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Review article

Review of sensor technologies, DC-DC converters, and power electronics for sustainable monitoring in precision livestock farming

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ABSTRACT

Traditional livestock farming relies on manual monitoring and management of animal health and environmental conditions, often leading to inefficiencies, delayed disease detection, and suboptimal resource utilization. These limitations contribute to increased operational costs, reduced productivity, and compromised animal welfare. Moreover, the conventional methods struggle to provide real-time data, making it difficult to implement timely interventions. To overcome these challenges, PLF has emerged as a transformative approach that integrates advanced sensor technologies, automation, and data-driven decision-making. PLF utilizes various animal-based sensors, including body temperature sensors, accelerometers, RFID tags, and biosensors, to continuously monitor vital physiological and behavioral parameters. A significant advancement in PLF involves the integration of consumer-grade electronics such as smartphones, edge AI platforms, and LoRa/Bluetooth modules, effectively bridging agricultural technology with mass-market electronics for scalable deployment. The reliability of these sensor systems critically depends on power management solutions, particularly DC-DC converters. This review provides a comprehensive comparative analysis of isolated versus non-isolated DC-DC converters, evaluating their suitability for different sensor types and livestock monitoring environments. Furthermore, it explores AI-driven power management strategies that optimize energy consumption in wearable and implantable sensors, ensuring prolonged operation and enhanced sustainability. By highlighting these novel integrations, this paper advances the understanding of energy-efficient, scalable PLF systems that improve livestock health, optimize feeding strategies, and enhance overall farm efficiency.

1. Introduction

For generations, the cornerstone of animal husbandry has been traditional livestock farming, which relies on human labor, free grazing, and small-scale management practices. Farmers mostly rely on natural feeding practices, in which cattle graze on open pastures or eat food that is readily accessible in the area. With no infrastructure for shelter, disease prevention, or scientific breeding initiatives, living circumstances are frequently subpar. Early disease detection is challenging in traditional systems of animal health management because they rely more on visual observation and expertise than on data-driven decision-making. Unpredictable growth rates and irregular output of meat, milk, or eggs are the results of a mostly uncontrolled breeding process. Furthermore, because agricultural systems are highly dependent on weather conditions, they remain vulnerable to extreme temperature fluctuations, floods, and droughts. Despite having supported communities for many

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generations, traditional agricultural practices are facing increasing difficulties because of the increasing demand for animal products worldwide, land scarcity, and the need for greater efficiency.

The main drawbacks of traditional cattle farming include its excessive reliance on physical labor, low productivity, and wasteful use of resources. Unoptimized breeding and feeding practices result in far lower rates of meat, milk, and egg production. It is also a major contributor to greenhouse gas emissions, with livestock accounting for approximately 14.5% of global anthropogenic emissions, according to the FAO. Methane emissions from cattle are particularly significant, with ruminants contributing nearly 40% of total agricultural methane emissions. Traditional cattle farming is labor-intensive, which raises operating expenses and makes it difficult to scale production effectively. Furthermore, market value and customer demand are impacted by uneven quality in animal products brought on by a lack of scientific breeding techniques. Farmers are forced to rely entirely on experience and intuition due to the lack of technology and data use, resulting in unpredictable production cycles and inefficiency. Fig. 1 gives an overall overview of the review paper.

The livestock sector has shifted to PLF [1], a cutting-edge, technologically advanced method that improves production, sustainability, and efficiency, to overcome these obstacles. To improve livestock management in real time, PLF combines ML, data analysis, AI, and an automated sensor system [2]. To minimize food waste and enhance development rates, intelligent feeding systems ensure that every animal receives the correct quantity of nutrients. Vital signs, such as temperature, movement, and eating habits, are continuously monitored by health monitoring devices, enabling early detection of disease and prompt treatment. In animal housing, automated environmental control systems regulate ventilation, humidity, and temperature, thereby improving overall well-being and reducing health problems associated with stress. Higher meat, milk, and egg outputs are guaranteed by advanced breeding programs that combine genetic data and AI-driven insights to increase livestock quality [3]. By improving production and decreasing resource use, PLF considerably lessens the environmental impact of cattle husbandry. PLF is an environmentally beneficial substitute for conventional techniques because of its sustainable practices [4], which include waste management, effective use of energy and water, and lower greenhouse gas emissions. The increasing global challenges of climate change, resource scarcity, and the rising demand for animal products are driving the adoption of PLF. PLF offers a solution by enhancing livestock management and resources. Moreover, Farmers may improve production, profitability, and food security by incorporating real-time data analytics into their choices. As global demand for animal products develops, PLF represents the future of the livestock farming business.

Recent studies (2023–2024) have demonstrated significant progress in integrating AI and ML for livestock health prediction, early disease detection, and behavioral pattern recognition, thereby improving welfare and productivity across herds [5,6]. Similarly, advanced energy harvesting approaches—such as solar, kinetic, and thermal energy recovery—have been successfully applied to power wearable and implantable livestock sensors, extending operational life while reducing battery dependency [7,8]. Furthermore, blockchain and IoT-based frameworks are emerging as robust solutions for data security, traceability, and transparent livestock management, ensuring reliable farm-to-fork traceability and enhancing consumer trust in precision livestock systems [9].

Sensor technology in cow farming has fundamentally revolutionized traditional livestock management by enabling real-time monitoring of animal health, behavior, and environmental conditions. These advanced sensors, which may be found in ear tags, collars, or implanted chips, enable the early diagnosis of diseases and suffering by continually monitoring critical indications such as body temperature, heart rate, breathing, and activity levels [10]. Recent advances in wearable consumer electronics and smart devices have made it feasible to deploy cost-effective, scalable health monitoring in livestock environments—bridging the domains of agricultural technology and consumer electronics. Many of the sensors and modules used in PLF—such as accelerometers, GPS modules, Bluetooth transceivers, and LoRaWAN nodes—are readily available as consumer-grade devices [11]. Moreover, smartphones, edge AI modules, and mobile dashboards are increasingly employed to display, analyze, and respond to livestock health data, further embedding consumer electronics into the core of modern precision livestock systems [12]. To identify lameness or unusual behavior that may indicate disease or injury, GPS and accelerometers are used to track movement patterns, grazing habits, and rest cycles. Milking sensors in dairy farming examine milk output, composition, and udder health to identify illnesses like mastitis before symptoms show up [13]. Individual feed intake is measured by sensors in automated feeding systems, which guarantee balanced nutrition and guard against malnutrition or overfeeding [14]. Breeding efficiency is increased, artificial insemination is optimized, and estrus cycles are detected using reproductive monitoring devices. To provide the best possible living circumstances for cattle, environmental sensors are also positioned in barns and grazing areas to track temperature, humidity, air quality, and ammonia levels [15]. By keeping livestock from wandering and maximizing grazing patterns, geofencing technology minimizes resource waste. These sensors enable farmers to make informed decisions, enhance livestock welfare, boost production, and reduce operating costs by leveraging IoT, AI, and big data analytics. Cattle farming has become more profitable, compassionate, and ecologically friendly because of the shift from traditional livestock management to sensor-based precision farming [16]. This shift has also improved sustainability, facilitated early disease identification, and optimized resource utilization.

Additionally, cutting-edge DC-DC converters reduce energy waste and heat dissipation, prolonging the battery life of portable monitoring equipment. These converters are crucial for preserving power stability [17], extending system lifespan, and lowering energy expenses in cattle farming, whether they are found in smart feeding stations, automated

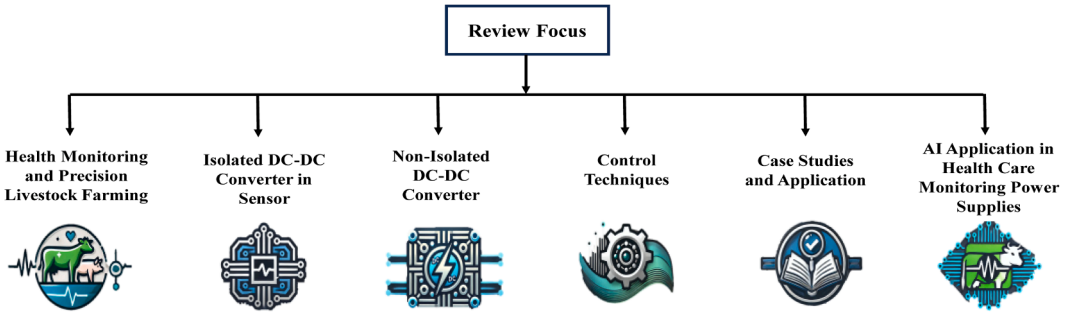


Fig. 1. Review Focus of Sensor Technologies in PLF, Covering Health Monitoring, DC-DC Converters, Control Techniques, Case Studies, and AI-based Power Monitoring.

milking systems, or health monitoring gadgets.

Fig. 2 presents the PRISMA flowchart outlining the systematic literature selection process. The literature search was conducted between October 2024 and March 2025 using databases such as CAB Abstracts and Agricultural Online Access. Keywords including *"Precision Livestock Farming," "cattle health monitoring," "sensor technologies,"* and *"DC–DC converters"* were combined with Boolean operators (AND, OR) to refine the search. The inclusion criteria focused on peer-reviewed studies addressing cattle health monitoring in PLF with quantitative data, while exclusion criteria removed articles with insufficient data quality or lacking methodological rigor. Titles, abstracts, and full texts were screened sequentially, and the PRISMA flowchart summarizes the identification, screening, and inclusion stages.

Depending on the power needs of various systems, both isolated and non-isolated DC-DC converters have essential uses in cattle health monitoring. Large-scale automated feeding machines, dairy milking systems, and environmental control units are just a few examples of high-power applications that benefit significantly from isolated converters [18], which uses transformers to separate input and output circuits. They guarantee equipment protection in challenging agricultural conditions by stopping the spread of electrical faults.

Conversely, non-isolated converters are more portable, effective, and appropriate for low-voltage applications like GPS trackers, wearable livestock health monitors [19], and tiny automated equipment. These converters are ideal for battery-powered farming tools, as they enhance power efficiency while reducing size and cost. Whether a smart farm's automated systems require compact, effective power regulation for lightweight devices or strong electrical isolation for safety, the use of both types of converters ensures that they all operate reliably. Modern cattle farming improves production and animal care by using these converters, which lead to increased automation, accuracy, and efficiency.

The paper thoroughly evaluates PLF development alongside analyzing how DC-DC converters serve as critical elements for the efficient operation of livestock monitoring infrastructure. Existing literature often overlooks the potential of consumer-grade electronics, such as smartphones, edge AI platforms, and low-cost wireless modules (e.g., LoRa and Bluetooth), which are increasingly being integrated into PLF systems. These technologies, which are affordable and widely available, offer scalable solutions for farmers, yet their application in PLF remains underexplored.

Importantly, the objectives of this review are strongly aligned with global sustainability priorities, particularly the United Nations Sustainable Development Goals (SDGs). The review supports SDG 2 (Zero Hunger) by promoting sustainable livestock productivity and food security through precision monitoring; SDG 7 (Affordable and Clean Energy) by emphasizing energy-efficient DC-DC converters and renewable power integration; and SDG 12 (Responsible Consumption and Production) by encouraging optimized resource utilization and reduction of waste in livestock systems. This alignment reinforces the paper's focus on advancing eco-efficient, data-driven, and sustainable agricultural technologies.

The main contributions of this work are highlighted as follows:

- This paper presents an in-depth review of the latest sensor technologies, including accelerometers, gyroscopes, GNSS, and UWB systems, used for real-time monitoring of cattle health, behavior, and environmental conditions. It highlights how these technologies have transformed traditional livestock farming into a data-driven, efficient, and sustainable practice.

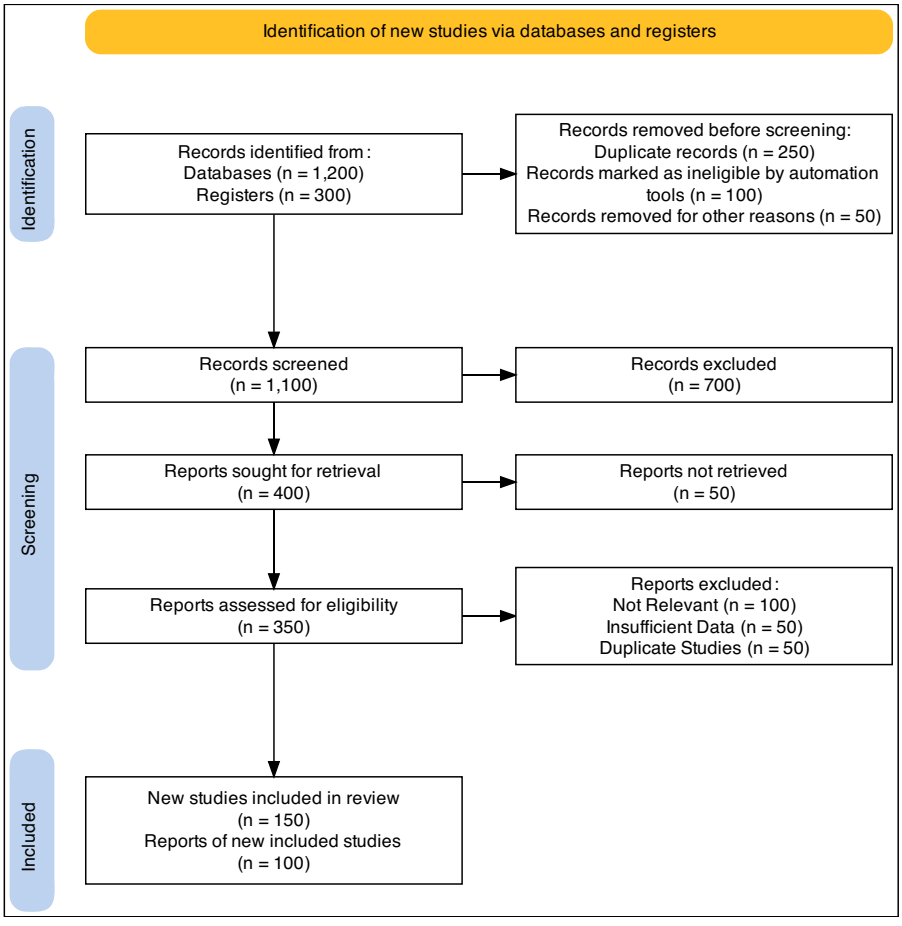


Fig. 2. Paper Selection Process utilizing PRISMA Flowchart of the Review Paper.

