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Review

Emerging Precision Management Methods in Poultry Sector

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Abstract: New approach to improve welfare in the poultry sector is targeted at the precise management of animals. In poultry production, we observe that birds' health and quality of poultry products depend significantly on good welfare conditions, affecting economic efficiency. Using technology solutions in different systems of animal production is an innovation that can help farmers more effectively control the environmental conditions and health of birds. In addition, rising public concern about poultry breeding and welfare leads to developing solutions to increase the efficiency of control and monitoring in this animal production branch. Precision livestock farming (PLF) collects real-time data of birds using different types of technologies for this process. It means that PLF can help prevent lowering animal welfare by detecting early stages of diseases and stressful situations during birds' management and allows steps to be taken quickly enough to limit the adverse effects. This review shows connections between the possibilities of using the latest technologies to monitor laying hens and broilers in developing precision livestock farming.

Keywords: precision livestock farming; intensive production; animal welfare; modern technology; sensors; laying hens; broiler chickens; microclimate

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1. Introduction

In the last 30 years, the production of chickens has more than doubled, reaching the number of birds of 25.9 billion in 2019 and an increase of as much as 80% in 2020 compared to the previous year [1]. In 2019 European Union produced 13.3 million tonnes of poultry meat, with Poland being the leading producer (2.6 million tonnes) and one of the biggest exporters in the world, generating a 9% share of total global exports (1.5 million tonnes) [2]. Poultry meat production remains the primary kind of total meat production [3], and it is expected to grow in the following years [4]. Thus, there is a constant need to pursue solutions to improve poultry production efficiency while improving quality and animal welfare. In poultry production, we observe that birds' health and quality of products depend significantly on good welfare conditions, which may affect economic efficiency [5].

A good level of welfare means that birds are healthy, have a positive affective state, and express natural behaviours [6]. One of the biggest challenges in the current poultry production that can significantly impact welfare is behavioural disorders, manifesting in various behaviours such as increased aggression, lameness, cannibalism, or feather pecking, leading to economic losses [7–12]. Further, today's poultry farms, constantly cutting costs, strive to reduce the number of employees while maintaining or increasing the number of birds, which leads to the herd's reduced welfare and the inability to exhibit a given species' behaviour characteristic [13]. Therefore, monitoring animal behaviours, feeding, and environmental conditions is essential to improve production performance and increase animal welfare.

Additionally, currently rising public concern about poultry breeding and welfare leads to the development of solutions increasing the efficiency of control and monitoring. Precision Livestock Farming (PLF) tools enable the unattended collection of broadly understood data on housing conditions and animals in a real-time manner using intelligent technologies, which allows obtaining reliable information due to the lack of direct human-animal contact [14]. Data from different sources collected by sensors or other equipment can be analysed and help create an automated management system based on real-time information (Figure 1) that allows control of animal welfare, health, and performance [15]. An important aspect that enables the effective use of PLF tools is the compatibility of precision tools with commercial poultry farm equipment based on the collected data [16]. PLF technologies can help detect problems with animal welfare early, improve and accelerate management decisions, and reduce economic losses at the end [17].

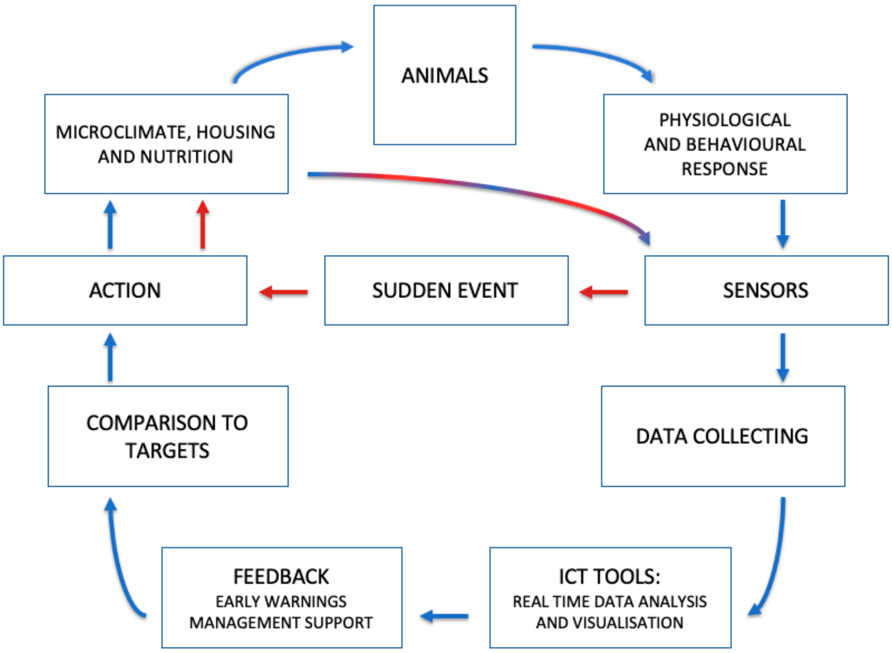

Figure 1. Schematic overview of farm management optimisation through the implementation of PLF tools [18–20]. The sensors are used both to collect data leading to the optimization of daily decisions in farm management and as an element of a direct response to microclimate changes occurring in the livestock building (marked with red arrows), which, in response to the needs, e.g., automatically controlling ventilation by adjusting the velocity in case of elevated temperature or humidity levels [21].

In this review, we show available technologies which can be used in poultry production systems for more effective control of the environment, health and welfare of poultry. The practical applications are described, and such technologies' potential impact on welfare are discussed.

2. Tools Used to Monitor Behaviour and Production Parameters

There are many PLF tools on the market for different purposes on the farm. The purpose of this paper is both a general overview of PLF tools currently available on the market and their potential in the commercial poultry sector, supported by scientific research conducted in large-scale farming conditions. This review focuses on optimizing production cycle management opportunities within five main areas-housing and microclimate control, weight monitoring, sound analysis, locomotion and activity tracking and disease detection and hygiene maintenance aspects, without focus on the direct use or adaptation of technology by farmers and associated socio-economic impact caused.

