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Advancing Dairy Cattle Farming: Integrating Herd Management, Automation and Artificial Intelligence for Elevated Productivity and Sustainable Practices

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Abstract: Effective management of dairy cattle herds constitutes a nuanced and intricate process, demanding a blend of technical proficiency, meticulous attention to animal well-being, quality assurance, and continuous monitoring of worker productivity and welfare. The successful execution of these tasks requires a thorough evaluation of diverse data using a well-defined logic, necessitating a professional approach to ensure precise decision-making. The integration of herd management systems, automation, and artificial intelligence applications has become increasingly vital within the realm of dairy farming. These advanced tools are becoming increasingly indispensable and play an important role in guaranteeing the sustainability and profitability of milk production in both the short and long term. From optimizing herd health to streamlining production processes, these innovative technologies contribute significantly to elevating the overall efficiency and sustainability of dairy farming operations. This review aims to examine the evolution and contemporary advantages of herd management systems, automation and artificial intelligence applications in the context of dairy farming.

Keywords: Artificial intelligence, Herd management, Husbandry.

Süt Sığırcılığında İlerleme: Sürü Yönetimi, Otomasyon ve Yapay Zekâ Entegrasyonu ile Artan Verimlilik ve Sürdürülebilir Uygulamalar

Özet: Süt sığırı sürülerinin etkin yönetimi, teknik beceri, hayvan sağlığı ve refahına dikkat, kalite güvencesi ve işçi verimliliği gibi unsurları içeren karmaşık bir süreçtir. Bu görevlerin başarılı bir şekilde yerine getirilmesi, çeşitli verilerin iyi tanımlanmış bir mantık kullanılarak kapsamlı bir şekilde değerlendirilmesini gerektirir ve kesin kararlar alabilmek için profesyonel bir yaklaşımı zorunlu kılar. Sürü yönetim sistemlerinin, otomasyonun ve yapay zekâ uygulamalarının entegrasyonu, süt hayvancılığı sektöründe giderek daha hayati bir rol oynamaktadır. Bu gelişmiş araçlar giderek vazgeçilmez olmakta ve süt üretiminin sürdürülebilirliği ile karlılığını hem kısa hem de uzun vadede garanti altına almada önemli bir rol oynamaktadır. Sürü sağlığını optimize etmekten üretim süreçlerini kolaylaştırmaya kadar, bu yenilikçi teknolojiler süt sığırcılığı operasyonlarının genel verimliliğini ve sürdürülebilirliğini önemli ölçüde artırmaktadır. Bu derleme, sürü yönetim sistemlerinin, otomasyonun ve yapay zekâ uygulamalarının evrimini ve yenilikçi avantajlarını özellikle süt sığırcılığının karmaşık bağlamı içinde incelemeyi amaçlamaktadır.

Anahtar Kelimeler: Yapay zekâ, Sürü yönetimi, Hayvancılık.

1. Introduction

Animal husbandry has been an integral part of human economic activities since time immemorial. As society's awareness of the importance of balanced nutrition grew, animal breeding evolved into a multifaceted endeavor, giving rise to intensive livestock enterprises focused on optimizing the yields of meat, milk, wool, and eggs. In these modern enterprises, a paramount concern is the welfare of the animals, while technology and machinery are harnessed to achieve this goal (1, 2).

In such livestock enterprises, an array of tasks, from herd management and insemination pairings to addressing temperature stress and fertilizer management, from maintaining udder health to monitoring estrus and fertility, as well as observing animal behavior and selection, are now conducted in digital environments. Modern animal husbandry encompasses the meticulous collection of data on productivity, behavior, and disease. Electronic identification materials, such as RFID tags, sensors, and cameras attached to animals' ears, ankles, and necks, record an extensive range of information, including the number of ruminations, movements, heat cycles, live weights, birth times, lying and standing times, feed consumption, body condition scores, milk yield and characteristics, feeding times, body temperatures, and various other parameters (3-6). Moreover, mechanization has greatly improved efficiency through the

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use of milking units, total mixed ration (TMR) preparation machines, and calf feeding robots, all managed through automation infrastructure (7). While these technologies have revolutionized data collection in modern animal husbandry, the current data primarily provide insights into the present situation, lacking predictive or prescriptive capabilities for the future.

