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Review on the Contribution of Digital Solutions to Sustainable Dairy Farming

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This paper explores digital technology advancements in dairy farming, focusing on cattle housing and farm sustainability. Optimal dairy management hinges on milk production quality, quantity, and profitability. Influenced by cattle genetics, feed, water quality, and farming conditions, these factors can be monitored and controlled via digital tools. Existing digital solutions often lack compatibility and underutilize data. Drawing from real cases, this study highlights the benefits of integrating location-specific microclimate data and operational monitoring into digital farm applications. This integration improves milk quality and quantity, empowering decision-makers to enhance sustainability and production efficiency. In conclusion, this paper effectively explains the capacity of digital technologies to amplify dairy operations' sustainability and profitability. It calls for a broader implementation of accessible and affordable circumstantial information and operational data to optimize dairy production practices.

1. Introduction

The imperative to address the escalating food requirements of an expanding global population, coupled with the complex challenges of climate volatility and stringent regulatory frameworks governing food production, has triggered a constant drive for innovation within the domain of dairy farming. Industrial dairy farming is a significant contributor to humanity's inventory of greenhouse gas (GHG) emissions. It is estimated that the sphere of global livestock production contributes approximately 14.5 % to the entirety of anthropogenic GHG emissions, with dairy production systems singularly responsible for nearly 30 % of this quantum (2.1 $GtCO_{2eq}$ per year) (Gerber et al., 2013).

Fundamental to the discourse of sustainability are several key factors: genetics, feed composition, water provisioning, and housing paradigms collectively orchestrate both the structure of production and the role of overarching sustainability. While genetics and feed formulations have been recipients of transformative developments in recent times, thereby enhancing the arsenal of sustainable practices (Ducrocq, 2010), housing conditions, despite its historical primacy, remain an area where the cultivation of data and its thoughtful analysis have yet to achieve extensive culmination. Heightened attention to farm operation sustainability arises partly due to energy cost fluctuations.

Berckmans (2017) defines PLF as an approach that includes continuous real-time monitoring of individual animal health, welfare, production/reproduction, and environmental impact. Individual animal monitoring aids in creating optimal environments, and while group or herd-level monitoring offers valuable insights, advancements in Internet of Things (IoT) technology have unlocked the potential for even more refined results. The integration of sensors and data from existing digital applications has demonstrated the capacity to enhance production, efficiency, and sustainability.

This study proceeds to address the primary sustainability challenges faced by the dairy industry and outlines the steps already taken to address them. Furthermore, it provides a concise overview of readily available digital solutions that underpin sustainable dairy farm operations. Real-world implementations will underscore the value of monitoring barn microclimate and farm equipment in advancing sustainable farming practices.

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2. Major sustainability issues of dairy farming

Greenhouse gas (GHG) emissions stand as a significant challenge to the sustainability of dairy farming. Dairy farming, despite progress, remains a notable contributor to emissions, with few industries demonstrating comparable reductions in environmental impact (McCabe, 2021). Within this context, the curbing of emissions, especially methane (CH_4) and nitrous oxide (N_2O), takes precedence, with some attention directed toward carbon dioxide (CO_2). Effective reduction strategies involve optimizing feed and adopting sustainable soil and crop management practices. The domain of farm machinery plays a critical role in agricultural operations but simultaneously contributes to energy consumption. Electricity, as the foremost energy resource, presents considerable variation in consumption, contingent on farm size and equipment employed (Upton et al., 2010).
Efficient water utilization assumes vital importance due to its multifaceted role encompassing cleaning, cooling, and milk production. The production of one liter of milk from Holstein cattle necessitates approximately 2.7 L of water (Jensen and Vestergaard, 2021). The emergence of technologies for wastewater treatment and water reuse offers promise, although their efficacy depends on robust infrastructure to prevent leakage and maintain water quality. Furthermore, the track of optimization and sustainability is inseparably intertwined with economic considerations, underlining the difference between regions. Advanced technology adoption in Western countries contrasts with resource-constrained settings dependent on traditional, less efficient methodologies.
The panorama of sustainable dairy farming, encapsulating the aspects relevant to this discourse, is visually depicted in Figure 1, as articulated by researchers from Wageningen University (WUR, 2020).

