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Review

Precision Livestock Farming Technology: Applications and Challenges of Animal Welfare and Climate Change

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Abstract: This study aimed to review recent developments in the agri-food industry, focusing on the integration of innovative digital systems into the livestock industry. Over the last 50 years, the production of animal-based foods has increased significantly due to the rising demand for meat. As a result, farms have increased their livestock numbers to meet consumer demand, which has exacerbated challenges related to environmental sustainability, human health, and animal welfare. In response to these challenges, precision livestock farming (PLF) technologies have emerged as a promising solution for sustainable livestock production. PLF technologies offer farmers the opportunity to increase efficiency while mitigating environmental impact, securing livelihoods, and promoting animal health and welfare. However, the adoption of PLF technologies poses several challenges for farmers and raises animal welfare concerns. Additionally, the existing legal framework for the use of PLF technologies is discussed. In summary, further research is needed to advance the scientific understanding of PLF technologies, and stakeholders, including researchers, policymakers, and funders, need to prioritize ethical considerations related to their implementation.

Keywords: animal welfare; farming; legislation; livestock; precision; technology

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1. Introduction

Over the past century, there has been a notable increase in animal food production due to rising demand, resulting in approximately 70 billion domestic animals being raised annually worldwide [1]. Every year, over 93 billion animals are slaughtered for human consumption, of which around 56 billion are mammals and birds [2]. According to the Food and Agriculture Organization (FAO), global meat consumption doubled between 1980 and 2002. Projections suggest that global meat production will double from 229 million tons in 1999 to 465 million tons by 2050, while milk production is anticipated to rise from 580 to 1043 million tons [3]. Therefore, every farm will keep more animals to meet consumer demands. A single farm could have 15,000 dairy cows, 30,000 fattening pigs, and several million broilers in the future. However, maintaining a large group of animals can have several implications [1,4].

The livestock industry serves as a fundamental pillar of global food security, with meat, milk, and eggs offering substantial contributions to both calorie and protein provisions on a worldwide scale [5]. Particularly in grazing systems, ruminant meat and milk production play pivotal roles, often utilizing land unsuitable for crop cultivation [6]. Moreover, agriculture provides a livelihood for over 844 million individuals, with the livestock sector significantly contributing to agricultural value-added [5]. Nonetheless, the sustainability of this sector, including its role in ensuring food security, confronts challenges posed by climate change, albeit with uncertain precise impacts [5].

Animal health and the constant monitoring it requires will be a major problem for the livestock sector. Infections in such large groups will become increasingly common. Considering the reduced use of antibiotics and the fact that the development of vaccines takes time and their efficiency in large herds needs to be monitored to improve them, we conclude that keeping large groups of animals on farms could have significant consequences for their health [7]. In addition, animal health is of great importance to human health, as the number of zoonoses that can be transmitted to humans is high. The safety and quality of food must therefore be always guaranteed [8]. Consequently, continuous monitoring of animal health is necessary, but this is difficult to achieve given the decreasing number of farmers and the increasing number of livestock [7,9]. Moreover, the widespread application of antimicrobial drugs in intensive farming practices underscores the pressing need for more sustainable agricultural approaches [10]. Prioritizing animal welfare emerges as a crucial solution to stimulate innovation within the livestock sector, thereby ensuring the preservation of human and animal health, as well as environmental protection [11].

2. Challenges and Demands of the Livestock Sector

2.1. Environmental Concerns

Animal agriculture significantly contributes to greenhouse gas (GHG) emissions and is recognized as a major factor in climate change [11]. The livestock sector is a significant contributor to anthropogenic greenhouse gas emissions, accounting for approximately 14.5% of total emissions [10]. To mitigate these emissions, various strategies involving changes to farming practices have been proposed. However, many commercial farming practices, especially in industrial agricultural systems, raise significant animal welfare concerns, prompting scrutiny from legislative, corporate, investment, and trade organizations worldwide [12].

Beyond concerns regarding animal health within the food industry, the substantial rise in animal product consumption profoundly impacts the environment [4]. A well-managed farm with effective disease control measures can substantially diminish its environmental impact [13,14]. Primarily, it contributes significantly to climate change due to the global greenhouse gas emissions attributed to the livestock sector [10]. Livestock significantly influences climate change through both direct and indirect pathways. Direct emissions encompass methane (CH_4) released from enteric fermentation and manure, whereas indirect emissions stem from feed production, alterations in land use, and transportation [11]. Addressing these emissions is imperative to attenuate the impact of animal agriculture on global warming [12,15]. This results in approximately 7516 million tons of carbon dioxide (CO_2) released annually, making the livestock industry the second-largest polluter after the electricity sector and more polluting than transportation, which contributes about 13% of emissions [16]. Most emissions from the livestock industry consist of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ammonia (NH_3). Domestic animals, as part of natural processes, emit carbon dioxide, which significantly contributes to global warming [17]. Experts caution that livestock rearing may lead us to surpass the 565 gigaton carbon dioxide limit by 2030. Furthermore, the production of beef and dairy accounts for 68% of enterogenic nitrous oxide emissions, a gas with a much higher potential for global warming and ozone layer deterioration than carbon dioxide. Livestock also contribute nearly 64% of total ammonia emissions, leading to acid rain and ecosystem acidification. Moreover, livestock is a major source of methane emissions, contributing 35–40% of global methane emissions. Methane has a significantly higher potential for global warming compared to carbon dioxide. According to the U.S. Environmental Protection Agency, methane emissions from pigs have increased by 37% and emissions from cattle by 50% over the last 15 years [16,18]. Furthermore, not all types of livestock have the same environmental impact, but the production of animal products may necessitate substantial land use. Livestock farms already occupy one-third of the world's total land and over two-thirds of its agricultural land [4]. The growing demand for animal products and limited available land have led to the livestock industry being a primary driver of deforestation, converting forests into grazing areas. According to the International Center for Forest Research (CIFOR), an area twice the size of Portugal was lost to pasture between 1990 and 2000 [4].