- This study offers a thorough examination of isolated DC-DC converters and their function in sensor-based applications, emphasizing their efficiency gains, design, and guiding principles. This study lays the groundwork for further investigations into improving converter efficiency and incorporating AI-powered control systems for intelligent power management.
- Non-isolated DC-DC converter topologies are reviewed in detail in this work, with an emphasis on their importance in the integration of renewable energy sources. It looks at the developments in buck-boost, SEPIC, Cuk, Z-source, and Zeta converters.
- This overview explores the integration of AI and ML in PLF systems to enhance decision-making, enable early disease detection, and support predictive maintenance. It highlights the role of AI in optimizing power usage and improving the overall efficiency of livestock monitoring systems.
- The review critically discusses emerging trends in PLF, with a particular focus on the integration of renewable energy sources, energy harvesting technologies, and sustainable power solutions to promote environmentally responsible practices. It provides insights into how future advancements in DC-DC converters and AI can further enhance the sustainability and efficiency of livestock farming.

2. Health monitoring in precision livestock farming

PLF combines advanced sensors, artificial intelligence, and real-time data analysis to transform the way livestock are managed. Instead of depending on occasional manual checks, PLF enables continuous and automated monitoring that tracks the health, activity, and behavior of animals in real time [20]. This approach helps detect diseases at an early stage, promotes better animal welfare, and boosts overall productivity by reducing the need for manual involvement and making decisions based on accurate, data-driven insights [21]. Advanced sensing technologies such as accelerometers, gyroscopes, magnetometers, GNSS, and UWB positioning systems play a pivotal role in tracking cattle movements [22,23] and physiological conditions with high accuracy.

2.1. Animal & sensor

Cattle are large and active animals, so monitoring their movement and health requires durable and dependable sensors that can withstand demanding farm conditions while providing accurate data. The types of common sensors used are shown in Fig. 3. Accelerometers are commonly used to measure linear acceleration, providing insights into activity levels, walking patterns, and rest periods [24].

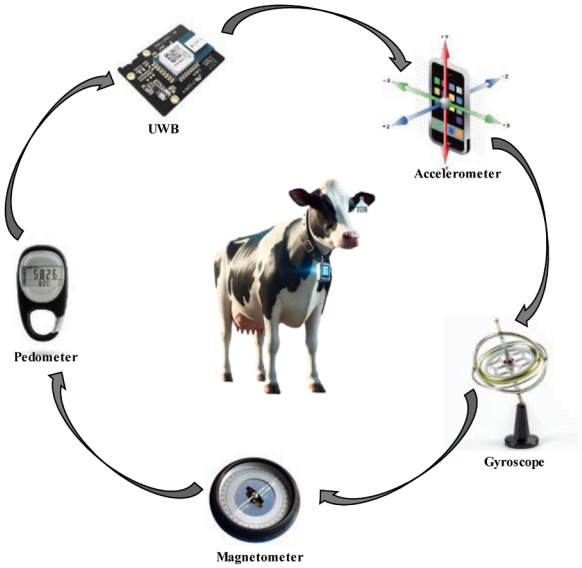


Fig. 3. Sensors Integrated in Cattle Monitoring Systems to Track Movement and Activity Patterns.

Gyroscopes work alongside accelerometers by measuring angular velocity, allowing for better analysis of posture and the detection of irregular gait patterns [25]. Magnetometers add another layer of precision by sensing the animal's orientation in relation to the Earth's magnetic field, which helps classify different types of movement more accurately [26].

GNSS technology is instrumental in tracking cattle movements over large grazing areas [27], enabling farmers to monitor grazing behavior, migration patterns, and resting zones with precise geolocation data. In indoor environments such as barns, GNSS accuracy is limited, making UWB positioning systems a superior alternative. UWB provides highly accurate indoor tracking by measuring the time it takes for radio signals to travel between sensors and reference points [28]. Together, these sensors create a comprehensive monitoring system that enables real-time observation of cattle behavior, improving both health management and farm efficiency [29].

These agricultural sensors and monitoring devices can be integrated with energy harvesting technologies. For example, the utilization of BioG and BioH2 biofuels in energy harvesting solutions [30]. Additionally, toxic waste and bio-waste can be treated with bacterial bioremediation techniques [31]. The use of Nano Phase Change Materials is also common in energy storage [32].

2.2. Sensor attachment & signal acquisition

The effectiveness of these sensors depends on their proper placement and the accuracy of signal acquisition. Different types of sensors are attached to specific body parts to ensure they capture the most relevant physiological and behavioral data [33]. Accelerometers, gyroscopes, and magnetometers are typically placed on a collar around the neck or mounted on the legs. Neck-mounted sensors are ideal for monitoring head movements, feeding behavior, and rumination, while leg-mounted sensors excel in detecting locomotion patterns, lameness, and weight-bearing activities [34].

As the animal moves, each sensor generates signals that capture unique aspects of its motion. The accelerometer measures changes in acceleration as the cattle walk, run, or remain still, producing time-series data that indicate varying movement intensities [35]. The gyroscope detects angular changes, helping identify whether movements are normal or indicate irregular behaviors such as stumbling or prolonged lying down [36]. The magnetometer measures orientation, and when its data are combined with readings from the accelerometer and gyroscope, it enables accurate tracking of the animal's overall movement and posture. GNSS sensors generate geolocation signals by communicating with satellites, continuously updating the animal's position in open grazing fields. In indoor environments, UWB systems emit short-range radio signals, and the time delay between transmission and reception is used to determine the exact position of the cattle. This comprehensive signal acquisition process ensures that movement patterns are accurately recorded and analyzed, as shown in Fig. 4.

2.3. Modeling activity inferences & conditions

The data collected from these sensors go through detailed processing to identify activity patterns and detect potential health issues. Machine learning algorithms analyze time-series data from accelerometers, gyroscopes, and magnetometers to classify different behaviors, such as walking, standing, lying down, or feeding [37]. By comparing real-time readings with historical activity patterns, AI models can spot irregularities that may signal early signs of illness or stress [38]. For instance, a sudden drop in movement intensity may indicate fatigue, lameness, or metabolic disorders, prompting timely intervention [39].

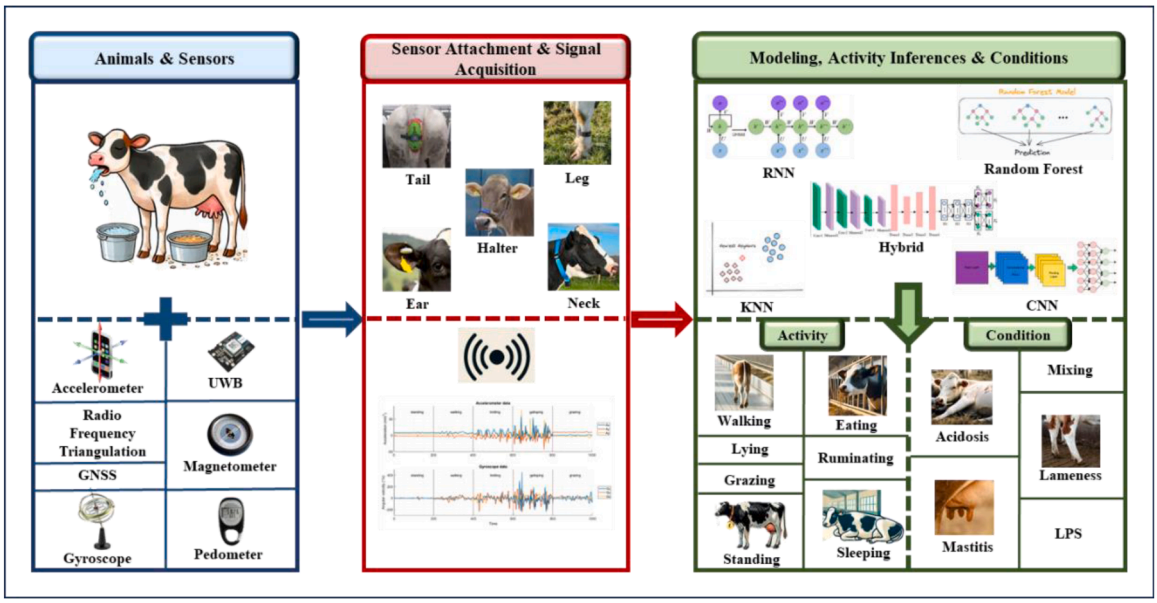


Fig. 4. Animal Activity Recognition Based on Wearable Sensors and Deep Learning Models.

In addition to basic activity recognition, advanced predictive models can detect specific diseases by identifying deviations from normal behavior [40]. One of the most important applications, lameness detection, relies on gait analysis using accelerometer and gyroscope data to recognize abnormal walking patterns. Likewise, prolonged inactivity captured by motion sensors can point to health problems such as ketosis or mastitis [41,42]. AI-based models are trained on labeled datasets containing examples of different conditions, enabling them to distinguish between healthy and unhealthy states. Techniques like CNNs and RNNs are commonly used to process sensor data and deliver real-time predictions [43].

By integrating sensor-based monitoring systems with AI-powered analytics, PLF allows farmers to take proactive measures in managing cattle health, improving productivity, and lowering veterinary expenses. The combination of multi-sensor data and predictive modeling strengthens the accuracy and dependability of livestock health monitoring, establishing it as a key element of modern sustainable farming [44].

2.4. Consumer-grade electronics in PLF

The advancement of low-cost, consumer-grade electronics has made PLF more accessible to smallholders and rural farms. Devices such as ESP32 microcontrollers, Raspberry Pi modules, and Jetson Nano edge AI platforms offer affordable, energy-efficient computing that can locally process data from accelerometers, gyroscopes, and environmental sensors. These modules support real-time analysis and wireless communication via Wi-Fi, Bluetooth, or LoRa, enabling decentralized and scalable PLF systems [45].

In contrast to industrial-grade sensor platforms—which are typically more robust and offer higher precision at increased costs—consumer-grade platforms are widely available, easy to program, and sufficiently accurate for many livestock applications. For example, commonly used modules like MPU6050 IMUs, HC-05 Bluetooth modules, and SX1276 LoRa chips have been effectively deployed in wearable livestock collars and barn monitors [46,47].

Furthermore, smartphones now act as intuitive interfaces for farmers to visualize health metrics, receive alerts, and control monitoring systems. These consumer devices, when combined with cloud platforms or on-device AI, enable real-time feedback on anomalies in movement, temperature, or feeding behavior—without needing expensive centralized infrastructure [48,49].

The use of consumer electronics in PLF not only reduces overall system costs but also promotes technology adoption in low-resource settings, creating a pathway for widespread digital transformation in agriculture.

2.5. Smartphone monitoring & mobile dashboards

The increasing accessibility of smartphones and mobile application development has paved the way for their integration into PLF as powerful, portable, and cost-effective monitoring platforms. Smartphones, equipped with built-in communication modules (e.g., Bluetooth, Wi-Fi, and LTE), serve as central hubs that collect, visualize, and analyze sensor data in real time. These devices provide an intuitive interface for farmers to monitor livestock health metrics such as temperature, movement, and activity patterns, directly from wearable or environmental sensors.

Many PLF systems now utilize BLE to transmit data from body-worn sensors—such as accelerometers and biosensors—to nearby smartphones. Android and iOS applications have been developed to support real-time dashboards, allowing farmers to receive alerts on abnormal behavior (e.g., signs of lameness, reduced feeding activity), track animal locations using GNSS data, and generate historical trends for performance optimization. These dashboards are often designed with user-friendly visualizations such as heatmaps, line graphs, or color-coded alerts to support rapid decision-making in field environments [50].

Furthermore, smartphone-based edge processing enables basic on-device analytics, which reduces reliance on cloud connectivity, especially in rural or remote farming locations with limited internet access. For example, classification of behavior states (e.g., walking, lying, ruminating) can be implemented using lightweight models directly on mobile devices, minimizing latency and conserving power on wearable sensors [51,52].

The integration of consumer-grade smartphones into livestock monitoring offers several advantages: affordability, scalability, ease of deployment, and enhanced user interaction. As smartphones continue to evolve with more computational capabilities and advanced sensors (e.g., thermal cameras, LiDAR), their utility in agriculture is expected to grow, further bridging the gap between consumer electronics and precision livestock systems [53,54].

2.6. Wireless connectivity: LoRaWAN & Bluetooth

Wireless communication plays a foundational role in enabling real-time livestock monitoring by facilitating data transmission between sensors, edge devices, and user interfaces such as smartphones or centralized servers [55,56]. Among the wide range of wireless technologies, LoRaWAN and Bluetooth have emerged as two prominent consumer-grade solutions in smart farming applications, offering complementary benefits in terms of range, power efficiency, and data rate.

LoRaWAN is an LPWAN protocol designed for long-range communication, often spanning several kilometers in open fields. Its low bandwidth and energy-efficient characteristics make it ideal for transmitting periodic health and location data from wearable livestock devices, especially in large-scale grazing environments where cellular or Wi-Fi connectivity may be unavailable. LoRa-enabled collars or ear tags can relay data such as body temperature, movement, and GPS location to a central LoRa gateway, which forwards the information to cloud platforms or local servers for further analysis. Its bi-directional communication support also enables remote configuration and firmware updates, minimizing the need for physical intervention in the field [55].

On the other hand, Bluetooth—particularly BLE—is well-suited for short-range, high-frequency communication. It is commonly used in barn-based systems and close-proximity monitoring setups. BLE sensors mounted on collars or harnesses can continuously stream real-time data to nearby smartphones, tablets, or Raspberry Pi devices. The low energy consumption of BLE allows for long-term operation on compact battery-powered devices, while its high availability in consumer smartphones ensures seamless connectivity and dashboard integration.