In dairy cattle farming enterprises, farm management is an especially intricate affair compared to other livestock operations. It demands a professional management style rooted in technical expertise, effective use of automation systems, and a keen ability to analyze the diverse data within a well-structured framework. Farm management is fundamentally about collaboration, organization, and specialization in farming activities, with the overarching goal of maximizing long-term profitability and achieving the enterprise's objectives (8).

Herd management within dairy cattle farming is of paramount importance, as it is a perpetual cycle that encompasses all stages from calf birth to their development into heifers and cows, as well as the tasks required for production and market readiness (9). The principal aim of herd management is to oversee the herd professionally, ensuring the welfare, comfort, and productivity of the animals. Irrespective of the herd size, these enterprises systematically gather information about various aspects of their animals, evaluate it based on their intended purposes, and make informed decisions for the betterment of the enterprise. This cycle is reiterated annually. The success of the enterprise hinges on the decisions made by the herd management business manager, encompassing goal setting, resource allocation, planning, implementation, assessment, and review (10). Within the enterprise, key managerial units should be established, including those for production, business, finance, marketing, employees, and data acquisition and analysis. It is the responsibility of the business owner to make crucial decisions in a timely and effective manner, ensuring the establishment and profitable operation of these enterprises by orchestrating necessary adjustments, preparations, measurement and evaluation, implementation, and activities (11).

The farm manager is instrumental in making these decisions within the broader framework of these goals, which often involve setting specific objectives. In farm management, there is no one-size-fits-all approach, as the farm manager must employ the most suitable problem-solving methods and stay attuned to developments that provide optimal solutions to their questions. While farm management practices may exhibit some regional variations, they are ultimately bound by a global economic context, necessitating an awareness of both local and global sector developments. Like crop production, human, physical, and economic factors play pivotal roles in animal production (12). Managing dairy cattle enterprises and herds today is a complex task that demands expertise across multiple domains, including zootechnics, production, human resources, and marketing. In this competitive environment, it underscores the crucial need for experienced individuals who have dedicated themselves to this field (13). A competent business manager should possess the ability to promptly access essential information and bridge knowledge gaps effectively.

Achieving sustainable success in herd management goes beyond just managerial skills; it necessitates the comprehensive assessment of factors such as capital, labor, and the productive potential of the animals in question. Agriculture and animal husbandry play pivotal roles in providing humanity's fundamental food needs. In Turkey, bovine and ovine breeding are conducted either together or separately, depending on regional and ecological considerations. Dairy cattle breeding holds a prominent position in the Turkish economy (14). Operating dairy cattle enterprises entails a profound understanding, skill set, capabilities, and financial resources for tasks like enterprise management, herd management, animal care and feeding, product diversification, and marketing (15).

Livestock automation systems are instrumental in a range of areas, serving purposes such as minimizing errors stemming from human intervention due to the dairy cattle industry's sensitivity, optimizing costs under current conditions, diagnosing animal ailments, conducting daily care and feeding efficiently, ensuring safe product retrieval from production, enhancing animal welfare, monitoring estrus and pregnancy, evaluating animal behavior, tracking production levels, and ensuring food safety and health (16). These automation systems are primarily integrated into herd management systems. Given the intensification of dairy cattle farming, herd management has become increasingly intricate for business owners. To make well-informed decisions concerning the herd, it is essential to gather more data on individual animals (17). Technological applications have transformed herd management from a group-oriented approach to an individual-focused one (18). These technological applications enable constant oversight of the production process by employing automatic animal recognition, detection, measurement, and computing technologies. This, in turn, optimizes outcomes related to profitability, health, quality, product safety, animal welfare, and environmental conservation (19). When information technology, particularly computers, forms the backbone of herd management systems, they are often referred to as computer-aided herd management systems. The components integrated into these systems include electronic animal identification systems (RFID), automated milk measurement integrated into milking systems, automatic animal weighing systems, activity meters, automated intensive feed units, roughage and water consumption measurement systems, feed mixers with electronic scales, image analysis systems,

ultrasonographic imaging devices, yield analysis systems, herd management software, and internet connectivity (20).

