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REVIEW ARTICLE

SMART DAIRY FARMING: ENHANCED EFFICIENCY, PRODUCTIVITY AND ANIMAL WELFARE THROUGH THE INTERNET OF THINGS AND CLOUD INTEGRATION

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ABSTRACT

Dairy industry faces numerous challenges today and, in the future, including labor shortage, stemming from economic pressure due to high cost and insufficient returns, and evolving marketing dynamics. In order to cope with these challenges, the integration of advance technologies such as automation and data analytics is indispensable. The Internet of Things (IoT) has enabled the development of "smart" devices installed with sensors such as smart collars, wearables, thermometer, hygrometer, and air quality detectors for efficient and sustainable dairy farming. Moreover, the vast volume of data generated by the IoT devices necessitates integration with cloud computing for effective handling. However, this integration presents challenges; in particular, data overload due to superfluous communication and noise. To address this, pre-processing and data trimming services such as smart gateways, smart networks, and fog computing have been employed. In livestock farming, CoT integration has revolutionized real-time monitoring, advanced care, in-time ovum pick-up, *in vitro* fertilization, embryo transfer, artificial insemination, milk production, and gene selection. Through IoT devices and sensors, real-time data regarding an animal's health (e.g., body temperature, level of reproductive hormones, and vaginal pH), behavior, and environment facilitated advanced animal welfare practices. The CoT's cloud-based infrastructure enables comprehensive analysis, leading to improved veterinary care, early disease detection, and insightful research into diverse species' health dynamics. Ultimately, the integration of IoT and CoT signify a paradigm shift in dairy farming, transcending mere automation to offer a holistic, data-driven approach that harmonizes productivity with animal welfare. By leveraging these innovations, the dairy sector has poised to achieve sustainable growth by saving 178% cost on feed pushing, 44.05% on milking, 121.97% on cleansing, 126.2% on herd monitoring, and 109.3% on analyzing real-time data generated by IoT devices and forecasting. This study falls under the umbrella of UNO's goals for sustainable development.

Keywords: Internet of Things, cloud computing, intelligent animal breeding, smart disease management, smart farm management

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INTRODUCTION

The Internet of Things (IoT) and cloud computing are key components for the future of computing, and their combination ushers in a fully automated digital era (Wu *et al*., 2010). Millions of people now connect their smart devices to the internet to exchange data and information. Anything can be connected to internet, from a beverage bottle to a leaf on a tree (Halim and Hutagalung, 2022). The development of next-generation internet (5G and 6G) and smart devices has further revolutionized the IoT. It is more than just a device with hardware and software integration, including social interaction (Kortuem *et al*., 2009); IoT presents important interactions between heterogeneous devices to pass the information to a central authority. IoT is critical for future computing and has now become integrated in every field of life, including transportation (Krasniqi and Hajrizi, 2016), healthcare (Darshan and Anandakumar, 2015), home automation (Abdulraheem *et al*., 2020), energy sector (Hossein Motlagh *et al*., 2020), and agriculture (Titovskaia *et al*., 2020).

Graphical Abstract

In IoT, machine-to-machine (M2M) communication occurs without human intervention, in which non-connected devices are linked via Bluetooth, radio frequency identification (RFID) tags, and barcodes (Table 1) (Pani *et al*., 2021). Figure 1 shows the IoT architectures contain the following layers: (1) business layer, (2) application layer, (3) middleware layer, (4) network layer, and (5) perception layer(Wu *et al*., 2010; Khan *et al*., 2012). The perception layer comprised RFID tags, barcodes, sensors, cameras, and a global positioning system (GPS), which collect raw data (Uckelmann *et al*., 2011). This data is then transferred to the network layer and interface gateways between the sensor and the internet are reassembled using an open-system interactions model, which is sometimes integrated with an information processing or network management center (Figure 1). The middleware layer is responsible for service management and data storage and also performs information processing and automated decision-making, the results of which are transferred to the application layer (Khan *et al*., 2012). The application layer then presents the data in the user's required format and offers global management of the application; for example, smart transportation, smart home management, smart cities, vehicle chasing, smart health, or smart farming (Khan *et al*., 2012). The business layer performs modeling and services to make profits. State-owned or non-profit IoT applications are also part of the business layer.

Conventional dairy farming is not sustainable due to shortage of labour, high costs of feed, equipment, fuel, veterinary care, and significant fluctuations in milk prices due to rise of plant-based alternatives and cell based dairy (Bojovic and McGregor, 2023; George, 2023). Extreme weather conditions such as rising temperature, drought, and floods has increased price feed prices. Cattle health issues such as lameness and mastitis have significantly affected productivity and animal welfare (Nielsen *et al*., 2023). Conventional housing and tie-stalling causes severe stress and health issues leading to significant conception rate and decrease in dairy production (Pagani *et al*., 2017). Moreover, integration of IoT and cloud computing have significantly enhanced efficiency and production of conventional dairy by; real-time monitoring, data collection and analysis leading towards precision livestock farming (PLF); cloud based data analytics and scalability; and cost reduction by resource management (Table 1) (Tangorra *et al*., 2024).