Another factor contributing to deforestation is the cultivation of crops for animal feed, with approximately 40% of global crop harvests serving this purpose [19]. Redirecting just half of these crops to feed humans could potentially address worldwide hunger issues. Massive deforestation not only results in habitat loss but also leads to the extinction of numerous plant and animal species, with up to 137 species disappearing daily [20]. Some experts, like Ceballos et al. [21], argue that this ongoing loss constitutes the most significant mass extinction event in the past 65 million years. The primary cause of water pollution in agriculture stems from the production of animal-based food items [4]. The escalating consumption of such products, notably in developing nations, exacerbates the strain on water sources [3]. This pollution arises from various sources within animal agriculture, including animal waste, antibiotics, hormones, fertilizers, pesticides used in feed cultivation, and runoff from pastures [3]. The U.S. Department of Agriculture (USDA) identifies animal byproducts and poultry waste as significant contributors to water pollution [4]. Additionally, the livestock sector is notorious for its substantial resource inefficiency, particularly regarding water consumption [3]. In the United States, for instance, animal agriculture accounts for about 55% of total water consumption, dwarfing the 5% attributed to residential use [22].

One potential strategy for lowering methane emissions is to increase the productivity and efficiency of animal farming. Increased efficiency lowers methane emissions per unit of product and allocates more feed energy toward valuable goods (such as milk and meat) [3]. In this context, selective breeding for high-performing animals—particularly poultry and monogastric animals—is seen as beneficial. As the production of dairy cows demonstrates, increased productivity frequently results in a decrease in the amount of feed required per unit of product. In particular, genetic selection, which has led to a higher milk yield per cow, and dietary improvements in ruminant nutrition (concentrate inclusions) are important factors that contribute to increasing productivity and consequently reducing the carbon footprint of dairy farming [23]. Nevertheless, these nutritional improvements might have unforeseen effects on animal health, like subacute ruminal acidosis or other digestive issues [24]. Even though their manure can be a substantial source of greenhouse gas emissions, pigs and poultry produce relatively less enteric methane. Methane and nitrous oxide (N_2O) emissions linked to the production of manure can be decreased by increasing feed conversion efficiency in these species [11]. Employing precision livestock farming (PLF) technologies and extending the life of dairy cows are two potential strategies to enhance animal welfare and lower emissions. PLF systems can monitor the health and feed intake of animals. In particular, by optimizing feed formulation and delivery, PLF can improve feed efficiency and reduce the amount of methane per unit of meat or milk produced. This can significantly reduce the GHG emissions associated with enteric fermentation. Another advantage of these technologies is that they enable real-time monitoring of animal health and welfare parameters. Early detection of diseases and health problems allows for rapid intervention, reducing the need for antibiotic treatments and minimizing the environmental impact of pharmaceutical residues in water. The precise adjustment of feed rations to the individual needs of the animals, which is possible with PLF technology, also minimizes excessive excretion of nutrients, especially nitrogen and phosphorus [25]. However, it is important to consider the risk of losing husbandry skills and the suitability of PLF in emerging nations [25]. Additional feeding management strategies, including enhancing silage quality, incorporating dietary fats, optimizing pasture management, and implementing precision feeding, present viable means to diminish emissions without compromising animal welfare [12]. These approaches provide pathways for sustainable livestock production, effectively addressing environmental and animal welfare considerations simultaneously.

2.2. Climate Change

Climate change significantly influences animal growth, production, and welfare through diverse mechanisms, including diminished feed intake, physiological and metabolic effects, and alterations in behavior [5,26,27]. These impacts stem from shifts in environmental conditions such as air temperature, humidity, precipitation, and occurrences of extreme weather events, resulting in both direct and indirect effects on animal health [28]. Direct consequences of climate change encompass temperature-related illnesses and mortality, while indirect impacts emerge from alterations in microbial density and distribution, the spread of vector-borne diseases, and the scarcity of food and water [29].

Furthermore, climate change impacts the prevalence of parasitic diseases, particularly gastrointestinal nematodes, which pose significant threats to livestock health. Given that a substantial portion of these parasites' life cycles occur outside the host, their survival and development are highly sensitive to climatic variations. These changes may lead to shifts in parasite distribution and increased mortality and morbidity among livestock populations [30].

