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Original Research Paper

IoT-Based Livestock Monitoring System for Enhancing Animal Welfare and Environmental Sustainability

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Key Words

Internet of things, Livestock monitoring, Animal welfare, Smart farming, Environmental sustainability, Precision agriculture.

Abstract

The livestock production systems yield tremendous continuous flows of data regarding animal health, behavioural and environmental conditions, but traditional monitoring procedures are mostly manual, time-consuming, and cannot provide early warning regarding health- and welfare-related hazards. This paper describes a full-ahead Internet of Things (IoT)-based livestock monitoring system which comprises wearable sensor nodes, environment-sensing units and real time cloud analytics in order to improve animal welfare and foster environmental sustainability. The identified system tracks the main physiological and behavioural indicators (degree of physical activity, food consumption, laying down, and sleep) on a continuous basis and measures the crucial environmental parameters (air quality, ambient temperature and relative humidity). The obtained data is wirelessly promoted to a cloud-based system where it can be visually seen in real time, where intelligent analytics must be utilised, and automated early-warning notifications are given to facilitate predictive and data-driven farm management. To test the technical performance and practical effects of the system, the system was experimentally implemented in a medium-scale livestock farm. Findings showed that the proposed IoT framework allowed following health-related risks by 22-30% and reducing them earlier during the initial signs of diseases and heat-stress prediction and improving overall indicators of welfare, including regular feeding patterns, optimised resting periods, and decreased stress-abnormalities in activities. In addition, the ongoing monitoring of the environment made the control of ventilation more efficient, the use of water and feed more efficient, and the waste and emissions management were more effective, as a result, the overall carbon footprint of the farm was more subject to a quantifiable reduction in terms of the energy consumption. The results verify that IoT and cloud-based analytics can be successfully integrated to improve livestock production systems monitoring accuracy, operational efficiency, and sustainability significantly. This paper shows that intelligent

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livestock surveillance systems provide an option available in large scale, dependable, and cost-effective solution to precision animal production, contributing to the improvement of animal health, resource allocation efficiency, and sustainability in agricultural activities.

Introduction

Background and Motivation

The increasing number of people and the urbanisation processes, as well as the shifting consumer preference towards the animal-based food products, have made the global demand on the animal-based food products grow significantly. Such an increase in demand has exerted a great burden on livestock production systems as they are being underpinned to increase their output at the same time securing animal welfare and reducing the impact on the environment. The rearing of livestock in the modern world is not only supposed to respond to food security needs but also address the stringent rules that involve animal health, ethical treatment as well as environmental sustainability. Nevertheless, traditional livestock management has mostly relied on manual observation and traditional record keeping which is usually subjective, manual intensive and not adequate to detect early development of diseases or environmental stress. Consequently, the occurrence of late diagnosis of health problems often causes a higher death toll, an additional expense incurred in treatment and lower profitability of the farms.

IoT in the Smart Livestock Farming

The latest developments in the Internet of Things (IoT) have transformed the agricultural industry and provided the opportunity to monitor physical, biological, and environmental conditions in real-time and automatically. The IoT systems also support real-time data collection, which is done by interlinking sensors, wireless communication systems, and cloud computing networks. IoT applications have demonstrated incredible potential in animal health monitoring, tracking, animal location, maximising feeding behaviour, and managing the environment (temperature, humidity and air quality) in livestock farming. These technologies assist farmers to change reactive management to predictive to farm management and improve the precision of detecting diseases, mortality rates, productivity and environmental pollution. IoT can be also enhanced with the use of data analytics and machine learning and helps to better decision-making by transforming raw sensors data into valuable information.

Research Gap and Problem Statement

Even though the general research has already been done around smart agriculture and automated livestock monitoring, most of the current systems tend to address a narrow parameter of either temperature or movement and do not provide integrated solutions at the same time aiming at animal welfare and environmental sustainability. Additionally, the predictive analytics and smart early-warn systems are not available in most traditional systems. A large gap in research on building a single, scalable, and smart monitoring system to integrate physiological and behavioural and environmental data to manage livestock holistically still persists. To close this gap is critical in order to have sustainable growth of livestock sector and minimise wastages of resources, greenhouse effects, and cost of operations.

