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PRECISION LIVESTOCK FARMING AND ITS ROLE FOR ASSURING A SUSTAINABLE CATTLE MANAGEMENT- A STUDY CASE ON CONNECTED COW

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Abstract

Precision Livestock Farming (PLF) has emerged to help animal husbandry to become more efficient and sustainable. In this context, the goal of this research study is to describe "Connected Cow" as a groundbreaking evolution moment in cattle management, because PLF technologies are destined to revolutionize traditional practices. For setting up this work, a large range of research studies, technical reports, and industry case studies published between 2010 and 2023 have been used, been carefully selected, logically structured and assessed in a critical manner. The results proved that by utilizing IoT devices, sensors, and data analytics, the connected cow framework enables real-time monitoring of health, behavior, feeding patterns, reproduction, and production. This approach allows for data-driven management decisions, enhancing productivity, improving animal welfare, and reducing environmental impact. This paper delves into the connected cow's role in shifting cattle management paradigms, offering insights into its operational benefits and challenges, including data integration, cost barriers, and technology adoption. Future advancements in AI and machine learning are also discussed as enablers of predictive and adaptive management solutions. By emphasizing the integration of connectivity and management, the connected cow highlights a transformative path toward sustainable, efficient, and welfare-focused livestock farming.

Key words**:** *connected cow, precision livestock farming, IoT, cattle management*

INTRODUCTION

A number of technologies have changed the way that dairy farming is practiced and managed. This includes the use of artificial insemination, mass production of high-quality silages, mechanization of milking, but most importantly, the ability to provide large amounts of highly digestible diets to high-producing cows [25, 13]. These and other mechanistic approaches have arguably contributed to the magnitude of production we observe today for high-yielding cows. Widespread implementation of suboptimal periodic events has gone uncontested, however. Generic approaches that treat animal groups or the herd as a whole can have deleterious effects on animals within that group that are overlooked.

The era of digital transformation of farm management has begun and AI applications have started to be used on a large scale with a beneficial impact on the sustainability in agriculture [10, 27, 28, 33].

The AI tools have a beneficial role for a better understanding of animal function and perception of animal welfare in management systems [3]. There is public concern regarding many aspects of farm animal welfare, including restraint, mutilation, confinement, sensory deprivation, chronic boredom, and fear that is only alleviated by the illusion of control. Efficient technological advancements at the farm level have been well adopted and increased efficiency. These are of clear importance from a sustainability perspective. Increasing societal pressure on the human-animal relationship and other animal welfare concerns influences consumer demands [23,18].

Currently, we observe a societal transition to more interest in animal welfare, including how dairy cows are managed. From a philanthropic viewpoint, an ideal farm would produce without regard for economics, but from an economic viewpoint, an ideal farm would be low cost, highly productive, and economically stable [23]. Although factors besides welfare and efficiency are important in many modern dairy farms, they are essentially what are needed for contemporary society. Unfortunately, although more precise technologies are developed that may change the landscape of precision livestock farming and automated assessment of health and welfare, many are not realized or steadily adopted [18, 34].

In this context, the paper aimed to approach Precision Livestock Farming (PLF) in cattle management describing and emphasizing how IoT devices, sensors, and data analytics, the connected cow framework assure the monitoring of health, behavior, feeding, reproduction, production and many other aspects related to economic efficiency and profitability which contribute to the development of sustainability in cattle farms.

MATERIALS AND METHODS

This paper follows a systematic review methodology to analyze and synthesize the current state of knowledge on the "connected cow" and its role in Precision Livestock Farming (PLF) (Figure 1).

The review process was conducted in four stages: (1) defining the research scope, (2) identifying relevant literature, (3) applying inclusion and exclusion criteria, and (4) synthesizing the findings.

The scope of the systematic review was defined to include research studies, technical reports, and industry case studies published between 2010 and 2023 that focus on IoT technologies, data analytics, and their applications in cattle management.

