Animal 19 (2025) 101527

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Review: Emerging sensors and instrumentation systems for bovine health monitoring

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ARTICLE INFO

Article history:
Received 4 November 2024
Revised 16 April 2025
Accepted 17 April 2025
Available online 25 April 2025

Keywords:
Livestock
Sensing
Smart bolus
Wearable
Welfare

ABSTRACT

This literature review examines the latest and emerging technologies used for monitoring bovine health. Global demand for animal products underscores the need to monitor livestock well-being for enhanced efficiency in the dairy industry and product quality. The study identifies the relevant parameters for monitoring and evaluating commercially available products and cutting-edge technologies. The study highlights key performance features of these technologies, such as communication protocol, size, and battery lifetime. The review also examines current and emerging sensor systems, such as smart boluses and wearable systems that can provide valuable information on bovine welfare, early disease detection, and animal tracking on the farm. By exploring the state-of-the-art technologies in this field, this literature review provides insights into the best technology solutions available for monitoring bovine health and elaborates potential future challenges and opportunities for creating an ideal bovine health monitoring system.

Implications

This literature review identified the essential parameters and emerging technologies used for effective bovine health monitoring. Following an extensive review of the literature, enabling technologies for improving animal health have been identified, which would facilitate minimising economic losses on farms. A comprehensive analysis of previously employed wearable and implantable monitoring technologies was described, highlighting critical performance features, such as communication protocol, size, and battery lifetime. This work analyses current and emerging animal monitoring technology solutions in-depth. It anticipates future challenges and opportunities in creating an ideal bovine health monitoring system benefiting farmers, consumers, and the environment.

Introduction

This review paper offers a comprehensive review of the key parameters and emerging technologies vital for effective bovine health monitoring. The escalating global demand for animal-derived products has highlighted the criticality of monitoring livestock well-being to improve the dairy industry's efficiency (Beauchemin et al., 2020; Henchion et al., 2021). Besides this, cattle herd management requires numerous decisions to ensure the well-being of the animals, while optimising costs and minimising environmental impacts. Consequently, this requires improved data collection and analytics tools, which are coupled with animal health surveillance to enable decision support for herd management and ensure the quality of dairy products.

Health monitoring tools can enable timely interventions when anomalies are detected, thereby reducing costs and minimising animal losses. Once an ideal device is achieved, there will be opportunities to facilitate decision-support tools on the farm that can reduce the economic impact of diseases (Hoischen-Taubner et al., 2021). In this light, the goal of this study is to identify the latest cutting-edge technologies and emerging trends in this domain and critically evaluate them. Nevertheless, while primarily focusing on devices and sensors used for continuous on-farm monitoring, these technologies also have the potential to be applied in research environments. For example, an effective health monitoring tool could become an asset for quantifying direct and/or indirect methane emissions, and take mitigation steps to reduce it as a source of greenhouse gas (**GHG**) emissions (Difford et al., 2018; UNEP, 2022).

Monitoring cattle health can be achieved through the employment of miniaturised electronic systems such as collars (Afimilk, n.d.), ear tags (CowManager, n.d.), and wireless ingestible capsules (smaXtec, n.d.), also known as smart boluses. Researchers are

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https://doi.org/10.1016/j.animal.2025.101527
1751-7311/

putting effort into the development of sensors and associated systems needed to bring these technologies towards further advancement. When designing an ideal monitoring device for cattle health, certain specifications such as cost, data management, usability, safety and others are of concern. The device should ensure animal safety and comfort during usage, coupled with easy deployment and removal (Buijs et al., 2023; Godyń et al., 2019; Sharma and Koundal, 2018). Real-time health and well-being data acquisition is necessary, allowing for prompt detection of any anomalies (Karthick et al., 2020; Neethirajan et al., 2017). Additionally, it should also facilitate multiparameter measurement (Neethirajan et al., 2017). Secure data storage, easy retrieval, and durability to endure the rigours of farm environments and prolonged lifespans are key aspects for ensuring commercial viability (Karthick et al., 2020). Affordable maintenance and seamless integration with farm technologies, encompassing feeding and management systems, are indispensable for a holistic monitoring solution (Karthick et al., 2020; Neethirajan et al., 2017; Wolfert et al., 2017). Nevertheless, data sharing with stakeholders like veterinarians, researchers, and agricultural professionals further amplifies the device's utility (Alipio and Villena, 2023; Karthick et al., 2020; Wolfert et al., 2017). Ultimately, the device should be easy to use, meaning user-friendly (Neethirajan et al., 2017). In addition, incorporating features like Artificial Intelligence (**AI**) and advanced data analytics for data interpretation have recently become essential for farm management and disease detection (Bao and Xie, 2022).

This paper is divided into two main sections, the first, "Biosensing", explores the physiological and biochemical parameters essential for assessing bovine health and well-being. The second, "Sensing Devices" examines the electronic components and modules used in health monitoring systems, offering insights into their operation and integration. By analysing the intersection of biosensors and electronics, this chapter identifies the knowledge gaps, ensuring a thorough understanding of the technologies that underpin the design and functionality of bovine monitoring devices. While other studies explored the use of wearable devices and their capabilities (Alipio and Villena, 2023), this paper focuses on parameters that have not yet been widely utilised in continuous monitoring. By highlighting emerging parameters and the instrumentation technology modules required for monitoring devices, this review aims to bridge knowledge gaps regarding the co-development of sensors and technology systems, thereby, contributing to the advancement of more effective and sophisticated monitoring tools for dairy cattle welfare.

Method for literature review

The following literature review followed the preferred reporting items for systematic reviews and meta-analyses (Takkouche and Norman, 2011) and an extension for scoping reviews (Tricco et al., 2018). To conduct this extensive review, the authors mainly used the following databases, Web of Science, NCBI, ScienceDirect, PubMed, and Google Scholar to cover publications in the field of engineering, health, and sensor technologies from both academia and industry. The search strategy was designed to focus specifically on emerging sensing technologies rather than digital biomarkers, emphasising technologies that are integrated into comprehensive monitoring systems. Terms such as (monitoring) OR/AND (smart bolus) OR/AND (ear tag) OR/AND (collar) OR/AND (tracking system) OR/AND (cattle) OR/AND (rumen monitoring) OR/AND (health) OR/AND (livestock), were used as keywords on the search items in all "fields". Therefore, these headings were meticulously analysed in the scope of developing technologies for the detection and measurement of biomarkers in cattle, rather than reiterating previous systematic reviews on digital biomarkers. All the papers were independently evaluated to ensure the complete comprehensiveness of the work done. No restrictions were imposed regarding the languages or region of the investigation. This paper reviewed 34 studies on technologies under development, 38 related to technology evaluation, and 21 focused on commercial products, covering research up to 2024, with the earliest reference dating back to 1957.

Biosensing

Numerous commercially available biosensing systems have emerged to facilitate the monitoring of bovine health. Some examples include smaXtec Bolus (smaXtec, n.d.), Cowlar (Cowlar, n.d.), and MooMonitor+ (Dairymaster, n.d.), among others. Beyond the current solutions, ongoing research and development are focused on biosensing for monitoring the health of cattle (Go et al., 2022). Biosensing is a well-established technology, and its application to monitoring the health of bovine animals by assessing a wide range of physical, physiological, chemical, and biochemical parameters is an emerging field (Neethirajan et al., 2017). Biosensors are transducers that detect and measure these parameters by converting biological signals into electrical signals that can be analysed and interpreted (Kim et al., 2019). By applying biosensors on farms, farmers and veterinarians can get real-time insights into the health and well-being of the herd.

Biosensors can be integrated into different platforms, such as wearable devices, implants, and remote monitoring systems. Depending on the parameters requirements and the desired application, different types of biosensors and platforms may be used. (Awasthi et al., 2016) explored the most common wearable devices in correlation with the measured parameters within cattle. The wide scope of measurable parameters highlights the growing need for advancements in biosensing systems, which are indispensable tools for bovine health monitoring.

Biometric parameters

An overview of multiple studies is provided in Table 1, focusing on the monitoring of biometric parameters in cattle, encompassing temperature, activity, and heart rate. The table outlines the specific parameters measured, device types, key specifications, and their associated limitations and advantages.

Temperature

A cow's normal body temperature, which reflects its physiological condition, typically ranges between 38 °C and 39 °C; thus, fever becomes an early indicator of infection or other health issues (AlZahal et al., 2011; Godyń et al., 2019). Conversely, temperature fluctuations can also provide insights into reproductive status, as temperature changes can be linked to ovulation or other reproductive stages (Rajamahendran et al., 1989).

However, interpreting elevated temperatures is challenging, because they can result from different causes, such as infections, environmental stress, or reproductive processes. For instance, elevated temperatures during pregnancy may indicate potential complications, including reduced fertility, embryonic loss, and pregnancy complications. On the other hand, temperature fluctuations related to the reproductive cycle, such as those associated with ovulation, may be temporary and less concerning (Kyle et al., 1998). Thus, if the temperature data are recorded over time, time series patterns associated with the cow's reproductive cycle can be compared to current data. Additionally, by combining temperature data with other factors, sensors can provide more context. Studies found another temperature-related parameter, the temperature-humidity index, which reflects the environmental

Table 1
Comparative analysis of physical parameter measurement devices in cattle monitoring.

Study	Features				
	Measured Parameter	Type of Device	Specifications	Limitations	Strengths
(Cowlar, n.d.)	Temperature	Collar	No details on accuracy and precision.	Affected by surroundings and animal activity.	Non-invasive.
(Dairymaster, n.d.)	Temperature	Collar	No details on accuracy and precision.	Affected by surroundings and animal activity.	Non-invasive.
(CowManager, n.d.)	Temperature and activity	Ear tag	Operating temperature ranges from −4 °C to 104 °C.	Affected by surroundings and animal activity.	Non-invasive. Required solar routers on the farm.
(smaXtec, n.d.)	Temperature	Smart bolus	Temperature ranges from 20 °C to 60 °C ± 0.01 °C.	Invasive.	Accurate internal body temperature measurement.
(eCow, n.d.)	Temperature	Smart bolus	Temperature ±0.1 °C.	Invasive.	Accurate internal body temperature measurement.
(Wang et al., 2020)	Temperature and activity	Intravaginal temperature device	Temperature sensor: ADT7320. Motion sensor: ADXL362.	Invasive.	Real-time measurements. Detected an increase of 0.3 °C during oestrus.
(Andersson et al., 2016)	Temperature and acceleration	Intravaginal probe	Temperature sensor: thermistor KS103J2. Accelerometer: ADXL362. Probe diameter 20 mm, and lengths of 120 mm and 160 mm.	An optimal probe size remains undetermined. The sizes used may induce internal bleeding. Challenges associated with measuring resistance.	Measured vaginal resistance associated with vaginal hydration levels. Also acquired data on acceleration.
(Chung et al., 2020)	Temperature	Implantable sensor	Temperature sensor integrated with a radio-frequency identification LifeChip Microchip with a precision of 0.1 °C.	Invasive procedure – the device is implanted at the base of an ear and the insertion needs to be performed by a qualified veterinarian. Limited number of subjects (n = 3).	Demonstrated accurate measurements of core body temperature.
(Wang et al., 2023)	Temperature	Thermal IR imaging of the eye and vulva	Temperature sensor: FLIR A310. Operational range from −20 °C to 120 °C, and an accuracy of ±2 °C.	Limited oestrus detection rate. Applicable mainly to small farms due to acquisition method constraints. The study lacked comprehensive measurements across the entire oestrous cycle.	Non-contact approach to mitigate animal stress.
(Iwasaki et al., 2019)	Temperature	Implantable sensors	Temperature sensor range 34 °C to 43 °C with an accuracy of 0.05 °C	Invasive method, the sensors are surgically implanted in 10 different spots on the animal.	Tail-based was identified as the best location for subcutaneous monitoring of body temperature in cows.
(Murugeswari et al., 2022)	Temperature	IR photodiode thermometer	Operating ranges of −10 °C to 50 °C. Sensor placed over the tail base and abdominal region.	Not suitable for wireless applications and large-scale farms.	Surface temperature measurements are non-invasive.
(Werner et al., 2018)	Activity	RumiWatchSystem	Pressure sensor in the head halter, and a pedometer on the leg. Raw data is saved on an SD card for 4 months.	Operates best with continuous data instead of periodical.	Accurate detection of rumination time.
(Kröger et al., 2016)	Activity	Noseband	RumiWatch	Low accuracy in calculating chews per minute per bolus, and number of boli.	Accurate measurements of ruminating time.
(Haladjian et al., 2018)	Activity	Wearable motion sensor	6-axis Inertial Measurement Unit (IMU) placed on the leg. Apply machine learning to determine abnormal patterns.	Space for improvements in accuracy, and sensitivity (74%). In abnormal patterns, 74.2% are detected, leaving 25.8% not detected.	Each cow's particular characteristics were taken into account.
(Davison et al., 2020)	Activity	Collar	Accelerometers from Afimilk Ltd.	Required a wider evaluation to determine accuracy.	Non-invasive. Detected heat stress.
(Voß et al., 2021)	Activity	Inclinometer	Sensor from Moocall Ltd. placed at the top of the tail.	Limited sensitivity, instances of device detachment and displacement, device-induced pressure marks, and occurrences of necrosis.	Wearable and non-invasive.
(Afimilk, n.d.)	Activity	Pedometer	Accelerometers attached to the leg.	Offers intermittent data collection at 15-min intervals and interfaces with the farmer's software once per hour.	Wearable and non-invasive.
(Dairymaster, 2016)	Activity	Collar	No details were provided.	Required its base station.	Wearable.
(Dutta et al., 2022)	Activity and temperature	Collar	Device MOOnitor with GPS, 3-axis accelerometer, and temperature sensor. Machine learning is applied to classify animal behaviour.	Required enhancements in device weight and dimensions.	Transmits data directly to a server and exhibits high precision in activity detection and identification.
(Sutter et al., 2020)	Heart rate	Magnetocardiography	Sensor: QuSpin QTFM	Practicality- the animal is enclosed in a metal structure.	Capable of capturing heart rate data, including beat timing and amplitude without contact.

