock breeding and management, their effectiveness is hindered by technical, economic, ethical, and practical limitations. Overcoming these challenges will require collaborative efforts among researchers, technology providers, and farmers, with a focus on developing cost-effective, secure, and animal-friendly solutions that can be adapted across different breeds, species, and farming systems.

8. CONCLUSION

The livestock industry forms a cornerstone of the global food supply chain, sustaining millions of livelihoods worldwide. To remain competitive and meet increasing demands for animal products, continuous improvements in efficiency and productivity are essential. Among the most critical aspects of livestock production is reproductive management, where timely and accurate estrus detection directly influences conception rates, calving intervals, and overall farm profitability.

Traditional estrus detection methods, primarily based on visual observation, are often time-intensive, labor-demanding, and prone to inaccuracies. Missed detections or false identifications can lead to reduced reproductive efficiency and higher breeding costs. The advent of Internet of Things (IoT) technologies offers an opportunity to overcome these limitations. Through the integration of wearable sensors, data transmission networks, cloud-based analytics, and machine learning algorithms, IoT-enabled systems can provide real-time, precise, and non-invasive monitoring of reproductive behaviors and physiological changes in livestock. These technologies not only reduce reliance on manual observation but also allow farmers to make timely decisions, such as artificial insemination, thereby improving herd fertility and economic returns.

This review has provided a comprehensive overview of IoT-based estrus detection in livestock, highlighting the technologies, sensors, data collection strategies, and analytical approaches currently in use. It has also examined commercial implementations, identified existing challenges and limitations, and assessed the potential implications for productivity and animal welfare. The findings suggest that IoT-based estrus detection has the capacity to significantly enhance reproductive efficiency, reduce costs, and support sustainable livestock farming when effectively integrated into farm management systems.

8.1. Future Directions

While significant progress has been achieved in IoT-based estrus detection, the next phase of research must move beyond conceptual feasibility toward technology-driven roadmaps that support scalable, reliable, and farm-ready deployment. Based on the synthesis of studies reviewed in this paper, several targeted research and development directions are identified:

- a) **Low-power IoT device optimization:** Future research should prioritize ultra-low-power sensing platforms through the joint optimization of hardware, firmware, and communication protocols. This includes duty-cycled sensing, event-driven data transmission, and the use of energy-efficient LPWAN technologies such as NB-IoT and LoRaWAN. Additionally, energy harvesting techniques, including solar-assisted collars and kinetic energy recovery from animal movement, should be explored to extend device lifetime and reduce maintenance overhead.
- b) **System-level integration with precision livestock farming platforms:** Rather than operating as standalone tools, IoT-based estrus detection systems should be natively integrated into precision livestock farming ecosystems. This requires interoperable architectures capable of synchronizing reproductive data with health, nutrition, and welfare indicators at the individual-animal level. Future platforms should support

standardized data formats and application programming interfaces (APIs) to enable seamless integration with farm management systems and automated decision-support tools.

- c) Next-generation machine learning and adaptive modeling: Although current machine learning models demonstrate promising accuracy, future work should focus on adaptive and transferable models that can generalize across breeds, species, and farming environments. Research efforts should explore domain-adaptive learning, federated learning, and continual learning approaches to reduce model retraining requirements while preserving data privacy. Incorporating uncertainty estimation into estrus prediction models will further improve system reliability and user trust.
- d) Secure and transparent data management frameworks: As IoT-based estrus detection systems generate sensitive reproductive and behavioral data, future architectures should incorporate security-by-design principles. Blockchain-enabled data frameworks can provide tamper-resistant data logging, transparent access control, and traceable data ownership. Research should focus on lightweight blockchain implementations compatible with resource-constrained IoT environments to ensure practicality and scalability.
- e) Large-scale validation and technology adoption studies: To transition from experimental prototypes to commercial adoption, future research must emphasize large-scale, longitudinal field trials across diverse geographic, climatic, and production systems. In parallel, socio-economic adoption studies should evaluate cost-benefit trade-offs, farmer acceptance, training requirements, and infrastructural constraints, providing evidence-based guidance for technology deployment strategies.
- f) Multi-sensor fusion and contextual intelligence: Single-sensor systems are inherently limited in their ability to capture the complexity of estrus behavior. Future research should focus on multi-sensor fusion frameworks that combine activity, temperature, acoustic, RFID, and vision-based data streams. Context-aware fusion models that incorporate environmental and physiological variables can significantly reduce false alarms and improve early estrus detection accuracy.
- g) Human-centered interface and decision-support design: Future IoT platforms must translate complex sensor data into intuitive, actionable insights for end users. Research should prioritize human-centered interface design, adaptive alert systems, and explainable AI outputs that support informed decision-making without overwhelming farmers. Mobile-first dashboards and customizable alert thresholds can further enhance usability and adoption.
- h) Cost-aware and scalable system design: For widespread adoption, future estrus detection solutions must balance performance with affordability. Research should explore modular system architectures, shared infrastructure models, and low-cost sensing alternatives that maintain detection accuracy while reducing deployment costs. Special attention should be given to small and medium-scale farms to ensure equitable access to advanced reproductive monitoring technologies.

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