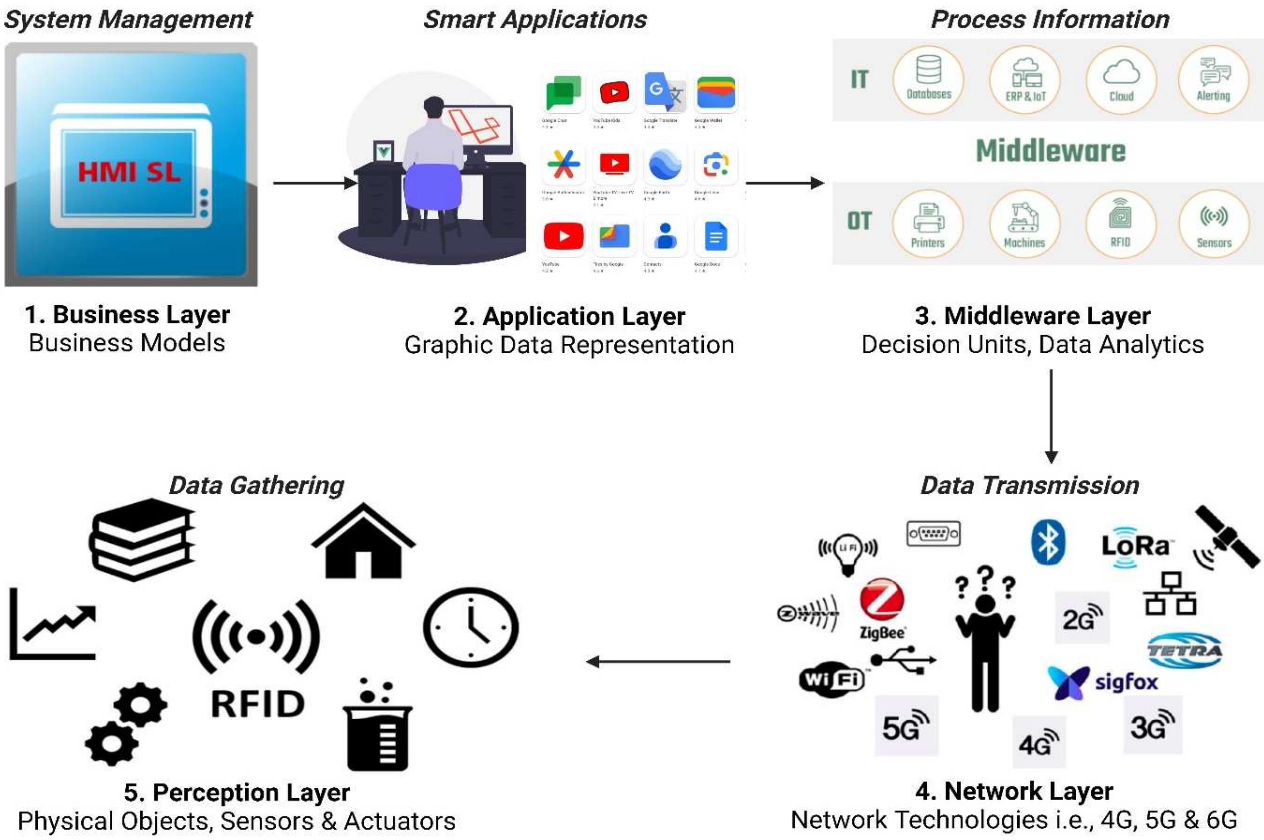

Figure 1. Internet of Things (IoT) and programmable object interface layers. (1) Business layer, (2) application layer, (3) middleware layer, (4) network layer, and (5) perception layer.

APPLICATIONS OF THE INTERNET OF THINGS IN AGRICULTURE AND DAIRY FARMING

Agriculture Drones and Satellite Imagery: In agriculture and animal farming, AI based drones and satellites technology has fostered precise and sustainable farm management practices (Gou *et al*., 2024; SS *et al*., 2024). Unmanned Aerial Vehicles (UAV) are revolutionizing modern agriculture and livestock farming by providing cutting edge crop monitoring and health assessment, precise and site specific pesticide and fertilizer application, planting and seeding, and monitoring health of animals (Anees *et al*., 2022; JOUAV, 2024). Satellite technology provides real-time crop health monitoring via multispectral imaging (Figure 2), extensive land use mapping and analysis, accurate weather forecasting for localized areas, soil moisture tracking to optimize irrigation, and early detection of insect pests and disease outbreaks (Ammar *et al*., 2024). JEEVN AI is an innovative personalized farm advisory tool developed by Farmonaut®, which provides accurate data about soil nutrient (N, P, K, S, and Z), recommend rate and time of irrigation, soil pH, pest-disease prediction and remedies, crop growth and yield forecasting, and satellite imagery (Farmonaut, 2023).

Automated Ploughing, Irrigation and Fertilization: Integration of IoT devices in auto-ploughing has enabled farmers to operate tractors and ploughing devices remotely via GPS 5G network represents significant advancement in precision farming (Mukherjee *et al*., 2021). IoT in auto-ploughing has following applications: auto-navigation and control, integration with drones, remote monitoring and management, a step forward in sustainable agriculture. Increasing water shortage has posed severe threat to agricultural practices, and increased use of inorganic fertilizers has affected soil texture (Figure 2). IoT devices have made possible to do automated precise irrigation and fertilization only in root zone available to plants. IoT integrated smart and intelligent irrigation devices synchronized with real-time weather data not only conserves water and fertilizers but also promote optimal and sustainable growth. In 2023, department of agriculture and livestock, Sharjah (UAE), installed AI based pivot irrigation system, soil sensors, satellites for thermal imaging, on-site weather station to forecast rain, wind, and temperature in Mleiha desert comprised of an area of 400-hectare and harvested 1,700 tonnes of wheat first time in history, managed by only two engineers and seven workers, with aim to expand on 1,900 hectares (Gupta, 2023).

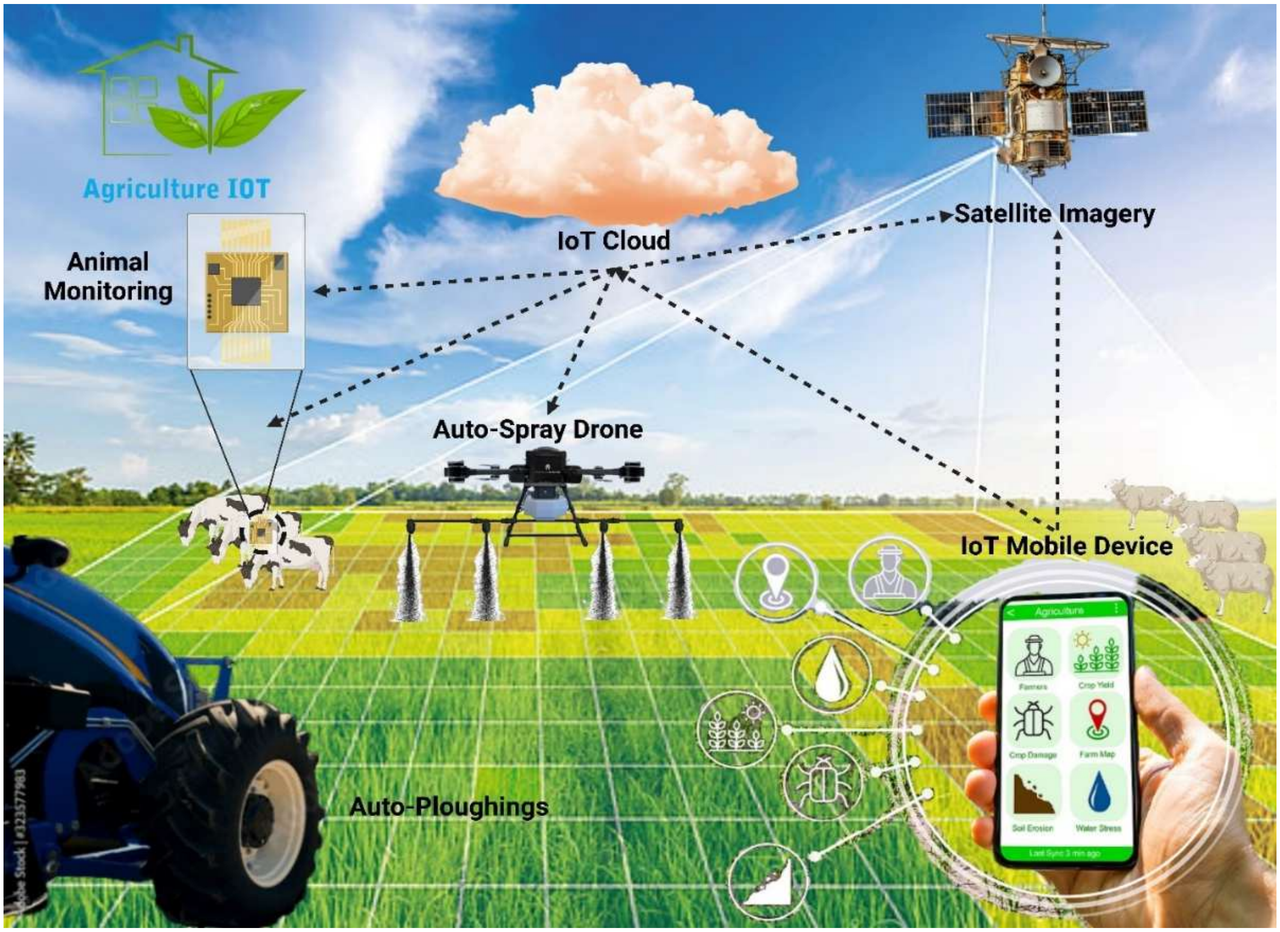

Figure 2. Cloud of Things (CoT) is the combination of the Internet of Things (IoT) and cloud computing to develop smart devices integrated agriculture satellites for real-time detection of pathogens and loss of nutrients, communication with; drones for auto-spraying of insecticides and pesticides, tractors and instruments with highly sensitive sensors installed for auto-ploughing.