Herd management systems implemented in dairy cattle breeding play a pivotal role in promoting sustainable milk production within the enterprise. They offer economic and ecological advantages while upholding high standards of environmental preservation, animal welfare, and consumer protection, along with ensuring top-tier quality benchmarks (21). The adoption of herd management systems offers a multitude of benefits, including minimizing the physical and psychological burdens on breeders, enhancing the overall success of the enterprise, reducing risks, optimizing resource utilization, ensuring the animals' needs are met to the fullest extent, providing human support for herd management tasks, enabling early disease detection, reducing the reliance on medications through early diagnosis and preventative measures, and harnessing the full potential of individual animals (22). These systems also provide breeders with more reliable data for animal selection, herd projections, and future planning. In dairy cattle farms, the utilization of these systems holds immense economic significance, particularly with larger herd sizes. Advanced herd management systems should deliver both economic and technical benefits to breeders, animals, and consumers. To realize these benefits, it's imperative to effectively implement and fully utilize the system, actively incorporating the vast amounts of data collected from various animals swiftly and accurately into decision-making processes concerning herds and individual animals. Users should also demonstrate proficiency in utilizing the hardware and software components of these systems (8).

In the contemporary context, technological advancements have led to the replacement of manual labor by machines. Concurrently, the development of computer systems and software has introduced subject areas like herd management systems, robotic systems, and artificial intelligence applications into the realm of animal husbandry. The prevailing approach focuses on harnessing technology efficiently to minimize workforce reliance and human errors, thus ensuring maximum productivity based on an array of numerical data obtained through herd management systems. It has been established that artificial intelligence applications, image-processing-based systems, and autonomous farming systems have the potential to reduce human error significantly while substantially enhancing the speed and quality of farm production. Artificial intelligence systems capable of autonomous decision-making in existing farms can identify animal diseases, optimize production, and enhance animal feeding (23). This study underscores the benefits of herd management and artificial intelligence applications in livestock farms, particularly within the context of dairy cattle farming, in light of the burgeoning advancements in computer technology.

1.1. Herd Management in Livestock

Recent advancements in computerized data recording techniques have significantly improved herd management systems. These technologies have streamlined the monitoring of herd health, productivity, performance, and production parameters. A variety of computer software programs have been specifically designed for use in large herd operations. These programs aim to enhance farm management and maximize farm income by analyzing reproductive health in dairy cattle and estimating the costs associated with increasing dairy substitutes. These software packages have been tailored to work seamlessly on various microcomputers (24).

In herd management systems, all animals in the herd, including those born on the farm and those introduced from external sources, are recorded with the assistance of a technician. Daily events, such as births, deaths, measurements, weighings, health assessments, and feeding records, are meticulously entered into the herd management system by the relevant technician. Herd management systems, like herd follow-up, enable objective evaluation of farm management decisions regarding the herd, breeding, and health procedures. This evaluation is based on a solid foundation, allowing for the identification of any deficiencies or areas for improvement. For a herd management system to succeed, the farm must recognize its benefits and assess it comprehensively. Successful implementation of this computer-based system at the farm level and maximizing its benefits are contingent upon breeders receiving proper training in system usage. Veterinarians must provide regular consultancy services on the farm. (25, 26).

Under the herd management system, detailed records are kept on aspects such as animal births, live weights at various stages, yield characteristics, health-related data, daily feeding practices, and environmental influences. These records play a vital role in ensuring the future productivity and health of the herd. They support practices such as health management, feed supply, feeding programs, animal breeding strategies, quality milk production, worker performance monitoring, and tracking income and expenses. These systems not only reduce the need for human labor but also minimize the potential for human errors (27).

Through the effective use of electronic animal identification, detection, measurement, feeding applications, and record-keeping technologies integrated into herd management systems, especially in commercial and large dairy cattle operations, continuous control of production processes has been achieved. Consequently, optimal results in terms of profitability, health, quality, product safety, animal welfare, and worker productivity and health have been realized. These systems also incorporate advanced technologies for production, fertility control, product quality, nutrition,

reproduction, and animal health management in dairy cattle (28).