The primary objectives of the review were to:
(i) analyze the key components of the connected cow framework,
(ii) evaluate its operational benefits and challenges, and
(iii) explore future advancements in AI and machine learning for predictive livestock management.

A comprehensive search was conducted across multiple scientific databases, including: Scopus, Web of Science, PubMed (for studies related to animal health and welfare), IEEE Xplore (for IoT and data analytics technologies), Agricultural & Environmental Science Collection. The keywords and Boolean operators used in the search included: "connected cow" OR "precision livestock farming" or "IoT in cattle management" "smart farming" and "cattle", "livestock sensors" and "data analytics", "real-time monitoring" and "animal welfare".

The search was supplemented by a manual review of references cited in key scientific journals and reports, as well as consultation with industry white papers and government publications. To ensure relevance and quality, specific inclusion and exclusion criteria were applied to filter the retrieved studies. Inclusion

Criteria included: Peer-reviewed articles, conference proceedings, and technical reports published in English between 2010 and 2023.

Studies focusing on IoT, sensors, and data analytics for cattle management, research discussing the operational benefits, challenges, or future trends of PLF technologies. Exclusion criteria included: Articles unrelated to cattle or livestock farming, studies focusing solely on other livestock species (e.g., poultry or swine),

Publications with insufficient technical detail or methodology. Data were extracted from the selected studies using a structured framework.

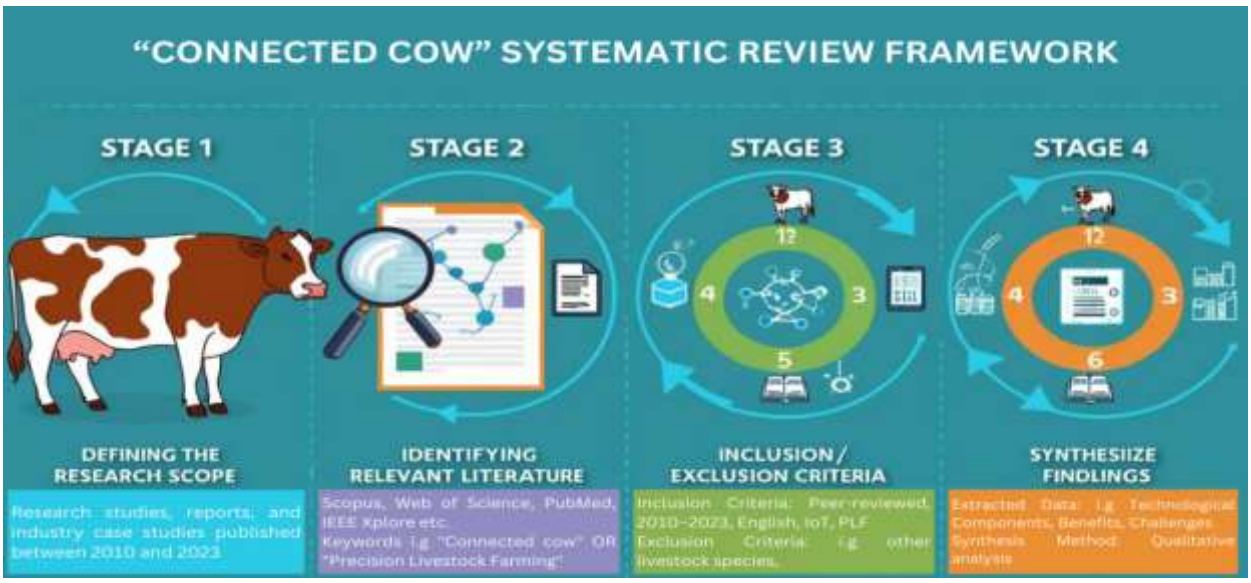

Fig. 1. Flow chart methodology used in thestudy.
Source: Author's own creation.