2.3. Heat Stress

Exposure to elevated ambient temperatures and humidity primarily induces heat stress in livestock, hindering their ability to dissipate heat to their surroundings, whether on the farm or during transportation. The consequences of heat stress typically manifest as reduced productivity and compromised animal welfare, although severe or prolonged conditions can lead to fatalities. The susceptibility to heat stress varies among animals depending on factors such as species, breed, life stage, genetic makeup, nutritional status, size, insulation level (including hide thickness or feather distribution), and previous exposure. Metabolically, heat stress induces physiological responses, including heightened respiratory and sweating rates, coupled with reduced feed intake, leading to diminished growth rates and decreased milk or egg production [31,32]. Studies in dairy cattle and pigs have revealed that prenatal heat stress diminishes milk yield in the first lactation [33–35] and alters nutrient allocation and carcass composition [36,37]. High-energy-demand individuals and breeds, such as high-yielding dairy cows, are particularly vulnerable to heat stress compared to beef cattle [38–40]. Furthermore, heat stress exacerbates metabolic disorders such as lameness stemming from ruminal acidosis or bicarbonate output, weight loss, ketosis, and liver lipidosis [29,41,42]. Heat stress also impacts fertility in livestock. In mammals and poultry, reduced ovarian function, sperm motility, and embryonic development are common fertility-related issues attributed to heat stress. Cattle and pigs also exhibit diminished estrus behavior, further hindering reproductive success [33,43]. Furthermore, heat stress compromises the quality of animal products, leading to smaller eggs, thinner eggshells [44], reduced fat and protein content in milk [45,46], and alterations in the color and water-holding capacity of both red and white meat [47].

Heat stress-induced oxidative stress exacerbates pathological conditions in animals, as indicated by diminished antioxidant status and heightened levels of reactive oxygen metabolite substances during hotter seasons [29]. Additionally, immune function is compromised under heat stress, impacting lymphocyte function and neutrophil activity and increasing susceptibility to diseases such as mastitis [29]. Heat stress can also weaken immune function and vaccine efficacy, increasing the likelihood of livestock diseases [47–49]. Heat-related mortalities increase during warmer months and extreme weather events, with heat waves being particularly lethal, leading to conditions like heat stroke, exhaustion, and organ dysfunction in both humans and animals [29]. The temperature–humidity index plays a crucial role as a predictor, signaling heightened risks of heat-induced fatalities beyond specific thresholds [29].

Furthermore, increased temperatures and humidity can promote the proliferation of mycotoxin-producing fungi, with growth patterns intricately linked to weather conditions during grain harvest and storage. Mycotoxins, when ingested by animals in significant amounts, can induce acute illnesses affecting multiple organs, including the liver, kidneys, brain, and reproductive tract. Even at lower concentrations, mycotoxins have the potential to impede growth in young animals and undermine immune function, thereby heightening susceptibility to infections [29].

PLF technologies can play a crucial role in alleviating animal welfare problems caused by heat stress. In particular, these systems can continuously monitor environmental conditions such as temperature and humidity in livestock facilities. Real-time data collection allows farmers to quickly identify and implement proactive measures to prevent or mitigate heat stress [25]. PLF technologies can also monitor individual animal behavior and physiological parameters such as body temperature, respiration rate, and feed intake. By monitoring these indicators, farmers can identify animals suffering from heat stress at an early stage and take targeted action to alleviate their discomfort. Livestock's feed intake and nutritional requirements are affected by heat stress. However, PLF technologies can adapt feeding strategies to the individual needs of the animals, optimize nutrient intake, and minimize the metabolic heat generated during digestion [25].

2.4. Transportation Stress

The long-distance transportation of livestock, frequently undertaken for market and slaughter objectives, encounters heightened vulnerabilities stemming from climate change-induced temperature rises and disruptions in transportation infrastructures. These conditions can exacerbate heat stress during transit, resulting in compromised animal welfare and heightened mortality rates [5]. Such challenges may necessitate the implementation of further regulations regarding animal transport, including constraints on the timing and duration of journeys [5].

Transportation presents a considerable challenge for animals and may result in unfavorable health and behavioral consequences [11]. Despite indications of potential stress-inducing effects, regulations concerning loading and unloading procedures for cattle are currently lacking [11]. In the case of broilers and other poultry, stress during transportation can lead to detrimental welfare outcomes and reduced yields at slaughter [11,50]. Stressful circumstances can weaken animals' ability to combat infections and increase their susceptibility to diseases [51,52].

2.5. Food-Chain Consequences and Sustainability

As outlined above, the livestock sector faces several challenges that could diminish consumer interest in animal products, increase waste, and reduce producer profits. Investing in animal welfare can bring economic benefits by increasing productivity and reducing the incidence of disease, as well as health interventions and mortality rates on farms [53]. Industrial livestock systems that use high-performance animals and intensive production methods are particularly vulnerable to climate extremes and supply chain disruptions. While these systems allow for more efficient disease management and production, they require significant investment in infrastructure to address risks such as heat stress and disease. However, their integration into streamlined value chains also exposes them to disruptions in transportation and energy supply. This highlights the complex relationship between climate change, livestock farming, food security, and the importance of animal welfare [5,53].

Efforts must be made to improve animal husbandry, reduce emissions, increase the efficiency of feed production, and promote sustainable land use to reduce the environmental impact of livestock farming while safeguarding global food security and the livelihoods of millions of people. The introduction of PLF technology is a promising route to sustainable livestock farming. It enables farmers to increase their productivity, reduce environmental damage, secure their livelihoods, and improve animal health and welfare. However, ethical concerns regarding its use remain an important issue.