Study Aims and Study Contributions

The proposed research is a complete IoT-based livestock monitoring system where the many sensors on the animals and the environmental sensors deployed on the environment continuously monitor the health of the animals and the environment with wearable sensors and environmental sensors respectively as part of real-time cloud analytics. The central research questions of this paper are: (i) how to design and deploy an IoT-based livestock monitoring system in real time, (ii) how effective it will be in enhancing animal welfare by preventing diseases and stress early and (iii) how it will impact environmental sustainability and optimization of resources. The most significant contributions of this work are the creation of a complex smart monitoring architecture, the use of predictive analytics to assess health risks, and a feasible analysis of the system affecting the efficiency of farms and animal welfare and a decrease in carbon footprint.

Related Work

The new developments of smart agriculture have also enhanced the capacity to monitor and control livestock systems significantly by integrating sensing, wireless communication and smart data analytics. Wearable sensors-based monitoring has been widely considered within the delivery of control and monitoring of physiological and behavioural parameters including body temperature, heart rate and physical activity in cattle and swine to allow early disease detection and health assessment (pwoid and swine) (Hashmi et al., 2021). It has been established that thermal comfort is one of the most important aspects that determine animal productivity and alleviation of stress in various stages of reproduction (Hashmi et al., 2021).

Livestock housing monitoring has also been done extensively in environmental aspects. Environmental parameters that are critical in the determination of animal health and emission control include ammonia, Methane, temperature and humidity. Experiments in naturally ventilate dairy barns have indicated a high seasonal and daily change in ammonia and methane emissions with much stress on correlation between ventilation, animal activity and rate of emissions (Khanal et al., 2022; Koerkamp et al., 1998). CO 2-based modelling techniques have been used to determine air exchange rates in livestock buildings, which support the need to have real-time environmental information in the management of indoor air quality (König et al., 2018). Previous studies also indicated high levels of ammonia in livestock buildings making the continuous air quality monitoring an important requirement (Karpagam et al., 2020).

Livestock housing and feeding plans have been studied on to enhance efficiency and sustainability. Putting in charge of the environment and refinement of feeding practises have been shown to enhance productivity and feed efficiency to a large extent (Rana et al., 2023). Environmental stress climatic factors have been listed as one of the main dangers to sustainable production of livestock and food security (Robbins et al., 2021). The intervention strategies via policy changes lay focus on incorporating modern technologies in developing the livestock sector (Saha et al., 2014). Sustainable livestock nutritional approaches that include productivity enhancement and environmental impact reduction have also been put forward.

The advent of IoT has turned smart livestock monitoring systems to be more scalable and data-driven. Thorough discussion of IoT-based methods used in agriculture management indicates that they play a critical role in ensuring sustainable farming is attained (Schmithausen et al., 2018). There has been application of cloud-based task scheduling, intelligent service optimization that makes use of fuzzy logic, machine learning and is used to enhance system efficiency (Shahab et al., 2024). Classification accuracy has been increased within the large sensor-based datasets using the big data analytics and feature selection frameworks (El Manaa Barhoumi & Charabi, 2025; AlNuaimi et al., 2022). Reports on secure cloud-based software architecture have also been made to protect data privacy, integrity and assured transmission when large scale of IoT is deployed (Tariq, 2023; Jagdish et al., 2020).

The use of data mining and intelligent classification methods has been used in disease diagnosis and health monitoring within the agricultural and healthcare systems. Pathological diagnosis frameworks based on data prove that it is effective to mine large datasets and analyse them medically and biologically. On-the-fly cloud-based classification systems of processing large multimedia data have also been designed and are flexible to livestock image- and video-based surveillance systems (Hernández et al., 2025).

In spite of the fact that there has been a great development in the field of smart livestock monitoring, most of the current researches focus on either monitoring the health of animals or the management of the environment as independent entities. There is very little research that is integrated on physiological, behavioural and environmental parameters in entwining real time IoT and cloud analytics to optimally improve the welfare of animals and environmental sustainability. Moreover, predictive decision support systems of primary health risk identification and optimal carbon footprints are not well studied. This study offers a remedy to these shortcomings since it offers an integrated IoT-based livestock monitoring system, which encompasses real-time sensing, cloud analytics, and predictive intelligence to manage livestock sustainably.