2.1. Housing and Microclimate Control

As part of the rearing conditions and their optimization using the associated PLF tools, the following overview takes into account successively such aspects as general herd maintenance guidelines, environmental conditions deviations, the need to monitor the ambient air temperature, the importance of ventilation, the influence of ventilation on other factors (including harmful gases), the lighting program and its detrimental effects and other uses of light.

It is essential to properly densify the kept herd to avoid lower welfare and increased stress levels in chicken meat/egg production as much as possible [22]. According to Directive 2007/43/EC [23], the maximum density in a farm or poultry house may not exceed 33 $kg \cdot m^{-2}$ at any production stage of chicken kept for meat production. Increasing this value is possible to 39 kg or even 42 $kg \cdot m^{-2}$ but only in case of meeting additional requirements [23]. In the case of laying hens, according to the council directive 1999/74/EC [24], the stocking density cannot exceed nine animals per m^2 of usable area (with the possibility of increasing the limit to 12 animals per m^2 provided that the relevant guidelines, such as a larger available substrate area, are met). Cage-kept laying hens require not less than 750 cm^2 of cage area per individual, with the cage not being lower than 35 cm at any point measured. It is challenging for farmers to monitor single individuals in a large-scale herd at high density.

PLF methods provide data on the entire herd, collected automatically 24 h a day, seven days a week, thanks to which the farm management is more optimised. Research by Hartung et al. [25] shows that farmers using PLF systems prefer integrated data compared to traditional management practices and generally do not see any negatives except high price possible. Still, at the same time, they believe that PLF can impact higher profits. Jones et al. [26] found that management practices had more excellent long-term effects on welfare and the environment than reducing stocking density. The large-scale study on 2.7 million birds kept in 5 different stocking densities shows that housing conditions may influence welfare even more than density itself [27]. Increased consumer awareness of the provided feed and the general housing conditions of birds led large-scale farming to the need for controlling animal welfare more in commercial farms [28]. More favourable environmental conditions and maintaining their desired level can be facilitated by using an autonomous farming system that can provide better feed and nutrient utilisation opportunities [29].

Environmental conditions deviating from the accepted norms may result in reduced feed intake, and thus slower growth [30], high-stress levels [31] and high mortality rates [32]. To maintain accurate welfare status, constant access to water is required, and feeders must allow animals to have access to complete feed mixtures adapted to their age and production needs [33]. The Kai-Zen Feeding Robot (Metabolic Robots, Kfar Tavor, Israel) is a helpful tool mainly used to adjust the feed dose to the needs of the herd at the current stage of development, which contributes to the optimisation and possible improvement of the Food Conversion Rate (FCR) by up to 4% [34]. The self-sufficient, solar Feed Cast (Little Bird Systems, Fayetteville, NC, USA) for monitoring the feed level in silos can be used to supplement feed intake control. Real-time feed use information and other data, such as water intake, help farmers precisely adjust proper feed formulation and environmental conditions, including temperature and lighting programs [35,36]. Modern poultry houses are equipped with water meters that might monitor water consumption by recording daily water use by each row and/or the entire house [37,38]. Water intake patterns based on collected data provides information helpful in diagnosing feed quality problems or general flock health. Usually, in the case of health problems of the flock, water intake is decreasing, while in the case of feed quality issues, e.g., higher salt levels–increasing [37]. Monitoring of water consumption can also detect leaking installation, which will generate additional costs for farmers. Due to the intensive nature of production, poultry producers must be careful to use resources as efficiently as possible [30]. Precision livestock farming can be used in the poultry industry by monitoring the real-time birds' behaviour and recording it. In large-scale farming, manual checking of the correct functioning of the equipment is a challenge due to the size of the installation. The use of the eYeNamic system (Fancom BV, Panningen, The Netherlands), combined with cameras and subsequent image processing methods in studies conducted by Kashiha et al. [39], made it possible to detect 95.24% of anomalies in real-time, clearly determining the usefulness of automatic monitoring in broiler houses. Based on collected data, reactions for replacing or repairing the broken pieces of the equipment, such as feeders, fans, and heating systems, might be faster and, therefore, more effective [16]. Such activities directly affect the health and welfare of birds, microclimate control, and the maintenance of typical gaseous pollutants.

When monitoring the impact of environmental conditions on the appearance of disturbances in broilers' chicken behaviour, it is also worth paying attention to the appropriate ambient temperature. It should not exceed 35 °C in the first week of the production cycle, then lower it by an average of 5 °C per week down to 21 °C or ambient temperature. This pattern reduces the likelihood of heat stress and related stress, and behavioural disorders [40]. Birds kept below a comfortable temperature use up to four times more energy to maintain proper body temperature with a simultaneous decrease in production parameters [41]. The fast growth rate of modern broilers does not allow for the development of the circulatory and respiratory systems adequate to the size of the animal and the needs related to it [42], which makes them more susceptible to heat stress as a result of genetic selection in terms of expected gains [43]. After 3 h of exposure of birds to heat stress (ambient temperature 36 °C), the temperature on the surface of their skin increased by 6 °C, and the body temperature increased by 3 °C [44,45]. The relationship between the body core and surficial temperature of broiler chickens is confirmed by the studies of Giloh et al. [46] based on measurements with a thermal imaging camera. This correlation was equally strong at all ages from 8 to 36 days during exposure to heat stress with or without adequate ventilation and after exposure to chronic exposure to high ambient temperature. Thanks to the use of temperature sensors, the data about the current temperature are continuously available, without the need for control measurements by the staff. The key is to place the sensors at the right height. Blanes-Vidal et al. [47] found that to obtain reliable and as close to reality as possible temperature values, it is necessary to place the sensor at the height of 0.6 m above the ground. Generally, the simplest method of controlling environmental conditions is maintaining the appropriate temperature by regulating ventilation and heating [48].