Each of these technologies offers distinct benefits depending on the deployment scale and application context. LoRaWAN is preferred in wide-area, off-grid, or outdoor environments due to its long transmission range and robustness to interference. Bluetooth, in contrast, excels in localized settings such as milking parlors, feeding stations, or enclosed barns, where direct interaction with a mobile device or gateway is feasible [56].

The integration of consumer-grade LoRa and Bluetooth modules (e.g., SX1276, HM-10, HC-05) into wearable and environmental sensors reflects the growing convergence between consumer electronics and smart livestock systems. Their affordability, interoperability, and ease of deployment enable scalable PLF solutions that are accessible to both industrial-scale farms and smallholder operations. Together, these wireless technologies form the backbone of intelligent livestock monitoring systems by enabling ubiquitous connectivity, low-latency data transfer, and interoperable communication with smartphones and edge devices.

2.7. Edge AI for health monitoring

The convergence of artificial intelligence and edge computing has significantly expanded the capabilities of consumer electronics in livestock monitoring applications. Edge AI platforms enable real-time inference and localized decision-making directly on the device, eliminating the need for continuous cloud connectivity and reducing latency, bandwidth usage, and energy consumption. This is particularly critical in rural and off-grid farming environments, where internet connectivity is often limited or unreliable.

Popular consumer-grade edge platforms such as the NVIDIA Jetson Nano, Raspberry Pi 4, Google Coral Dev Board, and ESP32 with TinyML support have demonstrated the feasibility of deploying lightweight AI models for health and activity monitoring of livestock. These platforms can process data from wearable sensors (e.g., accelerometers, gyroscopes, temperature sensors) and perform on-device classification of behaviors such as walking, resting, feeding, or signs of distress (e.g., limping or reduced mobility). Machine learning frameworks like TensorFlow Lite, PyTorch Mobile, and Edge Impulse support model training and deployment on these devices.

For instance, an accelerometer attached to a cow's collar can feed time-series data to a Jetson Nano unit, which uses a trained CNN to detect anomalies in movement indicative of lameness or fatigue. The results can be visualized in real-time on a smartphone dashboard via Bluetooth or Wi-Fi, allowing farmers to make immediate interventions without waiting for remote server responses.

Moreover, edge AI platforms reduce the energy burden on wearable sensors by offloading computation to nearby processing units, which may be solar- or battery-powered. This distributed architecture improves overall system efficiency and enables scalable deployments across larger herds or expansive pastures.

The affordability, portability, and low power consumption of these consumer-grade edge platforms make them well-suited for democratizing AI-powered livestock monitoring, bridging the gap between research-grade solutions and real-world, mass-adoptable tools. Their use strongly aligns with the principles of consumer electronics for smart farming, bringing AI-driven diagnostics and automation to resource-constrained agricultural settings.

3. Isolated DC-DC converter in sensor

A DC-DC converter is a device that converts one DC voltage to another by stepping it up or stepping it down, and sometimes both. It ensures efficient power management in various applications by providing stable and regulated voltage for optimal performance and energy efficiency, including batteries, portable electronics, and especially in medical devices [42]. It is commonly used in medical technologies, often referred to as the very backbone of health monitoring systems. The working procedure of the DC-DC converter is illustrated in Fig. 5.

DC-DC converters are mainly composed of isolated converters and non-isolated converters. A converter family tree is shown in Fig. 6. Isolated Converters provide electrical isolation between the input and output using transformers. The isolation ensures the safety of sensitive circuits, especially in high-voltage systems [48]. It also has a wider range of flexibility in voltage conversion. On the other hand, non-isolated converters do not provide electrical isolation. They are applicable in a low-voltage system where electrical isolation is not necessary [48].

3.1. Flyback converter

A flyback converter represents an isolated DC-DC converter that is dependent on a transformer to operate at high frequencies. The switch operates during an on-state to store energy within the transformer's magnetic field that becomes available after switch activation ends [58]. The design features basic construction along with low costs because switching takes a solitary transistor, while rectification depends on a diode [59]. Due to the missing continuous current flow, the output voltage ripple reaches high levels, which requires proper filter

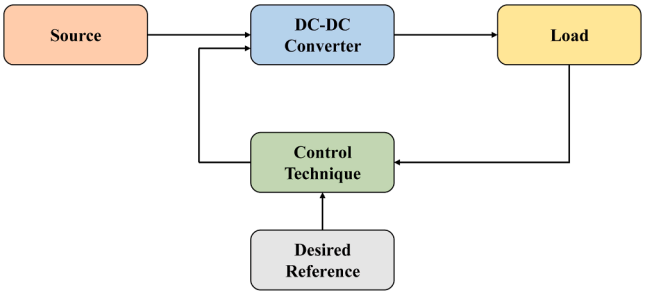


Fig. 5. Working Principle of a DC-DC Converter in a Sensor Node Showing Power Flow and Control Feedback [58].

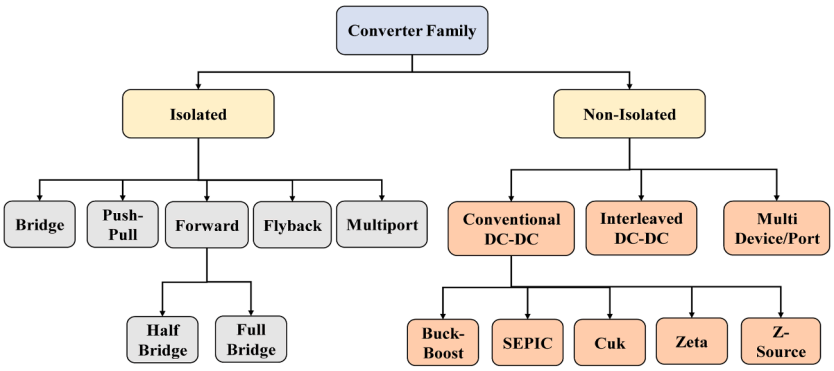


Fig. 6. Classification of Isolated and Non-Isolated DC-DC Converter Families [57].

implementation [59]. The flyback converter's operating mode depends on its design specifications and load requirements, as it can conduct either continuously or with discontinuous flow. This converter operates extensively in portable power systems, such as standby operations and LED power supplies, and mobile devices [60]. The isolation capabilities delivered by the transformer's primary benefit consumer electronics and medical devices, as they improve safety levels. This device is restricted and is well-suited for such applications. The switch operates under extreme voltage conditions, which call for careful evaluation of switching components. The two drawbacks of the flyback converter include leakage inductance [61] and energy losses from the transformer core [62] which reduces its overall efficiency when compared with alternative isolated topologies. The implementation of PWM control strategies improves performance while enhancing regulation properties [63]. Soft-switching methods optimize both efficiency and operational losses. The transformer winding of this topology allows the generation of multiple output voltages simultaneously. The power ranges from low to medium at levels below 150 W, making flyback converters the most suitable solution for these applications. Flyback converters are ideal for applications needing electrical isolation (e.g., high-voltage systems) and are good for powering sensors in harsh environments where safety is a priority. They are commonly used for higher power levels whereas SEPIC converters are more efficient for lower power applications and are ideal for scenarios where the input voltage can vary above or below the required output voltage.

3.2. Forward converter

The forward converter implements diode-based rectification with transformer-based power transport from source to load. The forward converter exclusively uses transformers to perform voltage conversion while storing energy in its core, as the flyback converter does [64]. This switching operation requires a MOSFET [65] or IGBT as the control element and makes the converter appropriate for applications that need medium to high power. The transformer core requires a demagnetizing winding, which serves as an essential part to reset the core, thus preventing saturation and ensuring the proper functionality [66]. The forward converter gives a better output ripple performance because it maintains continuous current throughout the operation [67]. The design of the forward converter achieves higher efficiency levels, thus making it suitable for server power systems [68] as well as industrial motor drives and telecom power supply [69]. The transformer provides safety assurance through electrical isolation, which becomes vital for critical applications. Forward converter power ranges typically operate from 50 W to 500 W, while the power capabilities stem from switching frequency selection along with transformer configuration [70]. Forward converters best serve steady and effective power conversion due to their better load handling and higher voltage regulation capabilities against flyback converters [71]. These converters become complicated due to the required elements that include output filters as well as freewheeling diodes. The switching frequency controls Size, efficiency, and EMI performance characteristics, which require proper adjustment. ZVS, alongside other soft-switching methods, brings increased efficiency while decreasing the stress on components [70]. Sophisticated control techniques, including PWM, enable precise voltage regulation systems [72]. Forward converters maintain a stable trade-off of isolation alongside stability and efficiency, and this makes them suitable for telecom and industrial applications.

3.3. Push-pull converter

Effective power transmission occurs in push-pull converters by employing two active switches to control a center-tapped transformer. The operation increases efficiency, along with decreasing core saturation, through the application of alternating current to control the transformer [73]. The push-pull converter design is suitable for applications requiring power levels ranging from 100 W to 500 W [74]. The push-pull converter demonstrates adaptability across various applications, as it operates both as a step-up and step-down converter, distributing power evenly. The transformer uses symmetrical operation to absorb power effectively during operation, thereby minimizing both the size and the cost of the transformer [75]. A thorough transformer design becomes necessary because of the DC bias to prevent core saturation. Adding a center-tapped transformer requires distributor space, as well as an increase in technical complexity increases [76]. The push-pull converter finds widespread use in telecommunications systems [77] and serves applications in automobile technology and powers industrial machinery systems [78]. The transformer windings determine the amount of output power it provides, while offering electrical isolation as its primary benefit. Higher frequency operation of the converter enables designers to use small inductors and capacitors, resulting in compact circuit designs. The implementation of voltage-current switching methods lowers the amount of losses [79]. Dead-time control must be deployed to stop cross-conduction during simultaneous transistor switching. To generate a smooth DC voltage output, the signal requires rectification and filtering processes.

3.4. Bridge converter

A bridge converter refers to a separate DC-DC converter device powered through full-bridge or half-bridge structural designs that transmit power effectively. The full-bridge converter operates at high power levels from 500 W to several kW because its four switches (MOSFETs or IGBTs arranged in an H-bridge configuration, deliver precise energy transfer control [80]. The management system needs complexity but delivers excellent voltage regulation and efficiency. The operation of the half-bridge converter relies on two switches and a center-tapped transformer to enable the processing of lower power

levels at reduced cost [81]. High-frequency operation delivers both topologies to produce smaller transformers while achieving greater efficiency levels. Soft-switching can be achieved through Phase-Shift Modulation when lowering losses [82]. Bridge converters achieve widespread industrial use in electric vehicles [83] and industrial power supplies and renewable energy systems [84] because they provide high efficiency and power-handling capabilities in addition to isolation.

3.5. Multiport converter

The multiport converter integrates multiple connected input and output ports, enabling simultaneous power delivery between sources and loads. The device serves multiple applications in electric cars and hybrid energy systems, as well as renewable power generation, because it ensures optimal control of solar panels, batteries, and supercapacitors [85]. The system achieves better efficiency and compact design through the removal of multiple independent converters by using multiport converters [86]. The energy flow optimization in multiport converters depends on advanced power electronic control methods, which use coupled inductors as well as time-sharing modulation methods [87]. A system of multiple voltage levels in these converters provides high adaptability and makes transferring energy between sources and loads more seamless [88]. Power sharing capability enhances both the stability and efficiency of the system, especially when handling varying power requirements. Energy efficiency through multiport converters depends on the implementation of smart control algorithms, including solar systems' MPPT [89]. These converters prove suitable for power storage systems because their design enables energy flow in both directions. Real-time monitoring with adaptive power management becomes possible because digital control systems are integrated into power management systems. The great dependability of this system depends on specific choices of its complex parts, along with temperature regulation [90]. Soft-switching technologies enhance the system efficiency alongside the minimization of switching losses [91]. Flexible power distribution across energy sources, combined with efficient operation through multiport converters, establishes them as vital components for advanced energy systems, as these elements reduce system expenses while increasing total energy utilization. Future energy systems heavily depend on these devices, as they operate in hybrid powertrains, electric vehicle stations, and microgrids.

Isolated converters are less common in general due to their high cost. They are essential for the safety of circuits in high-voltage systems and for reducing noise. They are mainly used in medical devices, industrial, and telecom applications where electrical isolation is the most important part [92]. On the other hand, non-isolated converters are simple, smaller, and cost-effective. More importantly, they are efficient for low to medium-power applications [93]. Agricultural applications use both isolated and non-isolated converters. For most battery-powered cattle monitoring sensors, non-isolated DC-DC converters are the preferred choice due to their higher efficiency, smaller size, and lower cost [94]. However, if the sensor system is exposed to high voltage, significant EMI, or safety risks, isolated DC-DC converters might be used.

4. Non-isolated DC-DC converter in sensor

DC-DC converters have a significant role in renewable energy generation, as previously mentioned. Nevertheless, non-isolated converters are more useful compared to standalone converters. Although there are a few drawbacks, considering low voltage gain, high duty cycle ratio, and extra circuitry, these topologies are more suitable for renewable energy integration than isolated converter topologies [95].