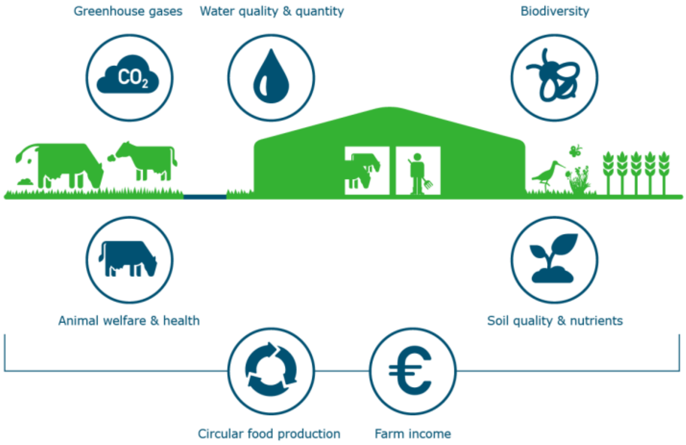

Figure 1: Dairy sustainability topics (WUR, 2020)

3. Steps taken towards sustainability in dairy farming

Dairy farming often emerges as a substantial contributor to global warming, leading to oversimplified judgments. To counter such perceptions, it is important to explore the nuanced trajectory of dairy farming's development and its implications for sustainability. Capper et al. (2009) explained significant advancements in productivity and sustainability within dairy farming between 1944 and 2007. Their research illuminated that modern dairy practices exhibit substantial resource efficiency gains compared to historical counterparts. “Modern dairy practices require considerably fewer resources than dairying in 1944 with 21 % of animals, 23 % of feedstuffs, 35 % of the water, and only 10 % of the land required to produce the same 1 billion kg of milk. Waste outputs were similarly reduced, with modern dairy systems producing 24 % of the manure, 43 % of CH_4, and 56 % of N_2O per billion kg of milk compared with equivalent milk from historical dairying. The carbon footprint per billion kilograms of milk produced in 2007 was 37 % of equivalent milk production in 1944.” (Capper et al., 2009). Their study, conducted in the US, showcased a reduction in resource requirements, waste outputs, and even carbon footprint per billion kilograms of milk produced. These findings, while US-focused, offer insights likely applicable to the European context. Similarly, European investigations such as Damiens et al. (2020) have examined dairy farming progress across six European countries. While outcomes vary across nations, the shared pursuit of sustainability underscores the significance of region-specific approaches.
An overarching consensus emerges from various studies, advocating the integration of sustainability dimensions into farming assessments. Lovarelli et al. (2020) identified that Precision Livestock Farming (PLF) generates ecological, economic, and social benefits, although quantification through specific sustainability assessment methods remains a critical avenue for future research. This trajectory of investigation necessitates not only

technological advancements in sensors and tools but also a comprehensive understanding of the environmental, economic, and social dimensions that resonate with farmers, communities, and consumers alike.
Zimmermann (2008) examined optimizing sustainable dairy cow feeding systems, highlighting the significant role of feed production in the environmental landscape of animal husbandry. Integrating life cycle assessment (LCA) and social indicators within a farm-level linear optimization model facilitated the evaluation of dairy cow feeding systems' sustainability. These multidimensional approaches allow for informed decisions considering various objectives within the optimization process. Further discussing the issue, de Vries and de Boer (2010) provide an extensive exploration of the utility and methodology of LCA, explaining its potential to comprehensively evaluate dairy farming's environmental impact.