3. Applications and Benefits of PLF in Livestock Production

PLF technology refers to the application of advanced technologies and data analytics in the management of livestock production systems to improve animal efficiency, health, and welfare while minimizing environmental impact and optimizing resource utilization. PLF typically refers to the utilization of technologies facilitating automated and ongoing monitoring of livestock in real-time. These technologies encompass cameras, sensors, and acoustic devices increasingly integrated with artificial intelligence, enabling data collection and analysis (Figure 1). This strategy enables farmers to make educated choices concerning animal health, welfare, and the sustainability of agricultural practices [7,54].

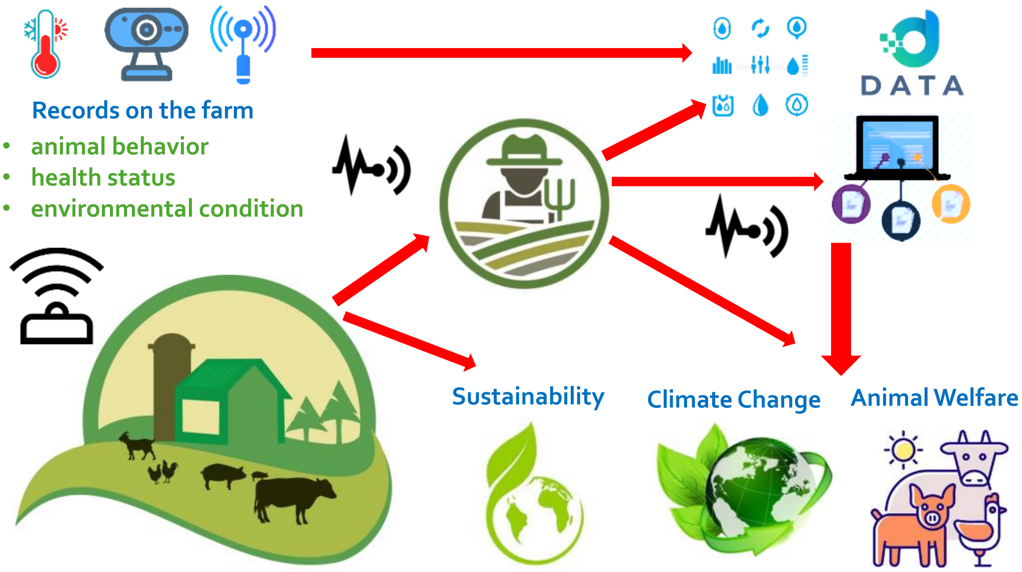

Figure 1. The concept of precision livestock farming (PLF) in modern livestock production.

Sensors play an essential role in PLF technology by gathering real-time data across various aspects of livestock production, including animal behavior, health status, and environmental conditions [7,55]. In particular, they can record movement and resting patterns, feeding behavior, and social interactions between animals and thus observe animal behavior. These sensors can also provide valuable information about the health status of the animals, as they record vital signs such as body temperature, heart rate, respiratory rate, and activity levels to detect signs of illness or stress. In terms of environmental conditions, they can measure factors such as temperature, humidity, air quality, and light conditions in the animals' environment. They are attached to the animals as portable devices, as environmental monitoring systems in barns or pastures, or as drones in the air. The collected data are then analyzed using advanced techniques, such as machine learning and artificial intelligence, to detect patterns and/or anomalies [55]. Decision support systems offer farmers actionable insights and recommendations to optimize management practices [7]. Moreover, PLF technology encompasses automation technologies such as automated feeding systems, milking robots, and waste disposal systems, which streamline labor-intensive tasks and ensure consistent, accurate management of livestock operations. These systems enable remote monitoring and control of livestock facilities via mobile applications or web-based interfaces, allowing farmers to access real-time data, receive alerts and notifications, and remotely manage various aspects of their operation from anywhere with an internet connection [7,25,55]. Additionally, PLF technology integrates with business management software platforms to facilitate seamless data exchange and integration with other business management processes like inventory management, financial planning, and regulatory compliance [55].

Through PLF technology, farmers can recognize signs of stress at an early stage. This is of great value, considering that stress can reduce feed intake and alter the microbial population and fermentation process in the rumen, leading to changes in methane production. In addition, stress triggers hormonal responses and metabolic changes that affect digestive efficiency and methane production [12]. Early detection of stress in livestock farming could, therefore, reduce methane emissions and indirectly curb greenhouse gas production. PLF also enables continuous monitoring of animal welfare. Detecting diseases promptly via abnormal data patterns facilitates swift intervention, thereby reducing suffering and treatment expenses. Moreover, by identifying infections early and monitoring stress levels, farmers can minimize veterinary costs by addressing issues before they escalate [25]. Ultimately, PLF contributes to enhancing animal welfare by promptly identifying diseases and monitoring stress levels. Farms applying PLF technology demonstrate their commitment to animal welfare and environmental protection and can thus improve their public perception. Upholding ethical treatment of animals and sustainable practices fosters trust and community support [7,25,55].