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Table 1 (*continued*)

Study	Features				
	Measured Parameter	Type of Device	Specifications	Limitations	Strengths
(Sairam et al., 2019)	Heart rate	Human heart pulse device	No details were given on the sensors used.	Absence of device body placement specification, further testing and validation are needed.	Radio frequency identification module technology.
(Salzer et al., 2022)	Heart rate	Nose ring	Sensor: MAX30101 (TinyCircuit, Akron, OH)	Susceptible to environmental temperature impact. Constrained availability of visual breathing count methods for reference.	Quantifies breathing rate and blood oxygen levels. It preserves the cow's natural behaviour unaffected.

conditions and is associated with advanced pregnancy (> 90 days) when it exceeds 84 (Leliveld et al., 2023).

Wearable devices such as collars (Cowlar, n.d.; Dairymaster, n.d.) and ear tags (CowManager, n.d.) measure temperature. However, these are external measurements and can be influenced by environmental factors like barn temperature, humidity, and the cow's behaviour, such as lying down or standing up. These external factors complicate the accuracy of body temperature readings (Godyń et al., 2019). In contrast, measuring temperature directly from within the gut provides a more accurate assessment of the cow's core body temperature, as it is less susceptible to external influences. Initial studies were focused on methods to access cattle's vaginal temperature using an intravaginal sensor (Andersson et al., 2016; Wang et al., 2020). Later, less invasive sensors were tested and used to alleviate the stress in the animals (Murugeswari et al., 2022; Wang et al., 2023). Recently, (Sakphrom and Chaimool, 2024) developed a rumen temperature bolus to assess the body temperature of the animals. However, this is limited to only temperature measurements and further studies need to be done to validate the technology used. Additionally, a study conducted by (Vakulya et al., 2024) has demonstrated how continuously monitoring temperature from the animal's rumen can be used to detect drinking patterns.

Furthermore, measuring temperature within the gut offers insights into the cow's digestive system function. The gut temperature reflects the activity of microorganisms involved in digestion, with temperature fluctuations indicating disruptions in these microorganisms and issues, such as acidosis or diarrhoea (Kyle et al., 1998). Moreover, cattle possess a distinctive thermoregulation mechanism, responsible for maintaining a relatively stable internal temperature. Hence, this measurement can also provide information about the cow's thermoregulation. Disruptions in this system can lead to heat stress, adversely affecting cow health and productivity (Kadzere et al., 2002). The collection of this parameter aids farmers and veterinarians in taking prompt action to treat any issues and improve the cow's well-being. Among commercially available devices for measuring gut temperature, the smaXtec Classic Bolus incorporated a temperature sensor with a range of 20 °C to 60 °C and an accuracy of ± 0.01 °C (smaXtec, n.d.). Despite the device's high accuracy, its practical significance may be diminished, considering that even for humans, the accuracy requirement of a hospital thermometer is ± 0.1 °C (Mah et al., 2021). This device is administered to each animal in the cattle herd. Similarly, the eBolus by eCow employed a temperature sensor with an accuracy of ± 0.1 °C (eCow, n.d.).

Motion

Cattle activity quantification is done through global positioning system (**GPS**) modules, accelerometers, and gyroscopes (Dang et al., 2022; Hanson and Mo, 2014). These components can be incorporated into wearable devices as tracking collars, as previously done (Benaissa et al., 2023). Collars are largely used due to affordability and efficiency to detect and track animal motion (Bailey et al., 2018). Similarly, ear tags have the potential to incorporate motion sensors, as previously done (Pereira et al., 2020). Some of the commercially available systems included a variety of devices, such as CowManager (CowManager, n.d.), MooMonitor + collar (Dairymaster, 2016), and AfiAct Pedometer (Afimilk, n.d.). A review conducted by (Riaboff et al., 2022) revealed methods employed in diverse systems for livestock behaviour prediction. A study conducted by (Vakulya et al., 2024) demonstrated that acceleration data from a rumen bolus can be utilised to detect rumination and monitor motion activities through the application of algorithms.

By scrutinising activity levels, farmers can identify signs of illness or discomfort. Reduced activity might indicate an animal is unwell and may need to be checked by a professional veterinarian (Hanson and Mo, 2014). Additionally, by coupling activity data with AI, it is possible to identify calving events, as demonstrated by (Miller et al., 2020). This study demonstrated that accelerometer data from tail-mounted sensors when fed into machine learning models, can accurately predict calving. Besides this, AI can enhance artificial insemination success when combined with temperature measurements, as reported by (Moonsyst, n.d.). A study conducted by (Wongvivatvaitaya et al., 2023) demonstrated that the combination of temperature and accelerometer data can be used to predict estrus. Moreover, this information can be used to improve the efficiency of the breeding programme and increase the overall productivity of the herd. Cattle activity levels are also interlinked with feeding patterns. More active cows usually exhibit a greater appetite; thus, activity monitoring can be used as a tool to identify feeding needs and others. This approach can improve cow health and productivity, as well as grassland management (Awasthi et al., 2016; Werner et al., 2018).

Heart rate

Measuring heart rate in cattle yields crucial information about animal health. This physiological parameter can increase in response to stress, making it a valuable indicator of the animal's condition (Kovács et al., 2014). Variations in heart rate can signify a range of health issues, encompassing heart disease, respiratory problems, and pain. Therefore, its utility extends to veterinary procedures (Waiblinger et al., 2004). Numerous techniques exist to monitor bovine heart rate, including electrocardiography, which involves placing electrodes on the animal's skin to record the electrical activity (Varshney and Varshney, 2020). Technological progress has facilitated initial investigations into measuring heart rate within the cow's rumen; however, these studies are still in their early stages (Hajnal et al., 2023).

Non-invasive heart rate monitoring devices, such as the Polar Sport Tester, can be placed and fixed to the animal's body for continuous heart rate tracking (Waiblinger et al., 2004). These devices

Table 2
Comparative analysis of chemical parameters measurement devices in cattle monitoring.

Study	Features				
	Measured Parameter	Type of Device	Specifications	Limitations	Strengths
(Wakatsuki et al., 2023)	Glucose	Glucometer FreeStyle Libre Sensor and LibrePro Sensor	The sensor is placed at the base of the ventral tail. The lower limit of detection was 40 mg/dL.	Requires calibration for cattle and lower measurement limits.	Capable of predicting calving within 24 h.
(Byrd et al., 2022)	Glucose	Interstitial glucose monitors	Sensors: FreeStyle Libre and Dexcom G6. Placed behind the cows' polls and beneath pin bones.	Limited accuracy (60.7%), inferior to blood glucometer. The limit of measurements was not appropriate for cows.	Identify sensor limitations.
(FreeStyle Libre, n.d.)	Glucose	FreeStyle Optium Neo	No details on accuracy and precision.	Tailored only for humans.	Portable ketone measurement device.
(Vetlab Supplies, n.d.)	Glucose	FASTest IgG Bovine	Sensitivity 95.5% and specificity 96.2%.	Restricted to veterinarians; expensive tool.	Applicable to calves and cattle, results in 5 min.
(Rapid Labs, n.d.)	Glucose	CentriVet™ GK Blood Glucose & Ketone Monitoring System	No details on accuracy and precision.	Not wearable or continuous; operator required.	Affordable and rapid results in seconds.
(Zoetis, n.d.)	Oxygen	VetScan iStat Alinity v	Capable of measuring multiple analytes from a blood sample.	Invasive and requires an operator.	Portable and delivers results in 2–3 min.
(Kanz et al., 2018)	Oxygen	Pulse oximeter	Sensor M−LNCS TF-I A, Masimo Corporation placed in interdigital space	Requires additional studies for continuous measurement across various activities.	Suitable for measuring oxygen levels and pulse rate.
(Calcante and Tangorra, 2021)	Oxygen	Pulse oximeter	Sensor: MAXREFDES117 (Maxim Integrated) measured haemoglobin oxygen saturation and pulse rate placed close to the mammary region.	–	Low-cost device; detected postmilking oxygen level variation.
(Ku-Vera et al., 2018)	Methane	Respiration chamber	Animals are placed in chambers	Data collection required animal confinement.	Approximation to methane emissions.
(Huhtanen et al., 2019)	Methane	Green feed	Estimated methane based on gas concentration and flux at a feeding stall.	Limited to measure ruminal fermentations (Zhao et al., 2020). Interferences can occur due to methane in the background.	Strong agreement with respiration chambers.
(Antanaitis et al., 2022)	Methane, pH	Laser methane detector and smaXtec bolus	Methane sensor: LMD HESAI HS4000. Cows were separated into groups according to ruminal pH, and methane emissions were measured.	Further validation studies are required.	Identified potential link between pH and methane.

are also known as photoplethysmography and have been incorporated into ear tags as a promising technology for continuous animal heart rate monitoring (Nie et al., 2020). Since photoplethysmography detects the blood volume changes, this method can be considered an indirect measurement of heart rate. Thus, photoplethysmography enables heart rate measurement from any location on the animal's body where blood vessels are close to the skin's surface (Jain and Tiwari, 2014).

Chemical & biochemical parameters

A vast variety of chemical and biochemical parameters can provide information about the animal's health. Several parameters related to the microbiome and metabolism, generated by the microbiota, can be identified, such as blood metabolites like glucose and lactate (Scarsella et al., 2021; Welch et al., 2022). Table 2 offers an overview of various studies.

Blood glucose

Glucose levels are related to milk quality and quantity (Rigout et al., 2003), and lactose levels in the animal (Bickerstaffe et al., 1974). Glucose serves as the primary source of lactose production in the mammary gland (Hettinga, 2019). Lactose is a key determinant of milk yield, influencing both milk quantity and composition. Low blood glucose may lead to reduced lactose synthesis, thus decreasing milk production. Low glucose levels can indicate conditions like ketosis, and high levels can be related to insulin resistance, both of which affect the cow's overall productivity and health (Lei and Simões, 2021).

Blood glucose can be measured using a glucose meter, which analyses a small blood sample typically obtained from the cow's ear or tail with a test strip. A recent study performed by (Byrd et al., 2022) demonstrated that human glucose monitors like FreeStyle Libre (FreeStyle Libre, n.d.) and Dexcom (Dexcom, n.d.) can be applied in cows to detect glucose variations, yet with less accuracy compared to blood-based systems. There are commercially available devices tailored for dairy cows, such as CentriVet GK Blood Glucose & Ketone Monitoring System – Dairy Cows, measuring blood glucose in 5 s within a range between 0.6 and 33.3 mmol/L (Rapid Labs, n.d.).

Monitoring blood glucose levels is critical for the early detection of metabolic disorders, particularly during the transition period around calving, when cows are highly susceptible to energy imbalances. Regular glucose measurements help identify cows at risk of conditions such as ketosis, enabling timely intervention and facilitating the monitoring of recovery after treatment. Furthermore, as blood glucose is directly linked to lactose synthesis, tracking its levels provides valuable insights into milk yield and quality, supporting the optimisation of dairy production. As technology continues to advance, a preliminary study by (Liu et al., 2024) proved the potential to detect glucose from artificial interstitial fluid using a wearable device. However, this study is still in its early stages, and further analysis is needed to address challenges such as microneedle interference, repeatability, and stability. In addition, future research should evaluate the impact of microneedle size and the associated effects of skin thickness in bovine applications. Additionally, the significance of measuring glucose from bovine interstitial fluid needs to be thoroughly investigated.