1.2. Automation in Animal Husbandry

When considering the spheres of economic management, labor, productivity, and cost, agriculture and animal husbandry assume paramount significance. However, these domains also present considerable complexities. In the contemporary context, marked by technological progress, the incorporation of automated management systems into these sectors has become an imperative, paralleling the adoption of automation in other industries. These systems assume a pivotal role in herd surveillance, optimization of economic efficacy, enhancement of animal health, delineation of augmented yields, assurance of production quality, and expeditious, accurate decision-making across extensive and commercially-oriented livestock enterprises (29, 30).

The reception of automated herd management and automation systems within dairy cattle breeding hinges decisively on their cost-effectiveness for practitioners. In other words, the economic feasibility of modern automatic herd management and automation systems in animal husbandry must be appraised to guide investment deliberations. Globally, a trend is discernible wherein automation has gained ground at various junctures of dairy farming. Central to this shift is the amelioration of labor costs and physical exertion (31). Automation has found favor due to its resonance with the contemporaneous trajectory toward fewer yet larger herds, slenderer profit margins relative to yesteryears, and the consistent advancement of cost-effective extant Technologies (32).

In the broader conceptualization, automation encompasses the utilization of machinery, control systems, and information technologies, with the overarching aim of heightening production efficiency Automation is conceived as a proactive approach to dairy farm management, endowing dairy farmers with the capability to oversee expansive herds, economize time, and garner perspicacious insights. It is crucial to underscore that automation systems and technologies, per se, do not proffer direct problem resolution but function as discerning indicators, revealing areas warranting amelioration. From this vantage point, automation confers an array of merits, including augmented profitability, enhanced animal welfare, amelioration of lifestyle, and fortification of milk quality (19).

Presently, the realm of herd management and integrated automation systems predominantly assumes a computerized character, whereby numerous corporate entities have engendered software tools tailored for deployment in agricultural establishments of the livestock domain. Recent iterations of these software packages span diverse categories, encompassing breeding-focused software, programs oriented toward livestock breeding and comprehensive data capture, management, and accounting software purposed for the perpetuation of current records spanning the pivotal facets of cattle husbandry (33).

These software solutions have instituted the integration of supplementary elements into herd management systems. These include electronic animal identification, quantification of milk yield, timing of milking processes, measurement of milk flow rates, evaluation of milk electrical conductivity, and the assimilation of automated milk measurement systems into the milking framework, thereby affording data pertinent to milk temperature. Moreover, ancillary components involve activity meters, automatic animal weighing systems, estrus tracking systems, automatic mixed-feed units, feeder systems equipped with instrumentation for measuring roughage consumption, water consumption-measuring drinker systems, roughage-intensive feed mixers and distributors equipped with electronic scales, image analysis systems, and data analysis systems (19, 34).

Automation technologies usher in a regime of precise data accrual at the level of individual animals on agricultural holdings, thereby facilitating the efficacious management of larger herds. Herd management systems are underpinned by state-of-the-art instruments that accumulate data, thereby furnishing farm custodians with the informational substratum requisite for judicious decision-making. The systematic elucidation of these systems, as delineated by Schulze et al. (2007) and Rutten et al. (2013), unfolds across four key phases (35, 36):

Sensors, tasked with data generation through the measurement of specific parameters pertaining to the animals, for instance, cow activity.

An algorithm, which harnesses sensor data to yield informational insights concerning the animals. In this stage, raw or processed sensor-derived data may be amalgamated with non-sensor data.

A managerial decision-making framework, which synthesizes information from the antecedent phase with supplementary data, spanning technical, economic, and comparable domains. The culmination of this phase yields actionable recommendations.

The execution of decisions, which transpires either through the agency of the farmer or autonomously via the system, exemplified by the management of a cow's access to a milking robot.

However, it is requisite to acknowledge that these systems exhibit certain limitations. These limitations encompass the interpretational intricacies inherent in the data emitted, a consequence of the distinctiveness of each cow, in conjunction with the challenge posed by the notable volume of false alarms, impeding the pragmatic implementation of

extant models for disease and mastitis detection, grounded in data collated by various sensors (e.g., milk yield, electrical conductivity, activity, and analogous parameters) (36). Decision-making should rest upon a foundation of cogent scientific principles and standardized operating procedures intertwined with the intelligence proffered by the herd management system. Beyond these, key determinants that galvanize the functionality of these systems in agricultural settings span the spheres of investment costs, socio-economic dimensions, time considerations, and the anticipated return on investment (35).