Environmental Monitoring for Precision Farming: One of the most promising market segments for the use of wireless identifiers and other IoT technologies in future is green applications and environmental preservation. Figure 2 shows that the use of wirelessly identifiable gadgets, edge computing, federated learning, and the integration of multi-functional sensors will strengthen efforts for monitoring of global environmental changes. Recently, Deere & Company (deere.com) signed a contract with SpaceX to provide satellite communications (SATCOM) to farmers to leverage precision agriculture (Moline, 2024). The cutting-edge applications of SATCOM and xarvio® FIELD MANAGER will enable farmers to accomplish the cultivation of corn in short windows of time to produce silage even in extremely cold areas such as northern China.

Advance Animal Healthcare, Enhanced Communication and Training: The IoT has a wide range of applications in the healthcare industry; for example, the use of mobile devices integrated with RFID sensors for the monitoring of medical parameters and precise drug delivery (Li *et al*., 2024). The IoT has enabled *ad hoc* diagnosis and prevention as well as quick medical intervention during an accident. IoT-integrated labeling with smart tags has enabled the monitoring of veterinary drug validity under cold conditions in the supply chain. Recent invention of cells interfaced with semi-conductor-based brain-computer interfaces or brain-machine interfaces, such as neuron chips, bionic chips, or brain chips (Figure 3), has enabled scientists to develop brain-controlled prosthetic limbs and devices like electroencephalography and smart prosthetic limbs (Clément, 2019). For instance, the Neuralink® chip's first recipient has achieved the ability to control a computer mouse with only their thoughts (Figure 3) (Agnihotri and Bhattacharya, 2023). Potentially, bionic chip could make possible direct communication for early disease detection and behaviour changes of animals, improved training methods, monitoring reproductive health, and genetic selection.

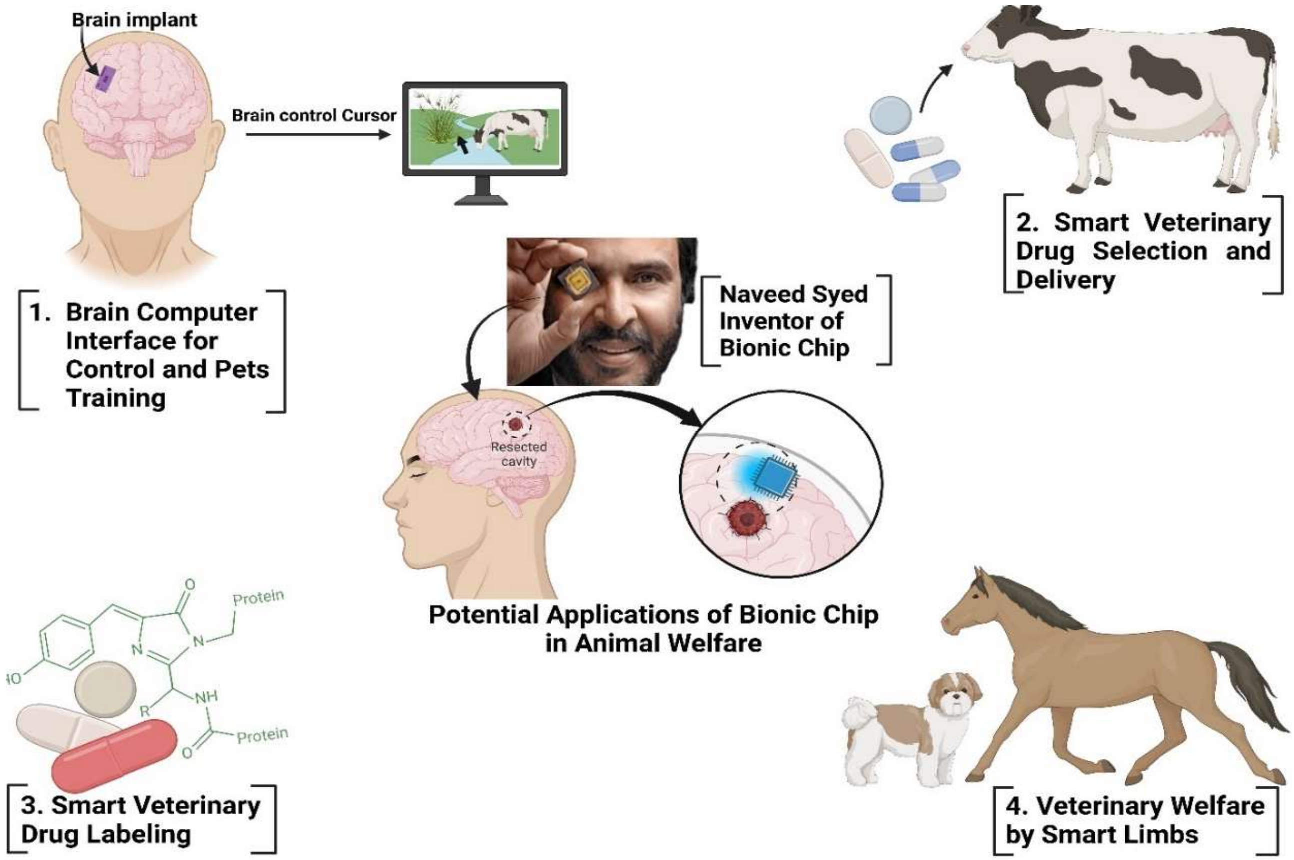

Figure 3. Protocol support in which smart chips, such as bionic chips or Neuralink chips are used for brain-computer interface (BCI) development for control and training of pets, veterinary welfare by smart prosthetic limbs, smart selection and precise drug delivery, and veterinary drug labelling.

Cloud Computing: Cloud computing is a comprehensive form of parallel, grid, and distributed computing (Gubbi *et al*., 2013). Smart devices have enabled direct cloud computers to save and access data worldwide. Cloud computing is being widely employed in market analysis (Wu *et al*., 2018), e-governance (Nanos *et al*., 2019), industry (Ooi *et al*., 2018), healthcare (Rajabion *et al*., 2019), e-education (Naveed *et al*., 2019), and e-dairy production (Barry *et al*., 2013). Cloud computing has enabled smart business decision-making and marketing, as well as online services such as degree verification, visa application, first information report registration, industry-centralized data storage, online classes, central patient history, and central ovine and bovine data collection for precise breeding management. The integration of the IoT with cloud computing has created an extended portfolio for smart communication and the quick development of services based on fog computing and smart gateways; this is known as the Cloud of Things (CoT) (Aazam and Huh, 2014b).

Blockchain and the Cloud of Things: Blockchain is a decentralized, immutable, secure, and transparent facility that records transactions and assets that everyone can assess, without tampering, through a network of nodes (Namasudra *et al*., 2021). Each node has the power to originate, authenticate, and validate a new transaction to verify the users' activities in the network. There are two types of blockchain: public (permission-less) and private (full-permission) (Dinh *et al*., 2018). Decentralization is a key feature of blockchain that means transactions are managed at numerous checkpoints to avoid tampering activity (Liu and Liu, 2019). In practical applications, blockchain offers high-security features. However, improved scalability and enhanced security measures and regulatory compliance, and integration with emerging technologies are urgently required.