Blood oxygen

Blood oxygen levels are equally pertinent, and reduced levels are associated with various respiratory or cardiovascular issues (Salzer et al., 2021). Reduced oxygen saturation, known as hypoxemia, can signal underlying health issues, such as respiratory distress, pneumonia, or circulatory problems, all of which can significantly impact the animal's productivity and overall well-being. Monitoring blood oxygen is essential, especially in high-risk periods such as after calving or during periods of heat stress, where respiratory demands may increase. Early detection of hypoxemia can help prevent the progression of serious conditions and guide timely interventions, improving animal health and reducing the likelihood of costly treatments or prolonged recovery times. In healthy cattle, the typical value for arterial plasma partial pressure of oxygen is above 80 mmHg (Morais and DiBartola, 2017).

A blood oximeter is an invasive method that requires to have direct access to the blood. These instruments are commercially available for veterinarian purposes, such as the VetScan iStat Alinity v (Zoetis, n.d.). An alternative method is to use a pulse oximeter, which utilises light beams through the skin to measure blood oxygen levels. Such devices have already been tested in cows and are considered suitable solutions to continuously monitor bovine blood oxygen levels (Kanz et al., 2018). Additionally, this technology benefits from the ability to also measure pulse rate.

Metabolites and microbiome

Ketone bodies are metabolites produced during ketosis, a metabolic state in which the body shifts to burning fat for energy, replacing glucose as the brain's primary fuel source when glucose levels are low. In particular, β-hydroxybutyrate detected in the blood is a key marker for diagnosing ketosis (Mair et al., 2016). Situations of elevated β-hydroxybutyrate levels indicate potential ketosis, negatively impacting health and productivity; thus, monitoring this parameter can help detect and address ketosis earlier.

The gut microbiota is a complex community of microorganisms, encompassing bacteria, viruses, and fungi are key elements in fermentation, synthesis of essential vitamins, immune system regulation, pathogen control, and regulation of metabolism (Welch et al., 2022). Disruptions to the gut microbiota can lead to digestive and metabolic issues and increased disease vulnerability. Therefore, real-time microbiome monitoring would be facilitated by a device capable of directly detecting disturbances in microbial communities. However, such a point-of-care instrument is not yet available (Sosnowski et al., 2020; Vidic et al., 2017).

To better understand the gut microbiome's influence on bovine health, researchers developed offline measuring techniques to be undertaken in a laboratory environment (Barcenilla et al., 2024). From these techniques, DNA sequencing provides a comprehensive understanding of microbiome composition and diversity (Buitenhuis et al., 2019), while metagenomics identifies the genetic material within a sample (Kim et al., 2017). Another technique was microarray-based analysis, such as phylogenetic microarray, and PCR-based methods, such as quantitative PCR enabled researchers to identify specific microbial species based on DNA and ribonucleic acid sequences, gene amplification, and other properties (Kim et al., 2017).

Methane

Methane forms within the digestive system through microbial fermentation of food in the rumen. It acts as an indicator of microbial activity in the rumen and the overall digestive health of ruminant animals (Lan and Yang, 2019). Numerous methodologies assess methane emissions from cows, including direct measurement through air collection and analysis using chambers, and indirect approaches by assessing feed intake and output (Bačėninaitė et al., 2022). Furthermore, remote sensing techniques, such as IR cameras and mathematical models, also play a role in estimating methane emissions. An in-depth overview of various techniques for quantifying methane emissions in cows is provided by (Bekele et al., 2022).

Methane production has a large contribution to global warming and climate change (Difford et al., 2018), in particular, ruminal methane accounts for 6% of the global GHG emissions (Beauchemin et al., 2020). Therefore, by using these methods, farmers can accurately measure and quantify methane emissions from the animals and develop strategies to reduce emissions (e.g. through modification of diet (Difford et al., 2018)) and mitigate the impact of livestock on the environment.

pH

The pH of a cow's blood is a measure of its acidity or alkalinity and is typically around 7.37 (Erickson and Kalscheur, 2020). Abnormal pH can indicate a problem related to acid-base balance and can be caused by a variety of health problems, such as respiratory or metabolic disorders (Erickson and Kalscheur, 2020). However, measuring pH in the blood has several disadvantages, including being an invasive procedure, often causing stress to the animal and requiring skilled personnel for collection. This makes frequent monitoring challenging and less practical for routine health assessment.

The rumen's pH is crucial for assessing the health of the digestive system. The rumen's pH should typically fall between 6.0 and 6.5 (Erickson and Kalscheur, 2020); however, in cases of high-grain diets, pH can range between 5.5 and 6.0 (Grünberg and Constable, 2009). Nevertheless, pH values between 5.0 and 5.5 are considered indicators of Subacute Ruminal Acidosis (**SARA**), while pH values between 5.6 and 5.8 lack a clear definition and can be classified as marginal (Duffield et al., 2004; O'Grady et al., 2008). On the other hand, elevated pH can suggest that the cow has difficulties breaking down feed, also leading to health problems (Fu et al., 2022). Regularly monitoring the pH of the rumen allows for early disease identification, allowing proactive measures to maintain the overall health of the herd.

Several methods exist for measuring the rumen's pH; a procedure referred to as rumenocentesis was once commonly used. This method involved the use of a needle and syringe to collect a sample of rumen fluid for pH analysis (Fu et al., 2022). Other methods for rumen fluid sampling include the oral stomach tube, which involves passing a tube through the mouth into the rumen to collect fluid (Ramos-Morales et al., 2014); and cannulation, which surgically creates an opening in the rumen to provide direct access for fluid collection (Castillo and Hernández, 2021). However, both of these methods have notable disadvantages. The oral stomach tube method can be invasive and stressful for the animal, and there is a risk of improper placement, which can lead to injury or complications, as well as contamination of the sample (Hagey et al., 2022). Cannulation, while providing direct and repeated access to rumen fluid, involves surgical intervention and can lead to complications such as infection, inflammation, or fistula formation (Martineau et al., 2015).

More recently, a rumen pH sensor bolus appeared to avoid issues with lesions and sample contamination. These devices have a pH sensor that can be inserted into the cow's rumen. Typically, the bolus is connected to a data logger that records pH values and wirelessly transmits them to a computer or mobile device. This approach permits continuous monitoring of rumen pH, providing detailed insights into pH changes over time. SmaXtec offered a pH plus bolus, which is administrated to between 6 and 10% of the herd, monitoring the group's feeding and health. The pH plus bolus has the same temperature range and accuracy as the classic bolus. The sensor can detect pH values from 3 to 9, with an accuracy of ± 0.2 during the first 90 days and ± 0.4 for up to 150 days (smaXtec, n.d.). Similarly, the eBolus incorporated a pH sensor with an accuracy of ± 0.1 and a lifetime of 90–150 days (eCow, n.d.).

Lactate

Lactate, particularly D-lactate levels, can contribute to detecting SARA since it reduces the rumen pH (Fu et al., 2022). High levels of ruminal lactate are related to situations where the animal is under stress, such as heat stress, and infections (Kim et al., 2022). Lactate is considered a byproduct of anaerobic metabolism that can indicate conditions of ketosis, where lactate levels rise due to the overproduction of glucose (Zhang and Ametaj, 2020). Devices based on enzyme-linked immunosorbent assay and spectrophotometry can be employed to measure lactate by analysing a small blood sample from the cow. However, these tool kits are expensive, limiting their accessibility for routine or widespread use in smaller farms or by individual farmers (abcam, n.d.; Sigma-Aldrich, n.d.). The need for blood samples also presents the challenge of invasive testing, making frequent monitoring more complicated. This makes the tools less practical for continuous or on-site monitoring of lactate levels in real-world farming scenarios.

Sensing devices

The above section provided a comprehensive understanding of biosensing analytes and the key parameters for bovine health monitoring. That knowledge served as the foundation for this section on the technological front, where the review meticulously delves into the devices utilised for the monitoring process. Advances in technology have revolutionised bovine health monitoring for farmers. Manual methods are being replaced by advanced electronic instruments, enabling real-time monitoring and increased efficiency on the farm. These instruments comprise several technology building blocks including sensors, a microcontroller unit (**MCU**), data storage components, and a wireless communication module. This technological integration bridges the gap between theoretical understanding and practical application, offering a holistic solution for enhancing bovine well-being and productivity.

A comprehensive analysis of currently available and under-development devices is detailed in Table 3 for bovine health monitoring. This table provided a breakdown of crucial attributes, including encapsulation material, overall dimensions, sensing parameters, communication frequency, battery lifetime, and weight to compare the different existing approaches.

Monitoring devices' architecture is similarly structured across different technologies, encompassing a data-capturing measurement unit, a base station as necessary, and, in select instances, supplementary elements like wearable gateway devices or charging stations to enhance system support and user experience.

Battery selection significantly impacts the performance of these technologies. For example, the smaXtec bolus battery endures for about 5 years—coinciding with a cow's fertilisation cycle—facilitating optimal fertilisation timing and calf birth prediction 15–20 h in advance (smaXtec, 2022). On the other hand, the eBolus, measuring the same variables, remained operational for only 2 years. Additionally, while smaXtec retained up to 6 days of data before overwriting, eCow stores data for 28 days. Accessing bolus data necessitates the animal's proximity, typically 5 m to 10 m from the base station, extendable to 120 m using a secondary device. The boluses are not reusable or replaceable, and once the battery runs low or a problem occurs in the sensing system, the device remains in the animal. Extracting boluses from a cow's gut remains challenging, possible only with fistulated cows due to rumen and reticulum accessibility. Despite being designed for a cow's life span (15–20 years), none of these technologies guarantee such longevity. As a result, a cow might require more than one bolus during its lifetime. The battery is not the major limiting factor, but rather the sensing systems. For instance, the pH sensor readings from the rumen become unreliable after 90–150 days of continuous use (Sleptsov et al., 2021). Therefore, advancements in electrochemistry are also necessary to address this challenge.

Table 3
Overview of the technological devices developed to monitor the health and well-being of cattle, along with a comparison to human gastrointestinal pills.

Device	Features						
	Type of Device	Dim. [1] (mm)	Measured Variables	Comm. Freq. [2] (Hz)	Bat. life[3]	Weight (g)	Ref. [4]
SmartPill Mobility	Smart pill for humans	26.8 × 11.7[a]	pH, temperature, pressure	434M	>5d	4.5	(Medtronic, n.d.)
smaXtec Classic	Smart bolus	105 × 35[a]	Temperature	433M	≈5y	210	(smaXtec, n.d.)
smaXtec pH Plus	Smart bolus	132 × 35[a]	pH, temperature	433M	≈5y	220	(smaXtec, n.d.)
Smart Rumen Bolus	Smart bolus	110 × 20[a]	pH, temperature, acceleration	868M	>6y	≈200	(Moonsyst, n.d.)
eBolus	Smart bolus	135 × 25[a]	pH, temperature	432M	2y	150	(eCow, n.d.)
MooMonitor+	Collar	–	Acceleration	13.56M	–	–	(Dairymaster, 2016)
CowLar	Collar	110 × 62 × 3[b]	Temperature, motion	–	6m	240	(Cowlar, n.d.)
CowManager	Ear tag	50 × 65 × 19[b]	Temperature, acceleration	2.4G	–	28	(CowManager, n.d.)
SmartBow	Ear tag	52 × 36 × 17[b]	Acceleration	–	–	34	(Gusterer et al., 2020)

[1] Dimensions.
[2] Communication frequency.
[3] Battery life-time.
[4] Reference.
[a] Length by diameter.
[b] Length by width by height.

Wearable devices such as ear tags (CowManager, n.d.), leg braces (Afimilk, n.d.; Icerobotics, n.d.), and collars (Afimilk, n.d.; Cowlar, n.d.; Dairymaster, n.d.) are monitoring devices that supply real-time data to the final user. The ear tags are designed to be lightweight and compact, allowing them to be attached to a cow's ear in various sizes and shapes. (Chung et al., 2023) demonstrated the use of an injectable temperature sensor placed behind the ear, to predict the animal's body temperature using regression models. Additionally, (Hu et al., 2024) showed how accelerometers integrated into ear tags can monitor the animals' activity levels and patterns by calculating statistics such as the mean and SD of the acceleration magnitude, as well as applying filters to process the data. Overall, ear tags can track the location, movement, and health through embedded sensors, transmitting this data to a base station. However, studies have shown negative impacts on the animals, including infections, injuries, and scarring (Wellnitz, 2023). Although ear tags may, in theory, be a valuable tool for real-time monitoring, with rechargeable batteries and long-term use over the animal's lifetime, further investigation is needed to minimise the associated health risks.