1.3. Artificial Intelligence in Animal Husbandry

The early stages of the industrial revolution aimed to develop machinery capable of substituting human physical strength. With the advent of industrialization, various purpose-built machines were introduced into society, gradually replacing human labor over centuries due to their superior performance. As technology continued to advance, the realm of human work and cognitive processes saw a transformation through the integration of artificial intelligence (AI) techniques. AI is a method designed to create devices that mimic the functionality of the human brain, understanding how the human brain functions, processes sensory input, interprets stimuli, and draws conclusions based on stored knowledge. Following data reception, these AI systems can generate responses by formulating novel ideas and offering the best possible solutions. Current examples of such AI-powered devices or machines include computers and robots. AI approaches endeavor to replicate human-like intelligence and problem-solving capabilities in machines (37).

In the context of digital agriculture, AI plays a pivotal role in the application and integration of digital data, sensors, and tools throughout agricultural practices, spanning from the farm to the end consumer. This technology encompasses various components, including big data, sensor technology, sensor networks, remote sensing, robotics, and unmanned aerial vehicles (UAVs). The processing of collected data is now achieved through cutting-edge technologies like computer vision, machine learning, and artificial intelligence, among other methods. The application of AI is poised to benefit not only high-tech systems like milking equipment but also traditional dairy farms, enhancing their competitiveness in the future (38).

An illustrative study demonstrates the use of AI in regulating the ambient temperature for animals through water spraying, reducing heat stress. To implement this cooling system, an AI system leverages data from meteorological stationsand information about individual cows, combined with environmental factors. This system automatically adjusts the cooling parameters to meet desired volume and milk quality thresholds in dairy farms based on relevant data. Additionally, the system autonomously controls gates to direct individual cows to cooling systems with water sprinklers to mitigate heat stress or to standard milking parlors (39)

Biometric sensors are pivotal in herd management technologies and automation systems. They continuously monitor the health and behavior of individual animals in real time, enabling farmers to integrate this data for population-level analysis. Real-time data from these biometric sensors can be processed through big data analytics systems using statistical algorithms, yielding trend models and decision-making tools that empower breeders (40). These technologies facilitate secure and verifiable traceability of animal products from farm to consumer, offering a significant advantage in disease outbreak monitoring, economic loss prevention, and food-related health issues. They contribute to greater transparency in animal production, fostering increased consumer confidence. To harness the full potential of next-generation technologies, predictive analytics platforms are required, capable of sifting through vast datasets with a high degree of confidence while accommodating specific variables accurately and accessibly. Additionally, addressing data privacy, security, and integration issues remains paramount (41).

The agricultural sector is presently in the midst of a rapid digital transformation, with increasingly sophisticated technologies such as artificial intelligence (AI) and computer vision taking center stage. Within this context, computer vision, a fundamental facet of AI, has emerged as a pivotal enabler of precision agriculture. By harnessing high-quality imagery captured by remote cameras, computer vision has facilitated the automation of various agricultural operations, ushering in the era of smart agriculture. In particular, computer vision methodologies, in conjunction with herd management and automation systems, are being comprehensively employed to furnish comprehensive insights into the health and performance of individual animals (29). Such systems offer real-time data that aids farmers in making strategic decisions. Notably, recent research has focused on the implementation of computer vision for the recognition of livestock behaviors, exemplified by the works of Bello et al. (2021), Kumar et al. (2017), Qiao et al. (2019), and Shen et al. (2020) (42-45). For instance, a notable study by Xiao et al. (2022) involved the use of a modified Mask-RCNN model, trained through the fusion of Mask-RCNN and support vector machines (SVM), to identify cows within a barn (46).

Conventional animal record-keeping on medium-sized farms has been characterized by a time-intensive process. In contrast, contemporary methods involve the widespread use of small chips implanted within animals, which can be promptly scanned when the animals pass through a reader or designated location. This approach enables the computerized retrieval of pertinent information, including details related to

age, breed, sex, pedigree, and health records, offering a marked improvement in efficiency relative to traditional record-keeping practices. Furthermore, the advent of ultrasound technology has revolutionized the precise determination of pregnancy in inseminated cattle and the diagnosis of a spectrum of animal maladies (37).