Maintaining stable environmental conditions during the growing period is key to avoiding heat stress [49]. Jones et al. [26] reported that fan ventilating systems with side inlet ventilation are better for temperature and relative humidity control than natural ventilation. Heating a building consumes over 80% and ventilation up to 40% of the total energy consumption in commercial facilities [50]. Recommended humidity in livestock buildings should not be less than 50 and not more than 70% [51,52]. It can also be controlled with adequate ventilation. A relative air humidity of less than 50% results in higher dust levels in the building [30]. In summer, birds may experience discomfort due to higher air humidity and high temperature [28]. Birds cannot sweat, so they mainly cool via lungs (evaporation) or raised wings (skin exposed to airflow). Heat stress can occur at different temperatures if ventilation is inefficient [30]. Airflow at a level not exceeding 2 $m \cdot s^{-1}$ enables the growth to be maintained at the expected level and effective thermoregulation by the birds [53]. Over-ventilation in winter can increase production costs by up to 30% [50]. Limiting ventilation efficiency, for example, to reduce energy and heating costs, increases ammonia levels in livestock buildings [54]. Insufficiently efficient ventilation leads to moisture accumulation in livestock buildings, leading to wet litter [54], an increase in bacterial multiplication, and higher nitrogen generation from nitrogen found in the faecal matter [55]. The problem that occurs more often than the accumulation of moisture is the higher concentration of NH_3, CO_2 and air dust in livestock buildings [54]. According to European standards, carbon dioxide and ammonia concentration should not be higher than 5000 ppm and 20 ppm, respectively [23].

Ventilation is a crucial factor influencing the temperature, humidity, and concentration of harmful gases in livestock buildings [56]. The research conducted by Czarick and Fairchild [57] showed that the concentration of CO_2 and NH_3 remained at the acceptable level, while the air temperature was within the normal range and relative air humidity was not exceeding 60%. An increase in humidity above 70% (at constant temperature) results in elevated levels of CO_2 (>5000 ppm) and NH_3 (>20 ppm). Carbon dioxide concentration on that high level leads to lower weight gains and lethargic chicks, while NH_3–increased susceptibility to disease. Air composition analysis can also be a valuable source of information about potential health problems. A pilot study by Grilli et al. [58], based on a comparative analysis of volatile organic compounds (VOCs) emitted by healthy and coccidiosis-infected animals, allowed early detection of the infection stage (250 oocysts per g^{-1}). Wang et al. [59] conducted a study on the effect of ammonia concentration (0, 13, 26 and 52 ppm) on the growth of broilers and their immune response to the Newcastle virus. The flock of one-day-old broilers (n = 480) was divided into four treatment groups consisting of equal numbers of males and females. Twelve birds from every group were randomly selected to determine the effects of ammonia concentration on development and the immune system. Using a MiniWarn Multi-Gas Monitor (Draeger Co., Germany), concentration was monitored several times a day during weeks 0–3 of the production cycle. The relative weight of a chick's lymphoid organ was not affected, but the weight of other organs decreased as ammonia concentration increased. Newcastle Disease Virus (NDV) hemagglutination inhibition antibody titer was significantly higher ($p < 0.05$) in the 52 ppm group than in 26 ppm. So, it is evident that monitoring environmental conditions in livestock buildings such as air humidity, ventilation, temperature and harmful gas concentrations can significantly improve bird farming [26].

In intensive poultry production, light and light-related issues, such as wavelength and intensity, and lighting programs, play an essential role [60,61]. Currently, light-emitting diodes (LEDs) are more often used in livestock buildings, providing monochromatic, full-spectrum light comparable with natural daylight, in contrast to the previously popular fluorescent lamps. LEDs' most significant advantages are their longer life span, lower energy consumption, and low maintenance costs [62,63]. It has also been shown that monochromatic light positively affects the values of production parameters [64–66]. Artificial lighting may affect animals because birds have four types of cones in the eye's retina, so birds see colours differently than humans (3 types of the cone) [67]. Poultry can see in the range from 315 up to 750 nm, and most of the occurring behaviours are stimulated by vision [63]. Due to that range, poultry can detect UV-A light [68]. The study conducted by James et al. [69] presents that UV-A wavelengths (100–400 nm) could reduce mortality (75% lower compared to the control group) and affect the economy of broiler production positively within the negative impact on weight gain during the production period. Chickens are more sensitive to red light (630–780 nm), which, as it is reported, provokes aggressive behaviour [66,70]. Providing the 6065 K light with a more significant proportion of the blue light spectrum can improve final live body weight (BW) and breast muscle yield [68]. The combination of blue and green light during the production cycle affects the immune system. Levels of IgG in green-blue lighting were elevated up to 40.3% (anti-Newcastle virus) and up to 48.7% (BSA) compared to a single monochromatic light group [71]. Dependency between BW, BW gain, and light colour was also shown in a different study by Olanrewaju et al. [72]. The group reared under cool led light values (5000 K, colour temperature expressed in kelvins) were significantly higher than the 2010 K ICD light group. Inadequately selected lighting/lighting programme influence is a stress factor for birds [73]. A widely accepted hypothesis is that brighter lighting reduces rearing efficiency due to increased bird activity [60]. It is assumed that the light intensity in broiler production cannot be lower than 20 lx measured on birds' eye level and have to cover at least 80% of the usable area not to affect the birds' feed intake and general welfare [23].