Key parameters recorded included technological components (i.g Types of IoT devices, sensors, and data analytics platforms discussed), operational benefits (i.g Metrics such as productivity gains, health monitoring improvements, and environmental outcomes), challenges (i.g. barriers to adoption, including cost, data integration, and farmer training), future opportunities (i.g Advancements in AI, machine learning, and predictive analytics). The extracted data were synthesized qualitatively to identify recurring themes and knowledge gaps.

To assess the methodological rigor of the included studies, each article was evaluated using the following criteria: clarity of objectives and methodology; relevance of results to the connected cow framework; robustness of data collection and analysis methods; peer-reviewed status of the publication; studies meeting at least 75% of these quality indicators were included in the final synthesis.

RESULTS AND DISCUSSIONS

This section presents and discusses the findings from the systematic review, organized into key themes: the evolution of cattle management, the concept of the connected cow, its operational benefits, and its transformative role in livestock farming. By tracing the progression of cattle management practices, we contextualize the significance of the connected cow within the broader framework of Precision Livestock Farming (PLF). The operational benefits, challenges, and implications of this technological shift are critically examined, along with insights into the paradigm shifts it drives in sustainable cattle farming.

Evolution of cattle management

On the Indian subcontinent, evidence of dairy cow management survives, inscribed in Harappan seals dating back to around 3300 B.C. or over 5000 years ago. This historical record attests that animals have been bred selectively worldwide for specific purposes, illustrating the close relationship and mutual dependency of humans with their cattle through generations [36]. This evolving relationship has fostered the rise of livestock farming, inadvertently shifting selected traits, such as hardiness, fertility, or milk and meat production to satisfy multiple human needs. Initially, on the extensive farm, farmers developed low-density mobility management systems for cattle in search of pastures and other natural resources, a lifestyle that has survived unchanged in some corners of the

world and was once essential for many trade routes. Enclosure systems allowed animals to move and graze freely without the risk of wolves and other predators becoming a challenge. The Roman author described how in southern Italy farmers moved their agricultural estate from winter to summer pastures [16, 14].

Traditional cattle management has relied on labor-intensive practices and empirical knowledge passed down through generations. Monitoring livestock health, reproduction, and feeding patterns was conducted through manual observation, often leading to delayed responses to health or productivity issues. While effective in smaller-scale farming, these methods struggled to meet the demands of modern, large-scale operations [24] (Fig.2).