4.1. Buck-boost converter

Fig. 7 depicts a buck-boost converter design, which combines two different converter topologies. This converter lowers the amount of voltage operation, whereas the boost portion of the converter increases it. This design is also often used in drive processing systems, as well as stand-alone and grid-connected PV generation systems. The buck-boost converter architecture is still being studied to increase the efficiency of PV energy generation. Researchers worldwide attempt to enhance the voltage gain of non-isolated DC-DC converters, resulting in the creation of different configuration converters with buck-boost topology. In [96], a novel design for a buck-boost converter using a dual-switching approach is introduced. This method has demonstrated the capability to adapt to varying power levels in solar applications while maintaining high efficiency under fluctuating load conditions [97]. An integrated fuel cell system utilizing an inductor-connected converter was detailed. This configuration enhances efficiency, produces a non-inverting output, and minimizes both input and output fluctuations, making it suitable for renewable energy applications. A bridgeless converter with a buck-boost structure intended for motor drive systems is presented in [98]. By integrating the converter with the electric drive mechanism, this approach eliminates AC-side losses from moving and transmission components, thereby improving system performance. In [99], a buck-boost-based converter that enhances power factor correction, achieving lower switching voltages and minimizing inductor losses and electromagnetic interference. For LED lighting, a specialized buck-boost configuration is utilized, involving two buck-boost stages controlled by a single switch to improve system efficiency and reduce the requirement for large capacitance values [100,101] a buck-boost converter designed for electric vehicle applications is introduced. This converter facilitates energy exchange between capacitors and batteries through a bidirectional control scheme implemented on an FPGA. In [102], a converter is tailored for use in telecommunications infrastructure, leveraging multiple compact energy sources via buck and buck-boost topologies to supply power to a centralized DC bus. In [103], presents a distinctive compensation technique that ensures a seamless transition between various operational modes in a noninverting buck-boost system.

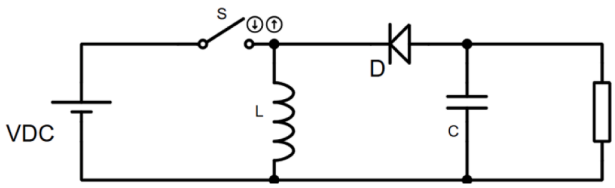


Fig. 7. Circuit Diagram of Buck-Boost Converter [104].

4.2. SEPIC

The SEPIC serves as an alternative to the buck-boost converter shown in Fig. 8, with the ability to regulate output voltage levels. SEPIC converters are commonly applied in systems requiring a steady DC output from thermal energy sources and are also effective in improving the power factor in AC circuits. Unlike buck-boost converters, SEPIC offers a non-inverting output, making it particularly advantageous for high-power operations. Achieving a higher voltage output with a SEPIC converter requires keeping the switch on for a longer duration than it is off; failing to do so results in insufficient voltage output. Due to their

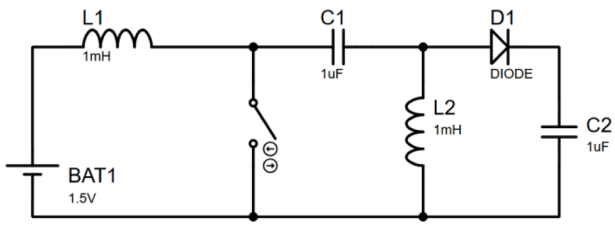


Fig. 8. Circuit Diagram of SEPIC [110].

flexibility and effectiveness, SEPIC converters are widely adopted across different domains. In [105], an inductor-coupled SEPIC was introduced for renewable energy systems. This configuration supports continuous current at the input, minimizes switching stress, and thus enhances power efficiency. The same study also proposed a novel SEPIC topology aimed at improving power factor correction. An isolated variation of the SEPIC converter, designed as a single-phase rectifier with sliding mode control, is detailed in [106]. In [107], a SEPIC architecture combining two high-gain converters was presented, aimed at renewable applications that benefit from high output voltages, low input requirements, and low switching losses. Further advancements include the dual-boost SEPIC (IDBS) introduced in [108] targeting photovoltaic and fuel cell systems. The device features one regulated switch and a pair of inductors. The architecture produces substantial voltage gain while maintaining a controlled duty cycle. SEPIC used in [109] improves the voltage gain and minimizes voltage stress on primary switches for alternative energy applications.

In this arrangement, the SEPIC configuration involves a connection to an inductor and two voltage multipliers. The continuous input current characteristic renders it suitable for applications in renewable and sustainable energy. In [109], SEPIC converters are explored for their ability to enhance voltage stability and reduce switching stress on primary switches—beneficial for sustainable energy technologies. These designs typically allow for a seamless transition between input sources, offering continuous current and improved efficiency.

4.3. Cuk converter

Fig. 9 presents a Cuk converter, a hybrid of buck and boost converter topologies. It is commonly employed in applications requiring controlled voltage outputs and improved power factor. The converter inverts the input polarity at the output, helping to minimize switching losses and enhance overall performance. The voltage generation process relies on switching cycles—during the ON phase, energy is stored in capacitors and inductors, whereas in the OFF phase, the diode prevents conduction and blocks current flow. Depending on the application, some systems utilize capacitors to store energy, while others rely more heavily on inductors. In [111], Cuk converters are used in photovoltaic AC modules featuring switched inductors to provide high static gain with low switching activity. In [112], the converter is integrated into a cell-based system to deliver high voltage output while maintaining a wide range of duty cycle control. In [113], The motor drive of an air conditioning system is supplied with power by a Cuk converter. The motor drive ran smoothly with no changes in the input AC lines. Throughout the operation, the converter maintained a specific power factor approaching unity in the AC mains. In addition, a Cuk converter is used for power adjustment in [114]. The enhanced bridgeless Cuk converter design reduces conduction and switching losses in rectifier applications and can minimize inductance for PFC. [115] presented a bridgeless Cuk converter for lighting applications. The topology was very efficient, resulting in fewer conduction and power utility components, increased efficiency, and lower losses. Ananthapadmanabha et al. [116] suggested replacing a double-stage converter with a single-stage converter to enhance battery charging efficiency for electric bikes. The topology improved overall efficiency.

4.4. Z-source converter

The Z-source converter is a unique power conversion topology that addresses the limitations of traditional voltage-source and current-source converters shown in Fig. 10. Unlike conventional converters that are either step-up or step-down in nature, the Z-source converter offers a single-stage power conversion system capable of both buck and boost operations. This is made possible through the use of a special impedance network—known as the Z-network—positioned between the power source and the converter's main switching devices. Under identical duty cycle conditions, it has the potential to enhance voltage output with greater efficiency compared to conventional boost converters. This converter architecture demonstrates superior performance compared to alternative designs regarding size and cost, all while ensuring acceptable efficiency levels. A specific Z-source converter architecture combining a Z-network, flyback converter, and voltage multiplier has demonstrated a conversion efficiency of approximately 89% [58]. To improve solar energy conversion, a modified Z-source converter was introduced in [117]. This approach reduces voltage ripple and minimizes switching losses, thereby enhancing overall system stability. In article [118], hybrid Z-source converter models tailored for motor drive applications were discussed. These models were integrated with PMSMs, using a Z-source converter to manage voltage and current flow. The control was achieved using a sliding mode control (SMC) technique, which improved voltage regulation and system efficiency. A study in [119] explored the use of Z-source converter architectures to improve power factor correction in mobile power systems, such as electric vehicles and public transport. These systems successfully maintained consistent voltage levels and high-power quality without the need for complex semiconductor integration or additional control systems. The findings support the feasibility of using Z-source converters for efficient energy conversion and power management in compact and mobile electrical applications.

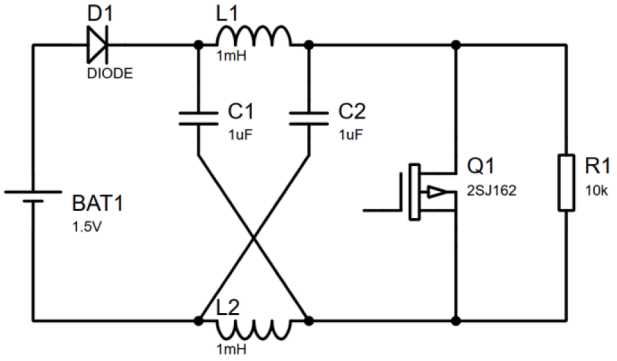


Fig. 10. Circuit Diagram of Z-Source Converter [120].

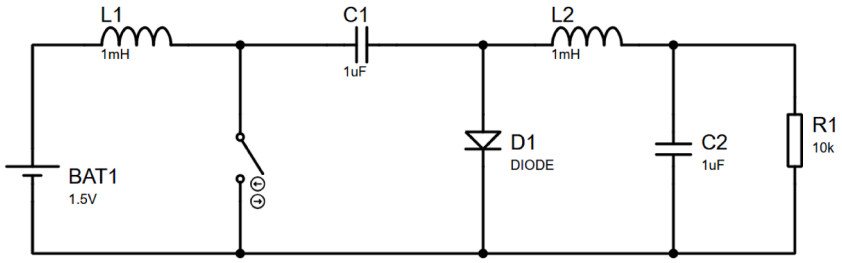


Fig. 9. Circuit Diagram of Cuk Converter [110].

4.5. Zeta converter

The Zeta converter (Fig. 11) is an advanced DC-DC power conversion topology primarily used as a power optimizer, particularly in renewable energy systems such as solar and wind applications. Functionally similar to SEPIC converters, the Zeta converter distinguishes itself through its non-inverting output, voltage regulation, and ability to sustain a continuous output current, making it suitable for systems where stable power delivery is essential. In [121], Zeta converters have been successfully integrated into solar-powered systems like BLDC-based water pumps, where they help reduce energy losses and improve photovoltaic module efficiency without needing extra power electronics.

Moreover, in wind turbine applications, they have demonstrated the capability to maintain stable output voltage under varying wind conditions, proving their reliability in fluctuating energy environments [122]. For high-voltage applications, modified Zeta converter designs have been developed to provide high voltage gain with enhanced efficiency.

These versions often utilize a single switching device that simplifies complex cascaded converter systems. In addition, the combination of Zeta and SEPIC topologies has found a niche in EV charging infrastructure, particularly in plug-in systems. Such architectures enable versatile charging modes, including plug-in charging, power factor correction, and regenerative braking, thus improving the overall energy management and adaptability of EVs [124]. Table 1 provides further details on the advantages and limitations of all isolated and non-isolated DC–DC converters.

4.6. Power management ICs in livestock monitoring devices

Power management is a critical aspect of livestock monitoring systems, particularly for wearable and remote sensors that operate under constrained energy budgets. Consumer-grade power management ICs offer a practical and efficient solution, providing voltage regulation, battery charging, and protection functionalities at a low cost and with minimal design complexity.

In PLF, these power management ICs are embedded within wearable sensor nodes such as GPS trackers, temperature loggers, accelerometers, and environmental monitors. Popular modules include the TP4056 (a lithium-ion battery charging controller), the LM2596 (a buck converter for step-down voltage regulation), and the MT3608 (a boost converter used to increase voltage from low battery levels). These widely available ICs are typically used in consumer electronics and have been successfully adapted to agricultural applications due to their affordability, compact form factor, and ease of integration with microcontrollers and wireless modules. Modern PMICs have evolved from simple converters into integrated power system architects. They act as a single chip that intelligently manages the entire energy lifecycle—from optimally harvesting energy from sources like solar panels using MPPT, to safely charging batteries with multi-stage algorithms, and finally to powering the complex subsystems with multiple, sequenced voltage rails. Crucially, they dynamically manage power consumption through low-power modes, scaling voltage in real-time with processor demand to maximize battery life. This integration of charging, harvesting, multi-rail regulation, and intelligent control is what makes PMICs fundamental to enabling the small size, efficiency, and advanced functionality of modern portable and IoT devices.

For instance, a wearable sensor node powered by a small lithium-ion battery can use the TP4056 module with onboard protection circuitry to ensure safe charging via solar panels or USB, while a buck converter like LM2596 efficiently regulates the voltage to power microcontrollers and communication modules such as ESP32 or LoRa transceivers. These ICs enable extended battery life, reduce energy loss, and support stable operation across varying input conditions—a critical requirement in outdoor and rural deployments.

Furthermore, consumer-grade power ICs support energy harvesting configurations, such as solar-powered collars or environmental monitors, which are becoming increasingly relevant in sustainable and low-maintenance livestock monitoring. These modules often include MPPT features or can be combined with low-dropout regulators to optimize energy utilization under varying solar conditions.

While industrial-grade power systems may offer higher reliability under extreme environmental stress, consumer-grade power ICs strike an ideal balance between cost, performance, and simplicity, making them highly suitable for small-to-medium-scale PLF deployments. Their plug-and-play compatibility with common sensors and microcontrollers enables rapid prototyping and deployment, accelerating the adoption of smart monitoring solutions in the livestock sector.

The increasing reliance on such consumer-grade power solutions demonstrates a clear intersection between consumer electronics and agricultural technology, further aligning PLF systems with the scope of modern mass-market electronic applications.

5. Control techniques

In modern power electronics and energy systems, control techniques form the backbone of operational stability, performance optimization, and fault resilience. As power converters increasingly permeate applications ranging from renewable energy integration and electric vehicle propulsion to industrial automation and smart grid infrastructure, the need for robust and intelligent control strategies has become more critical than ever. At their core, control techniques are responsible for managing the dynamic behavior of a system—ensuring that variables such as output voltage, current, power, and frequency adhere to desired reference values, even in the presence of external disturbances, nonlinearities, or parametric uncertainties. These techniques regulate the operation of switching devices within converters, coordinate energy flow between sources and loads, and maintain power quality metrics such as low THD, fast transient response, and efficient energy conversion [139]. Control approaches offer many properties, such as reaction time, efficiency, and resilience [140]. Different converter topologies have unique features to consider when integrating with DC-DC converters. To optimize the control mechanism, tradeoffs must be made for a few parameters based on the application's priorities. Certain converter topologies work well with various control techniques, making them ideal for a variety of applications.

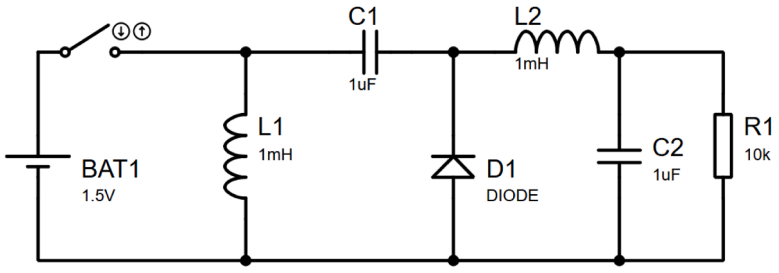


Fig. 11. Circuit Diagram of Zeta Converter [123].