Challenges associated with the iot and cot: The easy and free access to the commercial prospects of enterprises in hybrid clouds of the CoT makes it vulnerable to hacking attacks, which can compromise its security, privacy, and identity protection (Gubbi *et al*., 2013). The following issues therefore need to be addressed carefully:

Protocol Support: Different protocols are used to link various devices to the internet. Even for homogeneous entities, such as IoT sensors, it is possible that distinct protocols, such as wireless highway addressable remote transducers (WirelessHART), ZigBee, the Institute of Electrical and Electronic Engineers regulations (e.g., IEEE 1451), internet protocol version 6 (IPv6) low-power wireless personal area networks (6LOWPAN), are used for different sensors (Figure 4).

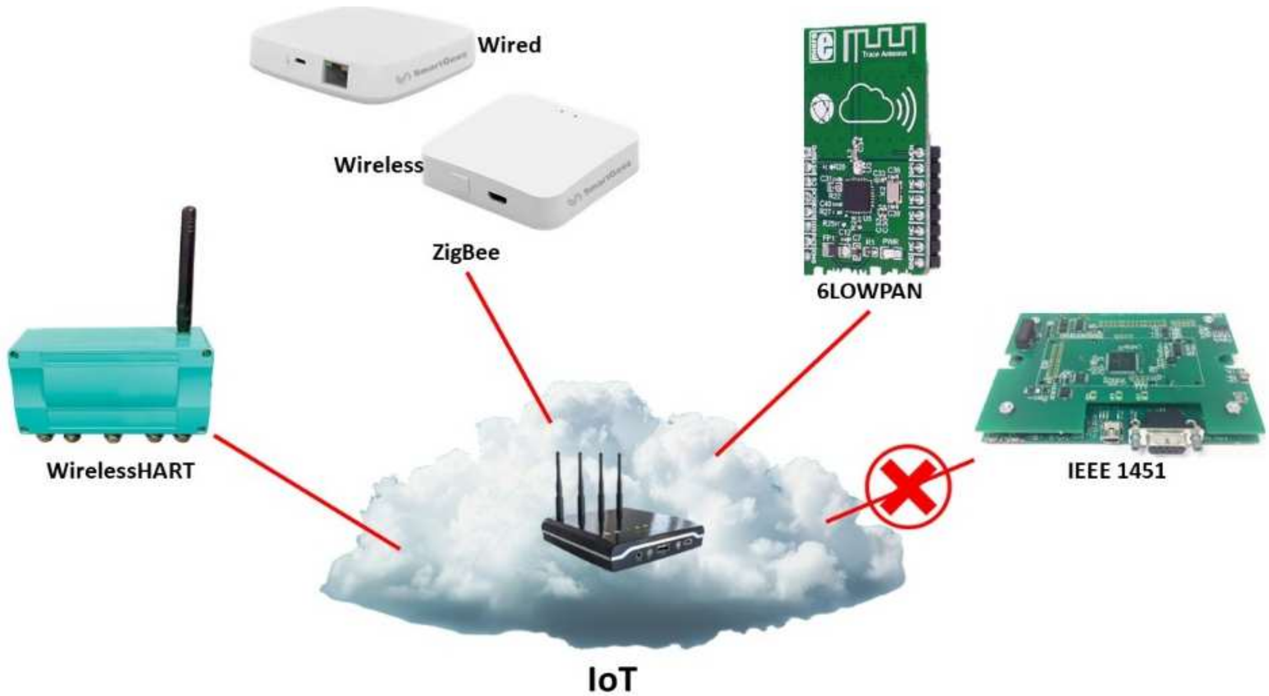

Figure 4. Smart network with smart gateway, comprised wireless highway addressable remote transducer, ZigBee, and 6LOWPAN.

Energy Efficiency: A standard wireless system has (a) a sensor device, (b) a processing unit, (c) a transmitter, and (d) a power unit (Amirinasab Nasab *et al*., 2020). The power unit plays key roles in video sensing, encoding, and decoding. Video encoding is more difficult than decoding because the encoders require access to the video's redundancy data for efficient compression (Chen, 2012). The cell-based temporary power supply requires regular replacement, which is not suitable for ever-sensors and low-power devices. Therefore, the development of sensors integrated with wind turbines and solar panels, and an efficient sleep mode is required.

Resource Allocation: Allocating resources in the IoT and CoT presents difficulties in handling unexpected and varied device requests in a cloud setting. The individualized nature of requests makes it impossible to forecast the precise resource requirements for any organization or IoT device. Therefore, mapping the type, amount, and frequency of data generation based on sensor types and utilization purposes is crucial. In addition, making test transmissions from newly installed nodes can help with resource allocation decisions. The crucial elements of IoT resource allocation are (a) allocating resources to the network edge to reduce latency and allow for real-time processing, (b) managing resources effectively in different cloud, fog, and edge computing settings, (c) algorithm optimization to minimize communication overheads, and (d) reinforced learning.

Identity Management: Over the internet, communicating nodes are uniquely recognized by their unique identities. Mobile devices must also have identity mapping in the new network they have just joined, such as mobile sensor nodes on automobiles and other objects. Assigning IPv6 addresses may be a reasonable solution in this respect because the address space available on IPv6 can enable this type of ubiquitous networking.

IPv6 Deployment: The assignment of IPv6 addresses presents a viable solution due to the extensive address space available, which can facilitate ubiquitous networking. In addition, mobile devices, including sensor nodes on vehicles and other objects, require identity mapping upon joining a new network. This ensures unique recognition of communicating nodes on the internet, each with distinct identities (Aazam and Huh, 2014a).

Service Discovery: In the realm of IoT and CoT, the cloud manager assumes the responsibility of identifying novel services for customers. The IoT encompasses a wide array of objects, with the potential for objects to enter or exit the network dynamically. Some IoT nodes may even be mobile. Consequently, locating and assessing new services, as well as updating service marketing, can pose challenges. In the case of intricate and expansive IoT ecosystems, an IoT manager is essential. This individual oversees the monitoring and management of newly integrated and existing IoT nodes, as well as tracking mobile nodes. An established service discovery process is indispensable in fulfilling these responsibilities.

Quality of Service Provision: As data volume grows and factors such as complexity and unpredictability emerge, ensuring quality of service (QoS) becomes challenging. Any data type, in any quantity, could be triggered at any time, potentially including critical information about emergencies. To address this, queries must be dynamically prioritized on the cloud side (Aazam *et al*., 2013).

Location of Data Storage: The geographical location plays a crucial role, particularly for sensitive data susceptible to jitter or latency. Time-critical content, such as videos, should be stored in proximity to the end-user to reduce the retrieval time for substantial data volumes. Regarding multimedia data, it is essential to designate the closest virtual storage server available.

Security and Privacy: The future expansion of ubiquitous computing will heighten security and privacy challenges. Data security concerns will emerge in cloud and IoT domains, paralleled by escalating privacy apprehensions. A 2013 disclosure by *The Independent* revealed that US authorities often access personal data of British internet users on leading cloud storage platforms.