4. The use of digital technologies in enhancing the sustainability of dairy farms

Drawing from a study by Lovarelli et al. (2020), the global proliferation of Precision Livestock Farming (PLF) transcends intensive and extensive livestock systems. While PLF's incorporation is a relatively recent development, the mounting significance of technological support on farms is driving its dissemination. Research and scientific inquiry have extensively explored the adoption of technology, sensors, and computer tools across various species (Lovarelli et al., 2020). The dairy sector has witnessed a distinct improvement in digital solution utilization designed to enhance dairy farms' efficiency, productivity, profitability, and sustainable practices.
Integral to this evolution are specific hardware devices, including sensors, pedometers, and other wearable technologies. These devices empower farmers to promptly discern potential health issues, mitigate disease transmission risks, optimize insemination timing, and refine feed management practices. The consequential outcomes incorporate heightened animal welfare, amplified milk production, and reduced environmental footprints. A promising frontline lies in the deployment of cameras as data sources. AI-assisted camera vision holds promise in assessing cattle conditions and monitoring feed consumption patterns.
It's essential to underscore that these solutions while possessing limited intervening capabilities in isolation, offer invaluable data and information. This dataset serves as a cornerstone for both human operatives and autonomous equipment, providing the necessary input for their respective operations. As an illustration, modern computer-controlled barn ventilation systems can capitalize on location-specific microclimate measurements to calibrate their functionality, leveraging nuanced indices like temperature-humidity index (THI) to optimize ventilation strategies. The precision of THI in determining cattle comfort surpasses mere temperature metrics, and its non-invasive nature reduces costs, offering a superior alternative to invasive measures like feeding boluses to animals.
There are several digital solutions available for monitoring circumstantial parameters, applying profound influence on farming sustainability. The convergence of microclimate measurement and farm-wide equipment monitoring provokes transformative change by leveraging automated measurements and transforming raw data into actionable insights. The ability to gather, interpret, and extrapolate appropriate conclusions from this data remains fundamental, though challenging.

4.1 Microclimate monitoring

Weather stands as a prominent cause shaping dairy farming outcomes. Cattle's sensitivity to climate concentrates on weather fluctuations, a crucial aspect impacting their overall well-being, with consequential implications for milk production. This reality holds even within intensive dairy farming contexts. A significant portion of barns remain insufficiently insulated from external weather, leading to a direct influence of external conditions on livestock's climatic environment. The contrast between external weather and indoor climate can be stark, as illustrated in Figure 2.

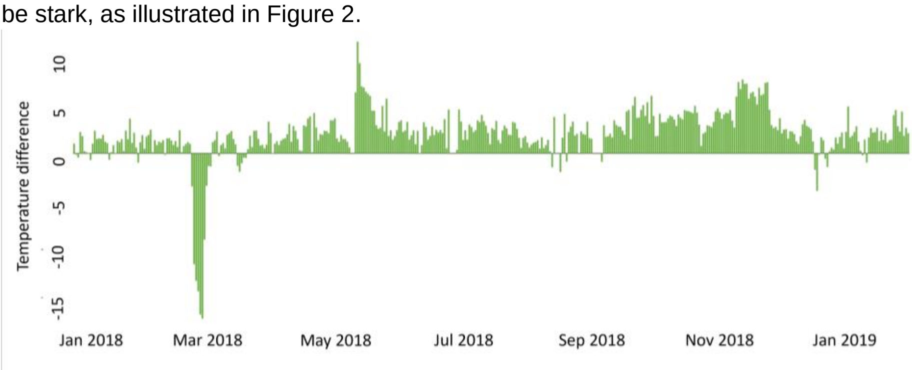

Figure 2: Difference between the external (meteorological) temperature and sensor-measured, inner-barn temperature (Data measured by Cubilog Ltd. during one year at a dairy farm in Western Hungary, figure by Tarr)