Table 1
Comparison of Isolated and Non-Isolated DC-DC Converter Topologies.

Converter Topology	Advantages	Limitations	References
Flyback	• Simple and low-cost design • Provides galvanic isolation • Capable of multiple outputs using transformer windings	• High output voltage ripple • Limited efficiency due to leakage inductance and core losses	[125,126]
Forward	• Better efficiency than flyback due to continuous current mode • Improved voltage regulation and lower output ripple	• Requires additional components (demagnetizing winding, filter) • Transformer core reset is mandatory • Limited scalability for very high power	[127,128]
Push-pull	• High power density with symmetrical operation • Efficient utilization of transformer core • Compact design and bidirectional capability	• Requires careful dead-time control to avoid cross-conduction • Complex design for high-frequency operation	[129,130]
Full-Bridge	• Provides excellent isolation and voltage regulation • Supports phase-shift modulation for soft-switching operation	• Bulky due to four-switch structure and large transformer • Requires sophisticated control circuitry	[130,131]
Buck Boost Converter	• Requires fewer components compared to other dual-mode converters. • Operates effectively across a broad range of input voltages • Suitable for space-constrained designs like embedded systems	• Voltage instability when configured for multiple input-output • Produces significant output ripple, which may need filtering • Requires a high duty cycle for substantial voltage gain	[96,99,101, 103]
SEPIC	• Delivers a non-inverting output, maintaining the same polarity as the input. • Effective in AC systems for power factor correction	• Challenging to regulate in multi-input/multi-output configurations. • Output voltage gain is typically low without large component sizes. • Operation demands a longer ON-time than OFF-time, complicating duty cycle control.	[105,109,132]
Cuk Converter	• Ideal for applications requiring low ripple current • Continuous current and soft switching help lower EMI • Maintains stable output under varying load conditions	• Involves more components, such as inductors and capacitors, increasing design complexity • May not be suitable for applications requiring the same polarity output • Non-minimum phase behavior can complicate controller design	[111,116,133, 134]
Z-Source Converter	• Provides non-inverting output with step-up/step-down capability using a unique impedance network. • Widely used in modern power electronics for robust voltage conversion. • Offers flexible control through a non-linear duty-output profile.	• Only supports unidirectional power flow. • Input current can be discontinuous, demanding additional filtering • Difficult to integrate in systems needing soft-start or multiple outputs.	[117–119]
Zeta Converter	• Suitable for sensitive loads like LED drivers and battery chargers. • Ensures better performance in precision applications. • Easier regulation compared to other topologies	• Not suitable for very high step-up or step-down ratios. • Key components like inductors and capacitors experience high ripple currents. • Increased conduction losses under heavy load condition.	[122,135–138]

5.1. PID control

The PID controller remains one of the most widely used and foundational control strategies in power electronic systems due to its simplicity, ease of implementation, and effectiveness in linear time-invariant systems. Table 2 shows that PID control is preferred over other control techniques due to its strong response across various operating circumstances and easy functioning. In PLF applications, it is particularly suitable for systems with moderate load variations and stable input sources, such as battery-powered sensors or low-power actuators. Although PID control may struggle under highly variable conditions, it is effective for applications where quick voltage or current adjustments are needed. PID control is still widely used in various applications, including regulating DC-DC converters. The schematic structure is shown in Fig. 12. PID controllers are typically deployed in voltage and current regulation loops.

While they offer good performance under nominal conditions, their effectiveness can degrade under highly nonlinear dynamics, parameter variations, or time delays. Nevertheless, their adaptability and tuning flexibility make them suitable for a wide range of industrial and energy-based applications. Recent advances have also introduced auto-tuning and adaptive PID schemes that dynamically adjust gains based on operating conditions.

5.2. SMC

SMC is a nonlinear control technique known for its robustness, especially under uncertain system parameters and external disturbances. The system intersects the sliding surface to decrease error and maintain stability. However, the chattering effect [142,143] occurs during this process. The chattering effect refers to oscillations that occur before the system settles into a continuous sliding state. SMC is used with other control mechanisms to address chattering errors.

SMC excels in handling external disturbances and uncertainties, which are common in PLF systems where environmental conditions and animal behavior can fluctuate. For systems like wearable sensors or environmental control units, SMC provides the necessary stability and resilience against sudden changes in power input. Fig. 13 illustrates the integration of the SMC control methodology. In power converters, SMC is particularly beneficial in renewable energy systems, such as solar inverters and wind energy conversion systems, where operating conditions vary unpredictably. Its ability to reject disturbances and handle parameter mismatches makes it suitable for DC-DC and DC-AC converters, where conventional linear controllers may fail to perform adequately [144].

5.3. MPC

MPC represents an advanced control framework that optimizes system behavior over a finite prediction horizon. It uses a dynamic model of the system to forecast future outputs and determines the optimal control actions by solving a constrained optimization problem at each sampling instance. In the MPC, precise current regulation is possible [145]. MPC can simultaneously handle multi-variable systems, constraints, and performance trade-offs, which are common in complex power conversion and distribution systems [146]. MPC is capable of managing multi-input and multi-output (MIMO) systems, as demonstrated in Table 2. In power electronics, MPC is particularly advantageous in

Table 2
The Characteristics Of Control Techniques.

Control Technique	Advantages	Limitations	References
PID	• Straightforward to design and implement in most systems. • Delivers a relatively fast response to changes. • Easily integrates with a wide range of other control strategies.	• Struggles to handle sudden or unpredictable load changes. • Can result in longer settling time and steady-state error. • Prone to overshooting the target value.	[141,152, 153]
SMC	• Easy to set up with minimal complexity. • Effective at dealing with external disturbances and noise. • Offers fast system dynamics and a quick response.	• Suffers from chattering, undesirable rapid switching • May lead to high overshoots during transitions. • Not ideal for applications needing smooth control signals.	[142,152, 154,155]
MPC	• Delivers optimal transient performance while handling constraints. • Fast and responsive under dynamic conditions.	• Highly dependent on accurate knowledge of the system's parameters • Computationally intensive and may require powerful processors. • Needs a precise and detailed system model for proper functioning.	[146,153, 156]
SSM	• Provides accurate tracking using estimation-based methods. • Handles fast changes effectively with better transient response. • Reduces overshooting under fluctuating load scenarios.	• Initial setup and modeling can be time-consuming. • Demands a complete and detailed model of the system. • May not be suitable for simple or small-scale systems due to setup complexity.	[147, 157–159]
FLC	• Naturally suppresses overshoot, leading to smoother transitions. • Tracks changes effectively even in non-linear systems. • Doesn't require a mathematical model—relies on intuitive rule-based logic.	• Computationally heavy, especially in large rule sets. • Needs a clear set of logical rules, which can be subjective or application-specific. • Typically has a slower response time compared to other techniques.	[148,160]

scenarios requiring precise tracking and constraint handling, such as grid-tied inverters, electric drives, and hybrid energy systems. Despite its computational complexity, the real-time implementation of MPC has become feasible due to the availability of high-speed processors and dedicated FPGAs or DSPs. As a result, MPC has gained FPGAs or DSPs. As a result, MPC has gained popularity in applications where both dynamic performance and operational constraints must be rigorously managed. Fig. 14 demonstrates the structure. In PLF applications, MPC can predict and optimize the performance of systems with solar power integration or hybrid battery setups. It is ideal for energy management in complex applications where inputs from renewable sources need to be dynamically adjusted based on variable energy availability and fluctuating power demands.

Moreover, MPC allows for the explicit inclusion of operational constraints—such as voltage and current limits, switching restrictions, and thermal boundaries—within its optimization framework, thereby enhancing system safety and reliability.

5.4. SSM

SSM provides a mathematical framework for representing and analyzing dynamic systems in terms of a set of first-order differential (or difference) equations. In the context of control systems, it enables the formulation of system behavior using state variables, which collectively describe the system's internal dynamics. This representation is particularly valuable for MIMO systems and time-varying or nonlinear systems [147]. Using state-space methods, optimal controllers such as LQR and Pole Placement can be designed to achieve desired performance objectives. In power converters, state-space modeling aids in the detailed analysis of system stability, control law synthesis, and real-time state estimation. Additionally, it forms the basis for observer-based control, where internal states that are not directly measurable are estimated using techniques such as Kalman Filters [59]. Fig. 15 illustrates the use of the state-space modeling approach in regulating the functioning of the DC-DC converter.

In PLF, SSM can be used to model and control systems with complex interactions, such as energy storage systems (e.g., solar and battery-powered devices) and livestock monitoring technologies. SSM allows for precise control of variable loads and inputs, such as when monitoring multiple animals simultaneously or managing power in environments with varying energy availability, ensuring both stability and optimal system performance. Table 2 presents the mathematical formulation of traditional non-isolated DC–DC converters.

5.5. FLC

FLC is classified as a nonconventional and nonlinear control approach. The schematic structure is seen in Fig. 16. FLC is a knowledge-based control strategy that mimics human reasoning by incorporating linguistic rules instead of relying solely on mathematical models. FLC can effectively adjust to changing power demands in wearable livestock sensors or environmental monitors, making it ideal for applications where traditional controllers like PID may not perform optimally due to the complex and dynamic nature of energy sources and system loads. In converter applications, fuzzy logic controllers have been used to regulate voltage, control power flow, and improve the dynamic response of systems where conventional controllers may not be effective. In addition to its various benefits, FLC also has several downsides, including increased processing time, as seen in Table 2. In recent years, FLC has evolved to support more advanced and intelligent energy management systems by enabling adaptive tuning and real-time decision-making without the need for an exact system model [148]. This is particularly advantageous in environments with rapidly changing conditions, such

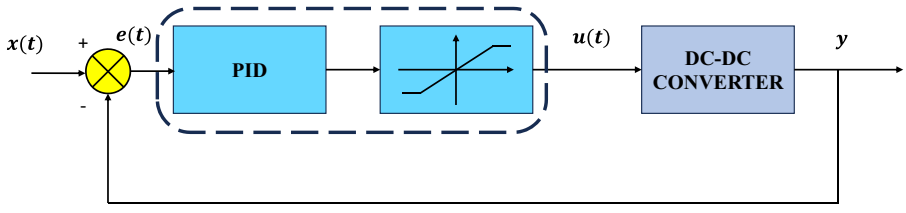


Fig. 12. PID Control for DC-DC Converter in Sensor Node [141].

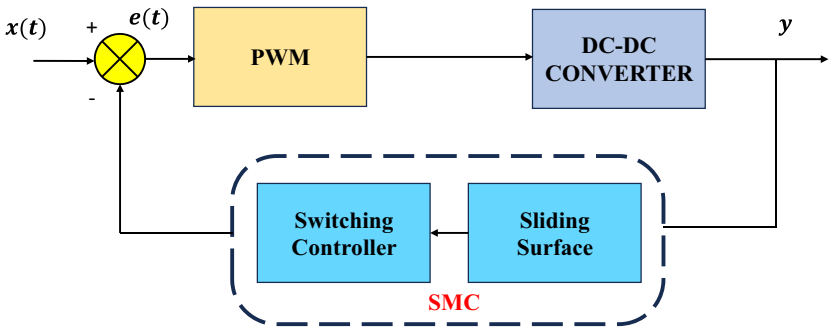


Fig. 13. SMC Integration with DC-DC Converter in Sensor Node [106].

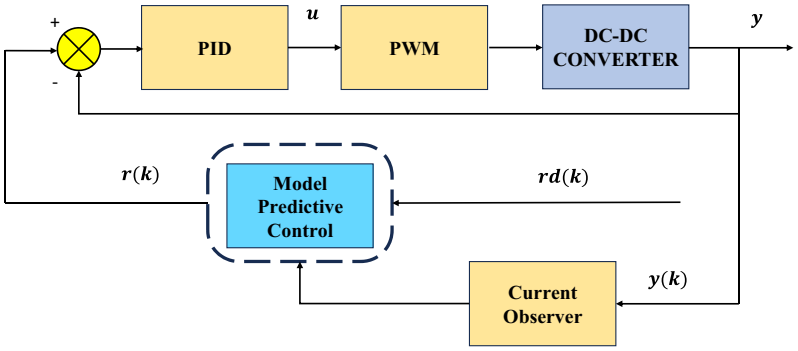


Fig. 14. MPC Control Technique with DC-DC Converter in Sensor Node [58].

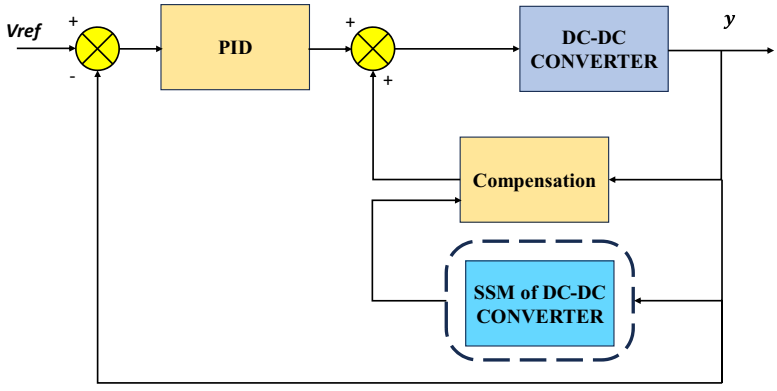


Fig. 15. SSM Control for DC-DC Converter in Sensor Node [58].