Leg wearable devices, attached to the animal limb, detect changes in walking patterns, which may indicate health issues such as lameness. (Haladjian et al., 2018) demonstrated the use of acceleration and orientation data collected from the leg, which is fed into machine learning to detect the animal's walking pattern and identify any anomalies. The collected data are transmitted to a base station and analysed to provide early alerts to farmers. Meanwhile, collar systems yield insights into animal behaviour and surroundings. Innovations like Dairymaster's Moomonitor+ (Dairymaster, n.d.), and CowManager's system (CowManager, n.d.) introduced methods for locating and tracking animals on the farm. Moomonitor+, a collar by Dairymaster commercialised in 2014, employed triaxial accelerometers to measure activity, feed intake, rumination, and lying time. This device made use of Near Field Communication (NFC) to access an individual cow's information and a base station to transfer and store data into the cloud. A study by (Versluijs et al., 2023) demonstrated the use of GPS collar data to detect behaviours using machine learning models. Overall, these collars contain sensors that measure the animal's temperature, and track their movements, providing data on the animal's feed intake and activity levels. The data from the collars are transmitted to a base station for analysis and can be accessed by farmers through a smart device.

Smart boluses emerged as a tool for assessing and tracking changes within the ruminal complex. An understanding of bovine anatomy, particularly the stomach, is imperative to comprehend the deployment of these devices. The cow's stomach is comprised of four compartments: the rumen, reticulum, omasum, and abomasum, each with a distinct function. The four compartments allow ruminant animals to digest grass or vegetation without fully chewing first. The rumen, facilitating fermentation and food storage, constitutes the largest stomach section. As a result of the fermentation, volatile fatty acids are generated in this section. The rumen and reticulum are not entirely separated, and this interlinked structure is also known as the ruminoreticulum (Church, 1993). The reticulum serves as a repository for foreign objects and dense feed particles (Church, 1993). The complexity of this compartmentalised stomach provides an opportunity to continuously monitor a cow's gut, providing insights into diet, nutrition, and overall health (Sleptsov et al., 2021).

Overall, smart boluses provided real-time internal data on bovine health, enabling a deeper understanding and more comprehensive evaluation of an animal's well-being. A study conducted by (Studer et al., 2023), demonstrated the potential of these devices to detect SARA by collecting continuous pH data over 80 days. However, commercially available smart boluses have limited sensing capabilities, typically measuring only temperature and pH. A more thorough analysis of these devices and their current limitations will be provided in the following sections. These devices have the potential to provide information regarding dietary trends, rumination patterns, and overall animal health, extending their utility and application on the farm.

Farm integration

Several companies have developed advanced monitoring devices to integrate into modern farming operations to enhance farm efficiency. Data-driven decision-making, enabled by real-time data acquisition and processing through advanced analytics and AI algorithms, facilitates the early detection of health issues, thereby enhancing animal welfare and optimising farm management practices. However, the adoption of these technologies faces challenges, including cost, ease of use, and the need for farmer training to maximise their utility.

In 2007, eCow Limited (Glasgow, Scotland) developed the eBolus, an ingestible device that measured temperature and pH in a cow's reticulum. Each animal can host a maximum of two capsules, with data transmitted to a base station accessible through smart devices. This device is widely used in academic investigations for monitoring ruminal pH (Castillo-Lopez et al., 2021; eCow, n.d.),

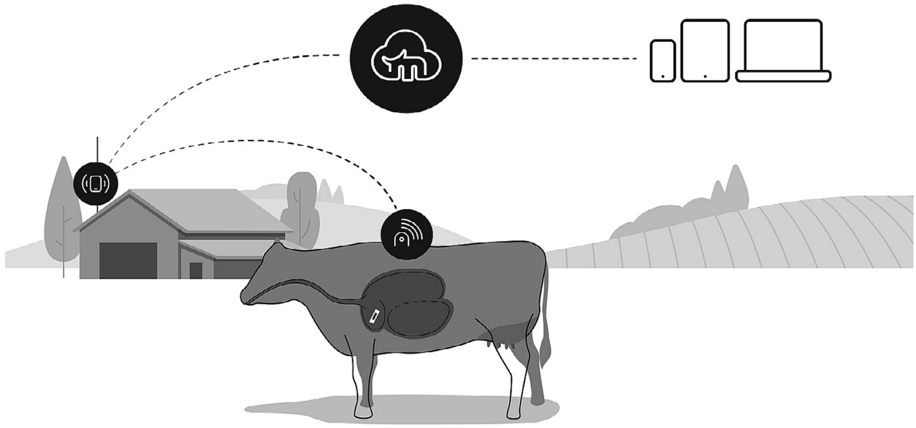

Fig. 1. Data flow on a livestock farm (*created by Moonsyst*).

but despite its adoption in research settings, its application remains limited to tracking only two parameters.

Likewise, smaXtec provided a bolus technology for monitoring rumen pH and temperature (Rosenkranz and Fallast, 2016; smaXtec, n.d.). This system also includes external sensors for motion activity, core temperature, and humidity monitoring. The data collected by multiple sensors are stored in an online database through a base station. If necessary, a repeater can be added to extend the range of the base station. A messenger device is incorporated to keep the end-user informed on the animals' health status. However, this technology is limited to animals weighing at least 300 kg (smaXtec, n.d.).

Moonsyst Industrial Technologies (Cork, Ireland) introduced the Smart Rumen Bolus, predicting animal welfare events using AI based on pH, temperature, and activity measurements. The data were accessible through cloud-based software (mooncloud™) on a smart device, as illustrated in Fig. 1 (Moonsyst, n.d.). The information is linked to each cow via the bolus' ID number. However, the bolus is only applied to animals weighing more than 350 kg. A smart collar was created to measure temperature for users not interested in bolus technology.

Power supply and lifetime

A critical evaluation of the power supply in smart devices highlights several challenges and opportunities for optimisation. One significant challenge is the choice of battery, which directly affects the device's functionality and sustainability. In certain cases where a short operating time is required, coin cell batteries, such as those with a capacity of 36 mAh, can be a viable option (Cherkasov et al., 2020). However, such disposable batteries raise concerns regarding environmental impact and long-term cost efficiency. Rechargeable batteries present a more sustainable alternative, particularly in wearable devices where frequent replacements can be avoided. An example was the collar proposed by (Deniz et al., 2017), where two 3.7 V lithium-ion polymer rechargeable batteries of 2 500 mAh (EB615268VU, Samsung) were implemented and recharged through a 1 W solar panel. Similarly, the eGazor collar used a 3.6 V, 13.4Ah lithium-ion battery recharged via six photovoltaic modules (Arablouei et al., 2023). However, the reliance on solar panels raises questions about their practicality in less sunny climates or during periods of low sunlight, potentially limiting their utility.

In encapsulated devices, such as capsules or boluses, the choice of battery and power consumption optimisation is even more critical due to restricted access. A study suggested powering a capsule with a single 3.7 V lithium polymer battery (GM301014H, PowerStream) with a capacity of 14 mAh, which lasted approximately 30 h (Stine et al., 2020). The device consumed 25 mA in active mode, 2.5 μA when in idle state, and had a quiescent current of 0.58 μA. While this demonstrated efficient power management, the limited operational duration necessitated frequent recharging or replacement, which could be impractical in agricultural settings.

For devices like smart bolus, where there is no direct access to the electronics, another challenge is the activation. This is commonly done by magnetic activation, which involves the interaction of magnets with an internal power trigger to switch the state of the capsule between on and off (Lee et al., 2014; smaXtec, n.d.). However, this approach might suffer from reliability issues in harsh environments. A hall switch, which functions as a power management tool, is an alternative option to turn off the circuitry when not in use (Zimmermann et al., 2013). Nevertheless, there is a dependence on consistent magnetic fields, which could also pose challenges in farm conditions. There is a constant trade-off between the size requirements and the limited small-size batteries that produce enough current for a long period. Hence, the choice of power management circuit and battery is crucial in determining the lifetime of a device. The smaXtec capsule employed a lithium metal battery to power the circuit, which included an STM32L431KC MCU (STMicroelectronics) and a LIS2DW12 (STMicroelectronics) three-axis accelerometer that consumes 1μA in its active low-power mode (smaXtec, n.d.). The smaXtec Classic Bolus has a lifespan of up to 5 years, with readings taken every 10 min. In comparison, the smaXtec pH Plus Bolus has the same battery duration with pH measurements lasting for 150 days (≈ 5 months) (Sleptsov et al., 2021). Moonsyst used a spiral battery with a 6 000 mAh capacity, providing a lifetime of 6 years, taking measurements every 10 min (Moonsyst, n.d.). Identically, the battery in eBolus by eCow ran for 4 years, although no details were found on the battery type. The limiting factor in the lifespan of a bolus is typically the pH (90–150 days), and temperature (2 years) sensors, which have a shorter lifespan than the battery (eCow, n.d.). This disparity indicates a critical limitation in sensor technology, highlighting the need for advancements to align sensor durability with the lifetime of the electronics. Ideally, the electronic device and its sensing capabilities should be designed to last throughout the animal's lifetime.

Recharging encapsulated devices, as smart boluses, introduces another layer of complexity. In a study conducted by (Zimmermann et al., 2013), a coin cell powered a capsule for 400 h, with a sampling rate of 240 per second via a hall switch. An innovative approach to power up implanted capsules has been developed by (Fischer et al., 2020), based on contactless charging through an induction coil. One coil is printed in a capsule and is combined with a transmitting coil capable of synchronously charging up to five sphere capsules. Each capsule circuitry was powered by a Li-ion battery (MS412F, Seiko Instruments Inc., Japan), powering an EFM8SB1 MCU (Silicon Laboratories, Inc., U.S.A), with a nominal capacity of 1 mAh (Lauterbach et al., 2019b). The induction coil and two capacitors created a parallel resonant circuit, generating a 13.56 MHz vibration used for capsule location identification (Fischer et al., 2020). While not specifically employed in animal health monitoring applications, these strategies can still offer valuable insights for future methodologies in the field. These approaches could be incorporated into a smart bolus, by integrating an induction coil within the bolus, which interacts with a transmitting coil located outside the body for wireless power transfer, ensuring compliance with safety regulations for inductive powering. This process can be performed in the parlour during milking or feeding. However, a crucial consideration is the attenuation effects of the power source due to fluids, tissues, and other biological materials present within the body.

(Khan and Desmulliez, 2019) investigated the body attenuation effects by using a miniaturised receiver (**RX**) wireless power transfer system powered by multiple transmitters (**TX**) to power implantable devices. The spiral TX coils weigh 2.8 g, with a thickness of 35 μm, and an outer diameter of 200 mm. In contrast, the RX coil had a diameter of 8.9 mm, including the miniaturised RX, and 4 mm diameter ferrite to improve power transfer efficiency. A frequency of 1 MHz is selected due to its low cost compared to the industrial, scientific and medical band frequencies and to ensure tissue safety. This study reported that 50mW of power was supplied to a tissue phantom in the worst-case scenario of angular and translational alignment, with a power transfer efficiency of 0.7%. To validate this study, a simulation on a phantom was used, predicting a maximum error of 12% between the calculated and measured trajectories of the capsule. Tests performed on a porcine gastrointestinal tract by (Lay et al., 2018) demonstrated that a power threshold of 100 mW is necessary for endoscopic capsules to prevent damage to the surrounding tissue. Despite these results being promising, the low efficiency and potential energy losses raise doubts about the viability of this technology for monitoring bovine health.

An alternative solution to extend the bolus longevity is to utilise energy from the surroundings to power the device. Thus, making it self-powered and self-sufficient with the potential for an infinite lifespan limited only by the lifetimes of the embedded components and sensors. This approach, known as energy harvesting, is a rapidly growing field of research and development. A review done by (Jiang et al., 2020) described implantable energy harvesting technologies for self-powered implantable devices. This included the work conducted by (Nadeau et al., 2017), on a self-powering ingestible capsule utilising gastric fluid as an electrolyte for a galvanic cell. The system delivered an average power density of 0.23 $\mu W/mm^2$ for 6.1 days, powering a temperature cell. The drawback of this type of battery is the lifespan of the electrodes. Additionally, (Stuart et al., 2021) conducted a comprehensive study on battery-free technologies available for human medical devices, which might be applied to bovine health monitoring systems. While significant progress has been made in power supply technologies for wearable and implantable devices, critical gaps persist. The areas of energy efficiency, the practicality of recharging, and energy harvesting systems remain vital for the continued advancement of the technology.