Instead of using average and approximate calculations, sensor-driven, location-specific, real-time microclimate monitoring emerges for determining the climatic conditions affecting cattle in the barn or at a certain location within the barn. To this end, temperature, humidity, and barometric pressure sensors are strategically positioned within barns to capture precise data. This data corpus facilitates the computation of the (THI) for the barn or specific zones within it, representing the most suitable measure for quantifying heat sensation. Unquestionably, heat stress constitutes the primary factor contributing to milk loss, historically manifesting between June and August. In recent times, however, its prevalence has expanded from April to October because of climate change. Predicting the tendency outlined by North et al. (2023), the aggregation of heat stress is anticipated in the foreseeable future. In this context, leveraging microclimate monitoring and advanced measuring methodologies becomes instrumental in preventing and mitigating the risks of heat stress. Observations across multiple dairy farms underscore the potential of environmental sensors to curtail milk loss by approximately 30 %. Transitioning from a season-based, temperature-oriented control paradigm to a THI-centric approach in barn climate management emerges as a transformative strategy. The sensible operation of ventilators and targeted supplementation of dairy feed with specialized electrolytes, informed by real-time microclimate insights, retards the escalation of heat stress impacts while fortifying cattle's water equilibrium.
Another captivating side of data-driven monitoring resides in its potential to unveil correlations through sustained data collection and analytical examination. Historical analysis, for instance, can verify whether the adverse implications of elevated barometric pressure on milk yields can indeed be counterbalanced through the realization of optimal humidity levels, as depicted in the heat map in Figure 3.

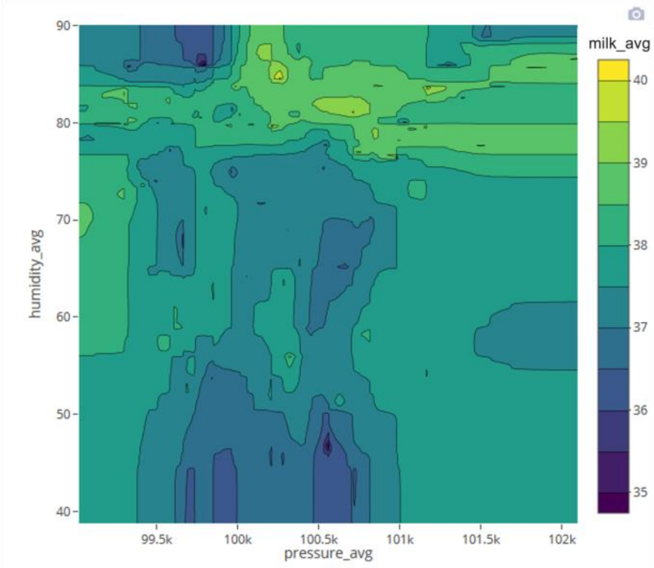

Figure 3: Complex Historical Data Analysis Example. It illustrates the intricate relationship between humidity and barometric pressure concerning milk production across a specific timeframe. Higher humidity levels aligned with relatively elevated barometric pressure exhibit a positive correlation with milk yield. Conversely, lower humidity levels in tandem with high barometric pressure are associated with diminished yields. (Based on data from a dairy farm in Western Hungary measured by Cubilog Ltd., figure by Tarr)

Further sensors can extend their utility to measure ambient light levels, specific gas concentrations, air movement dynamics, and additional relevant parameters. These nuanced factors collectively exercise an impact on cattle productivity, offering chances for adjustment where infrastructural feasibility permits. The amassed dataset, as exemplified in Figure 3, lends itself to visualization and analysis.
Sustainability is greatly enhanced by location-specific microclimate information, which can direct the use and fine-tuning of various energy-intensive barn equipment such as ventilation or humidification. Data-informed control mechanisms engender heightened adaptability to climatic nuances while optimizing energy consumption, thus enhancing cattle well-being and reducing the environmental footprint.

