DAIRY 4.0: INNOVATIVE DIGITAL TECHNOLOGIES IN DAIRY CATTLE AS PATHWAY TO IMPROVED PRODUCTIVITY IN THE CONTEXT OF CLIMATE CHANGE

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Abstract

Climate change is one of the significant challenges that dairy farmers confront, leading to adverse effects on milk production, animal well-being, and economic revenues of a dairy farm. The rising global temperatures call for designing new approaches for mitigating consequences of heat stress. Emerging technologies within the sector's digital revolution provides solution strategies for the animal husbandry business, including the dairy farming through real-time monitoring, predictive analytics, and adaptive management strategies in order to enhance productivity, sustainability, and resilience in farms. This paper explores the applications, benefits, challenges, and potential of innovative digital technologies including precision livestock farming (PLF), Internet of Things (IoT) sensors, artificial intelligence (AI), big data analytics, and blockchain, in transforming modern dairy farming and mitigating heat stress.

Key words: *Dairy 4.0, digital technologies, dairy cattle, climate change, precision livestock farming, sustainability, productivity, IoT, artificial intelligence*

INTRODUCTION

In the coming decades, Europe will face a number of challenges arising from increased competition for limited natural resources, the effects of climate change, especially on primary production systems (agriculture, including livestock and horticulture, forestry, fisheries and aquaculture) and the need to ensure a sustainable and safe supply of food, both for the European population and for the growing global population [1-2].

The need to improve resource efficiency, reduce greenhouse gas emissions and improve animal health and welfare has been highlighted by the EU, the Task Force on Animals, FAO and the GHG.

For agricultural research in Romania there is a major challenge to align with the level of scientific excellence at the international level [3-4]. The European Green Deal aims to transform the EU into a modern, resource-efficient and competitive economy. This is a challenge for the younger generations of livestock farmers and involves the development of management techniques and technologies that improve the efficiency and profitability of farms, ensure animal welfare and minimize the environmental impact associated with animal husbandry activities. The evolution of the agricultural field (production, manufacturing, trade) is extremely intense, thus creating the need for

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permanent training of farmers, so that they can face the new environment [5-6]. In this increasingly warm climate, millions of people depend on the ability of animals to respond to new challenges and cope with heat stress, as well as additional stressor such as solar radiation, pest insects and poor ventilation, which are often associated with an increased risk of mastitis, resulting in lower milk quality and reduced production [7-9].

Heat stress is a critical issue in dairy farming, especially as climate change continues to raise global temperatures. Cows are highly susceptible to heat stress due to their limited ability to dissipate heat efficiently. Prolonged exposure to high temperatures can lead to reduced feed intake, lower milk production, impaired reproductive performance, and increased susceptibility to diseases. The economic losses due to heat stress in dairy farming are substantial, making it essential to adopt innovative strategies to manage this problem [10].

Digital tools, including sensors, wearable devices, machine learning models, and automated cooling systems, have emerged as valuable resources for monitoring and mitigating heat stress in dairy cows. These technologies enable farmers to make data-driven decisions and implement targeted interventions to ensure animal well-being and maintain productivity during periods of heat stress.

MATERIAL AND METHODS

The paper explores the impact and implementation of digital technologies to mitigate heat stress in dairy cattle, with an emphasis on keywords such as Dairy 4.0, precision livestock farming (PLF), Internet of Things (IoT), artificial intelligence (AI), and big data analytics. The review methodology involved a systematic literature search using major academic databases and online platforms, including PubMed, Web of Science, ScienceDirect, and Google Scholar. These platforms were chosen for their extensive repositories of peer-reviewed journals and relevant research articles across fields of animal science, veterinary medicine, and agricultural technology. Selected studies were evaluated for their coverage of wearable sensors, automated cooling systems, environmental monitoring, and data analytics applications, specifically targeting heat stress indicators like the Temperature-Humidity Index (THI), body temperature, respiration rate, and milk production levels.