Overall, the utilization of PLF technology can lead to improved animal health and welfare, increased productivity and efficiency, reduced resource waste, enhanced decision-making, and overall sustainability of livestock systems. Particularly, through the incorporation of advanced technologies and data-driven insights, PLF technology has the potential to transform livestock husbandry and contribute to the development of more sustainable and resilient farming systems [25,56].

4. Challenges of PLF in Livestock Production

Despite the opportunities that PLF technologies offer, as they can improve animal welfare, increase production efficiency, and reduce environmental impact, they also present several challenges. In particular, PLF technologies also bring with them various challenges for farmers and animal welfare considerations [54].

4.1. Challenges for Farmers

Technical complexity is one of the main concerns in the validation of PLF technologies. The validation process is crucial as it demonstrates the ability of a system to achieve its goals in realistic scenarios. Given the multifaceted nature of livestock farming, validation requires testing the technology in different environments and circumstances. Challenges such as adverse weather conditions, the location of the animals, and limited internet connectivity in rural areas can hinder data collection, especially in extensive farming systems [53,56]. In addition, issues such as limited battery life and unsuitable building structures are not always compatible with the use of PLF technologies, while dirty or wet conditions can affect efficiency [54,57–59].

Various concerns regarding PLF technologies exist, such as significant investment needs, specialized operational knowledge, and the necessity for advisory assistance. The adoption of PLF may tend to benefit larger farms with more resources, as evidenced by research on robotic milking technologies [60]. Data integration poses a notable hurdle, given that PLF technologies generate specific datasets that could potentially overwhelm farmers and impede effective interpretation [59]. It is crucial to bridge the gap between theoretical promise and practical application, ensuring that farmers can confidently utilize precision farming advantages to enhance agricultural practices and outcomes. Currently, most commercially available technologies work independently of each other and are not interoperable. They generate large volumes of data on animal health, behavior, and performance. Therefore, they can overwhelm farmers when it comes to interpretation and decision-making, as they must have the necessary tools and skills to effectively collect, store, manage, and analyze these data. The intricacy of emerging technologies and the expertise required for their utilization may dissuade certain farmers from embracing them [61]. Additionally, concerns surface regarding the potential adverse effects of PLF on human–animal interactions and stockmanship skills, which could impact animal welfare [62,63]. It can also be a challenge for farmers without experience in data analysis to interpret the data and turn it into actionable insights [57–59].

PLF technology also brings with it various challenges in terms of data protection and security. In particular, its implementation involves the collection and storage of sensitive information, such as records of animal health and farm management practices. Farmers must address these concerns to protect their data from unauthorized access, cyberattacks, and breaches [64–68]. Another hurdle for farmers using precision livestock technology is regulatory compliance and industry standards. Compliance with legal obligations relating to data protection, animal welfare, and environmental protection requires careful attention and adherence to relevant guidelines [58,69]. While precision livestock technology can improve decision-making and productivity, there is a risk of overreliance on automated systems and algorithms. Farmers must maintain their expertise and intuition to accurately interpret data and minimize potential risks associated with overreliance on technology [67,69].

Another problem with the introduction of PLF technologies is the initial cost, which can be considerable. Farmers must purchase specialized equipment such as sensors, monitoring devices, automated feeding systems, GPS trackers, and milking robots, the cost of which can vary depending on type, quality, and quantity [70,71]. In addition, integrating this technology may require upgrading existing farm infrastructure, such as setting up Wi-Fi networks, improving cellular connectivity, or establishing power sources for remote monitoring devices, all of which add to implementation costs [72]. Farmers and farm workers may need to be trained to operate and manage precision livestock technology efficiently. Therefore, training programs, workshops, and technical support services may incur additional costs but are critical to proper implementation and maximizing the benefits of the technology [71,72].

Queries regarding farmers' autonomy and reliance on external devices contribute to apprehensions regarding the transformative impacts of PLF on the agricultural sector, potentially altering its appeal to newcomers [73]. Despite these challenges, PLF technologies possess the capacity to draw in fresh talent and transform farming methods. Nevertheless, addressing these concerns is vital for the responsible and sustainable integration of PLF into livestock farming operations.

4.2. Animal Welfare Considerations

Assessment protocols for animal welfare encompass both animal-based and non-animal-based indicators, focusing on scientifically validated measures that address all aspects of welfare [11]. The European Union (EU)'s Welfare Quality® project has played a crucial role in formulating on-farm welfare assessment protocols, which gauge adherence to fundamental welfare principles such as adequate feeding, housing, health, and behavior [74]. The EU has delineated specific objectives for the livestock sector through initiatives like the Green Deal and Farm to Fork strategies. These objectives entail reducing environmental impact, enhancing animal welfare, and limiting the use of veterinary drugs, particularly antimicrobials [11]. In alignment with its climate commitments, the EU aims to achieve climate neutrality by 2050 and decrease emissions by at least 55% by 2030 [11]. Recognizing animals as sentient beings, the EU and its Member States hold a legal and ethical obligation to prevent mistreatment and suffering [75]. This acknowledgment underscores the escalating societal demand for acknowledging animal dignity and welfare, transcending historical legal perspectives [11].

PLF, an emerging field, is experiencing rapid technological advances without considering the ethical implications for animal welfare and human–animal relationships. It is essential to question the ethical dimensions of the digitalization of modern livestock farming, particularly concerning the human–animal relationship and the risk of objectification [55,76,77].