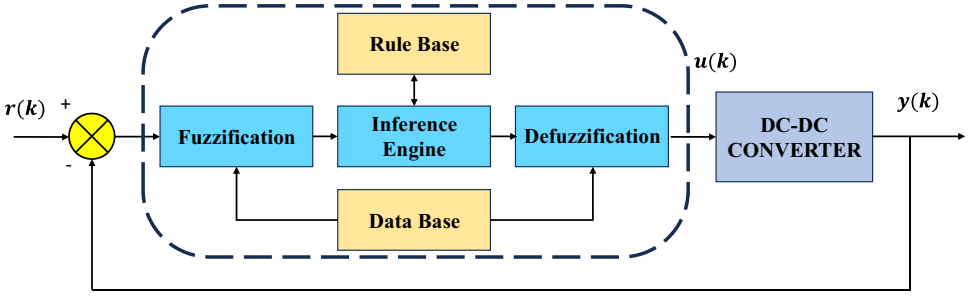


Fig. 16. Fuzzy Logic Control for DC-DC Converter in Sensor Node [58].

as solar photovoltaic systems affected by cloud shading or wind turbines operating under turbulent airflow [149]. FLC can be seamlessly combined with artificial intelligence techniques, such as neural networks or genetic algorithms, to form neuro-fuzzy or evolutionary fuzzy systems, which further enhance its learning and optimization capabilities [150]. In [151], the inherent linguistic and intuitive structure of FLC also makes it appealing for human-in-the-loop systems.

6. Case studies and applications

The integration of advanced converters in livestock systems produced significant gains in efficiency and sustainability in addition to welfare improvements. The wide range of applications for these technologies encompasses feeding system automation, as well as supporting renewable power generation and detailed animal health management.

6.1. Advanced converters in livestock systems

The DX-1100 controller demonstrates its worth through its utilization in automated livestock feeding systems. The DX-1100 controller serves as an automated feeder controller that tracks feed durations and amounts in addition to performing remote control operations through internet connections. Livestock feeding automation through this process enables better feeding efficiency and quick changes for proper animal nutrition [161]. This system has been deployed on medium-scale dairy farms in the United States, where trials showed a 15–20% improvement in feed utilization efficiency and a measurable reduction in manual labor.

Anaerobic digestion systems combined with CHP units have been implemented by renewable energy applications within livestock farms for biogas creation. The systems transform animal waste together with other scraps into biogas for producing electricity and thermal power. Pine Island Farm established an energy system that generated more than 1.1 million kilowatt-hours of renewable power during its initial eight-month operation, making the facility self-powered and able to provide excess electricity to the power grid [162]. This large-scale installation in Vermont, USA, demonstrated the practical viability of integrating waste-to-energy systems in livestock operations, reducing carbon emissions and operational energy costs by over 30%.

Agrivoltaics systems serve as innovative places for multi-use, combining crop growing with solar power generation and livestock management. The land management systems integrate sophisticated converter components to achieve maximum functionality between agricultural productivity and solar power operations. Studies show that AV systems reduce water usage by 40% while daytime cooling reaches 8.9 °C and annual solar panel efficiency goes up by 1% [163]. Recent case studies in India and Japan have validated these benefits at pilot-scale livestock farms, showing improved pasture quality and energy yield under hybrid agrivoltaic conditions. The integration of AI in PLF facilitates the analysis of large datasets, leading to more informed decision-making processes [164].

6.2. Energy optimization in feeding systems

Animal agriculture benefits from optimized energy utilization through livestock feeding systems because it allows operational efficiency and sustainability to improve. Organizations now direct their research efforts toward creating AFS that minimize energy usage along with decreasing staffing needs as well as environmental footprint.

The energy consumption of different AFS setups operating on Bavarian farms was researched by Oberschätzl et al. (2015). The research also showed that agricultural facilities used between 8.8 kWh as their minimum electrical consumption for semi-automated machines, up to 52.6 kWh for complete automation systems [165]. This study, conducted across multiple dairy farms in Bavaria, Germany, demonstrated that optimized automation could reduce total feeding energy costs by up to 25%, highlighting tangible sustainability benefits at the regional scale.

Da Borso et al. (2023) conducted further research that analyzed the effects of AFS systems on dairy farm feeding accuracy, together with energy usage [166]. The implementation of AFS systems resulted in reduced energy requirements, decreased feed waste, and improved welfare outcomes for animals. Their trials on mid-sized dairy farms in Italy showed a 12% improvement in feeding accuracy and a notable decrease in daily electricity consumption, supporting the practical efficiency of AFS adoption [153].

AI-based predictive models developed by Altshuler et al. (2023) empowered scientists to evaluate dairy cow feed additive effectiveness. The analyzed rumen microbial data through predictive models allowed scientists to determine additive efficiency, which supported the creation of improved feeding formulations for better milk production while decreasing methane production [167]. The study, conducted on commercial dairy herds in Israel, demonstrated up to a 10% increase in milk yield and an 18% reduction in methane emissions, underscoring the environmental and economic impact of AI-integrated feeding optimization.

6.3. Animal housing climatic control

Effective climatic control within animal housing is essential for maintaining animal welfare and optimizing productivity. Recent studies have explored various strategies and technologies to enhance environmental conditions in livestock facilities.

Mikovits et al. (2019) performed an extensive study that evaluated how global warming affects enclosed animal farming, including growing-fattening pork populations. A research simulation over 37 years in Central Europe showed that higher temperatures cause major negative effects on both animal performance levels and their well-being [168]. This large-scale analysis, based on Central European pig farms, revealed up to a 9% decline in growth rates during prolonged heat waves, emphasizing the regional vulnerability of intensive housing systems.

The multidisciplinary overview of hot climate housing explains that designers must establish ventilation systems to ensure thermal comfort for animals. The proposed research study suggested enhancing shed heights, together with applying reflective materials, which would enhance ventilation while minimizing heat retention [169]. Experimental trials in Southeast Asian poultry houses confirmed that increasing roof height by 1.5 m and using reflective coatings reduced indoor temperatures by 3–4 °C, improving bird comfort and productivity.

The development of CFD modeling has allowed for better design of microclimates within livestock housing facilities [170]. Research from 2018 to 2024 examined the implementation of sensors and automation systems to monitor and regulate environmental parameters. Field implementations in dairy barns across Europe and North America demonstrated that automated ventilation control reduced humidity fluctuations by 20–25%, leading to lower respiratory stress and higher milk yield stability. The implementation of these technologies makes it possible to make immediate changes to ventilation and cooling systems, which creates optimal conditions that improve livestock welfare [171].

Collectively, these studies underscore the critical role of climatic control in animal housing. Implementing adaptive designs, utilizing advanced modeling techniques, and integrating smart technologies are pivotal strategies for ensuring sustainable and humane livestock production systems in the context of evolving climatic circumstances.

6.4. Pumping and distribution systems

Efficient water pumping and distribution systems are vital for sustainable livestock farming, ensuring an adequate water supply while minimizing environmental impact. Recent studies have explored various technologies and strategies to enhance the efficiency and sustainability of these systems. This study, conducted on grazing farms across Missouri, USA, highlighted that optimized pump and pipe configurations reduced energy use by nearly 18% and improved water delivery consistency, benefiting herds of 50–200 cattle.

Evaluation of hydraulic ram pumps for livestock farming showed that their locally built versions operated with low efficiency because farmers lacked technical knowledge. The researchers found that

enhancing pumps' design procedures and deployment systems would lead to better supply reliability for livestock farm owners [14]. Field trials in rural Kenya and Uganda demonstrated that improved ram pump designs increased volumetric efficiency by 25–30%, ensuring continuous water access for smallholder livestock operations even in low-resource environments.

As stated by the FAO, farmers need to use integrated water resource management approaches designed explicitly for livestock systems based on production types, scale, and species, and local farming methods. Recent FAO-backed implementations in South Asia have shown that combining solar-powered pumping and optimized distribution reduced groundwater use by 20% while supporting sustainable hydration for mixed dairy and goat farms. Utilizing water efficiently during livestock beverage distribution and feed production remains crucial for sustainable farm management in agriculture [15].

6.5. Accurate livestock monitoring

The use of modern technology in livestock monitoring has markedly improved the accuracy of health evaluations and overall management in the agricultural industry. Recent studies have concentrated on the use of IoT, AI, and deep learning techniques to enhance the precision and efficiency of monitoring systems.

A study by Darvesh et al. (2023) explored the development of an IoT and AI-based smart cattle health monitoring system. The system was designed to monitor individual cattle health, enabling rapid diagnosis and treatment of illnesses. This method not only augments animal well-being but also boosts output by mitigating disease-related losses [172]. Conducted across dairy farms in India and the USA, the study demonstrated early disease detection with an average response time improvement of 30%, leading to healthier herds and reduced veterinary costs.

Similarly, Tangirala et al. (2021) proposed a livestock monitoring framework utilizing transformer architectures. This system executes concurrent instance-level segmentation, tracking, action recognition, and re-identification of livestock, tackling issues such as similar appearances among animals and fluctuating environmental circumstances [173]. Field validation in large cattle ranches in Australia showed over 92% action recognition accuracy and robust performance under variable lighting and weather conditions, proving its reliability for real-world deployments.

In another advancement, Schulthess et al. (2024) developed a LoRa-enabled, maintenance-free cow monitoring system designed for distant areas and mountain pastures. The system tracks cattle activity, including grazing and resting times, and transmits data over a LoRaWAN to a backend server. Notably, the sensor node achieved a battery life of up to six months with solar energy harvesting, demonstrating its practicality for extended deployments in challenging terrains [174]. This Swiss case study covered herds across alpine regions, confirming stable data transmission and effective tracking over distances exceeding 5 km.

Mhatre et al. (2020) introduced an IoT-based health monitoring system for dairy cattle, highlighting the need for real-time data acquisition and analysis to provide prompt treatments. The system's capacity to monitor essential indicators facilitates early illness identification and enhances herd management [175]. Trials on medium-scale dairy farms in Maharashtra, India, recorded a 20% reduction in illness-related downtime and a measurable increase in daily milk yield, validating the system's economic and health benefits.

To further illustrate the role of power electronics in enhancing livestock monitoring systems, Table 3 presents a comparative summary of various DC–DC converter topologies (Flyback, SEPIC, Cuk, and Buck-Boost) evaluated across representative PLF applications, including GPS collars, milking sensors, environmental monitors, smart feeders, and IoT-based energy-harvesting sensor nodes. The comparison highlights performance efficiency ranges, relative cost, and application suitability, emphasizing how converter selection directly affects system reliability, power autonomy, and deployment scalability. Notably, Buck-Boost and SEPIC converters exhibit superior adaptability and efficiency for low-power IoT and sensor-based systems, while Flyback converters remain favorable for isolated, medium-power applications such as GPS collars.

6.6. Implementations in smart farming

The advancement of modern technologies into agriculture, known as smart farming, has revolutionized traditional practices by enhancing efficiency, productivity, and sustainability. Recent studies have explored various implementations of smart farming technologies, highlighting their impact on modern agriculture.

Gyamfi et al. (2024) conducted research about Agriculture 4.0 through analysis of IoT and artificial intelligence alongside sensors to modernize conventional farming operations. These technologies demonstrate a capability to create value chain optimization while improving monitoring capacity and reducing labor expenses, according to the study findings [176]. The study, conducted across mixed crop-livestock farms in Ghana, revealed a 22% improvement in overall operational efficiency and a 15% reduction in manual labor hours, emphasizing measurable economic and sustainability gains.

The research by Suebsombut et al. (2023) employed bibliometric analysis to identify emerging trends in smart farming and explore potential future research avenues. The research investigation uncovered essential regions, which included soil carbon emission control and agricultural system management platforms, to understand smart agriculture development patterns [177]. Their analysis, covering over 800 global publications, showed that Asia and Europe are leading in smart agriculture research output, especially in data-driven soil management and carbon reduction technologies.

In practical deployments, PLF systems face several challenges. For example, sensors placed on livestock often get damaged due to rough conditions like constant animal movement or exposure to harsh weather, leading to maintenance issues. In remote areas, connectivity problems are common, with weak or unreliable network signals disrupting real-time data transfer. This affects the effectiveness of monitoring systems, especially when immediate actions are required. Power constraints are another issue—battery-powered devices, like wearables or environmental sensors, struggle with limited battery life, especially in off-grid areas.

To address these power-related limitations, a clear understanding of the energy profiles and efficiency characteristics of commonly used sensors in PLF is essential. Each sensor type exhibits distinct power consumption, efficiency, and resolution requirements that directly

Table 3
Summary Table for Performance, cost, and suitability of Converters Based on PLF Application.

PLF Applications	Performance (%)				Cost				Suitability			
	Flyback	SEPIC	Cuk	Buck-Boost	Flyback	SEPIC	Cuk	Buck-Boost	Flyback	SEPIC	Cuk	Buck-Boost
GPS Collar	86–95	71–85	71–85	>95	Medium	Medium	Medium	Low	Excellent	Fair	Fair	Best
Milking Sensor	71–85	86–95	60–70	71–85	Medium	Low	Low	Medium	Fair	Good	Good	Fair
Environmental Monitor	>95	71–85	86–95	86–95	High	Medium	Medium	High	Poor	Fair	Fair	Good
Smart Feeder	60–70	71–85	71–95	86–95	Medium	Medium	Medium	Low	Poor	Fair	Fair	Good
IoT Sensor (Energy Harvester)	60–70	71–85	71–95	86–95	High	Medium	Medium	Low	Poor	Good	Good	Best

influence data collection continuity, device autonomy, and converter selection. Table 4 summarizes representative sensors employed in livestock monitoring applications, highlighting their efficiency, power range, battery life, sensing resolution, and the most suitable DC–DC converter topologies to ensure stable and energy-efficient operation in field environments.

7. AI-driven power solutions for healthcare technologies

The use of AI in managing power supplies for healthcare devices is transforming the way medical equipment operates. It's bringing improvements in efficiency, reliability, and even sustainability. From wearable health trackers to life-saving implants, these devices depend on stable and efficient power sources. AI's role in optimizing power management is unlocking new possibilities and significantly improving device performance.