Fogging and Smart Gateway-based Communication: During IoT connectivity and data generation, there comes a point where data uploading becomes unnecessary or redundant. In such cases, devices or sources should have the capability to cease data production; alternatively, a designated gateway device can be instructed to regulate data transmission based on necessity. To address this, IoT gateway devices require additional permissions for preliminary data processing before transmission to the cloud and internet. These smart gateways, based on application feedback, manage data transmission timing and content, reducing unnecessary resource consumption (Aazam and Huh, 2014b; Aazam *et al*., 2014).

(a) Smart gateways: Fog computing is used globally, particularly in cities for centralized systems and apps that handle parking lots and traffic signals. Fog computing is used for various purposes, such as resource management (Wang *et al*., 2019; Ghobaei-Arani *et al*., 2020), mobile networks (Zhou *et al*., 2019), healthcare (Mutlag *et al*., 2019), and smart cities (Zahmatkesh and Al-Turjman, 2020). To improve traffic efficiency and data quality, smart gateways filter out extraneous data and intelligently manage data transmission. They are an essential component of the network devices of the future. They enable multi-hop communication (which involves indirect device connectivity) and single-hop communication (Ding *et al*., 2016a). Smart gateway architecture is critical in IoT ecosystems tasked with functions such as data collection, preprocessing, quality control, energy monitoring, and security. Depending on data flow, smart gateways can be categorized into direct and indirect communication types.

(i) Direct/single-hop communication smart gateways: This form of communication is employed in scenarios where there are few sending nodes, and each node has a limited role in providing the service. In a single-hop connection, sensors or devices are directly linked to the gateway, which receives and relays the data to the fog before transmitting it to the cloud. For example, in smart healthcare systems, sensors connect directly to the gateway (Aazam and Huh, 2014c). This setup facilitates quick response times and effective monitoring. In M2M scenarios, the gateway can relay data to the fog and then to the cloud. Smart gateway operations, such as security measures, data refinement, and filtering, can be tailored to meet specific requests in conjunction with fog computing (Khan *et al*., 2017).

(ii) Indirect/multi-hop communication smart gateways: Connecting numerous sensors to the IoT makes it difficult for the IoT to connect directly to the gateway. Base stations and sink nodes are common components of these networks. These nodes provide the gateway with data, which results in the setup of multi-hop communication. In this situation, due to the widely distributed nodes, the gateway receives heterogeneous data that requires in-depth processing and analysis. By enclosing the underlying sensors and equipment in a "black box," sink nodes improve security by adding another layer to messages. This adaptable security strategy complies with the needs of IoT systems and wireless sensor networks (WSNs). Sink nodes oversee sensor networks in accordance with their unique limitations. The gateway is an essential component in managing the variety of data that is received from heterogeneous equipment, IoT devices, and WSNs. In these configurations, achieving transcoding and interoperability becomes crucial. Large-scale WSNs and IoT deployments, such those for climate controllers, car trackers, and other mobile devices, are well-suited to this scenario (Abdul-Qawy *et al*., 2023).

(b) Fogging: Fog computing integrates networks with resources, extending cloud computing to the network edge for improved service provision. It virtualizes storage, computation, and networking for IoT devices, enhancing the application's performance (Bonomi *et al*., 2012). Fog computing optimizes applications via dispersed deployments, catering to low-latency needs, such gaming, augmented reality, and video streaming. Fog computing with a co-located smart gateway efficiently performs data security and privacy, preprocessing, and temporary storage. Fog computing preprocesses real-time data, addresses data heterogeneity, and facilitates IoT integration, enabling the creation of rich services. The layered architecture of the smart gateway manages network activities, monitors power consumption, and ensures data security before cloud upload (Figure 5) (Bonomi *et al*., 2012).

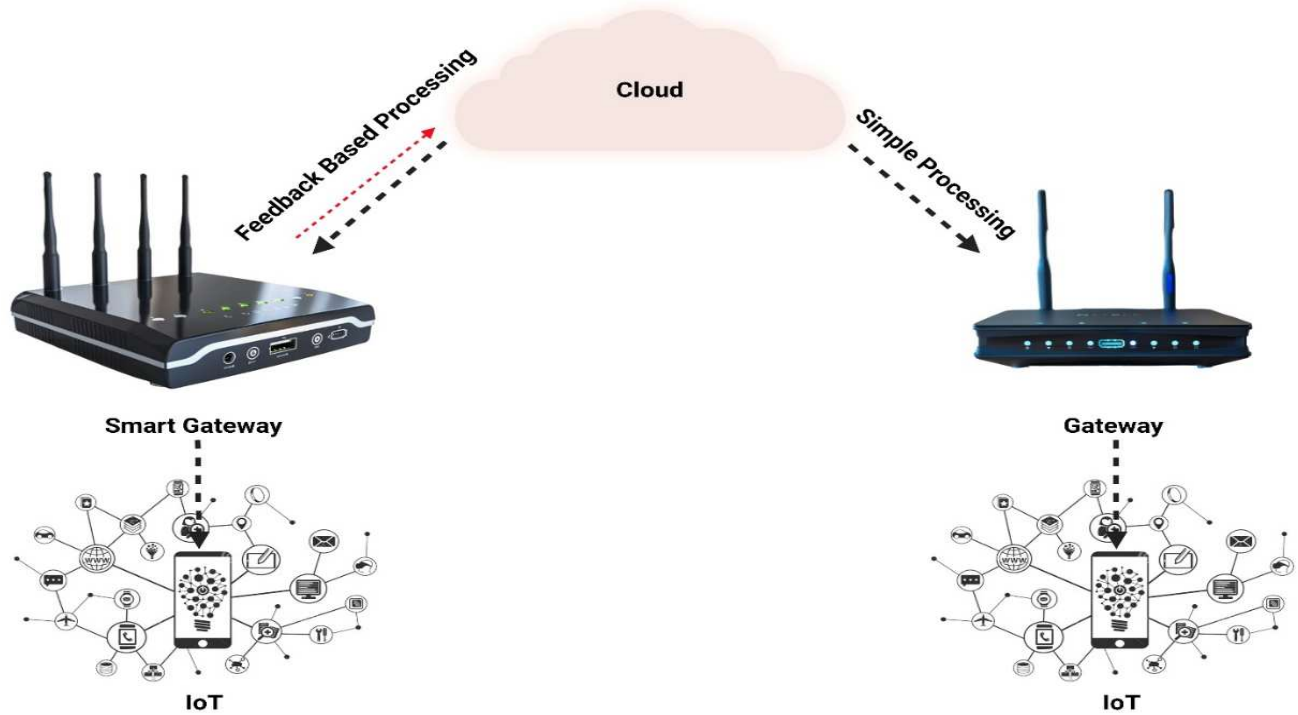

Figure 5. Layered architecture of the smart gateway. Smart gateway data communication is based on a feedback processing mechanism, while gateway data communication is based on simple processing.

The smart gateway's architecture (Figure 7) is made up of several layers for effective management and operation. The layers include (1) the virtualization and physical layer, which administers and preserves WSNs, physical nodes, virtual sensor networks, and virtual nodes in accordance with specifications; (2) the monitoring layer, where tasks, deadlines, and impending requirements for efficient operation are tracked by monitoring the activity of the underlying networks and nodes; (3) the power consumption monitoring layer, which monitors power usage across all devices or nodes and guarantees prompt action; (4) the preprocessing layer, which is responsible for data management duties such as trimming and filtering to extract relevant and essential data; (5) the fog resources layer, which temporarily stores processed data before sending it to the cloud; (6) the security layer, which provides secure transmission and storage of the sensitive and private data produced by WSNs, the IoT, and healthcare services; and (7) the transport layer, which facilitates the uploading of data to the cloud so that services can be created for users (Ding *et al*., 2016b).