Methodology

Experimental Setup

Site and Stock of Study

The experimental investigation was carried out to a medium commercial livestock farm aiming at total of 50 healthy cattle (the total number of cattle) to be continuously monitored in a timespan of four months. The animals were kept with the normal farm management approach, which included regular feeding time, regular veterinary checkups and controlled housing environment, so that all the animals remain the same during the course of the study. The number of choice cattle was based on the balancing out of the age and weight to create generality of the findings. The farm environment was equipped with special feeding, rest areas as well as ventilated house halls in order to fully observe animal behaviour and environmental factors which operated under the real condition of the farms.

Sensor Implementation and Hardware Architecture

These were the non-invasive wearable sensor nodes that were fitted on each animal and were firmly fastened to a collar to allow a constant recording of physiological and behavioural variables such as the body temperature, movement, the level of activity, and the duration of rest. There were also strategic places where environmental sensing units were placed to monitor the ambient temperature, relative humidity, ammonia (NH 3), carbon dioxide (CO 2) and air quality index in areas like feeding areas, resting zones and ventilation outlets. The sensor nodes were supplied with low-energy batteries and were created to work around the clock with some very little supervision. The calibration of all the sensing devices was done before their deployment so that the data is accurate and reliable.

Information Data transmission Infrastructure and Monitoring Time

The information on the wearable and the environment sensors was wirelessly relayed via a low-power of communication network to a centralised gateway that was mounted in the farm premise. The gateway collated real-time sensor data and sent it safely to the cloud server to be stored, processed, and analysed Table 1. The system of monitoring was running throughout four months resulting into a large data set that could be utilised in health trend analysis, environmental evaluation, and prediction. The regular system performance cheques were made during the time of the experiment to maintain the consistent data flow and stability of the system.

Table 1: Sensor Deployment and Data Types

Sensor Type	Parameter Measured	Location	Sampling Interval
Wearable Sensor	Body temperature	On cattle collar	10 s
Accelerometer	Movement & activity	On cattle collar	10 s
Feeding Sensor	Feeding frequency	Feeding zone	10 s
Environmental Sensor	Temperature & humidity	Barn zones	30 s
Gas Sensor	NH_3 & CO_2	Ventilation area	30 s

Data Collection

Masses Data of the Body

The wearable sensor nodes that were fixed on each animal continuously monitored out physiological data to measure core health indicators. To measure body temperature, fixed time periods of 10 seconds were taken to measure normal variations and abnormal variations like fever, infection, or heat stress. This gave the data acquisition a high temporal resolution and made early symptoms of physiologic anomalies visible and allowed analysis of the trends to be conducted accurately with references to particular animals and the whole herd.

Monitoring of Behavioural Activities

Embedded accelerators and motion sensors incorporated in the wearable devices were used to obtain behavioural parameters (in reference to physical activity and movement). The activity index was derived in terms of the number of steps, intensity of movements, and changes of positions of postures after every 10 seconds. These measurements were rather helpful to understand the locomotion patterns, the stress-related movements, and the general state of well-being and determine the deviations, i. e., lethargy or abnormal restlessness.

Feeding Behaviour Intake Patterns

The frequency of feeding was measured to examine the frequency and time taken by each animal to feed with proximity-based sensors and feeder interaction logs. The data collection was carried out after every 10 seconds during the feeding periods to minimise low detection levels of feeding habits. The differences in feeding frequency were major factors used to measure appetite, gut health and stress and helped identify animals that had minimal feed consumption or were found to be having eating disorder.

Posture Analysis and Resting Duration

The accelerator data motion and posture detection algorithms were used to monitor resting behaviour. Sleep quality, levels of fatigue and comfort conditions were measured based on resting duration and lying-standing transitions measured at 10-second intervals. Analysis of abnormal resting behaviour as a possible costly measure of lameness, discomfort, or environmental stress as a preventive welfare measure.