7.1. Reliable power in healthcare devices

In healthcare, the reliability of power supply is a critical aspect, as it impacts the functionality of life-saving medical devices and the overall well-being of patient care. The enhancement of power supply capability is shown in Fig. 17. Devices such as ventilators, infusion pumps, and wearable monitors are crucial for maintaining vital functions, administering treatments, and performing diagnostic tests. Any disruption in power supply can have dire consequences, delaying urgent medical interventions, jeopardizing patient safety, and, in the worst cases, leading to life-threatening scenarios. This concern becomes even more pressing during emergencies or in regions with limited power infrastructure, where the availability of stable electricity often dictates the level of healthcare that can be delivered. In such situations, the stakes are incredibly high, and even minor power interruptions can compromise critical processes, from operating sophisticated medical equipment to maintaining the environment needed for safe and effective treatment. To address these challenges, artificial intelligence plays a transformative role by predicting potential power failures or fluctuations before they occur. Through advanced analytics and real-time monitoring, AI systems can detect patterns and anticipate vulnerabilities in the power supply [181], and provide actionable insights to prevent disruptions. These technologies enable healthcare facilities to manage resources more efficiently, ensuring that backup systems are deployed effectively and that critical medical equipment remains operational at all times. In this way, AI not only enhances power supply reliability but also safeguards patient care, particularly in high-stakes situations where every second counts [182]. To strengthen power supply reliability, solar and wind power are being integrated into healthcare infrastructures. To ensure continuous power transfers during power outages and that medical equipment continues to function without a hitch, battery storage systems and uninterruptible power supplies (UPS) are also required. To further increase the resilience of healthcare facilities, smart grid technologies are also being developed to optimize energy delivery and reduce the likelihood of localized power outages [183]. Having an ongoing and unbroken source of power is highly essential because medical equipment is becoming increasingly digitalized and electronic-dependent. This is pushing relentless innovation in automatic control systems, forecasting analytics, and power management.

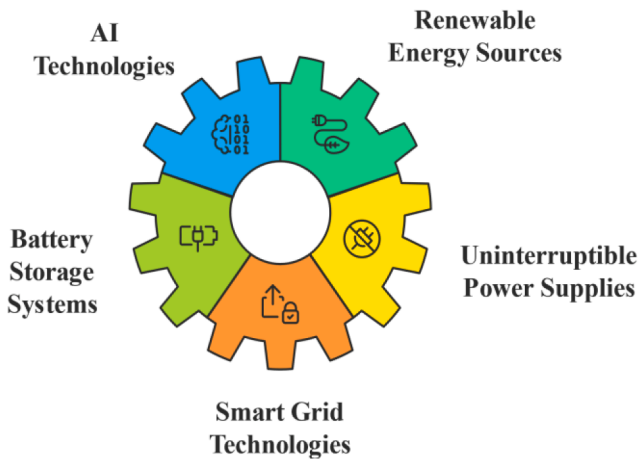


Fig. 17. Framework for Reliable Healthcare Power Supply using AI, Renewables, UPS, Smart Grids, and Battery Storage.

7.2. Power supply requirements

Medical devices often have specific power requirements based on their purpose. For example, wearable and implantable devices need lightweight and portable power systems to ensure patient comfort and convenience [184]. Efficiency is another key factor, and long-lasting batteries reduce the hassle of frequent replacements or recharges. Stability is crucial, too, as power fluctuations can interfere with sensitive sensors and diagnostic tools. In the case of devices like pacemakers, a reliable and long-lasting power source is non-negotiable, as replacements may involve risky surgical procedures [171].

Additionally, strict safety standards are crucial for protecting patients and devices from potential harm, such as overheating or electrical short circuits. Advanced power management technologies, including DC-DC converters, regulate voltage levels and improve energy efficiency to cater to these demands, making the devices function at maximum efficiency with less power loss. To provide a critical comparison of various converter topologies relevant to such applications, Table 5 presents a synthesized evaluation of widely used DC-DC converters, analyzing their isolation, power range, efficiency, cost, application suitability, and core strengths. This comparative view aids in selecting optimal power conversion strategies for different medical use cases, from wearable monitors to EMI-sensitive implantable devices. Additionally, wireless power transfer is making waves by lessening the need for battery replacement and facilitating non-invasive implant charging [185].

In addition, to improve the operating life of wearable and implantable devices, energy harvesting techniques such as body temperature or movement-induced energy generation are being investigated. In addition to efficiency, real-time power monitoring schemes assist in identifying and averting power faults, providing smooth operation [186]. Power supply system technologies will continue to play an important role in enhancing patient safety, comfort, and device long-term

Table 4
Summary of Sensor Efficiency, Power, and Resolution in Livestock Applications.

Sensor	Efficiency (η)	Power Range (W)	Battery Life	Sensing Resolution	Suitable Converter Topology	References
Accelerometer (3-axis)	~90%	0.05–0.2	2–3 months	±0.001 g	Buck	[178]
Gyroscope	~88%	0.1–0.3	1–2 months	±0.01 °/s	SEPIC	[179]
Magnetometer	~85%	0.05–0.1	3–4 months	±0.1 μT	Buck	[178]
GNSS Tracker	~70–80%	0.5–2.0	7–10 days	~2–5 m	Boost	[180]
UWB Indoor System	~75%	0.3–1.5	1–2 weeks	~10–30 cm	Flyback	[180]
Combined AI + Sensor Node	~65–80%	0.5–3.0	5–10 days	Dependent on sensor type	Buck-Boost	[179]

Table 5
Comparative Analysis of DC-DC Converter Topologies in Terms of Isolation, Efficiency, Cost, and Application Suitability.

Converter Type	Isolation	Power Range (W)	Typical Efficiency (%)	Cost	Key Advantages	Key Disadvantages	Specific PLF Use Cases
Flyback	Yes	1–100	70–85	Low	Simple, low-cost, provides isolation, and a wide input voltage range	Limited power handling, higher ripple, lower efficiency at high loads	Sub-100 W isolated bias supplies for stationary health monitoring devices and low-power control modules
Forward	Yes	10–200	80–90	Medium	Continuous current, better regulation, and higher efficiency than flyback	Requires more components (reset winding, filter), limited scalability	Feeding system controllers, medium-power motor drivers
Push-Pull	Yes	50–500	75–88	Medium	High power density, compact, transformer utilization	Switching stress, imbalance issues, EMI concerns	Medium-scale automation units, distributed power modules in barns
Full-Bridge	Yes	100–1000+	85–95	High	Very high efficiency, handles high power, strong isolation	Expensive, complex design, bulky	Farm-wide control systems, centralized power hubs for PLF
Buck-Boost	No	1–50	70–85	Low	Step-up/step-down in one stage, bidirectional support	Poor efficiency at extremes, high ripple, no isolation	GPS trackers on livestock, portable sensors with variable input supply
SEPIC	No	1–50	75–88	Medium	Non-inverting output, wide input range, low EMI	More complex than buck-boost, higher component count	Wireless sensor nodes and energy harvesting modules (e.g., solar for collars)
Ćuk	No	1–50	80–92	Medium	Low ripple, high efficiency, continuous input/output current	Requires a coupled inductor, design complexity	EMI-sensitive PLF sensors, low-noise monitoring devices
Z-Source	Yes	50–500	85–93	High	Single-stage buck-boost, high reliability, fault-tolerant	Relatively new, design is less mature, higher cost	Inverter-based renewable setups (e.g., solar-powered PLF farms)
Zeta	No	1–50	75–88	Medium	Stable non-inverting output, compact, continuous current	Moderate efficiency, less common topology	Renewable-powered distributed sensors, IoT gateways in barns

performance, driven by advancements in medical technology. Fig. 18 depicts how the power supply in medical devices is being optimized.

7.3. AI integration with power supplies

AI is being integrated into power management systems to enhance their intelligence and improve efficiency. By monitoring power usage patterns, AI algorithms can adjust in real time to meet a device's needs. Fig. 19 picturizes some of the AI-driven power management innovations. For example, AI can detect early signs of battery wear and notify users before a failure occurs, preventing unexpected downtime. It can also allocate energy dynamically, prioritizing critical functions when necessary. Predictive maintenance is another game-changer, as AI utilizes machine learning to forecast potential power issues and address them proactively. These advanced capabilities help minimize disruptions and ensure devices operate smoothly. AI optimization techniques also increase energy efficiency by maximizing battery life, minimizing waste, and efficiently distributing power [187]. AI ensures a balance between supply and demand in renewable energy systems, maintaining consistent operations despite fluctuations. Additionally, by dynamic load adjustments and avoiding overloads or failures, AI smart grids maximize power management in hospitals. AI is also supplemented by

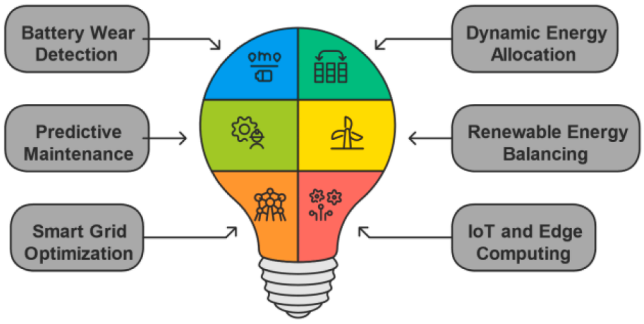


Fig. 19. AI-Driven Power Management Integrating Predictive Maintenance, Smart grids, Renewable Balancing, and IoT-Edge Computing.

IoT connectivity and edge computing, which support real-time decision-making at the device level and guarantee prompt response to power fluctuations [188]. Tomorrow's medical and industrial systems will be more efficient and robust as AI continues to develop and is integrated into power management, yielding greater reliability, sustainability, and automation. AI algorithms like CNNs and RNNs are used in PLF for tasks

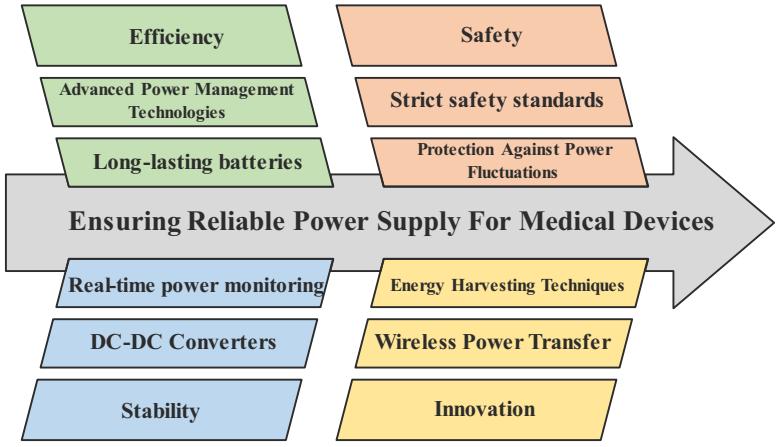


Fig. 18. Optimizing Medical Device Power Supply through Efficiency, Safety, Real-time Monitoring, DC-DC Converters, and Energy Harvesting.

like disease detection and behavior analysis, but they have high computational requirements. CNNs are ideal for analyzing visual data, such as detecting lameness from images, while RNNs are better for processing time-series sensor data to track movement patterns. Running these models on edge devices like Raspberry Pi and Jetson Nano can be challenging due to their limited processing power. The Raspberry Pi works best for simpler models, often requiring optimizations like model pruning to reduce load. Jetson Nano, with its GPU, can handle more complex tasks but still needs efficient power and resource management to run real-time AI tasks in field applications.

7.4. AI integration and implementation challenges in PLF

The integration of AI in PLF has transformed animal management into a data-driven, predictive process. AI enables automated behavior recognition, disease detection, and environmental monitoring by analyzing multimodal data from wearable, environmental, and imaging sensors. ML and DL models such as CNNs, RNNs, and Transformers effectively capture spatial and temporal patterns from these data streams for real-time decision support. However, effective AI deployment depends on the availability and quality of annotated datasets. Many farms lack standardized and sufficiently large datasets due to variations in breed, environment, and sensor configuration. Limited open-access repositories further restrict model reproducibility and generalization. Data imbalance is another issue, as normal behaviors dominate datasets while abnormal events remain underrepresented, leading to biased model performance [33].

Computational and communication constraints also pose major challenges. Running complex models on edge devices requires lightweight architectures, compression, and optimization techniques such as pruning, quantization, and knowledge distillation. Federated learning offers a promising solution by enabling decentralized model training while preserving data privacy—ideal for distributed farms with limited connectivity. Another critical aspect is model interpretability and trust. Farmers and veterinarians require transparent systems capable of explaining predictions. XAI methods such as SHAP and Grad-CAM can improve trust by identifying key features influencing model outcomes. Ethical deployment is equally essential, ensuring that continuous monitoring does not compromise animal welfare or data privacy [50].

In summary, AI holds immense potential to make PLF systems more intelligent and sustainable. Real-world adoption, however, requires addressing challenges in data quality, computational efficiency, interpretability, and ethics to unlock its full benefits for modern livestock management.

7.5. AI for power optimization in healthcare devices

AI also plays a big role in reducing energy waste and optimizing power use. By analyzing data in real time, it identifies inefficient processes and ensures energy is distributed wisely. Fig. 20 shows some examples of AI-driven energy optimization. For multi-functional devices, AI balances power consumption across components, giving priority to essential features. Remote monitoring via AI allows healthcare professionals to tweak power settings, extending battery life when it matters most. Edge computing, powered by AI, is another innovative approach to processing data locally instead of relying on energy-hungry cloud communication, resulting in substantial energy savings. Furthermore, by real-world usage patterns, AI adaptive power control adjusts energy consumption to avoid wasteful drain and maximize device life [189]. AI foresees battery charge cycles in medical devices with battery power, avoiding abrupt failure and optimizing recharging schedules. Self-learning algorithms continually optimize power management techniques to maximize performance under diverse scenarios. In addition, AI improves fault detection by immediately detecting anomalies and taking remedial action before faults arise [190]. AI dynamically controls energy input through the assistance of renewable energy

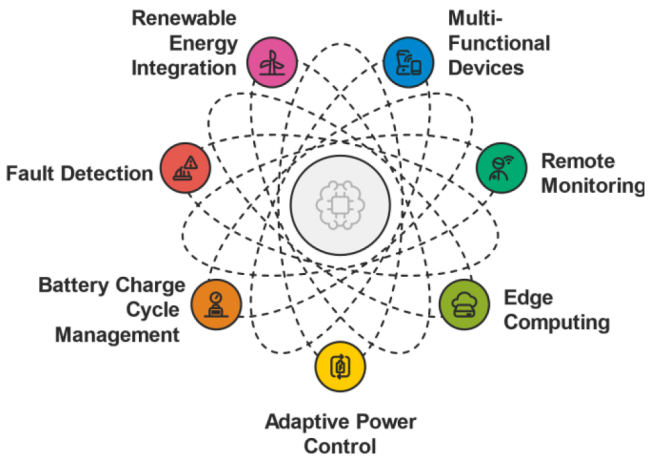


Fig. 20. AI-Driven Energy Optimization Integrating Adaptive Power Control, Fault Detection, Renewable Integration, and Edge-based Remote Monitoring.

sources, providing smooth operation in emergencies or off-grid situations. All these technologies come together to make medical and industrial power systems intelligent, reliable, and energy efficient.