Light's detrimental effect is usually due to too low intensity, resulting in altered behavioural expression and increased fearfulness of the birds. Higher light levels improved well-being, resulting in natural behaviours [60]. Other studies showed that birds kept at lower intensity conditions (5 lx) were more active and had an even distribution of behaviours during the 24 h phase than in 50 and 200 lx, respectively [74,75]. However, the broiler industry uses sub-standard lighting (<5 lux) regardless of the published data on its negative impact [60]. The length of the light day also plays an important regulatory role. Light regime negatively impacts feeding patterns and general animal welfare [76]. Birds kept under 16 h of light (L) and 8 h of dark (D) show higher activity than those maintained under 24 h of light [77]. Bayram and Özkan [78] investigated a herd of Cobb broiler males in which behaviours such as resting, walking-standing, pecking and eating were observed for the 16L:8D settings compared to 24 h continuous light schedule (control group). The experiment results indicate a higher degree of socialisation in the herd and, at the same time, lower susceptibility to stress than the control group. Less sleeping and resting time, possibly due to more frequent feeding, drinking, pecking, is a potential cause of more frequent aggression in the herd. A more extended day may hypothetically reduce aggression and similar behaviours. It is worth noting that such a solution potentially reduces feed intake [36,79]. Light parameters monitoring might improve animal welfare, reduce stress, consciously control their behaviour (including aggressive ones), and regulate fed patterns. The reading from the light measuring sensors placed in the building is helpful, but, as mentioned before, it must be analogous to the bird's eye level to give reliable measurement results.

The research shows that light stimuli can also be used in other ways. By utilising an enrichment in the form of point lasers to arouse the bird's curiosity, it was possible to effectively stimulate activity and feed intake of the birds without adversely affecting leg health [80]. With pulsed light with an appropriate spectrum, Lasagabaster et al. [81] obtained promising results for surface decontamination for Salmonella. The great advantage of such a procedure is the lack of temperature changes of eggs during disinfection and the possibility of carrying out the process at low humidity, which is a potential alternative to washing eggs and thus violating their natural protective barriers.

2.2. Weight Monitoring

The following chapter presents automatic weighing methods, both those used commercially and those more innovative, with the potential for use in large-scale farming.

In large-scale production, focused on profit from an economic point of view, an essential factor is the reduction of costs incurred, such as service costs. The regular weighing of a large herd in commonly known form requires much time and effort from the farmer and the handler. Most often, it is carried out with step-on-scale [82]. The automatic weighing system, e.g., pan scales, are a solution that requires much less active human labour. Pan scales have the form of a platform suspended low above the litter, which, thanks to the connection with the electronic calculating unit, measures the weight of the individual that has currently stepped on it [83]. Placing the scales as an obstacle that the animal has to overcome to the drinker/feeder or additional enrichment may allow for collecting a higher number of measurements. The solution used in the case of the laying hens is scales placed within the nests (e.g., at the entrance), also used in monitoring wild birds [84]. Additionally, thanks to automatic measurements, chickens do not experience the stress stimulus associated with catching and general interactions with humans [85]. The collected data is accessible for the farmer in real-time. Obtaining information about the current increments in real-time is an essential component of efficient farm management, which helps to estimate the achievement of predetermined goals [85] and the potential nutritional deficiencies occurrence [86], especially in the case of broilers. Despite the same environmental conditions and feed availability within one livestock building, birds do not gain weight at the same rate [87]. The problem in weighing with the automatic system is the lower mobility of older birds, especially after 28 days of age, which do not step on scales as often as the more active, younger ones [88]. An example of trying to determine the flock uniformity with a promising result is using a rod-platform weighing system, which cleverly takes advantage of the natural perching behaviour of the chickens. Another more innovative approach to optimisation of the entire weight measurement process without disturbing and stressing animals is the application of audio recordings analysis. Birds' vocalisation frequency range is inversely proportional to their age and weight–the older the bird, the lower the peak frequency [89]. Research by Fontana et al. [90] during eight production cycles on two different farms results in no significant differences between observed and expected BW (p = 0.4513, except last week). Aydin et al. [91] used sound analysis to predict real-time feed intakes of multiple broiler chickens in a fully automated way. Results show a high correlation (R^2 = 0.994) between conventional feed intake, measured by a weighing scale installed under a commercial feeder, and collected data, while 86% of feed intake was monitored correctly using audio analysis of recorded pecking sounds. Real-time feed use data, along with other performance data (egg production and body weight), will be a helpful tool in fine-tuning feed formulation, the set-point temperature of the house, and possibly even lighting programs in the future [37].

The problem with using audio analysis might be machine emitted noise. High intensity of audio stimuli might be the direct cause of decreased welfare. With age, and therefore with a higher gas concentration, air humidity and higher forage requirements, machines have to work more efficiently, which often means louder. In his research, Aydin et al. [92] eliminate additional sounds from the environment by filtering specific frequencies (range between 1000 and 5000 Hz) that are higher than birds' vocalisation. Curtin et al. [93] report that using a vocalisation detection algorithm combined with the spectral oversubscription method is an effective tool in stressful conditions detecting. Understanding the vocal information given by animals can be an effective tool in improving animal welfare [94]. The great advantage of audio analysis is that it is a non-invasive method, and thus it is a less stressful stimulus for kept animals.

2.3. *Sound Analysis*

Another form of environmental control is sound analysis, which in recent years has become a valuable tool for monitoring animal behaviour and welfare [95]. There are two types of vocalisations–between individuals, for recognition in the herd, and within the same animal, which is used to monitor and determine the condition of individuals [96]. Manteuffel et al. [97] distinguish between different methods of describing vocalisation characteristics, such as complex and standard statistical methods, neural networks and Hidden Markov models (HMMs). Neural networks are a method that works well in a noisy environment. HMMs can analyse any number of different vocalisations and are very effective in speech recognition [94]. It is also more and more often used in bioacoustics due to the possibility of incorporating limitation or complex language recognition, easy extendibility to continuous speech recognition, and handling duration variability [30]. Steen et al. [98], in a study on goose vocal behaviour (flushing, landing and foraging), used Support Vector Machines (SVM) over HMMs because of the better generalisation ability of the classifier based on structural risk minimisation. SVM was used to classify one of three behaviours based on their vocalisations. The classification accuracy for all three tested behaviours was over 90%. The HMM model has been used by Ren et al. [99] for assessing the correlation between vocalisation patterns and environmental stress stimuli (human presence) to check vocalisation as stress indicator suitability. The study provided accuracy above 90% with human presence as stress cause.