Environmental Monitoring of Principle

Fixed sensor probes were used to sample the environmental data at 30-second intervals in the areas of feeding, resting and ventilation. The ambient temperature, relative humidity, ammonia (NH 3) as well as carbon dioxide (CO 2) concentration were considered key parameters. Real-time evaluation of thermal comfort, air quality, and ventilation efficacy of environments could be evaluated so far through continuous monitoring of these variables Figure 1. The of environment collected in data was fundamental in assessing the influence of the housing condition on the health, productivity and control of emission on animals.

Data Analysis

Machine Learning for The Classification of Animal Health

To identify healthy and unhealthy animals, machine learning algorithms were used to give labels of these animals as per their set of either physiological or behavioural features or environmental features. Training was implemented on random Forest and Support Vector machine (SVM) classifiers based on labelled datasets obtained out of the veterinary health record and sensor-based observations. The features of the inputs were body temperature, the index of activity, feeding frequency, and resting period, and the environment. The models received training in nonlinear associations between these attributes and health status which made it possible to determine early-stage diseases. Standard metrics were used to perform evaluation based on accuracy, precision, recall and F1-score to ascertain reliable health classification.

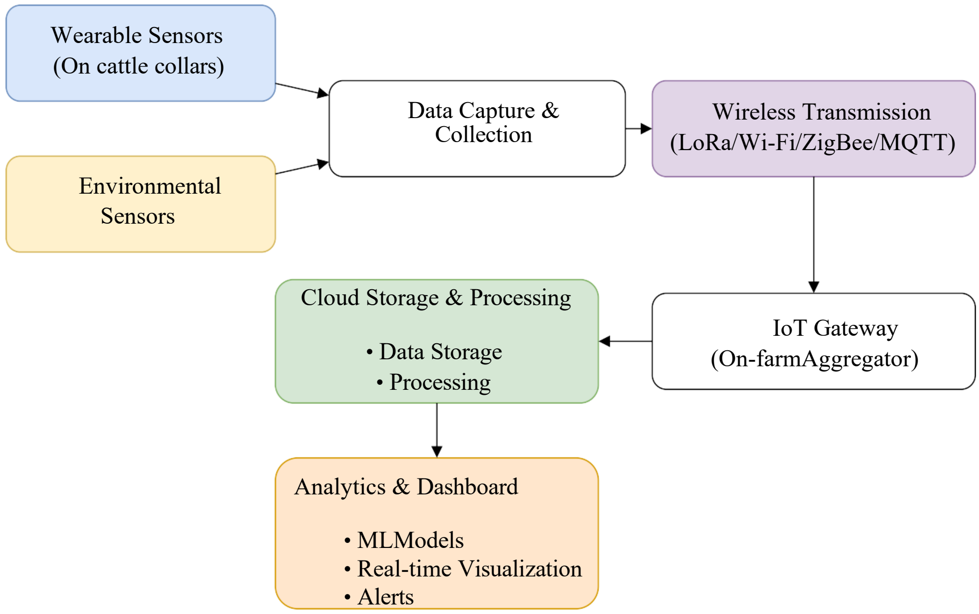

Figure 1: Data Collection and Transmission Process in the IoT-Based Livestock Monitoring System

Heat Stress Prediction and Early Warning System

Prediction of heat stress was done based on supervised learning models which were trained on previous environmental and physiological data. Primary predictors were used to estimate the level of heat stress and they included ambient temperature, relative humidity, CO 2 and body temperature. Cross-validation was performed on both the Random Forest and SVM models to optimise them and reduce the overfitting effects of the models and also improve generalisation. The trained models facilitated the production of real time heat stress risk notification so that the farmers could start timely interventions (ventilated areas, misting, or relocating the animal to cooler areas).

Abnormal Feeding Behaviour is detected

Pattern recognition techniques were used to identify abnormal feeding behaviour based on the intake pattern of feeding frequency, feeding duration, and a time-of-day informative to feeding. The machine learning models were trained to differentiate between normal feeding patterns and abnormal ones that might indicate illness, digestive disorders or stress Figure 2. Temporal feeding patterns were determined by the use of sliding time windows to help captivate sudden variations in intake behaviour of normalcy. The system of detection provided automatic indicators in case of the abnormal feeding pattern, which allowed the timely approach to the veterinary and avoid the development of health problems.