Evolution of cloud-to-gateway communication: The performance evaluation of cloud-to-gateway communication involved testing on a dedicated test bed with cloud and gateway devices. Two datasets were utilized: bulk data and multimedia (audio/video) files. The evaluation of multimedia data was conducted for IoT devices such as visual sensor networks generating audio/video data, while heterogeneous files are used for bulk data sets, encompassing varying sizes, types, and formats. Scheduling algorithms employed by the cloud, such as first-in-first-out and shortest-job-first, impact the overall data storage performance. To mitigate network condition impacts, exhaustive evaluations were conducted over six weeks at varying times of the day and week. The average upload time for a 30-MB video file to the cloud was 97 seconds (Figure 6a). For content relocation or attribute alterations, uniform resource locator reconfiguration and synchronization are necessary. The time for data synchronization, shown in

Figure 6b, is crucial for collaborative environments accessed by multiple users or nodes, and is especially significant for multimedia content, affecting the performance during the transcoding and harmonization of content from various IoTs. In the second evaluation, 200-MB bulk datasets were included, but, for simplicity, only a 15-MB dataset is presented (Figure 6c). Synchronization delays were more pronounced for bulk data, as shown in Figure 6d, where the synchronization time for 30-MB multimedia files was more than double that of 15-MB bulk data (Figure 6d).

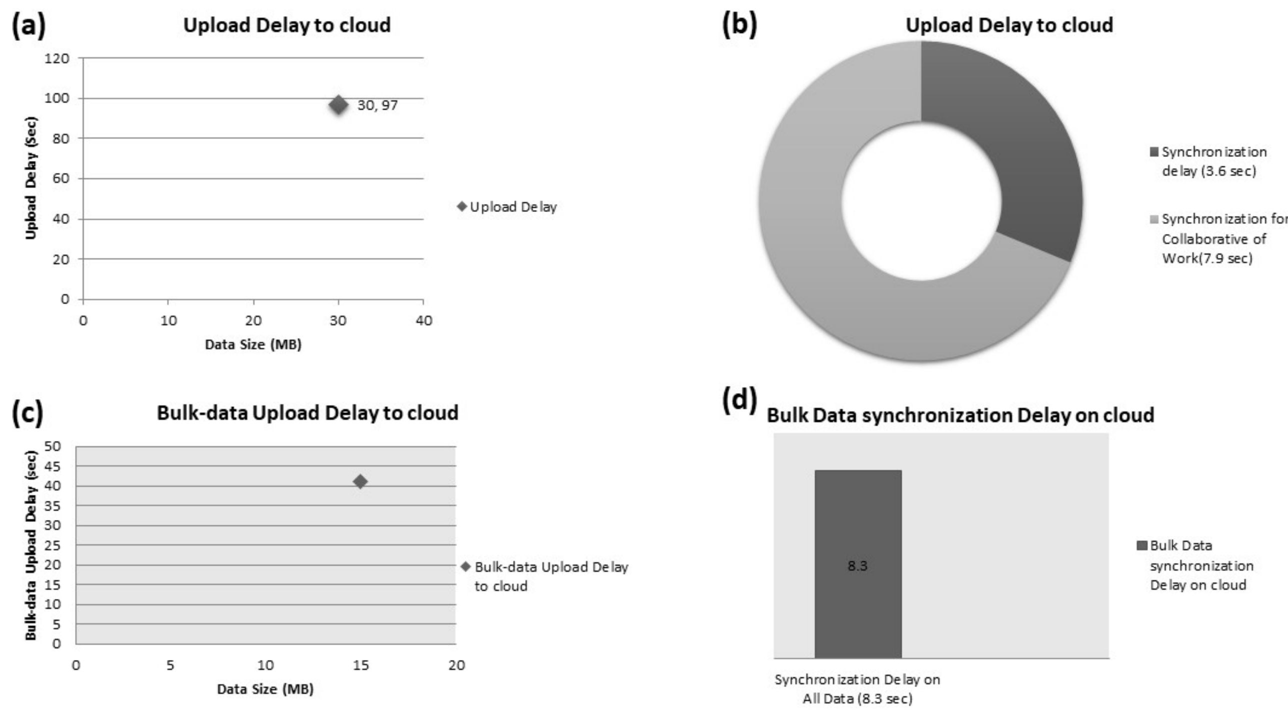

Figure 6. Cloud-to-gateway communication data transfer delay: (a) upload delay to cloud, (b) donut presentation of synchronization and work collaboration delay, (c) bulk data uploads delay to cloud, and (d) bulk data synchronization to cloud delay.

APPLICATIONS OF CLOUD OF THINGS IN ANIMAL SCIENCES

Precision Animal Farming and Veterinary Practices: The adoption of state-of-the-art farm technologies enhances animal protein production, reduces costs (Pampori and Sheikh, 2023), and enables the real-time assessment of animal welfare indicators (Neethirajan, 2017). Various sensing technologies, such as video and photo sensors, infrared thermography, pressure mats, motion sensors, accelerometers, and microfluidics-based biosensors, are employed in real-time monitoring of gait behavior, rutting span, back posture, body temperature fluctuations for timely insemination, grazing & feeding patterns and their effect on weight gain, water consumption, milking, respiration, health, and as well as data management and decision support in livestock such as cattle, sheep, goats, pigs, and broilers (Table 2) (Jorquera-Chavez *et al*., 2019). In animal and veterinary sciences, the integration of the CoT has revolutionized care, monitoring, and research (Karthick *et al*., 2020; Vigneswari, 2021), enabling real-time data collection on animal health, behavior, and environmental conditions (Neethirajan, 2017; Halachmi *et al*., 2019). These devices, integrated in wearables or strategically placed in animal habitats, facilitate continuous monitoring and data collection (Makiyama *et al*., 2015). The CoT's cloud-based infrastructure allows for comprehensive insights into animal well-being and behavior patterns (Verma and Sood, 2018; Aloulou *et al*., 2020), facilitating advanced monitoring and data-driven decision-making in precision farming to improve animal welfare, optimize breeding programs, and allow efficient resource utilization in agriculture, ultimately contributing to the sustainability and productivity of veterinary practices (Morrone *et al*., 2022). The adoption of cloud-based solutions and data integration promotes precise animal farming and veterinary practices.

Bovine and Ovine Reproduction: IoT sensors can be used to identify optimal ovine and bovine breeding pairs (Table 2), detect estrus signs, and monitor fertility parameters such as hormone levels, body temperature, and vaginal pH, enabling precise breeding timing.