A key ethical concern is a potential reduction in human–animal interaction due to digital animal husbandry technologies, which could have a detrimental effect on animal welfare. Strong human–animal relationships are central to the efficiency of farming [76]. The use of digital tools in animal husbandry is changing traditional relationships by reducing direct human involvement in animal care and turning farmers into supervisors. Automated systems can, for example, deprive animals of necessary physical contact and socialization, thereby compromising their welfare. Take the example of automatic feeding systems in large pig or poultry farms. These systems are designed to efficiently supply the animals with feed without the need for direct human intervention. While this automation can increase efficiency and reduce labor costs, it also means that farmers have less opportunity to interact directly with the animals. Strong human–animal relationships are central to the efficiency of farming. Specifically, human–animal interaction has benefits for both animals and humans. For the animals, positive interactions with caregivers can reduce stress levels and improve overall well-being. For humans, interacting with animals can provide a sense of fulfillment and connection with the animals in their care [78,79]. It is, therefore, crucial to maintain the relationship between humans and animals and ensure that animals receive appropriate care and social interaction despite digital advancements [80,81].

In addition, there is a risk that animals will be objectified as mere data points through sensing and monitoring technologies [76,79]. Recording and monitoring technologies often focus on quantifiable aspects of animal behavior, such as movement patterns, physiological parameters, or vocalizations. Furthermore, the availability and advancement of recording and monitoring technologies can drive research agendas and bias scientific inquiry towards the capabilities of the technology rather than the needs and interests of the animals or ecosystems [77]. While these data are valuable for understanding animal ecology and behavior, they can oversimplify the complexity of animal life and interactions within their ecosystems. Addressing these risks requires a multidisciplinary approach that incorporates ethical considerations, animal welfare principles, and a broader understanding of animal ecology and behavior [80,81]. Researchers and practitioners must strive for responsible use of measurement and monitoring technologies, recognizing the intrinsic value of animals and the importance of maintaining their welfare and ecological integrity. It is important to recognize the sentience and complex needs of animals, and the application of these technologies must not neglect animal welfare or diminish human responsibility towards them.

The fact that PLF relies on algorithms to analyze data and make decisions raises ethical issues, as it can lead to discrimination and unfair treatment. Algorithms used in PLF can have biases, either due to the data on which they were trained or due to the design of the algorithm itself [79]. Biased algorithms can lead to unfair treatment of animals or inaccurate decisions, affecting animal welfare and farm productivity. In particular, they can overlook the diversity of animal breeds and individual differences in behavior, leading to inaccurate predictions or decisions. In addition, the complexity of these algorithms can make it difficult to understand the decision-making process [76,77]. A lack of transparency can lead to mistrust among stakeholders and hinder accountability for decisions made based on algorithms [81]. Ensuring fairness, transparency, and impartiality of algorithms through regular testing and validation is essential.

Moreover, several studies have highlighted the diversity of production systems, which include variations in species, genetic diversity, rearing environment, and individual behavioral traits such as feeding and drinking behavior [7,55,57,59,62]. So, devices that are not specifically designed for a particular species or repurposed for different species may not always be suitable. There is a risk that such devices may cause physical harm, e.g., by carrying a heavy sensor or influencing animal behavior, especially if multiple devices are carried by a single animal [57]. There is also concern that the introduction of PLF could lead to adjustments in farm management to accommodate the technology rather than prioritizing animal welfare. For example, adjustments such as extended light exposure for cameras or simplification of housing environments to improve camera efficiency could be made [57,62].

4.3. Environmental Impact

While digital animal husbandry promises to improve environmental sustainability by optimizing resource use and minimizing waste, it also brings with it problems such as increased energy consumption, e-waste, and carbon emissions in the manufacture, maintenance, and disposal of equipment [7,55,79]. The manufacture and maintenance of precision livestock farming (PLF) systems can have an indirect impact on soil and water quality through various mechanisms. Hazardous substances, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), may be used during production, which can contaminate soil and water if not handled properly. During maintenance work, the use of chemicals can release pollutants into the environment [55,79]. Some aspects of PLF, such as automated equipment and machinery, can contribute to noise pollution on farms. This could affect both animals and local residents if not managed properly [79]. Furthermore, various electronic devices, sensors, and data management systems are generally used in digital animal husbandry. Energy is required to operate these devices, whether through direct electrical energy or the use of batteries. The data centers and servers required to store and process the vast amounts of data generated by digital systems also consume significant amounts of energy. The energy consumption associated with these activities can contribute to the overall environmental impact, especially if the energy comes from nonrenewable sources [7,55,77]. In addition, PLF devices, like all electronic devices, have a limited lifespan and will eventually become obsolete. The disposal of these devices can lead to a significant amount of e-waste if not handled responsibly. Improper disposal methods, such as landfilling or incineration, can release toxic substances into the environment and contribute to soil, water, and air pollution [76,79]. The use of renewable energy sources, the proper disposal of electronic waste, and the reduction in energy consumption are crucial for reducing the negative impact on the environment [80,81].