IMPACT OF HEAT STRESS ON DAIRY COWS

Prior to investigating the application of digital technologies, it is fundamental to comprehend how heat stress affects dairy cows physiologically and behaviorally:

- ***Reduced Feed Intake***: During heat stress, cows decrease feed intake, which reduces the energy available for milk production. A study carried out by Chen et al., (2024) showed that heat stress decreased dry matter intake (DMI) and energy-corrected milk (ECM) [11].
- ***Decreased Milk Production***: Heat-stressed cows produce less milk due to lower feed intake and metabolic disruptions [11].
- ***Reproductive Challenges***: Heat stress affects reproductive efficiency, leading to lower conception rates and increased embryonic losses [12-13].
- ***Health Problems***: Heat stress weakens the immune system, making cows more vulnerable to diseases like mastitis and respiratory infections [14-15].

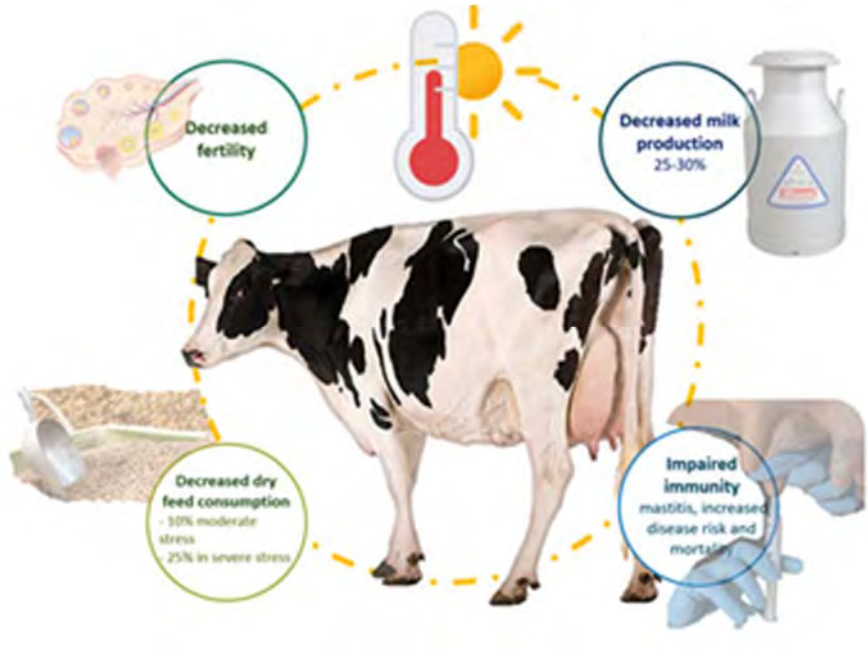

Fig. 1 Impact of heat stress on dairy cowS

Given these consequences, proactive management is crucial. Digital tools are increasingly being used to help farmers manage heat stress by monitoring the environment, animal behavior, and physiological responses [16-17].

TYPES OF DIGITAL TOOLS FOR MANAGING HEAT STRESS

Environmental Monitoring Systems

Environmental monitoring systems play a critical role in detecting conditions that could lead to heat stress. These systems typically consist of sensors placed throughout the farm to track temperature, humidity, air quality, and solar radiation in real time. Heat stress is often quantified using the Temperature Humidity Index (THI). Digital sensors installed in barns or milking areas continuously measure temperature and humidity, providing farmers with THI values to assess the level of heat stress risk. Advanced weather prediction models and apps integrate real-time data with local weather forecasts, allowing farmers to anticipate heat stress and implement proactive cooling strategies [17].

Wearable Technology

Wearable sensors: attached to cows have become a popular solution for real-time monitoring of individual animals. These devices track physiological parameters such as body temperature, heart rate, respiration rate, and movement patterns, providing early warning signs of heat stress.

Fig. 2 Tools to enhance animal welfare and productivity by providing real-time responses

Some collars or ear tags are equipped with sensors to monitor core body temperature, respiration rate, and activity levels. This data helps farmers detect early signs of heat stress and initiate cooling measures such as misting or fan activation.