Specifically designed to detect reproductive hormones such as estrogen, progesterone, luteinizing hormone, and follicle-stimulating hormone, these sensors can be integrated into wearables or implanted for continuous real-time monitoring (Figure 7). Through the integration of various sensors and devices, the IoT facilitates continuous data collection and analysis, offering valuable insights into reproductive health, behavior, and environmental conditions. Combined with data analysis algorithms, hormone level data from IoT sensors can be used to identify patterns, trends, and anomalies to predict the best times to breed and identify reproductive disorders. When hormone levels deviate from the norm, IoT sensor systems can send alerts or notifications to veterinarians. Wireless IoT sensors send hormone data to centralized databases or cloud platforms for remote monitoring and analysis. However, data integration with predictive analytics, auto-alert and notifications systems, and regular calibration are required to ensure sustainability of the system. Meanwhile, the development of state-of-art smart artificial insemination and embryo transplant are needed to achieve the highest success rates.

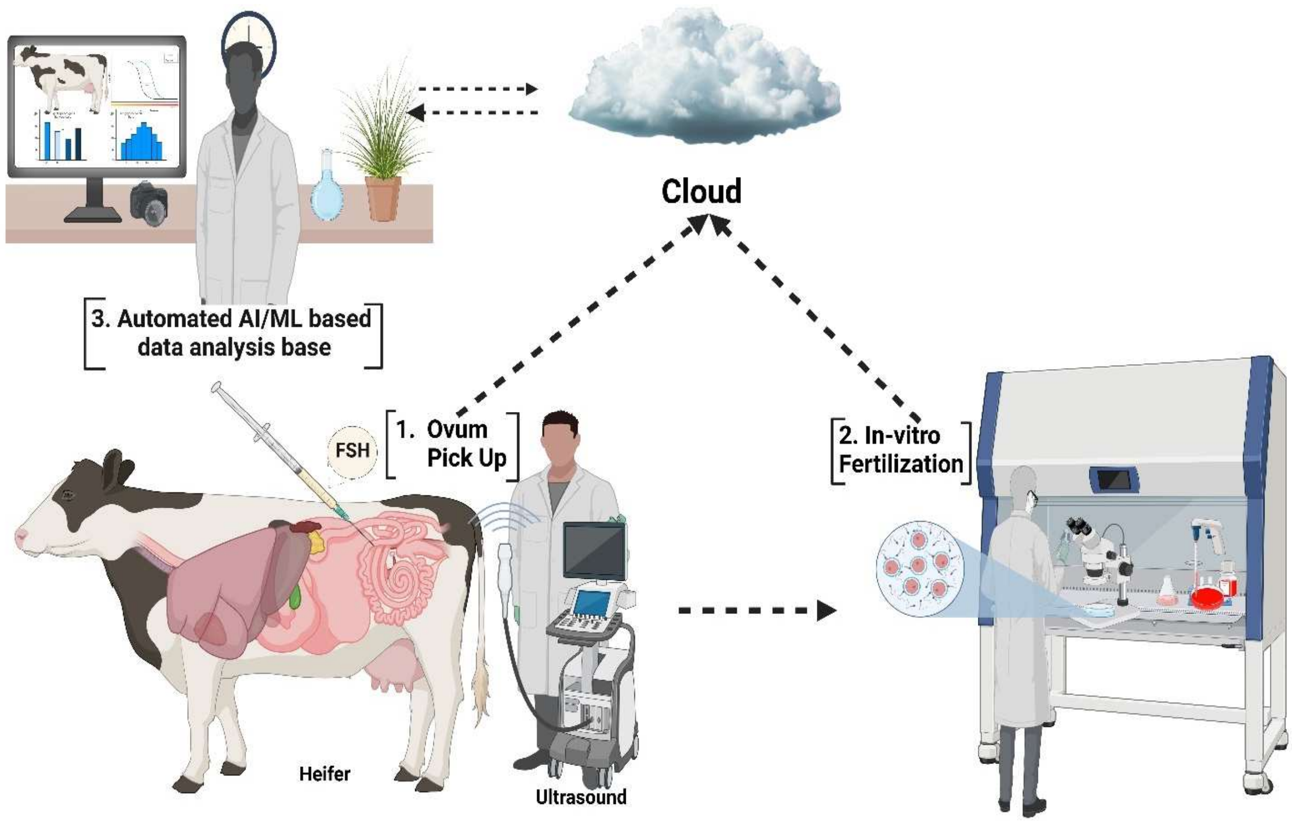

Figure 7. Illustration depicting the role of IoT sensor-integrated devices such as smart hormone meter to foster reproduction in bovines and ovines. These devices share real-time data with a control room to timely manage ovum pick-up and to perform in vitro fertilization, embryo transfer, and artificial insemination.

Wearables and Sensors in Animal Health Monitoring: Wearables and sensors are crucial for non-intrusive and continuous monitoring and to collect real-time animal health data streams including heart rate, temperature, activity levels, location, behaviors, and physiological changes (Neethirajan, 2020; Brennan *et al*., 2021), aiding in early diagnosis and prevention of diseases (Table 1). Wireless rumen pH meters, smart ear tags, and implantable microchips operate in real-time to record pH, temperature, and movement, in turn monitoring the health of individual animals (Chung *et al*., 2020; Pandey *et al*., 2021; Džermeikaitė *et al*., 2023). CoT-integrated wearables transmit data to the cloud for centralized storage to help veterinarians make informed decisions (Makiyama *et al*., 2015). Al-Tamimi *et al*. (2019) explored the efficacy of the Wolff–Chaikoff effect in mitigating the thermophysiological responses to acute heat stress in rats, and Zanella *et al*. (2014) utilized radio-telemetric transmitters connected to compatible receivers to enable real-time measurement of core body temperature, locomotive activity, and heart rate at 30 min intervals. However, these wearable sensors require improvements in battery life, connectivity, scalability, integration in farm management systems, and cost effectiveness.

Real-time Data Collection, Analysis, and Sharing: In veterinary practice, continuous monitoring via real-time data can help practitioners to swiftly detect abnormal behavior, anomalies in vital parameter, or early signs of illness. This allows veterinarians to intervene promptly, providing timely medical attention and enhancing treatment outcomes. Beyond diagnostics, real-time data empowers professionals to make informed decisions promptly, leading to enhanced overall health, reduced mortality rates, and improved resource allocation (Table 1). Continuous and real-time data acquisition through the IoT enables efficient analysis and storage of data in the cloud (Holmstrom and Beckham, 2017). The CoT streamlines decision-making processes across various domains by automating data collection and analysis, fostering a more agile and responsive approach to information management (Malik and Om, 2018). In smart dairy farming, the IoT facilitates resource monitoring by linking various substances, including constructions, equipment, trucks, and animals. Implementing IoT schemes and structures can reduce the costs associated with resource management in the cloud, improving service response times and the QoS (Alonso *et al*., 2020). However, for a more comprehensive implementation, the following concomitant recommendations should be considered: integration with AI and ML, interoperability, robust data security and privacy, and data backup and recovery plans.

CoT-enabled Centralized Storage of Veterinary Data: The CoT has revolutionized veterinary data management by facilitating centralized storage. In traditional veterinary practices, patient records, test results, and health histories are often dispersed across various physical locations or systems, making access and collaboration challenging (Table 1). In contrast, by leveraging cloud computing infrastructure, the CoT allows for the secure and centralized storage of vast amounts of veterinary data. Cloud-based storage enhances collaboration among veterinary professionals, enabling seamless sharing of data for consultations, research, or second opinions. This paradigm shift in data storage not only improves the efficiency of veterinary practices but also lays the foundation for advanced analytics and ML applications (Table 1), fostering a more data-driven and collaborative approach to animal healthcare (Iqbal *et al*., 2021). However, further integration with AI and ML, interoperability, data backup and disaster recovery, customizable dashboards, and cost-effective solutions will pave the way to a more secure, efficient, and intelligent veterinary health system.