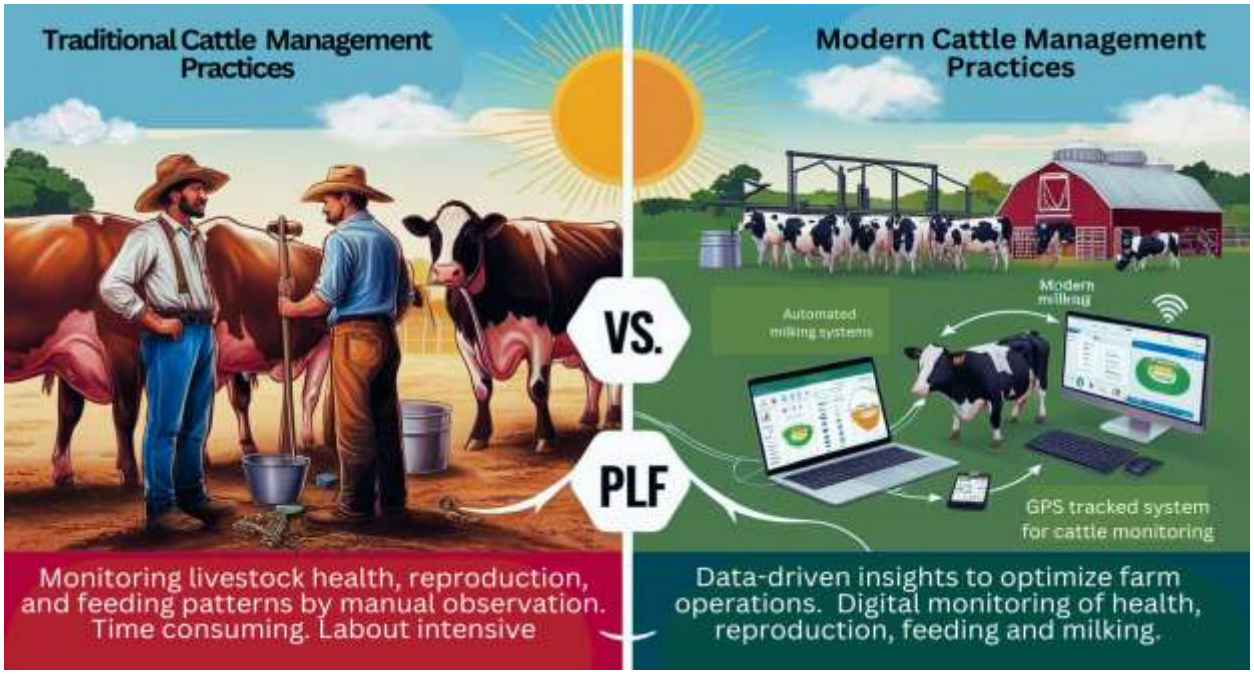

Fig. 2 Traditional cattle management practices vs. Moderna Cattle Management Practices based on Precision Livestock Farming (PLF)
Source: Author's own creation.

The concept of the "Connected Cow"

Today's conscientious consumer is increasingly focused on knowing about the products they're buying after witnessing many cases of lax regulation in consumer goods. It's no wonder so many people are demanding a higher standard as consumers [1, 30]. Yet much of the food produced in the world today comes from animals that are not fully tracked or managed using current technology to reach these higher standards.

It's hard to rectify the information age with a person's desire to know more about where their red meat or dairy products are coming from if no one knows where the cow has been [30, 17, 9, 19, 12].

The connected cow represents integrated system where individual cattle are equipped with IoT devices and sensors to collect data on health, behavior, feeding patterns, and reproductive status. These components work in tandem with cloud-based platforms, enabling farmers to access actionable insights via smartphones or computers [5, 31].

IoT devices such as wearable collars, ear tags, and rumen sensors serve as the backbone of the connected cow system (Fig. 3). These devices collect critical data points, including body temperature, activity levels, and feed intake. Advanced sensors can even detect early signs of illness or stress, prompting timely intervention and reducing the need for antibiotics or other reactive measures [20].

The data generated by IoT devices is processed using cloud computing and advanced analytics tools. Real-time

dashboards and predictive algorithms allow farmers to monitor herd health, identify estrus cycles for improved breeding, and optimize feed efficiency. Machine learning algorithms are increasingly being utilized to detect patterns and predict potential health or productivity issues before they occur [4, 35, 29, 2]. Connected cow systems contribute to higher productivity by enabling precise monitoring of feeding and reproduction. For example, optimized feed intake monitoring reduces waste and ensures optimal nutrition, leading to higher milk yields and faster growth rates [35, 2]. Moreover, early detection of reproductive cycles allows for targeted breeding, improving reproductive efficiency [4].

Fig. 3 Precision livestock tools used within the "Connected Cow" Framework
Source: Author's own creation.

Real-time monitoring promotes animal welfare by enabling farmers to address health concerns at their earliest stages. Sensors can detect subtle changes in behavior or physiology that may indicate stress or illness, allowing for prompt intervention. By reducing the need for reactive treatments, the connected cow fosters a preventive approach to health management [32].

Efficient resource management enabled by connected cow systems helps minimize the environmental footprint of cattle farming. By optimizing feed conversion ratios and reducing methane emissions through better herd health, farmers can contribute to sustainable livestock production. Additionally, reduced reliance on antibiotics and other treatments aligns with global efforts to combat antimicrobial resistance [11, 26].