7.6. Emerging materials & technologies for power solutions

Exciting new technologies are paving the way for better power solutions in healthcare. The Solid-state batteries that are known for their high energy density and safety are perfect for compact and wearable devices. Graphene-based supercapacitors offer rapid charging and discharging, making them ideal for emergency medical equipment [191]. Flexible batteries are being developed for ergonomic and patient-friendly devices, while wireless charging systems are eliminating the need for physical connectors. Nanoelectronics is another breakthrough, enabling ultra-miniaturized power systems that fit seamlessly into the smallest devices without compromising efficiency. Healthcare power solutions are revolutionized by emerging technologies that make them more sustainable, reliable, and efficient. Solid-state batteries are suitable for wearable and compact devices because they have a very high energy density and safety [192].

Graphene supercapacitors allow rapid charging, which is essential for rescue equipment. Wireless charging eliminates the need for physical connectors, and flexible batteries make patient-friendly devices more convenient. Power systems are miniaturized through nanoelectronics that maximize space without compromising efficiency. Biofuel cells increase the lifespan of implantable devices by powering them from body fluids. Thermoelectric generators minimize the need for external recharging by drawing power from body heat [193]. AI-powered hospital smart grids guarantee a continuous power supply to critical machinery. Self-healing battery materials maximize lifespan and reduce malfunction. These developments collectively enhance power management in medical devices, ensuring that life-supporting devices continue to operate reliably, regardless of the circumstances. Fig. 21 here shows power solutions in revolutionizing healthcare.

7.7. Sustainability and energy-efficient designs

Sustainability is becoming a major focus in designing healthcare power systems. Energy harvesting technologies—such as those that capture kinetic, thermal, or solar energy—are being integrated into devices to reduce dependence on traditional batteries. Fig. 22 shows some of the sustainable innovations in healthcare power systems. For instance, implantable devices powered by the body's natural movements eliminate the need for frequent battery replacements [194]. Biodegradable batteries are another step toward reducing medical waste and promoting environmental responsibility. Additionally, efficient

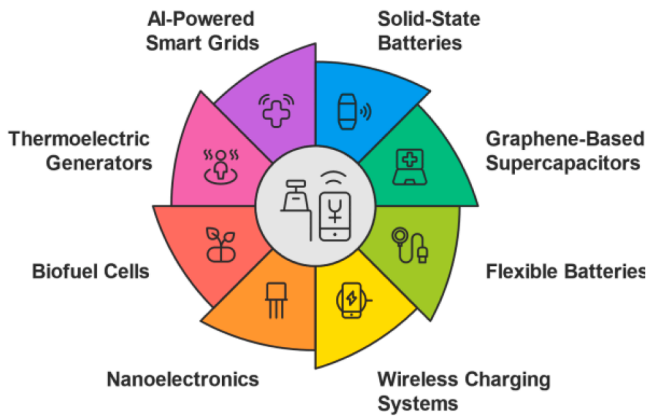


Fig. 21. Emerging Healthcare Power Solutions Combining AI-Powered Smart Grids, Advanced Batteries, Supercapacitors, Biofuel Cells, and Wireless Charging Technologies.

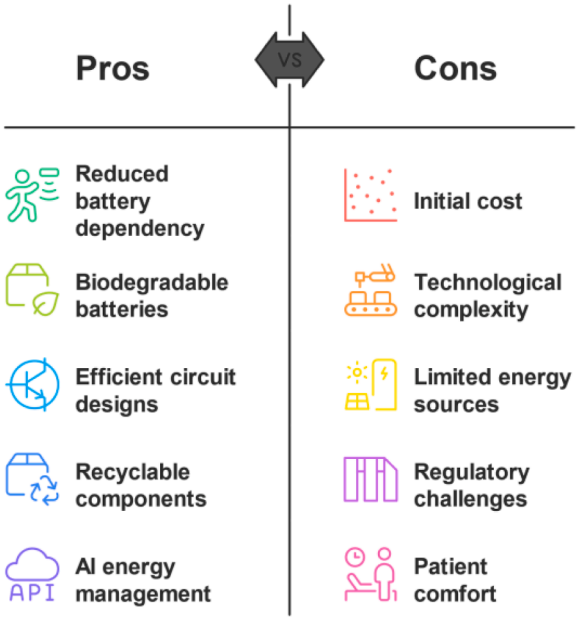


Fig. 22. Pros and Cons of Sustainable Innovations in Healthcare Power Systems.

circuit designs help minimize power consumption, and efforts to create recyclable components and batteries align with broader sustainability goals [195]. Medical power systems place significant emphasis on sustainability, and energy-harvesting devices minimize the utilization of conventional batteries. Devices harvest increasingly more thermal, kinetic, or solar energy so that a longer life cycle is guaranteed. The comfort of patients is enhanced through implanted devices that operate by body motion, eliminating the need for frequent battery replacement. Biodegradable batteries encourage green solutions by minimizing medical waste.

Power usage is minimized via efficient circuit designs to increase overall energy efficiency. Batteries and recyclable materials contribute to global sustainability efforts by minimizing their environmental impact. Energy management through AI maximizes utilization, while wireless power delivery makes disposable batteries obsolete. Green medical solutions are supported by ultra-efficient energy storage facilitated by breakthroughs in nanotechnology. Together, these technologies enhance medical equipment's reliability, effectiveness, and sustainability and will define the future of healthcare technology.

Furthermore, the shift toward circular economy principles in medical power systems is gaining momentum. This involves designing devices not only for operational efficiency but also for ease of disassembly, reuse, and material recovery. Incorporating LCA frameworks allows stakeholders to quantify environmental impacts throughout a product's lifespan, from raw material extraction to end-of-life disposal. Additionally, integrating AI-driven optimization can dynamically regulate power consumption based on contextual usage, thereby minimizing unnecessary energy drain and maximizing operational sustainability. Future healthcare systems are expected to prioritize net-zero energy consumption by combining low-power hardware architectures, intelligent control algorithms, and environmentally friendly materials. These practices collectively reinforce the commitment to long-term environmental stewardship, reduce carbon footprints, and align with global sustainability goals such as the UN SDGs.

7.8. Data & model challenges in livestock AI

The use of AI in PLF is very promising, but not without challenges [196]. Most current applications utilize machine learning techniques such as CNNs, RNNs, and SVMs for behavior classification and disease detection [197]. These techniques often utilize time-series sensor data (e.g., accelerometer and gyroscope data) to determine the activity of animals [198]. However, a major bottleneck is the lack of large annotated datasets specific to livestock settings. Data scarcity not only hinders model training but also reduces generalizability across breeds, farm types, or climates [199]. Model overfitting is also a significant problem, especially for small or biased datasets. Models may learn well on training sets but fail to generalize in dynamic, real-world operating environments. Model drift—when the model & epoch accuracy weaken over time due to changes in animal behavior or sensor conditions—is also an attack on system reliability. Explainability is also paramount; black-box AI solutions can be highly accurate but not explainable, so the farmer or vet may not be able to interpret findings or trust counsel [200]. To address such challenges, research in the future should center on XAI techniques, synthetic data augmentation, domain adaptation, and continuous learning architectures. There should be an open-access benchmark dataset built and a cross-disciplinary collaboration between animal specialists and AI engineers established. Overcoming these limitations is critical to building reliable, scalable, and robust AI tools for sustainable livestock health monitoring.

8. Key findings and future directions

This research demonstrates how PLF, by incorporating sensor-based monitoring, AI, and innovative power solutions, has transformed cattle care. Monitoring animal health, movement, and environmental conditions in real-time is now possible because of the use of accelerometers, gyroscopes, GNSS, and UWB systems. This has improved decision-making and minimized the need for physical monitoring. Moreover, ML models play an important role in disease prediction, behavior analysis, and anomaly detection, enabling early intervention, increased productivity, and minimizing financial loss. PLF is more eco-friendly as the application of isolated and non-isolated DC-DC converter topologies provides secure and efficient power management for such systems.

However, one of the key challenges in implementing AI/ML-based livestock health prediction is the "cold-start" problem, where models initially struggle due to limited or unlabeled datasets. Small-scale farmers, in particular, face barriers because they often lack sufficient annotated data or computational infrastructure to train robust models. Recent studies have proposed federated learning as a practical solution, enabling multiple farms to collaboratively train shared models on decentralized data without exchanging sensitive or proprietary information. This privacy-preserving approach not only reduces the dependency on large centralized datasets but also empowers local farmers to benefit from collective intelligence while maintaining data

ownership.

The integration of digital twins, blockchain, and 5 G will revolutionize future PLF systems. Digital twins will enable real-time, virtual simulations of livestock and farming environments, allowing for predictive analysis and proactive management of animal health and farm operations. Blockchain can provide secure, transparent tracking of data across the entire supply chain, ensuring the integrity of sensor data and improving traceability of livestock health and origin. 5 G connectivity will enhance the communication between devices, enabling faster, more reliable data transfer for real-time monitoring and decision-making, especially in large-scale and remote farming operations.

Future PLF frameworks must also address ethical considerations, including animal welfare and data privacy. Continuous monitoring should be implemented with minimal animal stress, ensuring that wearable sensors are non-invasive and comfortable. Moreover, strict data governance protocols—supported by blockchain and federated learning—are essential to safeguard farm and animal data against unauthorized access and misuse.

PLF can further contribute to circular economy principles by encouraging the use of recyclable and biodegradable sensor materials, modular hardware designs, and energy-neutral systems powered by renewable sources. These strategies will reduce electronic waste, promote sustainable manufacturing, and enhance the environmental resilience of smart farming ecosystems.

9. Conclusion

This review highlights the transformative potential of PLF by integrating cutting-edge sensor technologies, energy-efficient power management systems, and AI-driven solutions. The integration of electronics such as smartphones, edge AI platforms, and LoRa/Bluetooth modules into PLF systems represents a critical step in bridging agricultural technology with mass-market electronics, enhancing accessibility and scalability for farmers across various scales of operation. Furthermore, this review has provided a detailed comparison of isolated and non-isolated DC-DC converters, emphasizing their suitability for different sensor types and environmental conditions in livestock monitoring. PLF is inherently interdisciplinary, combining advancements in sensor technology, power management, AI, and sustainability practices. The future of PLF relies on close collaboration between engineers, farmers, and policymakers. By addressing challenges such as data security, model accuracy, and real-time decision-making, the future of PLF will undoubtedly play a pivotal role in achieving the UN Sustainable Development Goals, particularly in areas like food security and sustainable agricultural practices.

CRediT authorship contribution statement

Fariya Bintay Shafi: Writing – original draft, Resources, Methodology, Data curation. **Md. Faysal Ahamed:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Md. Fahmidun Nabi:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Amith Khandakar:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Wesam Rohouma:** Writing – review & editing, Methodology. **Mohamed Arselene Ayari:** Supervision, Investigation. **Kevin Thomas:** Methodology, Data curation. **Ahasanur Rahman:** Methodology, Data curation. **Mamun Bin Ibne Reaz:** Writing – original draft, Methodology. **Fida Haq:** Writing – review & editing, Resources. **Shady S. Refaat:** Writing – review & editing, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Acronym Table of the Provided Short Forms in the Manuscript

Acronym	Full Form
AI	Artificial Intelligence
AFS	Automated Feeding Systems
AV	Agrivoltaics
BLE	Bluetooth Low Energy
BLDC	Brushless Direct Current
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CNN	Convolutional Neural Network
DC	Direct Current
DC-DC	Direct Current to Direct Current
DL	Deep Learning
DSP	Digital Signal Processor
EMI	Electromagnetic Interference
EV	Electric Vehicle
FAO	Food and Agriculture Organization
FLC	Fuzzy Logic Control
FPGA	Field Programmable Gate Array
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IC	Integrated Circuit
IDBS	Integrated Double-Boost SEPIC
IGBT	Insulated Gate Bipolar Transistor
IMU	Inertial Measurement Unit

(*continued on next page*)

(*continued*)

Acronym	Full Form
IoT	Internet of Things
LCA	Lifecycle Assessment
LED	Light Emitting Diode
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LPWAN	Low-Power Wide Area Network
LQR	Linear Quadratic Regulator
LiDAR	Light Detection and Ranging
MPPT	Maximum Power Point Tracking
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
PCM	Phase Change Materials
PFC	Power Factor Correction
PID	Proportional Integral Derivative
PLF	Precision Livestock Farming
PMIC	Power Management Integrated Circuit
PMSM	Permanent Magnet Synchronous Machine
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Photovoltaic
PWM	Pulse-Width Modulation
RFID	Radio Frequency Identification
RNN	Recurrent Neural Network
SDG	Sustainable Development Goal
SEPIC	Single-Ended Primary Inductor Converter
SHAP	SHapley Additive exPlanations
SMC	Sliding Mode Control
SSM	State-Space Modeling
SVM	Support Vector Machine
THD	Total Harmonic Distortion
UN	United Nations
UPS	Uninterruptible Power Supply
USB	Universal Serial Bus
UWB	Ultra-Wideband
XAI	Explainable Artificial Intelligence
ZVS	Zero-Voltage Switching
LTE	Long-Term Evolution
MIMO	Multi-Input Multi-Output
ML	Machine Learning
MPC	Model Predictive Control

Data availability

No data was used for the research described in the article.

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