Communication protocol

The transmission of information in real-time is an attractive feature for health devices, enabling fast intervention when required. However, achieving this relies heavily on the design of a well-functioning radio frequency system. The industrial, scientific and medical applications have reserved a frequency band from 6.78 kHz to 245 GHz within the radio spectrum (Kumbhar, 2017). In Europe, the most commonly used is around 433 MHz, extending from 433.050 MHz to 434.790 MHz with a spacing of 25 kHz (Kumbhar, 2017). Similarly, the United States Federal Communication Commission defined the Medical Device Radiocommunications Service band from 401 Hz to 457 MHz and includes subregions ("Medical Device Radiocommunications Service (MedRadio) | Federal Communications Commission," n.d.). Frequencies such as 433 MHz (Gasteiner et al., 2015; Lauterbach et al., 2019a; SmartINST, n.d.), and 434 MHz (Maqbool et al., 2009) are commonly incorporated in various systems, including wireless sensor networks for monitoring animal health, and intra-body communication. Other frequencies including 868 MHz (Moonsyst, n.d.) have been investigated for their potential in wireless data transmission. The 2.45 GHz band is globally popular, owing to its widespread availability and cost-effectiveness, making it a standard choice for wireless Internet of Things and wireless local area network applications (CowManager, n.d.; Kumbhar, 2017). Despite the versatility of these frequency bands, each has limitations that must be critically evaluated before selection. Therefore, environmental and farm-specific conditions, such as structural barriers and electromagnetic interference, need to be taken into account in the choice of frequency.

The design of antennas for medical implant devices poses a significant challenge. Efforts have been invested in minimising antenna dimensions, considering the direct relationship between communication frequency and signal wavelength. Antennas designed for intra-body communication must meet specific requirements, including high efficiency, patient safety and comfort, and technical specifications such as high permittivity and impedance matching (Patil and Rufus, 2020). Due to variations in the conductivity and permittivity of different body substances, designing robust antennas to ensure efficient data transfer poses a challenge. For example, the permittivity of skin tissue is 46.7, while that of muscle tissue is 58.8, making consistent signal transmission challenging (Kim and Rahmat-Samii, 2004). To overcome these challenges, several antenna designs have been developed for capsule applications, including the conformal chandelier meandered dipole antenna (Izdebski et al., 2009), and the conformal helix antenna (Faerber et al., 2017). Additionally, a study by (Lauterbach et al., 2019a) demonstrated that placing an antenna at the centre of a sphere increased the gain by using the sphere's diameter as the antenna's size, achieved through a flexible printed circuit board. Despite these advancements, further research is needed to test these designs under diverse environmental conditions and to assess their reliability and adaptability in smart bolus systems. Challenges remain in ensuring proper antenna alignment with an external receiver, particularly in dynamic environments where the orientation of the device may shift within the animal's digestive system.

Further advances in communication have explored using the body's electrical conductivity for intra-body communication, as a power-efficient alternative to traditional radio frequency systems (Maity et al., 2019). The emerging approaches for intra-body communication include capacitive (Zhu et al., 2021) and galvanic (Noormohammadi et al., 2021) coupling techniques. A study carried out by (Noormohammadi et al., 2021) showed that galvanic coupling had the potential for deep implants due to its low path loss, simplicity in electronic design, and energy efficiency. In this technique, a weak electrical current was injected and flew through tissue, transmitting the signal to the implant through modulation. The study used an on-body receiver antenna consisting of two 20 mm squared electrodes placed 120 mm apart and a transmitter circuit enclosed in a 7 mm by 40 mm capsule powered by a 5 mAh battery and an in-body transmitter antenna. *In vivo* testing on porcine subjects was conducted at a frequency of 10 kHz to 10 MHz, a maximum of 2.5% bit error rate, and 45 μW total power consumption at 10 cm distance, with a data rate of 64kbps. While this approach shows potential, it faces limitations in scaling for deeper implants or longer transmission ranges (Li et al., 2019). Additionally, the developed system must meet the safety standards concerning the prolonged effects of weak electrical currents on biological tissue.

Efficient wireless data transmission from smart devices to base stations is critical for integrating monitoring systems on farms. To address this challenge, Moonsyst implemented a SIM card solution for gateway devices (Moonsyst, n.d.). In comparison, (Germani et al., 2019) implemented a long-range (**LoRa**) low–power wide area network communication protocol, using Adafruit Feather M0 with RFM95 (Adafruit Industries). Similarly, eCow used LoRa at 432 MHz to transfer data from the eBolus to the base station. The sensors on the bolus sampled every minute and averaged every 15 min, resulting in 96 daily readings. To transmit these readings, the bolus (i.e. the animal) must be positioned within a range of 200 m to 500 m from the base station, sending updates every 2 h. However, if not within the range, the measurements are saved up to 28 days before overwriting (eCow, n.d.). CowManager utilised radio-frequency identification equipped sensors with QR-coded ear tags, connected to routers for data collection (CowManager, n.d.). Routers are placed indoors or outside the parlour, collecting data from the sensors. The continuous operation is guaranteed by solar routers across the farm, supporting 24/7 monitoring and 7-day internal data storage.

Effective communication systems for livestock health monitoring require careful selection of frequency bands. While advancements in antenna design and intra-body communication techniques have improved efficiency and adaptability, significant challenges remain, particularly in safety and reliability. Wireless data transmission protocols, such as LoRa and radio-frequency identification, showed promise, but require further optimisation for seamless integration into farm environments. Key gaps include testing antenna designs under varied conditions, evaluating the long-term safety of intra-body communication methods, and refining wireless transmission protocols for large-scale deployments.

Size and material

When considering the size and material of a device designed for monitoring bovine health, it is crucial to distinguish whether the device is wearable or ingestible. In the case of a wearable device, it is imperative to be lightweight and compact to avoid causing discomfort to the animal. Additionally, the device should exhibit robust resistance to impacts and be waterproof to withstand various environmental conditions. Consequently, a device would possess an ingress protection code, with IP67 being the minimum requirement for health devices (Bisenius, 2012). This is essential to guarantee the animals' well-being and the longevity of the monitoring equipment.

In the case of smart boluses, these can benefit from size-reduction techniques used in human health devices, such as the thin land grid array packaging. This package involves using metal pads arranged in a grid or array underneath the component's body for external electrical connections. This helps achieve a smaller size, measuring 105 × 35 mm (length × diameter) (smaXtec, n.d.). Incorporating sensors influences bolus size, e.g., pH sensor addition increased the diameter by 27 mm (Gasteiner et al., 2015). While size reduction is a critical goal, there is a trade-off between reduced size and performance, such as signal transmission, battery life, and sensor integration. For example, eCow proposed the use of an additional metal cap to protect the pH sensor from the content in the rumen and reticulum. With a diameter of 25 mm, length of 135 mm, and weight of 150 g, this bolus proved to be suitable for insertion into animals weighing over 80 kg and having a body condition score ranging from 1 to 3.5 (eCow, n.d.). Before being inserted in the rumen, the smart bolus is sterilised by applying ethylene oxide and/or steam at 120 °C (SmartINST, n.d.). The device is then orally introduced into the cow's reticulum using a standard bolus gun, a specialised tool designed to facilitate safe and efficient placement (Moonsyst, n.d.).

The biocompatibility of the material is critical to avoid inflammation, irritation or harm (Kiradzhiyska and Mantcheva, 2019). It is vital to comply with the US Food and Drug Administration ISO10993-1 recommendation, which mandates biological toxicological evaluation of medical devices (Health, 2023). The choice of packaging material is a fundamental aspect of devices that remain within the rumen. In the case of the smaXtec bolus, the materials employed have undergone rigorous testing by the German Agricultural Society, confirming their resilience to rumen fluid (smaXtec, n.d.). The utilisation of acid-proof resin can be adopted to safeguard the electronic components from contamination and to assure the well-being of the animal (Moonsyst, n.d.). Other materials used include polyurethane (Lee et al., 2014), polyoxymethylene (Moonsyst, n.d.), MED610 (Stine et al., 2020), and Polypropylene, such as Bormed HD810MO (Borealis A/S, Denmark) (Lauterbach et al., 2019a). Additionally, adaptive design strategies can be implemented when required, including reducing capsule size. This approach is frequently applied in the development of bioreactor monitoring devices, achieving sizes such as 60 mm (Stine et al., 2020), and 25 mm with 8 g packaging (SmartINST, n.d.), and in some cases, as small as 7.9 mm diameter. Achieving this compactness involved using techniques such as dividing electronic circuitry into multiple printed circuit boards.

Currently, smart boluses are retained within the animal's rumen. However, there is potential to investigate strategies that utilise advanced materials to design a smart bolus that remains in the rumen until it reaches a reliable operational period, considering sensor limitations, and subsequently safely exiting the animal's body. For example, (Liu et al., 2019) proposed a method that could potentially be applied to a bolus. The strategy consisted of an ingestible pill encased in a material that expanded 100 times its original size within 10 min of entering the stomach, allowing it to remain there for up to a month. This material is comprised of two hydrogel components: superabsorbent particles called polyacrylic acid and a substance composed of minute crystalline polyvinyl alcohol chains. The latter acts as a protective layer, preventing the initial material from disintegrating during the expansion process. Upon exposure to a drinking solution containing calcium chloride ions, the hydrogel contracts within 10 min, rendering it suitable for further applications. This strategy can be beneficial in the context of dairy health monitoring within the rumen. By employing a monitoring device with lower density than traditional smart boluses, the device would not be retained in the reticulum, passing to the rumen. There, the material would expand, remaining in the rumen for an extended period, until exposure to the drinking solution triggers the shrinking and consequently, the exit from the animal's digestive system. Another application of this approach could be in the case of a low battery. If the battery runs low, a signal could be sent to notify the user that the bolus will become inactive within a few hours or days. This way, a shrinking process could be triggered and the device can exit the animal. This approach would prevent the animal from retaining an inactive electronic device and would allow for tracking and retrieval of the device from the field before reaching the waste tank. Additionally, it enables the reuse and recycling of materials, thereby reducing economic impact.

Discussion and conclusion

Designing a comprehensive system for bovine health monitoring presents significant challenges and requires a multidisciplinary approach. This literature review has helped to identify key analytes for assessing animal health, highlighting the need for further exploration in the rumen. In this context, many analytes remain underexplored in the ruminal complex, which represents valuable opportunities to enhance the understanding of bovine physiology. This gap underscored the need for further interdisciplinary research combining engineering and electrochemistry to broaden the scope of measurable parameters in livestock monitoring.

The review also identified smart boluses as a promising technology for monitoring bovine health. These devices provide the potential for continuous, real-time data collection, which is crucial for early disease detection and timely interventions. This review pointed out a big gap in the validations of commercial tools available to the public domain, highlighting the need for real-world testing and the establishment of standards for performance capabilities moving forward. The main limitation of current smart boluses was their restricted sensing capabilities, typically limited to temperature and pH. While these are critical indicators, they alone do not provide a full comprehensive view of the animal's internal state. This narrow focus constrains the practical utility of smart boluses and limits their contribution to precision farming. Additionally, due to their inability to be retrieved after deployment, smart boluses must be designed for long-term reliability and should leverage all interesting sensing capabilities to maximise their utility. Expanding the range of parameters that can be monitored would enhance these devices' contribution to animal health and welfare, enabling farmers to detect and manage health issues more effectively. Consequently, the availability of additional data requires not only technological innovation but also the integration of AI for data processing and advanced data analytics. This approach should prioritise user-centred design to ensure the technology is accessible, practical, and readily adopted in real-world settings. For instance, understanding how farmers interpret and utilise this expanded data is essential for delivering actionable insights through intuitive decision-support tools. Thus, more studies into human factors are essential to assess the specific requirements, preferences, and challenges faced by farmers. These studies should explore how farmers interact with data-driven tools, the training needed for effective use, and how such tools can be tailored to align with diverse farming practices and technological literacy levels.

Furthermore, the potential for smart boluses extends beyond individual animal health.

These devices could support broader goals, such as reducing GHG emissions. By monitoring digestive processes and understanding the impacts of diet and medication, smart boluses could support strategies aimed at mitigating methane emissions, a significant contributor to GHG emissions in livestock farming. This gap in smart boluses points to the need for the development of multiparametric sensing systems within the smart bolus technology. Although this application is promising, it is largely theoretical at this stage. More focused research is required to validate the practical effectiveness of smart boluses in environmental management. This requires the development of multiparametric devices capable of supporting such investigations, enabling a more comprehensive understanding of their functionality.