Research shows that age makes vocalisation patterns more repeatable, varied, and easier to detect. An experiment conducted by de Moura et al. [100] showed the correlation between vocalisation during high heat stress conditions and the grouping pattern of the birds. The stressed bird's vocalisation is also more intense. In different studies [101] based on audio analysis (microphone placed 0.2 m and camera 2 m above the box), birds were placed in a closed environment (3 m^2) with decreasing temperature (from 30.2 to 24.98 °C, ±1.3 °C). During lower temperature conditions, it was found that vocalisation increased, and chicks were gathering to reduce flock heat loss. Bright [102] reports that the number of total vocalisations, especially squawks, in laying hens flock with feather pecking incidents was significantly higher. Birds communicate with each other, and audio analysis is helpful in the whole chicken production process, even before hatching. Exadaktylos et al. [103] used frequency analysis to estimate the internal pipping stage of incubated eggs by an algorithm developed using Digital Signal Processor for a real-time environment. Results showed assessed time was 93–98% accurately calculated.

2.4. Locomotion and Activity Tracking

With the increasing weight of the birds, the level of their physical activity changes. A significant welfare problem due to the fast growth rates achieved by modern broiler chickens is the reduced level of animal locomotion [104]. This part of the overview focuses on methods of monitoring both the whole herd and individuals through the use of modern technology, both less and more costly, with an emphasis on using these methods to monitor locomotion problems.

Despite many years of work by breeding companies on the selection for leg disorders [100,101], it is still a common health problem in broilers, which should be monitored to avoid further development of the problem [105,106] and, as a result, reduce the comfort of birds. Due to the increasing demand in the Asian market, broiler's feet are the third trait of high value, after breasts and wings [107]. Due to the nature of broiler production, deviations from the norm in terms of movement are an essential welfare indicator [108–110]. The decreased activity level of animals is most often associated with the occurrence of footpad dermatitis (FPD), also called pododermatitis/footpad lesions (ulcers on the underside of the feet) and hock burn (discolouration and lesions of the hocks), thus being a big problem in broiler production [111–114]. Both diseases are genetic and related to living conditions, particularly poor-quality litter [111,115,116]. Foot lesions cause pain, reduce locomotor abilities, and thus feed and water intake, and decrease weight gain [117,118]. In the case of widely spread intensive production, regular observation of each bird in the herd is almost impossible in a commonly used form [110].

Another form of individual tracking is radio frequency identification devices (RFID). Monitoring the activity and location of individuals with RFID tags has been successfully used for other animal species [119]. Due to the low weight of the tags, wearing them does not affect the level of activity and the health of the birds' legs [120]. However, their use in commercial farms requires further adjustments due to the high application costs and sensor accuracy problems in commercial flocks [35]. Attempts to locate individual birds in a flock were made by Rodenburg et al. [121] in the PhenoLab project. For this purpose, two localisation methods were used-video (EthoVision) and ultra-wideband (TrackLab) tracking. The analysis of the obtained data shows that the accuracy of the distance measured with the TrackLab was 96% compared to the results obtained from video observations. However, data on the entire herd can also be a valuable source of information about the current problems of the individuals. Recording animals in terms of the "optical flow" of the herd, i.e., detecting the speed of brightness changes in various parts of the recording [114,122], is a method that does not require markers or additional sensors.

The use of automatic measurements of the herd's optical flow can be used for the continuous observation of the kept animals and thus a quick response to the appearance of gait scores, which is an objective, less labour-intensive and therefore more effective method than manual assessment by service employees [123]. Thanks to the analysis of data obtained from the herd's optical flow recordings in the study by Dawkins et al. [124], it was possible to predict the gait score at 28 days of life of chickens, which was several days ahead of the manual/visual assessment. Similarly, based on the analysis of data skew and kurtosis, and in conjunction with data modelling and Bayesian regression, Roberts et al. [125] made it possible to predict up to several weeks before symptoms appeared in chickens at three days of age. Fernandez et al. [126] examined the broiler occupation patterns based on observations through camera-based methods of 9 complete cycles of commercial herds. The obtained results clearly show statistically significant correlations between occupation deviations, footpad lesions, and hock burns. During recording, the image may become distorted by the "fish-eye" effect that can be minimised using the correction algorithm described by Altera [127].

Optical flow and flock behaviour monitoring based on thermal imaging cameras as an automated way to welfare assessment has potential for use in commercial farms conditions [128–132]. Kristensen and Cornou [133] used activity level measurements based on image analysis in the first three weeks of life of broiler chickens, which, combined with a filtering model for abnormal results, could be a practical way to provide a maintenance-free system for detecting bird mobility problems. Similarly, in a study by Jacob et al. [107], it was possible to diagnose footpad lesions using infrared thermography earlier than with standard visual assessment. Automatic lameness assessment using image analysis also gives satisfactory results for the early gait score assessment in relatively healthy birds (score range from 1.4–1.9) [134]. Naas et al. [135] applied piezoelectric crystal sensors to examine the peak vertical force on both feet during walking episodes to determine locomotion deficiencies. Thanks to sensor technology, it was possible to detect an asymmetry in walking of male broilers, which may lead to real-time gait assessment [110]. One of the main consequences of lower activity levels is decreased drinking and feeding behaviour. EyeNamic, a tool designed specifically for behaviour monitoring, can capture the chickens' activity level and general movement and report related irregularities, such as crowding or improper distribution of the birds [136]. Wireless accelerometer sensors are used in poultry production to monitor the location and activity of the birds [137]. Kozak et al. [138] applied accelerometers in their research on physical activity levels of laying hens. The prediction level of low (egg-laying, sleeping, small postural body movements), moderate (eating, drinking, stretching) and intense (walking, running, wing lapping) activity of the birds, based on collected data (combined with random forest model), achieved 98% accuracy. Leroy et al. [139] replaced the time-consuming and labour-intensive in-person behavioural observation methods with image processing techniques and inexpensive cameras to distinguish between standing, walking and scratching in real-time. Machine vision methods for monitoring were also used by Zaninelli et al. [140] during the research on multiple nest occupation problems in laying hens kept in the free-range system. The installed sensor acquired thermographic images of the birds using the nest. In the case of double occupation, the sensitivity and specificity of the sensor were 73.8% and 94.8%, respectively, while the triple sensor was 80% and 94.8%, respectively.