Integrated systems that track heat stress alongside other health metrics (e.g., rumination, feed intake, and milk production) provide a comprehensive understanding of how heat stress affects individual cows, allowing for tailored interventions [18-19].

Automated Cooling Systems

Automated cooling systems, which include fans, misters, and sprinklers, can be activated based on data from environmental monitoring systems or wearable devices. By automating the cooling process, farmers can ensure that cows receive timely relief from heat stress. Fans and misters can be programmed to activate when THI reaches a critical threshold. These systems adjust airflow and water misting according to real-time conditions, maintaining a cooler environment in the barn or milking parlor.

Automated sprinklers can be integrated with wearable technology or environmental sensors to deliver water at optimal times, cooling cows without excessive water use. A recent study highlights that cooling systems integrating fans and sprinklers can significantly reduce heat stress in dairy cows, improving both comfort and milk production, especially in warmer climates [20].

Data Analytics and Machine Learning

Data analytics and machine learning are transforming the way farmers manage heat stress. These tools analyze vast amounts of data collected from sensors, wearable devices, and other sources to generate predictive models and optimize heat stress mitigation strategies. Machine learning algorithms can analyze historical data on weather conditions, animal performance, and health outcomes to predict when and where heat stress will occur. This allows farmers to deploy cooling measures in advance [21-22].

Consequently, based on data analytics, farmers may create customized plans for different groups of cows, considering factors such as breed, lactation stage, and individual sensitivity to heat.

Farm Management Software

Farm management software platforms integrate data from various digital tools and

provide farmers with a centralized dashboard for decision-making [22]. These platforms enable farmers to monitor heat stress levels across the herd, track the effectiveness of cooling interventions, and adjust management strategies as needed.

Farm management software can send real-time alerts to farmers when heat stress thresholds are exceeded, ensuring timely action to protect animal welfare. Software solutions also offer analytics on how heat stress impacts productivity and health, helping farmers refine their heat stress management approaches over time [23-24].

BENEFITS OF DIGITAL TOOLS IN MITIGATING HEAT STRESS

The adoption of digital tools in dairy farming has several key benefits:

- **Enhanced Animal Welfare:** Continuous monitoring and timely interventions improve cow comfort, reducing the risk of health issues associated with heat stress [25-26]
- **Increased Productivity**: By maintaining cows in their thermal comfort zone, farmers can sustain milk production levels and prevent significant production losses during hot periods[25].
- **Improved Reproductive Performance**: Early detection and mitigation of heat stress help protect reproductive health, leading to higher fertility rates and improved calving intervals [27].
- **Data-Driven Decision-Making**: Farmers can use data to optimize cooling strategies, improving efficiency and reducing operational costs associated with heat stress management.
- **Sustainability:** Automated systems reduce water and energy usage by only activating when needed, making heat stress management more sustainable.

Challenges and Future Directions

While digital tools offer significant advantages in mitigating heat stress, there are challenges to consider:

Cost: The initial investment in digital tools, including sensors, wearable devices, and automation systems, can be high, especially for small-scale farmers.

Data Integration: Integrating data from multiple devices and systems into a unified platform requires advanced farm management software, which may require additional training.

Data Privacy: As farms collect more data, there are concerns about data security and privacy, particularly when using cloud-based systems [28].

Looking ahead, the development of more affordable and user-friendly digital tools will be crucial in making these technologies accessible to a broader range of farmers. Additionally, advancements in artificial intelligence and machine learning will enable even more precise predictions and interventions, further enhancing the ability of farmers to manage heat stress proactively.

CONCLUSION

Digital tools have the potential to revolutionize how dairy farms mitigate heat stress. By leveraging real-time data, predictive analytics, and automated systems, farmers can improve animal welfare, maintain productivity, and reduce economic losses associated with heat stress. As climate change continues to increase the frequency and intensity of heat events, the adoption of these technologies will be essential for the sustainability and resilience of the dairy industry. Future research and development should focus on making these tools more accessible and affordable for all dairy farmers, regardless of farm size or location.

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