Advantages and Challenges Associated with IoT and CoT in Dairy Farming: Advantages of integration of IoT and CoT includes livestock management through advanced monitoring, productivity enhancement, resource optimization, and profitability improvement (Table 3) (Taneja *et al*., 2019). Real-time health tracking via smart collars and sensors enables continuous monitoring of vital indicators such as temperature, heat rate, and activity level, ensuring early disease detection and enhanced animal welfare (Hassan *et al*., 2023). Precision livestock farming leverages IoT and CoT to optimize individual animal management, while automation in milking, feeding, and heat detection reduces labor costs and improves efficiency (Table 3). Data-driven decision making powered by cloud computing facilitates precise herd management, from breeding to feeding strategies. Furthermore, IoT systems enhance resource management by tracking water and feed usage, minimizing waste, and promoting sustainable practices. Significant challenges in implementing IoT and CoT in dairy farming include high initial investment costs for gadgets such a sensor, cloud services, continuous personal training and support (Kazi, 2025). Management of excessive data generated by these smart devices and connectivity issues in remote farming due to limited internet access further impede real-time monitoring and cloud functionalities.

Table 1. Comparison of parameters between IoT and CoT technologies.

Parameter	IoT Technologies	CoT Technologies	References
Data Collection	Smart collars, environmental sensors, wearables	Cloud based platforms for data aggregation	(Zhang *et al*., 2021; Eti *et al*., 2024)
Communication Protocols	NB-IoT, LPWAN (Low Power Wide Area Network)	Cloud APIs for data access and management	(Çorak *et al*., 2018; Yang *et al*., 2020)
Analytics	Basic data analysis for health monitoring	Advanced analyst using AI and ML	(Adi *et al*., 2020; Savanur, 2020)
User Interface	Mobile Apps for real-time monitoring	Web dashboard for comprehensive data visualization	(Sobrino *et al*., 2013; de la Torre *et al*., 2022)
Integration	Connects various farm devices	Integrates IoT data with enterprise systems	(Stergiou *et al*., 2018; Hawkins and Gravier, 2019)

Table 2. Precise animal farming using artificial intelligence, Internet of Things, and Cloud of Things.

Purpose	Specific Function	Instrument	References
Breeding Optimization	Selection of suitable traits, monitoring reproductive health, and genetic and reproductive data management	GeneSeek®, Select Sires®, CRV's Better Life Health	(Schuppli *et al*., 2014)
Feed Optimization	Suitable feeding schedules and quantities, monitor feed consumption and animal growth, and data synchronization.	NutriOpt, Evonik's AMINONIR®	(Schuppli *et al*., 2014; Liakos *et al*., 2018)
Monitoring Animal Health	Early detection of vital signs, behavior, and diseases, real-time health data collection and integration.	Cainthus, Telesense, SenseTime	(Wu *et al*., 2017; Vilvert *et al*., 2018)
Automated Milking Systems	Efficient robotic milking, monitor udder health and milk yield, and data integration for improved management.	Lely Astronaut, DeLaval VMS, GEA DairyRobot R9500, BouMatic Robotics MRS1, Fullwood Packo M²erlin	(Fuentes *et al*., 2020)
Disease Prediction and Management	Prediction and prevention of outbreaks and track symptoms and disease vectors, Large-scale data integration.	TensorFlow, Google Cloud AutoML, RapidMiner	(Wu *et al*., 2017; Liakos *et al*., 2018)
Behavioral Analysis	Monitor abnormalities, record behavioral data, and analysis.	Allflex Smart Collars, Moocall, CowManager	(Jukan *et al*., 2017; Vilvert *et al*., 2018)
Precision Livestock Farming	Farm management, real-time monitoring of farm operations, data management and analysis.	Smartbow, Quantified Ag, SCR Heatime® Pro System	(Schuppli *et al*., 2014; Jukan *et al*., 2017)
Economic Analysis	Data analysis to increase farm profit, real-time financial metrics, and data integration and analysis.	AgriNET, SMARTBOW, DairyComp 305, Cainthus, HerdInsights	(Sutton and Punja, 2017; Liakos *et al*., 2018)
Waste Management	Efficient waste disposal, monitoring waste levels, and waste data management.	Delmer, Agromaster, Dairymaster	(Jukan *et al*., 2017)
Supply Chain Optimization	Optimization of supply chain from farm to market and tracking and data integration.	Agrivi, Moomonitor +, Connecterra, Cainthus, HerdInsights	(Fuentes *et al*., 2020)

Conclusions: This study examines the integration of IoT devices with cloud computing to optimize resource utilization and enhance user services. Preprocessing data before transferring it to the cloud is crucial for efficient service delivery. Recent advancements in computer science, particularly smart gateways and fog computing, alleviate communication overheads and enable real-time, delay-sensitive applications. The CoT model, along with smart communication facilitated by smart gateways and fog computing, offers a robust portfolio of services. Performance assessment across multiple parameters is essential for rapid advancement in digital services. In animal and veterinary sciences, the adoption of the CoT brings transformative benefits through seamlessly integration of IoT devices, wearables, and cloud computing. Real-time data collection and analysis empower stakeholders with immediate insights into animal health, facilitating early disease detection and improved care. The centralized storage of veterinary data enhances collaboration and decision-making. The CoT extends its impact to diverse environments, enabling remote monitoring in wildlife conservation, precision farming, and large-scale agriculture. Additionally, it supports sustainable agricultural practices by optimizing resource utilization. In summary, the CoT elevates the quality of care, fosters research advancements, and enhances the overall management of animal health.

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Table 3. Role of available IoT based tools in cost reduction and profit improvement on various dairy farms around the world.

IoT tool	Function	Manufacturer	Farm Location	Tool Cost (USD)	Labor Cost (USD)	Saving (%)	References
Lely Vector	Robotic Suckler Beef Feeding System	LELY®	Northampton, UK	254,756.50	445,823.88	75	(Lely, 2024)
Yihe Feed Pusher	Robotic Suckler Feed Pusher	Yihe®	Saikexing Beef Cattle Farm, Hohhot, China	19986.68	45486.67	178	Personal Data
Lely Astronaut	Automated Milking System	LELY®	Jesper Vestergaard's Dairy Farim, Denmark	200,000	357,700	44.05	(Lely, 2024)
Lely Discovery 120 Collector	Cleaning Robot	LELY®	Toop Farms Ltd., British Columbia, Canada	54,000	298,570	121.97	(Lely, 2024)
DeLaval Herd Navigator ™ System	Dairy Herd Monitoring	DeLaval®	Middag Family Farm, Wapse, Holland	44,000	212,430	126.2	(Delaval, 2024)
Lely Horizon Advance Package	Data Analysis and Forecasting	LELY®	Horizon Dairy Farms, Ontario, Canada	20,000	350,980	109.3	(Horizon, 2024)

List of Abbreviations:

6LOWPAN	Ipv6 over Low-power wireless Personal Area Networks
AI	Artificial Intelligence
CoT	Cloud of Things
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IPv6	Internet Protocol Version 6
M2M	Machine-to-Machine
ML	Machine Learning
QoS	Quality of Service
RIFD	Radio Frequency Identification
SUP	Suspected Unapproved Parts

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