The economic impact of Precision Livestock Farming (PLF) in dairy farms

Precision Livestock Farming (PLF) significantly enhances the economic efficiency and sustainability of dairy farms by optimizing resource use, increasing productivity, and boosting profitability. The usage of land, animal shelters, herds, crops, materials, and labor may all be optimized with the implementation of PLF technologies. By automating processes such as feeding and milking, automated systems lower the amount of feed that is wasted, improve the management of animal health, and reduce the amount of work that is required. Consequently, this results in improved resource allocation and cost reductions.

Forage production and feed quality may also be improved through advanced monitoring

tools. This, in turn, boosts milk production and quality, meeting higher standards and improving traceability. Better herd health management through PLF reduces veterinary costs and improves reproductive performance, further contributing to increased productivity.

By lowering production costs per animal and reducing the cost of milk per kilogram, PLF promotes economic sustainability. Higher revenues are generated from improved milk quality, increased calf sales, and higher gross output per cow. Financial performance indicators such as total profit, profit margins, and profit per cow or per liter of milk are significantly improved through efficient resource allocation and production optimization.

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Role in shifting cattle management paradigms

The concept involved in the connected cow framework means a major shift from clarification methods and reactive solutions to preventive and predictive methods [7]. Apart from the conventional rearing systems, the adoption of PLF technologies is of particularly importance for organic dairy systems, where the focus is on sustainable practices and minimizing environmental impact. Technologies such as real-time pasture monitoring, non-invasive health tracking, and automated manure management help organic farms maintain compliance with strict standards while improving productivity and profitability. For example, pasture management tools may help farmers to ensure optimal grazing without overuse, preserving soil health. Reducing the reliance on antibiotics and supporting of organic certification may be supported by the implementation of Non-invasive monitoring systems that allow for early disease detection.

Manure management technologies could contribute to the optimization of nutrient recycling, reducing environmental footprint and supporting sustainable farming practices.

The risks related to the implementation of PLF

PLF fosters sustainable cattle management by integrating technological advancements that not only reduce costs but also enhance profitability, paving the way for a more efficient and economically viable dairy farming industry. Yet, the widespread implementation of this framework is challenging, with data merging, equipment costs, and digital literacy of farmers being the primary barriers [21, 22, 6, 15]. Operating within the connected cow framework requires a team that includes technologists to address these challenges, while farming experts and policymakers play a vital role in overcoming these obstacles.

One significant risk is the high cost of integrating advanced technologies into farms, which creates financial strain, especially for smaller operations. The limited access to PLF tools based on farm size and available resources can exacerbate inequality among farmers, leaving many unable to adopt these innovations.

In large-scale farms, the reliance on fully integrated and automated systems poses another critical risk. A system failure could have devastating consequences, halting operations and causing significant economic losses. Furthermore, the use of intrusive tags and monitoring devices could impact animal welfare, raising ethical concerns and potentially influencing public perception.

As PLF expands, the close relationship between food security and animal welfare becomes more apparent. The improper implementation of PLF could jeopardize this balance, making it vital to ensure that sustainability goals do not compromise the welfare of livestock or the resilience of food systems.

CONCLUSIONS

The "connected cow" concept demonstrates that the cattle industry is capable of using technology in ways that dramatically change cattle operations and management in the PLF era. With the use of IoT devices, data analytics and real-time monitoring, this approach optimizes production and efficiency, promotes proper treatment of animals and minimizes negative effects on the environment. However, there is still a significant way to go for deep market penetration, some of which entails costs, data interface, and farmer education. The on-going development of artificial intelligence and machine learning will lead to the discovery of new forms of predictive and adaptive management that can likely enhance the productivity of herds. Thus, the concept of a connected cow is an evolving one, and it is the way to achieve the ever-increasingly more efficient, sustainable, and welfare-friendly form of livestock farming that can begin a new chapter in the agricultural history.

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