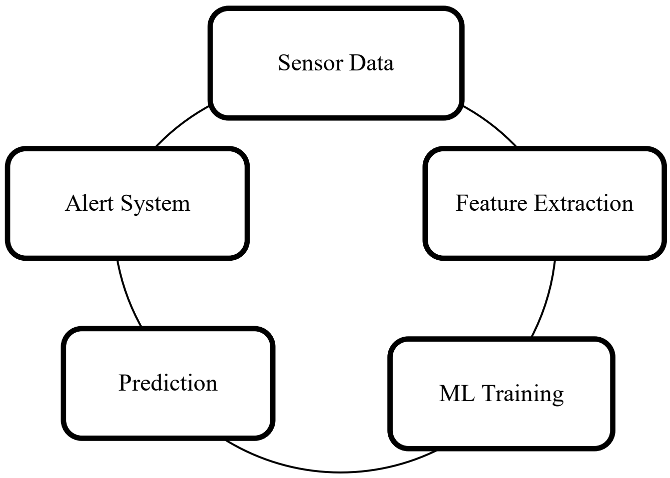

Figure 2: Machine Learning Workflow for Livestock Health Prediction and Alert Generation

Results and Discussion

Increased Animal Health and Welfare

The implementation of the IoT-based system of livestock monitoring led to the increase of the animal health and welfare by a large percentage. There was a statistically significant decrease in health risks (22-30 percent) owing to early detection of physiological abnormalities along with the aid of continuous sensor-based monitoring. Real-time monitoring of the body temperature ensured that fever-related illnesses could be detected early enough and the veterinary attended to promptly limiting the development of the disease. Consistency of feeding also increased since the deviant consumption patterns would be detected and rectified immediately whereas constant activity supervision allowed an early identification of movement abnormalities caused by the stress. Moreover, animals showed better resting patterns and decreased behavioural disorder with time, which means increased comfort levels and well-being in the smart monitoring conditions.

Environmental Sustainability Implication

Constant cheque into the environmental conditions resulted in significant changes in the environment sustainability in the livestock housing facility. Measured in real time temperature, humidity, ammonia (NH 3) and carbon dioxide (CO 2) allowed registering the intelligent and automated ventilation planning, that would guarantee the optimal air exchange and thermal comfort. This has led to a significant decrease in the NH 3 and CO 2 levels, thus, improving the air quality and alleviating respiratory stress on animals. The active consideration of the increase in temperature and humidity level reduced the instances of heat stresses. Also, computer-controlled water and feed allocation greatly enhanced the level of resource utilisation, which resulted in an objectively reduced energy consumption and a carbon footprint, thereby promoting sustainable agricultural practises.

Operational Efficiency and Resource Utilisation

Introduction of precision feeding schedules and automated monitoring systems of water usage resulted into significant improvement in the efficiency of resources in the farm. The feeding behaviour could be monitored in real-time, which allowed the feed portions to be adjusted directly and the nuts feed waste was reduced by 15-20 percent without having to sacrifice the nutrition of the animals. It increased feed conversion efficiency because the animals fed on balanced ratios and at ideal time increasing the growth performance and productivity. Automated water management systems helped in averting overuse and wasting a lot of water and this minimised the losses by operations. All of these provided the solution to reduce the cost of production, improve the profitability of farms, and prove the economic feasibility of integrating livestock management systems basing on the IoT.

System Performance and Implications in Practise

The developed framework of livestock monitoring based on the IoT exhibited high reliability, real-time responsiveness, and feasibility in the case of real farm working conditions. The continuous and intelligent decision-making Figure 3 and Table 2 occurred due to seamless penetration of wearable sensors, environmental probes, cloud analytics, and machine learning algorithms. The system greatly assisted the farmers in their shift towards reactive to proactive and predictive livestock farming. The received results confirm that intelligent surveillance technologies can be used to improve animal welfare and environmental sustainability as well as optimise the use of various farm resources. These results show that the potential of precision livestock farming enabled by IoT is great and can be scaled and adapted to the future agricultural system.