Nest monitoring is a valuable tool as it also allows you to monitor the laying itself closely. Thanks to the use of radio frequency identification (RFID) sensors (on the bottom of the nest and the hens' legs) in combination with the Internet of Things (IoT) platform, Chien and Chen [141] created a kind of intelligent nest box based on which it is possible to analyse the number and weight of eggs laid daily by each hen in the flock. Lightweight, body-mounted accelerometer sensors were also used to collect data on jumps from perch to the ground occurrence as well as time and force of landing of laying hens. The provision of perches in laying hens housing is being used to improve the welfare of the birds and encourage natural behaviours. However, perches might also be the source of pain or possible injuries. To minimise its negative impact, it is necessary to use a suitable perch for the animals. Pickel et al. [142] analysed the effect of perch shape on keel bone and foot pad problems with pressure sensors wrapped around the perches and additional software and determined that square and oval shapes were most advantageous in comparison to round and square options. Similar needs for behavioral expression are observed in fattening chickens [143], but due to frequent leg problems caused by intensive gains and higher body weight than in laying hens, the use of perches in a similar form is not so attractive to explore. The study of the perch shape in slaughter chickens shows that the safer, more often chosen and more ergonomic option are perches in the form of platforms [144]. A study conducted by Bokkers et al. [145] shows that the activity level of slaughter chickens does not depend only on age but bodyweight and the motivation initiating/continuing physical activity. Bizeray et al. [146] investigated the effect of environmental variations as a stimulus to increase motor activity in broiler chickens. The variety of equipment in the form of additional barriers on the way to the water and feeder resulted in increased perching behaviour. Essential equipment and additional enrichments, however, constitute an obstacle to image analysis by partially obscuring the assessed birds. Guo et al. [147] developed linear elliptic fitting restoration methods of image recovery. As a result, the restoration efficiency was over 80%. Thanks to the practical use of these methods, behavioural observations regarding environmental enrichment can be carried out automatically, without disturbing behaviour in the form of human presence.

2.5. Diseases Detection and Hygiene Maintenance

In recent years, animal welfare measures have been developed, e.g., the Welfare Quality [148] and AWIN [149] protocols. To estimate the level of welfare and general health, more than one indicator is used to achieve the most comprehensive assessment of the condition of the animals. Due to the large groups of animals kept in the same or very similar environmental conditions, both within one and several different farms, it is possible to use sensors to monitor the herd for diseases. Carpentier et al. [150] developed an automated system to detect potential respiratory diseases based on an algorithm that detects sneezing in the herd, recorded with a microphone placed in the box. The algorithm used showed an accuracy of 88.4% and a sensitivity of 66.7%. Thanks to the monitoring based on sound analysis, observations can be carried out 24 h a day, also during the dark period in the livestock building. Okada et al. [151] reported that highly pathogenic avian influenza (HPAI) was detected 10 h earlier with the use of a wireless sensor node (WSN) with accelerometer and thermometer attached to 5% of the flock than with regular monitoring by farmworkers and showed that higher body temperature and weakness are early signs of a possible outbreak. The great advantage of the device is that it can work continuously for two years without battery replacement, so using it for longer production cycles, used in the case of laying hens, does not involve the risk of discharge or stoppage of the device due to insufficient battery life.

To monitor deep body temperature (DBT), it is helpful to apply a radio telemetry system in the form of an implantable, wireless sensor network (WSN) [152,153]. The study reports that the DBT of broiler chickens measured with the WSN method could be assessed with ±0.1 °C accuracy. In addition, infrared thermal measurements allow for the early detection of diseases [154]. Noh et al. [155] successfully used a thermal imaging camera to detect HPAI from peak body temperature measurements. Infrared-based techniques are a non-invasive and non-contact temperature control method on the body surface. The conversion of the infrared radiation emitted by the body into pixel intensity leads to the preparation of a thermogram, i.e., a kind of map of the temperature distribution on the animal's surface [156,157]. The accuracy of body surface temperature readings using infrared techniques is not comparable to solid sensors [49].

Another factor that directly affects the occurrence of diseases is the hygiene of the livestock building. An innovative solution in the form of autonomously driven commercially available robots such as Octopus Poultry Safe (OPS) (Octopus Robots, Cholet, France), a robot designed specifically for poultry industries that can clean and sanitise poultry houses in the animal presence and collect environmental conditions data simultaneously. Thanks to the systematic turning of the litter over, it is possible to aerate it and thus reduce moisture and the development of pathogenic or potentially problematic microorganisms such as Aspergillus fungus and aspergillosis, but also problems such as footpad dermatitis and hock and breasts injuries. Precision livestock farming gives countless possibilities regarding unattended animal care and controlling the environment to be safe for the herd's health.

An essential aspect in protecting the herd against diseases is detecting and removing dead individuals. Employees most often perform this activity. When handling a large-scale herd of tens of thousands of individuals, such activity is both time and labour-consuming, and the animals themselves may be in hardly noticeable places. The ChickenBoy monitor device distinguishes live and dead animals by applying thermographic images. It is an example of a lightweight monitor device that collects data on, among other things, humidity, temperature, ammonia and CO_2 levels, as well as airspeed in poultry houses [136]. The use of automated robots or other automated systems that can locate and even pick up deceased individuals may be more effective, making the service of PLF extremely helpful in maintaining production hygiene.