In conclusion, smart bolus technology holds immense potential, which extends beyond monitoring bovine health; it can also serve as a tool for validating scientific findings related to livestock management and environmental sustainability. This technology showed great promise; however, there are still significant opportunities for innovation, particularly in expanding the range of measurable parameters. Further research is required into sensor integration and device optimisation, enhancing sensing capabilities. By leveraging knowledge from electronic engineering and electrochemistry, the development of a robust, multiparametric smart bolus could revolutionise livestock health management and contribute to global sustainability efforts.

Ethics approval

Not Applicable.

Data and model availability statement

Not applicable. No data models were used. Information can be made available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

Acknowledgements

None.

Financial support statement

This research was funded in part by a grant from Research Ireland and the Irish Department of Agriculture, Food, and the Marine through the VistaMilk Research Ireland Centre (grant number 16/RC/3835), and in part from the Insight Research Ireland Centre for Data Analytics (grant number 12/RC/2289-P2), which is co-funded by the European Regional Development Fund. For the purpose of Open Access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission.

References

abcam, n.d. . L-Lactate Assay Kit Color. Ab65331. URL https://www.abcam.com/products/assay-kits/l-lactate-assay-kit-colorimetric-ab65331.html (accessed 8.21.23).
Afimilk, n.d. . Automating Dairy Farms. URL https://www.afimilk.com/ (accessed 1.16.23).

Alipio, M., Villena, M.L., 2023. Intelligent wearable devices and biosensors for monitoring cattle health conditions: a review and classification. Smart Health 27, 100369. https://doi.org/10.1016/j.smhl.2022.100369.

AlZahal, O., AlZahal, H., Steele, M., Van Schaik, M., Kyriazakis, I., Duffield, T., McBride, B., 2011. The use of a radiotelemetric ruminal bolus to detect body temperature changes in lactating dairy cattle. Journal of Dairy Science 94, 3568–3574.

Andersson, L.M., Okada, H., Miura, R., Zhang, Y., Yoshioka, K., Aso, H., Itoh, T., 2016. Wearable wireless estrus detection sensor for cows. Computers and Electronics in Agriculture 127, 101–108.

Antanaitis, R., Anskienė, L., Rapaliutė, E., Bilskis, R., Džermeikaitė, K., Bačėninaitė, D., Juškienė, V., Juška, R., Meškinytė, E., 2022. Relationship between reticulorumen parameters measured in real time and methane emission and heat stress risk in dairy cows. Animals 12, 3257.

Arablouei, R., Wang, L., Currie, L., Yates, J., Alvarenga, F.A., Bishop-Hurley, G.J., 2023. Animal behavior classification via deep learning on embedded systems. Computers and Electronics in Agriculture 207, 107707.

Awasthi, A., Awasthi, A., Riordan, D., Walsh, J., 2016. Non-invasive sensor technology for the development of a dairy cattle health monitoring system. Computers 5, 23.

Bačėninaitė, D., Džermeikaitė, K., Antanaitis, R., 2022. Global warming and dairy cattle: How to control and reduce methane emission. Animals 12, 2687.

Bailey, D.W., Trotter, M.G., Knight, C.W., Thomas, M.G., 2018. Use of GPS tracking collars and accelerometers for rangeland livestock production research. Translational Animal Science 2, 81–88.

Bao, J., Xie, Q., 2022. Artificial intelligence in animal farming: a systematic literature review. Journal of Cleaner Production 331, 129956. https://doi.org/10.1016/j.jclepro.2021.129956.

Barcenilla, C., Cobo-Díaz, J.F., De Filippis, F., Valentino, V., Cabrera Rubio, R., O'Neil, D., Mahler de Sanchez, L., Armanini, F., Carlino, N., Blanco-Míguez, A., 2024. Improved sampling and DNA extraction procedures for microbiome analysis in food-processing environments. Nature Protocols 19, 1291–1310.

Beauchemin, K.A., Ungerfeld, E.M., Eckard, R.J., Wang, M., 2020. Review: fifty years of research on rumen methanogenesis: lessons learned and future challenges for mitigation. Animal 14, s2–s16. https://doi.org/10.1017/S1751731119003100.

Bekele, W., Guinguina, A., Zegeye, A., Simachew, A., Ramin, M., 2022. Contemporary methods of measuring and estimating methane emission from ruminants. Methane 1, 82–95.

Benaissa, S., Tuyttens, F.A.M., Plets, D., Martens, L., Vandaele, L., Joseph, W., Sonck, B., 2023. Improved cattle behaviour monitoring by combining Ultra-Wideband location and accelerometer data. Animal 17, 100730. https://doi.org/10.1016/j.animal.2023.100730.

Bickerstaffe, R., Annison, E., Linzell, J., 1974. The metabolism of glucose, acetate, lipids and amino acids in lactating dairy cows. The Journal of Agricultural Science 82, 71–85.

Bisenius, W.S., 2012. Ingress protection: The system of tests and meaning of codes. Published online. Retrieved 29 of March 2019 from https://www.webcitation.org/6DGYoRMwp?url¼http://www.ce- mag.com/archive/06/ARG/bisenius.htm.

Buijs, S., Weller, J., Budan, A., 2023. When the measurement affects the object – Impact of a multi-part head/neck mounted wearable device on dairy cow behaviour, health and productivity. Applied Animal Behaviour Science 263, 105937. https://doi.org/10.1016/j.applanim.2023.105937.

Buitenhuis, B., Lassen, J., Noel, S.J., Plichta, D.R., Sørensen, P., Difford, G.F., Poulsen, N. A., 2019. Impact of the rumen microbiome on milk fatty acid composition of Holstein cattle. Genetics Selection Evolution 51, 1–8.

Byrd, M., Arneson, A., Soffa, D., Stewart, J., Rhoads, M.L., 2022. Human continuous glucose monitors for measurement of glucose in dairy cows. JDS Communications 3, 78–83.

Calcante, A., Tangorra, F.M., 2021. Measuring oxygen saturation and pulse rate in dairy cows before and after machine milking using a low-cost pulse oximeter. Journal of Agricultural Engineering 52, 1155.

Castillo, C., Hernández, J., 2021. Ruminal fistulation and cannulation: a necessary procedure for the advancement of biotechnological research in ruminants. Animals 11, 1870. https://doi.org/10.3390/ani11071870.

Castillo-Lopez, E., Petri, R.M., Ricci, S., Rivera-Chacon, R., Sener-Aydemir, A., Sharma, S., Reisinger, N., Zebeli, Q., 2021. Dynamic changes in salivation, salivary composition, and rumen fermentation associated with duration of high-grain feeding in cows. Journal of Dairy Science 104, 4875–4892. https://doi.org/10.3168/jds.2020-19142.

Cherkasov, N., Baldwin, S., Gibbons, G.J., Isakov, D., 2020. Monitoring chemistry in situ with a smart stirrer: a magnetic stirrer bar with an integrated process monitoring system. ACS Sensors 5, 2497–2502.

Chung, H., Li, J., Kim, Y., Van Os, J.M., Brounts, S.H., Choi, C.Y., 2020. Using implantable biosensors and wearable scanners to monitor dairy cattle's core body temperature in real-time. Computers and Electronics in Agriculture 174, 105453.

Chung, H., Vu, H., Kim, Y., Choi, C.Y., 2023. Subcutaneous temperature monitoring through ear tag for heat stress detection in dairy cows. Biosystems Engineering 235, 202–214. https://doi.org/10.1016/j.biosystemseng.2023.10.001.

Church, D.C., 1993. The ruminant animal: digestive physiology and nutrition. Waveland press, Long Grove, IL, USA.

Cowlar, n.d. . Smart Neck Collars Dairy Cows. URL https://www.dairy.cowlar.com/ (accessed 1.16.23).

CowManager, n.d. . 247 Control Your Cows. URL https://www.cowmanager.com/en-us/ (accessed 5.4.22).

Dairymaster, 2016. , TAG2-1 MooMonitor+ Activity Meter for Bovine Animals User Manual Manufacturing Procedure Dairymaster. Dairymaster, Causeway, Co. Kerry, Ireland.

Dairymaster, n.d. . Dairymaster Moonmonitor. URL https://www.dairymaster.com/products/moomonitor/ (accessed 4.27.22).

Dang, T.H., Dang, N.H., Tran, V.T., Chung, W.Y., 2022, October. A LoRaWAN-based smart sensor tag for cow behavior monitoring. Paper presented at the 2022 IEEE Sensors Conference, October 30–November 2, 2022, Dallas, TX, USA, pp. 1–4.

Davison, C., Michie, C., Hamilton, A., Tachtatzis, C., Andonovic, I., Gilroy, M., 2020. Detecting heat stress in dairy cattle using neck-mounted activity collars. Agriculture 10, 210.

de Morais, H.A., DiBartola, S.P., 2017. Advances in fluid, electrolyte, and acid-base disorders. Veterinary Clinics of North America: Small Animal Practice 47, 359–372.

Deniz, N.N., Chelotti, J.O., Galli, J.R., Planisich, A.M., Larripa, M.J., Rufiner, H.L., Giovanini, L.L., 2017. Embedded system for real-time monitoring of foraging behavior of grazing cattle using acoustic signals. Computers and Electronics in Agriculture 138, 167–174.

Dexcom, n.d. . Power Manage Your Diabetes Confid. URL https://www.dexcom.com/ (accessed 1.20.23).

Difford, G.F., Plichta, D.R., Løvendahl, P., Lassen, J., Noel, S.J., Højberg, O., Wright, A.-D.-G., Zhu, Z., Kristensen, L., Nielsen, H.B., 2018. Host genetics and the rumen microbiome jointly associate with methane emissions in dairy cows. PLoS Genetics 14, e1007580.

Duffield, T., Plaizier, J., Fairfield, A., Bagg, R., Vessie, G., Dick, P., Wilson, J., Aramini, J., McBride, B., 2004. Comparison of techniques for measurement of rumen pH in lactating dairy cows. Journal of Dairy Science 87, 59–66.

Dutta, D., Natta, D., Mandal, S., Ghosh, N., 2022. MOOnitor: an IoT based multi-sensory intelligent device for cattle activity monitoring. Sensors and Actuators A: Physical 333, 113271.

eCow, n.d. . Rumen Sens. Insights Maximise Farm Profits. URL https://wolf-hound.com/ (accessed 4.24.22).

Erickson, P.S., Kalscheur, K.F., 2020. Nutrition and feeding of dairy cattle. In: Pond, W.G., Bell, A.W. (Eds.), Animal Agriculture. Elsevier, Amsterdam, Netherlands, pp. 157–180.

Faerber, J., Cummins, G., Pavuluri, S.K., Record, P., Rodriguez, A.R.A., Lay, H.S., McPhillips, R., Cox, B.F., Connor, C., Gregson, R., 2017. In vivo characterization of a wireless telemetry module for a capsule endoscopy system utilizing a conformal antenna. IEEE Transactions on Biomedical Circuits and Systems 12, 95–105.

Fischer, H., Lohmann, D., Buchner, P., Moll, R., Uhlig, P., 2020. Sens-o-Spheres III–ein extrem miniaturisierter, drahtloser Sensor zur Prozessüberwachung in Bioreaktorsystemen. Paper presented at the 2nd Symposium Elektronik und Systemintegration ESI 2020: Intelligent Systems and Their Components—Research and Industrial Applications, October 8–9, 2020, Leipzig, Germany, pp. 84–91.

FreeStyle Libre, n.d. . Real-Time Glucose Read. URL https://www.freestyle.abbott/ie-en/home.html (accessed 1.20.23).

Fu, Y., He, Y., Xiang, K., Zhao, C., He, Z., Qiu, M., Hu, X., Zhang, N., 2022. The role of rumen microbiota and its metabolites in subacute ruminal acidosis (SARA)-induced inflammatory diseases of ruminants. Microorganisms 10, 1495.

Gasteiner, J., Horn, M., Steinwidder, A., 2015. Continuous measurement of reticuloruminal pH values in dairy cows during the transition period from barn to pasture feeding using an indwelling wireless data transmitting unit. Journal of Animal Physiology and Animal Nutrition 99, 273–280.

Germani, L., Mecarelli, V., Baruffa, G., Rugini, L., Frescura, F., 2019. An IoT architecture for continuous livestock monitoring using LoRa LPWAN. Electronics 8, 1435.

Go, A.E., Reyes, B.A., Lii, J.S., Alipio, M., Hall, S.S., Evanoso, J.C., 2022. A taxonomy of intelligent wearable devices and biosensors for cattle health monitoring. Paper presented at the 37th International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC), July 4–6, 2022, Nagoya, Japan, pp. 403–406.

Godyń, D., Herbut, P., Angrecka, S., 2019. Measurements of peripheral and deep body temperature in cattle–A review. Journal of Thermal Biology 79, 42–49.