As the awareness of animal welfare and emotional states in farm animals continues to mount, there exists an imperative to develop effective and precise monitoring techniques. Presently, there is a notable dearth of scientifically validated criteria for the quantification of transient emotional states in farm animals, as well as a conspicuous absence of established metrics for the assessment of animal well-being. Biometric sensor data, driven by AI, is emerging as a non-invasive solution for the monitoring of livestock. Notably, social network analysis has begun to gain traction as a means of modeling emotional dynamics and contagion among animals, facilitating the collection of extensive data pertaining to livestock emotions at the group level. AI technologies are playing a pivotal role in recognizing and comprehending the emotional states of animals, thereby facilitating improvements in their well-being and overall productivity (29).

Recent research endeavors have been directed towards the modeling of physiological responses in Holstein Friesian cows, encompassing parameters such as rectal temperature and respiratory rate, through the utilization of neural networks grounded in AI and neuro-fuzzy networks. These models exhibit predictive capabilities with regard to these physiological variables and, as such, have the potential to contribute significantly to the decision-making process (40). Moreover, contemporary investigations have explored the application of computer vision and machine learning for the prediction of parameters including heart rate, respiratory rate, eye temperature, milk production, and quality. These technologies have demonstrated efficacy in the enhancement of animal welfare and stress monitoring (40)

Traditional visual health assessments conducted by professionals and veterinarians can be inherently subjective, costly, and necessitate the presence of trained personnel. Recent advances in remote sensing, computer vision, and AI have paved the way for the development of innovative biometric techniques for the assessment of livestock health and welfare. Additionally, these techniques serve to facilitate livestock identification for the purposes of traceability, as well as the integration of machine and deep learning methodologies to tackle complex challenges encountered within the realm of livestock farming. Notwithstanding prior research efforts primarily centered on model development, there exists an exigent need for the formulation of more efficient, non-invasive, and dependable AI-driven techniques geared towards the assessment of animal health, welfare, and productivity. In this context, it is crucial to advocate for multidisciplinary team collaboration during the stages of model development and deployment, alongside the seamless integration of emerging digital technologies with AI development and deployment strategies. Such an approach is poised to facilitate the efficacious and scalable deployment of AI applications within the domain of animal husbandry (37).

2. Discussion and Conclusion

In conclusion, enhancing productivity and profitability within the realm of animal husbandry necessitates the precise evaluation of the extensive data at our disposal and the ability to make forward-looking predictions. Modern animal husbandry often relies on mechanistic models to assess data within the constraints of the specific system under investigation. These models, however, are primarily valuable for addressing intricate issues with a limited number of variables. The resolution of complex challenges in animal husbandry entails the systematic collection and analysis of vast datasets. To make accurate predictions and forecasts in livestock production, an array of diverse data sets, encompassing factors like weather, air quality, animal vocal signals, and visual animal behavior, must be collected. Given the impracticality of storing and processing such substantial volumes of text, audio, and video data using standard computers, there arises a pressing need for increased computing and storage capacity. This is precisely where Artificial Intelligence technologies, including sensors, big data, cloud computing, and machine learning algorithms, assume a pivotal role. The methodology devised to address business challenges or attain specific objectives, and the associated procedural steps, are collectively referred to as algorithms. Advanced Artificial Intelligence and Machine Learning Algorithms are harnessed for cloud-based analysis of big data, facilitating predictions of future events and recommendations for livestock managers. Big data analytics and machine learning algorithms scrutinize the collected data to detect deviations from standard models and offer insights into prospective developments. These insights can, in certain cases, trigger automated actions, providing individuals with the information needed to make informed decisions. Consequently, the integration of machine learning and human expertise leads to mutually informed decisions. Moreover, the application of these technologies enables the early detection of various diseases by monitoring irregular body movements and diminished activity in animals. The use of artificial intelligence in animal husbandry presents a solution to challenges that may be exceedingly challenging or even insurmountable through conventional means. This not only safeguards animal health but also drives up productivity, thereby ensuring the profitability and sustainability of livestock enterprises.

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