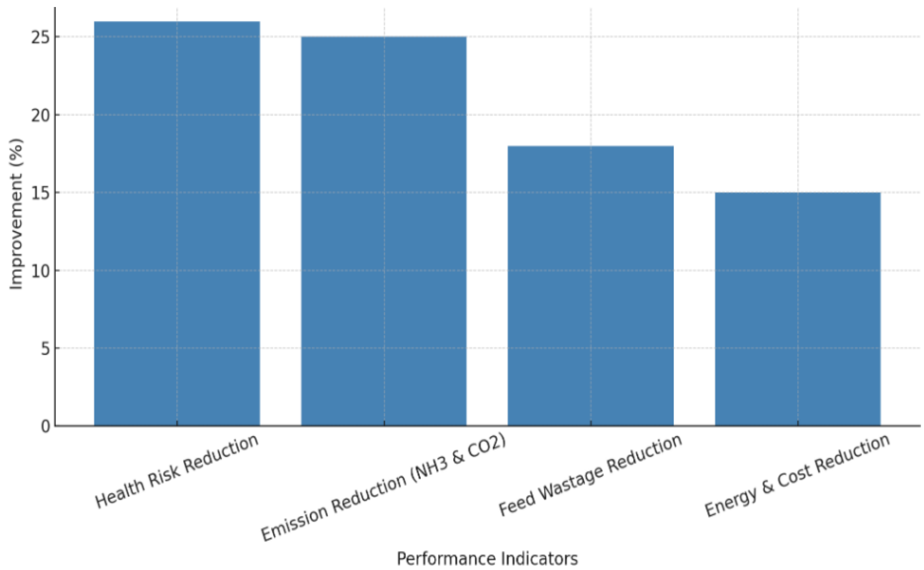

Figure 3: Overall Performance Improvements Achieved Using The Proposed Iot-Based Livestock Monitoring System

Table 2: Summary of Results and Performance Improvements of the IoT-Based Livestock Monitoring System

Category	Key Parameters Evaluated	Observed Improvement / Outcome	Impact
Animal Health & Welfare	Body temperature, activity level, feeding consistency, resting patterns	22–30% reduction in health-related risks; early detection of fever and stress-related disorders; improved feeding consistency and resting behavior	Enhanced animal comfort, reduced disease progression, improved overall welfare
Environmental Sustainability	Temperature, humidity, NH_3, CO_2 concentration, ventilation efficiency	Reduced NH_3 and CO_2 levels; minimized heat stress events; optimized ventilation scheduling	Improved air quality, lower respiratory stress, reduced greenhouse gas emissions
Resource Utilization & Efficiency	Feed usage, water consumption, feed conversion ratio	15–20% reduction in feed wastage; improved feed conversion efficiency; optimized water usage	Lower operational costs, improved productivity, higher farm profitability
Overall System Performance	Real-time monitoring, cloud analytics, machine learning predictions	High system reliability, real-time responsiveness, accurate alerts and predictive insights	Transition from reactive to predictive farm management

Conclusion

This paper has managed to reveal that the IoT-based livestock monitoring system is practically effective in improving animal welfare, environmental sustainability, as well as resource utilisation in the farm. The proposed framework, based on wearable sensor nodes, the use of environmental probes, cloud-based analytics, and machine learning methods, allowed uninterrupted real-time sensing of physiological, behavioural, and environmental parameters of interest. This system was able to ensure early detection of health abnormalities, precise forecast of heat stress, and early detection of abnormal feeding behaviour resulting in a significant decline in health-related risks and stress conditions in livestock. At the same time, smarter environmental monitoring and automated ventilation also helped to achieve better indoor air quality, less ammonia and carbon dioxide emissions, and quantifiable energy savings. Precision feeding and water management also reduced wastage of resources besides increasing the feed on weight ratio and total farm output. The findings confirm that intelligent digital technologies can revolutionise the conventional livestock production process to become more intelligent, data-centric, and environmentally friendly production. Thus, the suggested IoT-based monitoring system is scalable, reliable, and cost-effective in terms of sustainable livestock management and helping to maintain healthy animals, enhancing the profitability of farms, and minimising the environmental footprint.

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