5. The Legislative Framework for Animal Welfare and Climate Change

The rapidly evolving agri-food sector, coupled with technological progress and innovation, has further highlighted the need for environmental, social, and governance (ESG) initiatives. Considering the fourth industrial revolution, it is apparent that the incorporation of industrial practices into agriculture and livestock farming, coupled with inadequate education and the absence of legislative regulations, can impact climate change. Within the framework of European integration and the biodiversity strategy for 2030, the European Union is striving to legislate the complex and multilevel agri-food sector. Therefore, to achieve the Sustainable Development Goals (SDGs) outlined in the 2030 Agenda, its efforts are directed towards ensuring animal welfare, limiting industrial pollution emissions, and combating deforestation [82].

Specifically, concerning the ESG dimensions in the agri-food sector, from an environmental perspective, the impacts of livestock farming on climate change are evident. Greenhouse gas emissions, agri-food industry waste, and pollution affect biodiversity, natural resources, and water conservation. From a social perspective, the adoption of measures focuses on addressing pandemics and ensuring food and feed safety, intending to safeguard human health, nutrition, and overall animal welfare. Additionally, within the framework of corporate governance in the agri-food sector, emphasis is placed on the transparency of systems and decision-making processes, as well as on the management, monitoring, assessment, and traceability of animal welfare. It is thus evident that animal welfare and climate change fully align with the ESG aspects and EU's broader goals for environmental sustainability.

In light of the European Green Deal, the EU's Biodiversity Strategy, and the New EU Forest Strategy for 2030, Regulation (EU) 2023/1115 [83] addresses operators and traders within the EU, prohibiting the placing on the European market or export of certain commodities and products (including cattle and animal feed) produced on "deforested" or "degraded lands". The EU's objectives are to minimize its contribution to the "global trend" of deforestation and forest degradation, biodiversity loss, and greenhouse gas emissions.

The Regulation (EU) 2016/429 [8], also known as the "The EU Animal Health Law", is grounded in the sectors of livestock farming and food production, complementing and replacing existing EU rules, providing a single legislative text aimed at addressing animal diseases. Specifically, it establishes the framework for the control, eradication, and prevention of diseases, as well as measures to prohibit the transportation of animals and procedures for slaughter, vaccination, or biosecurity in the event of a new outbreak. It also introduces requirements for traceability, identification, and registration, as well as entry or movement conditions for animals and animal products in the EU. The Member States and competent national authorities, operators responsible for animals, as well as veterinarians and those handling pathogenic agents, vaccines, and other biological products (i.e., laboratories, units, and entities), are responsible for safeguarding animal health. It should be noted that the aforementioned Regulation may not provide direct protection regarding the welfare of animals; however, the indirect link between animal health and their welfare has been recognized. In the same context of disease management, Regulation (EC) No 999/2001 [84] establishes rules for the prevention, control, and eradication of transmissible spongiform encephalopathies (TSEs) at every stage of production, distribution, and export of animal and animal products. To achieve the objectives set by the aforementioned Regulation, national reference laboratories and obligations of Member States are defined, monitoring, testing, and detection programs for diseases (such as BSE or scrapie) are implemented, and procedures for sharing information to competent authorities are established to ensure uniform compliance with the rules and prompt disease response. Additionally, the Directive 2003/99/EC [85] on the monitoring of zoonoses and zoonotic agents complements existing requirements to enhance monitoring systems for diseases and infections that can be transmitted directly or indirectly between animals and humans. To support monitoring and information exchange, the Rapid Alert System for Food and Feed (RASFF) is implemented.

Regarding ensuring the welfare of animals, the EU has established the minimum compliance requirements for Member States, competent national authorities, and individuals operating at each stage of the agri-food chain, especially in the breeding, slaughter, and transportation of animals. The foundation for the protection of animals during transportation was laid down by Council Regulation (EC) No 1/2005 [86], which mandates adherence to appropriate practices. The primary aim is to meet the animals' needs, minimize journey duration, and avoid undue stress and injury. The fundamental principles governing animal transportation can be summarized as follows: Firstly, animals must be fit for transport. Transport vehicles for long road and sea journeys must meet design, construction, maintenance, and operational standards, along with providing adequate loading and unloading facilities to ensure animal health and safety. Pretransport checks of sufficient floor area and height clearance of the transport vehicle and adequate training of accompanying personnel handling animals are required. Regular checks during each stage of animal transportation are imperative to ensure their welfare, including continuous provision of water, feed, and resting conditions. Hence, it is understood that ensuring the safety and health of animals is a moral obligation of Member States, necessitating comprehensive legislative regulation to guarantee their welfare.

The above EU regulations are reinforced by Regulation (EU) 2017/625 [87], which introduces official controls and enforcement measures throughout the agri-food chain. Specifically, it aims to ensure proper implementation of legislation concerning animal health and welfare, plant health, and plant protection products. Based on the principle of animal welfare, it modifies and regulates the framework of official controls and the actions of competent national authorities during the transportation, breeding, and slaughter of animals. Cooperation among Member States is required to ensure animal welfare, and thus, this regulation establishes EU reference centers to assist in the official controls of Member States, providing scientific and technical expertise.

To strengthen legislative regulations and achieve the EU's goals of safeguarding animal health and addressing climate change, Regulation (EU) 2018/848 [88] on organic production and labelling of organic products was introduced. It is noteworthy that a fundamental principle of organic farming is ensuring high standards of living conditions and respecting animal health. Moreover, organic farming focuses on the reproductive value, adaptability, longevity, vitality, and disease resistance of animals.