Grünberg, W., Constable, P.D., 2009. CHAPTER 6 - Function and Dysfunction of the Ruminant Forestomach, In: Anderson, D.E., Rings, D.M. (Eds.), Food Animal Practice (Fifth Edition). W.B. Saunders, Saint Louis, MO, USA, pp. 12–19. https://doi.org/10.1016/B978-141603591-6.10006-5.

Gusterer, E., Kanz, P., Krieger, S., Schweinzer, V., Süss, D., Lidauer, L., Kickinger, F., Öhlschuster, M., Auer, W., Drillich, M., 2020. Sensor technology to support herd health monitoring: using rumination duration and activity measures as unspecific variables for the early detection of dairy cows with health deviations. Theriogenology 157, 61–69.

Hagey, J.V., Laabs, M., Maga, E.A., DePeters, E.J., 2022. Rumen sampling methods bias bacterial communities observed. PLoS One1 17, e0258176. https://doi.org/10.1371/journal.pone.0258176.

Hajnal, É., Vakulya, G., Udvardy, P., 2023. Heart Rate (HR) Detection by Cattle Rumen Bolus. Paper presented at the 27th International Conference on Intelligent Engineering Systems (INES), July 20–22, 2023, Budapest, Hungary, pp. 155–160.

Haladjian, J., Haug, J., Nüske, S., Bruegge, B., 2018. A wearable sensor system for lameness detection in dairy cattle. Multimodal Technologies and Interaction 2, 27.

Hanson, D., Mo, C., 2014. Monitoring cattle motion using 3-axis acceleration and GPS data. Journal of Research in Agriculture and Animal Science 2, 01–08.

Health, C. for D. and R., 2023. Use of International Standard ISO 10993-1, "Biological evaluation of medical devices - Part 1: Evaluation and testing within a risk management process" [WWW Document]. URL https://www.fda.gov/regulatory-information/search-fda-guidance-documents/use-international-standard-iso-10993-1-biological-evaluation-medical-devices-part-1-evaluation-and (accessed 3.15.24).
Henchion, M., Moloney, A.P., Hyland, J., Zimmermann, J., McCarthy, S., 2021. Review: Trends for meat, milk and egg consumption for the next decades and the role played by livestock systems in the global production of proteins. Animal 15. https://doi.org/10.1016/j.animal.2021.100287.
Hettinga, K.A., 2019. Chapter 6 - Lactose in the dairy production chain. In: Paques, M., Lindner, C. (Eds.), Lactose. Academic Press, Cambridge, MA, USA, pp. 231–266. https://doi.org/10.1016/B978-0-12-811720-0.00006-4.
Hoischen-Taubner, S., Habel, J., Uhlig, V., Schwabenbauer, E.-M., Rumphorst, T., Ebert, L., Möller, D., Sundrum, A., 2021. The whole and the parts—A new perspective on production diseases and economic sustainability in dairy farming. Sustainability 13, 9044. https://doi.org/10.3390/su13169044.
Hu, S., Reverter, A., Arablouei, R., Bishop-Hurley, G., McNally, J., Alvarenga, F., Ingham, A., 2024. Analyzing cattle activity patterns with ear tag accelerometer data. Animals 14, 301. https://doi.org/10.3390/ani14020301.
Huhtanen, P., Ramin, M., Hristov, A., 2019. Enteric methane emission can be reliably measured by the GreenFeed monitoring unit. Livestock Science 222, 31–40.
Icerobotics, n.d. . Cow Alert - Autom. Monit. Cow Fertil. Health Lameness. URL https://www.icerobotics.com/ (accessed 1.16.23).
Iwasaki, W., Ishida, S., Kondo, D., Ito, Y., Tateno, J., Tomioka, M., 2019. Monitoring of the core body temperature of cows using implantable wireless thermometers. Computers and Electronics in Agriculture 163, 104849.
Izdebski, P.M., Rajagopalan, H., Rahmat-Samii, Y., 2009. Conformal ingestible capsule antenna: A novel chandelier meandered design. IEEE Transactions on Antennas and Propagation 57, 900–909.
Jain, P.K., Tiwari, A.K., 2014. Heart monitoring systems—A review. Computers in Biology and Medicine 54, 1–13.
Jiang, D., Shi, B., Ouyang, H., Fan, Y., Wang, Z.L., Li, Z., 2020. Emerging implantable energy harvesters and self-powered implantable medical electronics. ACS Nano 14, 6436–6448.
Kadzere, C.T., Murphy, M.R., Silanikove, N., Maltz, E., 2002. Heat stress in lactating dairy cows: a review. Livestock Production Science 77, 59–91.
Kanz, P., Krieger, S., Drillich, M., Iwersen, M., 2018. evaluation of a wireless pulse oximeter for measuring arterial oxygen saturation and pulse rate in newborn Holstein Friesian calves. Journal Dairy Science 101, 6437–6442.
Karthick, G., Sridhar, M., Pankajavalli, P., 2020. Internet of things in animal healthcare (IoTAH): review of recent advancements in architecture, sensing technologies and real-time monitoring. SN Computer Science 1, 301.
Khan, S.R., Desmulliez, M.P., 2019. Towards a miniaturized 3d receiver wpt system for capsule endoscopy. Micromachines 10, 545.
Kim, J., Campbell, A.S., de Ávila, B.-E.-F., Wang, J., 2019. Wearable biosensors for healthcare monitoring. Nature Biotechnology 37, 389–406. https://doi.org/10.1038/s41587-019-0045-y.
Kim, M., Park, T., Yu, Z., 2017. Metagenomic investigation of gastrointestinal microbiome in cattle. Asian-Australasian Journal of Animal Sciences 30, 1515.
Kim, J., Rahmat-Samii, Y., 2004. Implanted antennas inside a human body: Simulations, designs, and characterizations. IEEE Transactions on Microwave Theory and Techniques 52, 1934–1943.
Kim, S.H., Ramos, S.C., Valencia, R.A., Cho, Y.I., Lee, S.S., 2022. Heat stress: effects on rumen microbes and host physiology, and strategies to alleviate the negative impacts on lactating dairy cows. Frontiers in Microbiology 13, 804562.
Kiradzhiyska, D.D., Mantcheva, R.D., 2019. Overview of biocompatible materials and their use in medicine. Folia Med (plovdiv) 61, 34–40.
Kovács, L., Jurkovich, V., Bakony, M., Szenci, O., Póti, P., Tőzsér, J., 2014. Welfare implication of measuring heart rate and heart rate variability in dairy cattle: literature review and conclusions for future research. Animal 8, 316–330.
Kröger, I., Humer, E., Neubauer, V., Kraft, N., Ertl, P., Zebeli, Q., 2016. Validation of a noseband sensor system for monitoring ruminating activity in cows under different feeding regimens. Livestock Science 193, 118–122.
Kumbhar, A., 2017. Overview of ISM bands and software-defined radio experimentation. Wireless Personal Communications 97, 3743–3756.
Ku-Vera, J.C., Valencia-Salazar, S.S., Piñeiro-Vázquez, A.T., Molina-Botero, I.C., Arroyave-Jaramillo, J., Montoya-Flores, M.D., Lazos-Balbuena, F.J., Canul-Solís, J.R., Arceo-Castillo, J.I., Ramírez-Cancino, L., 2018. Determination of methane yield in cattle fed tropical grasses as measured in open-circuit respiration chambers. Agricultural and Forest Meteorology 258, 3–7.
Kyle, B., Kennedy, A., Small, J., 1998. Measurement of vaginal temperature by radiotelemetry for the prediction of estrus in beef cows. Theriogenology 49, 1437–1449.
Lan, W., Yang, C., 2019. Ruminal methane production: associated microorganisms and the potential of applying hydrogen-utilizing bacteria for mitigation. Science of the Total Environment 654, 1270–1283.
Lauterbach, T., Lüke, T., Büker, M.-J., Hedayat, C., Gernandt, T., Moll, R., Grösel, M., Lenk, S., Seidel, F., Brunner, D., Bley, T., Walther, T., Lenk, F., 2019a. Measurements on the fly– Introducing mobile micro-sensors for biotechnological applications. Sensors and Actuators a: Physical 287, 29–38. https://doi.org/10.1016/j.sna.2019.01.003.
Lauterbach, T., Ziebart, N., Bley, T., Walther, T., Lenk, F., 2019b. Mobile sensors for biotechnology–location-independent, miniaturized process measurement. Chemie Ingenieur Technik 91, 1827–1832.
Lay, H.S., Cummins, G., Cox, B.F., Qiu, Y., Turcanu, M.V., McPhillips, R., Connor, C., Gregson, R., Clutton, E., Desmulliez, M.P., 2018. In-vivo evaluation of microultrasound and thermometric capsule endoscopes. IEEE Transactions on Biomedical Engineering 66, 632–639.
Lee, Y.Y., Erdogan, A., Rao, S.S., 2014. How to assess regional and whole gut transit time with wireless motility capsule. Journal of Neurogastroenterology and Motility 20, 265.
Lei, M.A.C., Simões, J., 2021. Invited review: ketosis diagnosis and monitoring in high-producing dairy cows. Dairy 2, 303–325. https://doi.org/10.3390/dairy2020025.
Leliveld, L.M., Lovarelli, D., Finzi, A., Riva, E., Provolo, G., 2023. Effects of cow reproductive status, parity and lactation stage on behaviour and heavy breathing indications of a commercial accelerometer during hot weather conditions. International Journal of Biometeorology 67, 1263–1272.
Li, M., Song, Y., Hou, Y., Li, N., Jiang, Y., Sulaman, M., Hao, Q., 2019. Comparable investigation of characteristics for implant intra-body communication based on galvanic and capacitive coupling. IEEE Transactions on Biomedical Circuits and Systems 13, 1747–1758.
Liu, G., Arjun, A.M., Vulpe, G., Deshpande, S., Neary, J., Smith, R., Sharma, S., 2024. Continuous monitoring of bovine well-being using wearable biosensing devices. Paper presented at the 2024 IEEE BioSensors Conference, June 10–12, 2024, Barcelona, Spain, pp. 1–4. https://doi.org/10.1109/BioSensors61405.2024.10712717.
Liu, X., Steiger, C., Lin, S., Parada, G.A., Liu, J., Chan, H.F., Yuk, H., Phan, N.V., Collins, J., Tamang, S., 2019. Ingestible hydrogel device. Nature Communications 10, 493.
Mah, A.J., Ghazi Zadeh, L., Khoshnam Tehrani, M., Askari, S., Gandjbakhche, A.H., Shadgan, B., 2021. Studying the accuracy and function of different thermometry techniques for measuring body temperature. Biology 10, 1327.
Mair, B., Drillich, M., Klein-Jöbstl, D., Kanz, P., Borchardt, S., Meyer, L., Schwendenwein, I., Iwersen, M., 2016. Glucose concentration in capillary blood of dairy cows obtained by a minimally invasive lancet technique and determined with three different hand-held devices. BMC Veterinary Research 12, 1–11.
Maity, S., Chatterjee, B., Chang, G., Sen, S., 2019. BodyWire: A 6.3-pJ/b 30-Mb/s– 30-dB SIR-tolerant broadband interference-robust human body communication transceiver using time domain interference rejection. IEEE Journal of Solid-State Circuits 54, 2892–2906.
Maqbool, S., Parkman, H.P., Friedenberg, F.K., 2009. Wireless capsule motility: comparison of the SmartPill® GI monitoring system with scintigraphy for measuring whole gut transit. Digestive Diseases and Sciences 54, 2167–2174.
Martineau, R., Proulx, J.G., Côrtes, C., Brito, A.F., Duffield, T.F., 2015. Two-stage rumen cannulation technique in dairy cows. Veterinary Surgery 44, 551–556. https://doi.org/10.1111/vsu.12318.
Medical Device Radiocommunications Service (MedRadio) | Federal Communications Commission [WWW Document], n.d. URL https://www.fcc.gov/medical-device-radiocommunications-service-medradio (accessed 7.15.24).
Medtronic, n.d. . Smartpill Mobil. Test. Syst. URL https://www.medtronic.com/covidien/en-us/products/motility-testing/smartpill-motility-testing-system.html (accessed 4.15.22).
Miller, G.A., Mitchell, M., Barker, Z.E., Giebel, K., Codling, E.A., Amory, J.R., Michie, C., Davison, C., Tachtatzis, C., Andonovic, I., Duthie, C.-A., 2020. Using animal-mounted sensor technology and machine learning to predict time-to-calving in beef and dairy cows. Animal 14, 1304–1312. https://doi.org/10.1017/S1751731119003380.
Moonsyst, n.d. . Rumen Bolus Solut. URL https://moonsyst.com/ (accessed 3.1.22).
Murugeswari, S., Murugan, K., Rajathi, S., Kumar, M.S., 2022. Monitoring body temperature of cattle using an innovative infrared photodiode thermometer. Computers and Electronics in Agriculture 198, 107120.
Nadeau, P., El-Damak, D., Glettig, D., Kong, Y.L., Mo, S., Cleveland, C., Booth, L., Roxhed, N., Langer, R., Chandrakasan, A.P., 2017. Prolonged energy harvesting for ingestible devices. Nature Biomedical Engineering 1, 0022.
Neethirajan, S., Tuteja, S.K., Huang, S.-T., Kelton, D., 2017. Recent advancement in biosensors technology for animal and livestock health management. Biosensors and Bioelectronics 98, 398–407.
Nie, L., Berckmans, D., Wang, C., Li, B., 2020. Is continuous heart rate monitoring of livestock a dream or is it realistic? A review. Sensors 20, 2291.
Noormohammadi, R., Khaleghi, A., Balasingham, I., 2021. Galvanic impulse wireless communication for biomedical implants. IEEE Access 9, 38602–38610.
O'Grady, L., Doherty, M.L., Mulligan, F.J., 2008. Subacute ruminal acidosis (SARA) in grazing Irish dairy cows. The Veterinary Journal 176, 44–49.
Patil, K.S., Rufus, E., 2020. A review on antennas for biomedical implants used for IoT based health care. Sensor Review 40, 273–280.
Pereira, G.M., Heins, B.J., O'Brien, B., McDonagh, A., Lidauer, L., Kickinger, F., 2020. Validation of an ear tag–based accelerometer system for detecting grazing behavior of dairy cows. Journal of Dairy Science 103, 3529–3544. https://doi.org/10.3168/jds.2019-17269.
Rajamahendran, R., Robinson, J., Desbottes, S., Walton, J., 1989. Temporal relationships among estrus, body temperature, milk yield, progesterone and luteinizing hormone levels, and ovulation in dairy cows. Theriogenology 31, 1173–1182.
Ramos-Morales, E., Arco-Pérez, A., Martín-García, A.I., Yáñez-Ruiz, D.R., Frutos, P., Hervás, G., 2014. Use of stomach tubing as an alternative to rumen cannulation to study ruminal fermentation and microbiota in sheep and goats. Animal Feed