The benefit of continuous, automatic monitoring of animals is receiving current information on the health condition and faster response, which saves on treatment and the drugs themselves [18,39,132,158].

3. Limitations and Perspectives

Despite the described advantages and functionalities provided by the PLF to poultry producers, many authors point out the limitations of this technology's use and rapid development.

One of the main challenges is the availability of capital to supply the farm with new PLF solutions. Usually, these are high costs that do not pay off in the short term, meaning that mainly larger producers have this ability, which exacerbates the technological delay of small and medium-sized poultry producers [159]. Therefore, a good solution could be a system of financial funding, indirectly supported by local authorities and national programs promoting PLF technologies [160–162]. Werkheiser [163] also draws attention to the fact that employees will be limited on farms that implement PLF solutions, as it is evident that such technology is very automated. As a result, employees with less experience and poorer skills will be employed, which may deteriorate the quality of their work.

Perhaps the biggest obstacle in popularising the PLF technology among poultry producers was indicated by Banhazi et al. [164]. The lack of a comprehensive offer on the market, under which farmers would receive appropriate tools and the online interpretation of data collected by sensors, simple instructions on how to behave in crises or proposals to solve the problem in the long term as well as customer service allowing to dispel current doubts or help solve minor technical defects. Those implementing the PLF solution should also maintain a constant dialogue with poultry producers, involving them in developing technology and using their accumulated years of experience. Scientists and programmers should also be interested in this type of communication, which would result in the creation of more effective solutions. Unfortunately, this means involvement in the development research of a large budget, which only a few can afford.

Moreover, Bahlo et al. [165] point out that farm owners will not necessarily want to share all the information obtained thanks to implementing PLF technology with the external environment. This applies to the broadly understood privacy and the fear of gaining an advantage by competitors on the market [166]. The authors emphasise the importance of so-called feedback previously mentioned by Banhazi et al. [164]. Farmers are not interested in collecting data but quickly interpreting specific information or recommendations for appropriate actions.

Given that medical research for animal agriculture has generally been an offshoot of medical research for humans, it is interesting that there are concerns that PLF solutions tested in animal production can be used for human monitoring. This is a very controversial premise, but it is not without sense. The tested predictive algorithms and technologies for identifying animals, including their voice, will monitor people, e.g., through the increasingly popular home electronics devices. Therefore, the rapid development of PLF technology should go hand in hand with work on appropriate legal regulations that will protect the ordinary citizen [167].

4. Conclusions

Technologies creating PLF can help control many physical and chemical factors, improving the definition of birds' physiological status and adaptation to farm conditions. These measurements include body temperature, movement, vocalisation, feeding and water intake, activity, and social behaviour. Table 1 compares the capabilities of the commercially used PLF tools mentioned previously.

Table 1. Capabilities of exemplary PLF tools used in poultry sector. Green dots indicate available functions of devices shown in the table, red dots refer to unavailable equipment.

	Kai–Zen Robot	**Feed Cast**	**eYenamic System**	**Octopus Poultry Safe**	**ChickenBoy**
Gas measurement	🔴	🔴	🔴	🔴	🟢
Temperature monitoring	🔴	🔴	🔴	🔴	🟢
Ventilation monitoring	🔴	🔴	🔴	🔴	🟢
Humidity monitoring	🔴	🔴	🔴	🔴	🟢
Light sensors	🔴	🔴	🔴	🔴	🟢
Feed/water management	🟢	🟢	🟢	🔴	🔴
Technical condition of the building	🟢	🔴	🟢	🔴	🔴
Noise level monitoring	🔴	🔴	🔴	🔴	🟢
Litter disinfection	🔴	🔴	🔴	🟢	🟢
Removal of dead individuals	🔴	🔴	🔴	🔴	🟢
AI algorithms	🔴	🔴	🔴	🟢	🟢
Use of cameras	🔴	🔴	🟢	🔴	🟢
Use of infrared cameras	🔴	🔴	🔴	🔴	🟢
Activity tracking	🔴	🔴	🟢	🟢	🟢
Flock distribution monitoring	🟢	🔴	🟢	🔴	🟢

Precise management gives farmers opportunities for reliable, real-time and non-invasive measurements of birds' behaviour and physiology by integrating many technology solutions. Automated techniques to assess physiological and behavioural parameters can provide invaluable benefits and tools to maximise poultry welfare by providing better alternatives to evaluate bird health and response, thereby minimising production losses. This is the hope of implementing new solutions in farm management which will supply good quality and safe food for customers. PLF technologies for poultry sector are still at the beginning of development and implementation on farms. Several challenges will need to be solved for farmers' and consumers' broad acceptance of these technologies. These primary challenges include the machine learning process and data analysing for large scale, more sensitivity and resistant sensors used in PLF, and educating potential users who need the necessary skills to use such solutions. Hi-tech poultry production farms can offer the opportunity to connect farmers' and consumers' interests while increasing the emphasis on improving poultry welfare.