EU has defined requirements and regulations for digitalization and PLF as part of its Common Agricultural Policy (CAP). The CAP is reformed at regular intervals, most recently with the post-2020 CAP reform [89]. Although PLF is not explicitly mentioned, the CAP emphasizes innovation and sustainability in agriculture. The requirements for digitalization and PLF in the EU are embedded in broader agricultural, environmental, and data protection legislation, which has already been reported on. In addition, the EU funds research and innovation projects through programs such as Horizon Europe and the European Innovation Partnership for Agriculture (EIP-AGRI). These programs support the development and adoption of digital technologies in agriculture, including PLF, through funding, knowledge exchange, and networking opportunities [89]. Overall, the EU's overarching objectives to promote sustainability, innovation, and efficiency in agriculture can serve as a framework for promoting the uptake of PLF technologies in the Member States.

In conclusion, within the framework of the "Common Agricultural Policy: 2023–2027" and considering the "Farm to Fork" and Biodiversity strategies, rules supporting the strategic plans of the common agricultural policy have been established. Particularly, Regulation (EU) 2021/2115 [90] sets the groundwork for improving animal welfare and combating antimicrobial resistance on the one hand and modernizing agriculture through digitization, innovation, research access, training, and knowledge exchange on the other. Simultaneously, the aim is to mitigate and adapt to climate change by reducing greenhouse gas emissions, enhancing carbon dioxide sequestration, and promoting sustainable energy.

Based on the above indicative reference to EU legislation, it is evident that while the European Union has regulated the minimum requirements for Member States, competent national authorities, and individuals involved in the breeding, slaughter, and transportation of animals, its legislative framework falls short in fully ensuring the welfare of animals.

6. Assessing the Modernity of EU Legislation on Animal Welfare and Climate Change

It should be noted that the need for legislative protection regarding the welfare of animals has been recognized since 1974. The current legislation for the protection of animals during transport (Regulation (EC) No 1255/97 and Regulation (EC) No 1/2005), which has been in place for over two decades, demonstrates its timelessness. However, scientific and technological advancements, changes in social preferences, and increasing sustainability challenges are no longer reflected in the existing regulations. Therefore, the need for higher standards of animal welfare during transport has led to the submission to the Council of the European Union of a Proposal Regulation as of 7 December 2023, concerning the protection of animals during transport and related activities and amending Regulation (EC) No 1255/97 of the Council and repealing Regulation (EC) No 1/2005 of the Council. The purpose of the above proposal is to work in synergy with other EU initiatives and policies concerning animals as well as their transport. Specifically, the proposal includes new and clearer provisions regarding the rules of animal welfare applicable to the transport of animals from third countries to the EU and vice versa (i.e., imports and exports), as well as rules for data protection (especially the General Data Protection Regulation) within the framework of real-time vehicle monitoring.

The legislative timetable of the EU indeed demonstrates the perennial regulation of issues such as animal welfare and disease management while simultaneously highlighting the effort for further institutionalization to fully harmonize with the technological and scientific advancements of the agri-food sector. Specifically, Regulation (EU) 2018/848 solidified the fundamental principle of organic farming, namely ensuring high standards of living conditions and respect for animal health. Furthermore, with Regulation (EU) 2021/2115, the groundwork was laid for improving animal welfare, modernizing agriculture, and adapting to climate change. Finally, with the most recent Regulation (EU) 2023/1115, the EU seeks to minimize its contribution to deforestation and degradation, biodiversity loss, and greenhouse gas emissions.

The present chapter, through bibliographic and legislative review, has demonstrated the contemporary trends in the agri-food sector, particularly highlighting technological advancements through the implementation of innovative digital systems in livestock. The issue of animal welfare moves between technological evolution and the conservative legislative approach of the EU. Based on the above analysis, it is evident that the EU is progressing slowly in terms of legislative regulation of the agri-food sector, especially concerning the assurance of animal welfare and climate change mitigation. Given the future challenges regarding sustainability and animal protection and considering scientific and technological progress, the need for a "legislative leap" by the EU arises to harmonize existing practices and procedures with the digital era.

7. Conclusions

Precision livestock farming (PLF) represents a tantalizing vision for the future of sustainable agriculture. It presents a data- and technology-driven strategy that provides a systematic approach to management and decision-making through the collection, processing, understanding, and application of information. This approach can facilitate the cost-effective, efficient, and safe expansion of factory farming and achieve the modernization of livestock production. However, addressing the challenges related to cost, complexity, and animal welfare is critical to realize the full potential of this approach and ensure its broad adoption in the livestock industry. The integration of PLF with the principles of sustainable agriculture is, therefore, a promising way forward. It represents the notion that technology and sustainability can complement each other to meet the world's food needs while protecting the health of the planet and the welfare of its inhabitants. Future research in PLF should prioritize cross-institutional and interdisciplinary communication and collaboration. In addition, social science aspects should be adequately addressed in PLF, and the incorporation of smart technologies in animal husbandry should be improved, with a focus on animal welfare and the environmental impact of animal husbandry to promote sustainable progress.

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