4.2 Farm-wide equipment monitoring

Efficient farm machinery monitoring stands as a formidable tool in ensuring optimal operational performance and security. By harnessing technologies and methodologies from the Industry 4.0 framework, farm operation monitoring transplants advanced practices into the agricultural context. The heart of this endeavor lies in the attentive tracking of equipment-generated data, culminating in the explanation of operational parameters and the early detection of malfunctions. Remote machinery and pump monitoring offer preemptive capabilities, alerting operators to potential risks and promptly notifying them of faults. This proactive approach expedites the problem identification process, facilitating swift interventions.

Of paramount importance is the surveillance of feed- and manure-management-related machinery. The seamless functioning of these systems is critical for farm sustainability, as failures can cause profound functional and ecological ramifications. Additionally, consumption monitoring stands as a valuable area for comprehending machinery operations and upkeep requirements. Insight gathered from Upton et al. (2010) reveals that farms exhibit an average electricity consumption range of 0.57-1.04 kWh/cow/day. While a substantial portion powers milk cooling, other energy-intensive activities, such as ventilation in cross-ventilated barns, are also notable contributors. Water consumption tracked either at drinkers or barn levels, offers a crucial aspect for analyzing milk production trends and unearths anomalies like leakage within water systems.

The granularity of consumption measurements gives farmers the insight to identify instances of overconsumption and suboptimal system utilization. Armed with data interpretations, farmers can plan interventions with tangible impacts. Noticeable savings emerge through targeted measures, such as curbing standby electricity consumption caused by equipment misconfigurations. Energy expenditure persists even when production is inactive due to faulty settings. Moreover, the combination of renewable energy integration and equipment upgrades works in harmony to enhance efficiency. A growing body of energy-focused research, exemplified by Maffini et al. (2023), sheds light on the effectiveness of these optimization approaches and the integration of alternative energy sources.

Farm machinery monitoring solutions operate synergistically with existing control systems, supplementing security surveillance through camera systems and dispatch services. This operational symbiosis empowers interventions via staff or autonomous control mechanisms informed by data derived from monitoring solutions. The information gained from these systems goes beyond operational awareness, highlighting details that might otherwise go unnoticed.

Extending this to all farm machinery provides a full picture of equipment management. Studies show that using monitoring systems can lead to around 30 % less energy use, improving sustainability. This information also helps create more savings, boosting farm efficiency and supporting sustainability efforts.

4.3 Integration of the various digital solutions to multiply positive effects

While individual digital solutions tailored to specific tasks can enhance farming operations, even greater potential emerges when these solutions are seamlessly integrated with sensor-driven data. The data collected from diverse autonomous digital systems can be aggregated within an application or dashboard, furnishing not only contextual visualization but also comprehensive reports and analyses amplified by AI-driven advanced analytics. This incorporation of data from various sources provides a nuanced understanding of how distinct variables influence both farming and sustainability, offering a streamlined experience for farmers.

However, a significant challenge in this data integration journey is the reluctance of many technology providers to engage in collaboration, thus impeding seamless data access and utilization. The insights assembled from meticulous data analysis provide invaluable takeaways, stimulating advancements in genetics, feed optimization, and cattle housing conditions. Many untapped opportunities are on the horizon, ready to drive significant progress toward more sustainable dairy farming.

5. Conclusions

Looking at the operation of dairy farming, we have seen that major developments have been realized over the past decades, affecting the efficiency and sustainability of farming. More conscious and effective milk production requires the implementation of digital solutions, including location-specific microclimate and farm machinery monitoring. These sensor-based digital solutions enhance operational security and contribute to animal welfare, resource efficiency, and cost reduction by providing data for decision-making and proper interventions. Sustainability can be achieved and enhanced by reducing energy use by 5-30 %, optimizing feed distribution, and applying preventive actions based on the analysis of acquired data. Savings in milk production can contribute to the increase of farm income by up to 8-15 %. In most cases, the implementation costs of these solutions return within one year. The integration and collaboration of digital systems can highlight new correlations and multiply the positive effects of the use of data. We believe that all these developments will spread shortly, regardless of the size of the dairy farm, thus increasing the efficiency and sustainability of production.

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