Science and Technology 198, 57–66. https://doi.org/10.1016/j.anifeedsci.2014.09.016.
Rapid Labs, n.d. . CentriVet™ GK Blood Glucose Ketone Monit. Syst. – Dairy Cows. URL https://www.rapidlabs.co.uk/ (accessed 1.20.23).
Riaboff, L., Shalloo, L., Smeaton, A.F., Couvreur, S., Madouasse, A., Keane, M.T., 2022. Predicting livestock behaviour using accelerometers: A systematic review of processing techniques for ruminant behaviour prediction from raw accelerometer data. Computers and Electronics in Agriculture 192, 106610.
Rigout, S., Hurtaud, C., Lemosquet, S., Bach, A., Rulquin, H., 2003. Lactational effect of propionic acid and duodenal glucose in cows. Journal of Dairy Science 86, 243–253.
Rosenkranz, S., Fallast, M., 2016. Device for the measurement of individual farm animal data. Paper presented at the 2016 International Conference on Precision Livestock Farming, July 15–17, 2016, Vienna, Austria.
Sairam, A., Induri, T.R., Bagyaveereswaran, V., 2019. Validation of wearable sensors and RFID for real time monitoring of cattle farming using internet of things. Paper presented at the 2019 Innovations in Power and Advanced Computing Technologies (i-PACT), March 22–23, 2019, Vellore, India, pp.1–4.
Sakphrom, S., Chaimool, S., 2024. Development and evaluation of a wireless system for remote monitoring of rumen temperature in dairy cows. Paper presented at the 21st International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), June 5–7, 2024, Chiang Mai, Thailand, pp.1–4. https://doi.org/10.1109/ECTI-CON60892.2024.10594821.
Salzer, Y., Honig, H.H., Shaked, R., Abeles, E., Kleinjan-Elazary, A., Berger, K., Jacoby, S., Fishbain, B., Kendler, S., 2021. Towards on-site automatic detection of noxious events in dairy cows. Applied Animal Behaviour Science 236, 105260.
Salzer, Y., Lidor, G., Rosenfeld, L., Reshef, L., Shaked, B., Grinshpun, J., Honig, H.H., Kamer, H., Balaklav, M., Ross, M., 2022. a nose ring sensor system to monitor dairy cow cardiovascular and respiratory metrics. Journal of Animal Science 100, skac240.
Scarsella, E., Zecconi, A., Cintio, M., Stefanon, B., 2021. Characterization of microbiome on feces, blood and milk in dairy cows with different milk leucocyte pattern. Animals 11, 1463.
Sharma, B., Koundal, D., 2018. Cattle health monitoring system using wireless sensor network: a survey from innovation perspective. IET Wireless Sensor Systems 8, 143–151.
Sigma-Aldrich, n.d. . Lact. Assay Kit - MAK064. URL https://www.sigmaaldrich.com/ (accessed 8.21.23).
Sleptsov, I., Martynov, A., Vasiliev, Y.S., 2021. Introduction of digital technologies in beef breeding of the Republic of Sakha (Yakutia) on the use of smaxtec internal monitoring system for kalmyk bulls autumn fattening. Paper presented at the IOP Conference Series: Earth and Environmental Science, October 6–8, 2021, Yakutsk, Russia, p. 012138.
SmartINST, n.d. . Our Innov. Technol. URL https://webma9021.wixsite.com/smartinstnew/process-optimization (accessed 2.16.22).
smaXtec, 2022. SmaXtec STM32WL ST MEMS Better Inseminate Cows Prevent Drug-Resistance Bacteria. URL https://blog.st.com/smaxtec/ (accessed 7.15.23).
smaXtec, n.d. . Be Success. Healthy Dairy Cows. URL https://smaxtec.com/en/ (accessed 1.16.23).
Sosnowski, K., Akarapipad, P., Yoon, J., 2020. The future of microbiome analysis: Biosensor methods for big data collection and clinical diagnostics. Medical Devices & Sensors 3, e10085.
Stine, J.M., Beardslee, L.A., Sathyam, R.M., Bentley, W.E., Ghodssi, R., 2020. Electrochemical dissolved oxygen sensor-integrated platform for wireless in situ bioprocess monitoring. Sensors and Actuators b: Chemical 320, 128381.
Stuart, T., Cai, L., Burton, A., Gutruf, P., 2021. Wireless and battery-free platforms for collection of biosignals. Biosensors and Bioelectronics 178, 113007. https://doi.org/10.1016/j.bios.2021.113007.
Studer, E., Alsaaod, M., Steiner, A., Becker, J., 2023. Application note for the use of a wireless device measuring reticular pH under practice conditions in a Swiss dairy herd. Smart Agricultural Technology 4, 100170. https://doi.org/10.1016/j.atech.2022.100170.
Sutter, J.U., Lewis, O., Robinson, C., McMahon, A., Boyce, R., Bragg, R., Macrae, A., Orton, J., Shah, V., Ingleby, S.J., 2020. Recording the heart beat of cattle using a gradiometer system of optically pumped magnetometers. Computers and Electronics in Agriculture 177, 105651.
Takkouche, B., Norman, G., 2011. PRISMA statement. Epidemiology 22, 128.
Tricco, A.C., Lillie, E., Zarin, W., O'Brien, K.K., Colquhoun, H., Levac, D., Moher, D., Peters, M.D., Horsley, T., Weeks, L., 2018. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Annals of Internal Medicine 169, 467–473.
UNEP, 2022. Emissions Gap Report 2022: The Closing Window. Climate Crisis Calls for Rapid Transformation of Societies. United Nations Environmental Programme, Nairobi, Kenya.
Vakulya, G., Hajnal, É., Udvardy, P., Simon, G., 2024. In-depth development of a versatile rumen bolus sensor for dairy cattle. Sensors 24, 6976. https://doi.org/10.3390/s24216976.
Varshney, J., Varshney, J., 2020. Electrocardiography in Ruminants. Electrocardiography in Veterinary Medicine. Springer, Singapore city, Singapore, pp.245–259. https://doi.org/10.1007/978-981-15-3699-1_18.
Versluijs, E., Niccolai, L.J., Spedener, M., Zimmermann, B., Hessle, A., Tofastrud, M., Devineau, O., Evans, A.L., 2023. Classification of behaviors of free-ranging cattle using accelerometry signatures collected by virtual fence collars. Frontiers in Animal Science 4, 1083272. https://doi.org/10.3389/fanim.2023.1083272.
Vetlab Supplies, n.d. . FASTest IgG Bov. URL https://vetlabsupplies.co.uk/products/diagnostic-kits/fastest-igg-bovine/ (accessed 11.8.23).
Vidic, J., Manzano, M., Chang, C.-M., Jaffrezic-Renault, N., 2017. Advanced biosensors for detection of pathogens related to livestock and poultry. Veterinary Research 48, 1–22.
Voß, A., Fischer-Tenhagen, C., Bartel, A., Heuwieser, W., 2021. Sensitivity and specificity of a tail-activity measuring device for calving prediction in dairy cattle. Journal of Dairy Science 104, 3353–3363.
Waiblinger, S., Menke, C., Korff, J., Bucher, A., 2004. Previous handling and gentle interactions affect behaviour and heart rate of dairy cows during a veterinary procedure. Applied Animal Behaviour Science 85, 31–42.
Wakatsuki, T., Nakamura, T., Ishii, A., Konishi, K., Okubo, M., Souma, K., Hirayama, H., 2023. Calving prediction with continuous measurement of subcutaneous tissue glucose concentration in pregnant cows. Theriogenology 202, 119–124.
Wang, Z., Wang, S., Wang, C., Zhang, Y., Zong, Z., Wang, H., Su, L., Du, Y., 2023. A non-contact cow estrus monitoring method based on the thermal infrared images of cows. Agriculture 13, 385.
Wang, S., Zhang, H., Tian, H., Chen, X., Li, S., Lu, Y., Li, L., Wang, D., 2020. Alterations in vaginal temperature during the estrous cycle in dairy cows detected by a new intravaginal device—a pilot study. Tropical Animal Health and Production 52, 2265–2271.
Welch, C.B., Ryman, V.E., Pringle, T.D., Lourenco, J.M., 2022. Utilizing the gastrointestinal microbiota to modulate cattle health through the microbiome-gut-organ axes. Microorganisms 10, 1391.
Wellnitz, D.O., 2023. Effects of sensor ear tags with twin pin fixing system on health and well-being of cattle. Doctoral dissertation, University of Bern, Bern, Switzerland.
Werner, J., Leso, L., Umstatter, C., Niederhauser, J., Kennedy, E., Geoghegan, A., Shalloo, L., Schick, M., O'Brien, B., 2018. Evaluation of the RumiWatchSystem for measuring grazing behaviour of cows. Journal of Neuroscience Methods 300, 138–146.
Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M.-J., 2017. Big data in smart farming–a review. Agricultural Systems 153, 69–80.
Wongvivatvaitaya, P., Boonto, S., Silapunt, R., 2023. An Investigation of Surface Temperature Effect on Estrus Detection of Dairy Cows using Supervised Learning, in: 2023 Third International Symposium on Instrumentation, Control, Artificial Intelligence, and Robotics (ICA-SYMP). Paper presented at the Third International Symposium on Instrumentation, Control, Artificial Intelligence, and Robotics (ICA-SYMP), June 21–23, 2023, Bangkok, Thailand, pp. 49–52. https://doi.org/10.1109/ICA-SYMP56348.2023.10044943.
Zhang, G., Ametaj, B.N., 2020. Ketosis an old story under a new approach. Dairy 1, 5.
Zhao, Y., Nan, X., Yang, L., Zheng, S., Jiang, L., Xiong, B., 2020. A review of enteric methane emission measurement techniques in ruminants. Animals 10, 1004.
Zhu, W., Zhou, T., Zhou, Y., Li, M., Chen, Y., Zhao, Y., Song, Y., 2021. An audio transmission system based on capacitive coupling intra-body communication. Paper presented at the 2021 International Conference on Communications, Information System and Computer Engineering (CISCE), May 14–16, 2021, Beijing, China, pp. 183–187.
Zimmermann, R., Fiabane, L., Gasteuil, Y., Volk, R., Pinton, J.-F., 2013. Measuring Lagrangian accelerations using an instrumented particle. Physica Scripta 2013, 014063.
Zoetis, n.d. Veterinary Diagnostics. URL https://www2.zoetisus.com/products/diagnostics/ (accessed 1.24.23).