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References

1. Yildiz, D. Global Poultry Industry and Trends. Available online: https://www.feedandadditive.com/global-poultry-industry-and-trends/ (accessed on 10 March 2022).
2. European Union/Eurostat. Production of Meat: Poultry [TAG 00043], 2021. Available online: https://ec.europa.eu/eurostat/databrowser/view/TAG00043/default/table (accessed on 10 March 2022).
3. OECD-FAO. *OECD-FAO Agricultural Outlook 2021–2030*; OECD: Paris, France, 2021.
4. Limbergen, T.; Sarrazin, S.; Chantziaras, I.; Dewulf, J.; Ducatelle, R.; Kyriazakis, I.; McMullin, P.; Méndez, J.; Niemi, J.; Papasolomontos, S.; et al. Risk Factors for Poor Health and Performance in European Broiler Production Systems. *BMC Vet. Res.* **2020**, *3*, 287. [CrossRef] [PubMed]
5. Gocsik; Silvera, A.M.; Hansson, H.; Saatkamp, H.W.; Blokhuis, H.J. Exploring the Economic Potential of Reducing Broiler Lameness. *Br. Poult. Sci.* **2017**, *58*, 337–347. [CrossRef] [PubMed]
6. Sih, A.; Bell, A.M.; Johnson, J.C.; Ziemba, R.E. Behavioral Syndromes: An Integrative Overview. *Q. Rev. Biol.* **2004**, *79*, 241–277. [CrossRef]
7. Tablante, N.L.; Vaillancourt, J.P.; Martin, S.W.; Shoukri, M.; Estevez, I. Spatial Distribution of Cannibalism Mortalities in Commercial Laying Hens. *Poult. Sci.* **2000**, *79*, 705–708. [CrossRef] [PubMed]
8. Brunberg, E.; Jensen, P.; Isaksson, A.; Keeling, L. Feather Pecking Behavior in Laying Hens: Hypothalamic Gene Expression in Birds Performing and Receiving Pecks. *Poult. Sci.* **2011**, *90*, 1145–1152. [CrossRef] [PubMed]
9. Blokhuis, H.J.; van Fiks Niekerk, T.; Bessei, W.; Elson, A.; Guémené, D.; Kjaer, J.B.; Maria Levrino, G.A.; Nicol, C.J.; Tauson, R.; Weeks, C.A.; et al. The LayWel Project: Welfare Implications of Changes in Production Systems for Laying Hens. *World's Poult. Sci. J.* **2007**, *63*, 101–114. [CrossRef]
10. Peguri, A.; Coon, C. Effect of Feather Coverage and Temperature on Layer Performance. *Poult. Sci.* **1993**, *72*, 1318–1329. [CrossRef]
11. Huber-Eicher, B.; Sebo, F. The Prevalence of Feather Pecking and Development in Commercial flocks of Laying Hens. *Appl. Anim. Behav. Sci.* **2001**, *74*, 223–231. [CrossRef]
12. Granquist, E.G.; Vasdal, G.; de Jong, I.C.; Moe, R.O. Lameness and Its Relationship with Health and Production Measures in Broiler Chickens. *Animal* **2019**, *13*, 2365–2372. [CrossRef]
13. Bracke, M.B.M.; Hopster, H. Assessing the Importance of Natural Behavior for Animal Welfare. *J. Agric. Environ. Ethics* **2006**, *19*, 77–89. [CrossRef]
14. Maharjan, P.; Liang, Y. Precision Livestock Farming: The Opportunities in Poultry Sector. *J. Agric. Sci. Technol. A* **2020**, *10*, 45–53. [CrossRef]
15. Berckmans, D. Precision Livestock Farming Technologies for Welfare Management in Intensive Livestock Systems. *Rev. Sci. Tech.* **2014**, *33*, 189–196. [CrossRef] [PubMed]
16. Mollo, M.; Vendrametto, O.; Okano, M. Precision Livestock Tools to Improve Products and Processes in Broiler Production: A Review. *Braz. J. Poult. Sci.* **2009**, *11*, 211–218. [CrossRef]
17. Buller, H.; Blokhuis, H.; Lokhorst, K.; Silberberg, M.; Veissier, I. Animal Welfare Management in a Digital World. *Animals* **2020**, *10*, 1779. [CrossRef] [PubMed]
18. Wathes, C.M.; Kristensen, H.H.; Aerts, J.M.; Berckmans, D. Is Precision Livestock Farming an Engineer's Daydream or Nightmare, an Animal's Friend or Foe, and a Farmer's Panacea or Pitfall? *Comput. Electron. Agric.* **2008**, *64*, 2–10. [CrossRef]
19. Berckmans, D. General Introduction to Precision Livestock Farming. *Anim. Front.* **2017**, *7*, 6–11. [CrossRef]
20. Fournel, S.; Laberge, B.; Rousseau, A.N. Rethinking Environment Control Strategy of Confined Animal Housing Systems through Precision Livestock Farming. *Biosyst. Eng.* **2017**, *155*, 96–123. [CrossRef]
21. Detsch, D.T.; Conti, D.; Diniz-Ehrhardt, M.A.; Martínez, J.M. On the Controlling of Temperature: A Proposal for a Real-Time Controller in Broiler Houses. *Sci. Agric.* **2018**, *75*, 445–451. [CrossRef]
22. Thomas, D.G.; Son, J.-H.; Ravindran, V.; Thomas, D.V. The Effect of Stocking Density on the Behaviour of Broiler Chickens. *Korean J. Poult. Sci.* **2011**, *38*, 1–4. [CrossRef]
23. European Union Council Directive 2007/43/EC of 28 June 2007 Laying down Minimum Rules for the Protection of Chickens Kept for Meat Production. *Off. J. Eur. Union* **2007**, *182*, 19–28.
24. EC Council Directive Council Directive 99/74/EC of 19 July 1999 Laying down Minimum Standards for the Protection of Laying Hens. *Off. J. Eur. Communities* **1999**, 53–57.
25. Hartung, J.; Banhazi, T.; Vranken, E.; Guarino, M. European Farmers' Experiences with Precision Livestock Farming Systems. *Anim. Front.* **2017**, *7*, 38–44. [CrossRef]
26. Jones, T.A.; Donnelly, C.A.; Dawkins, M.S. Environmental and Management Factors Affecting the Welfare of Chickens on Commercial Farms in the United Kingdom and Denmark Stocked at Five Densities. *Poult. Sci.* **2005**, *84*, 1155–1165. [CrossRef] [PubMed]
27. Dawkins, M.S.; Donnelly, C.A.; Jones, T.A. Chicken Welfare Is Influenced More by Housing Conditions than by Stocking Density. *Nature* **2004**, *427*, 342–344. [CrossRef] [PubMed]
28. Meluzzi, A.; Sirri, F. Welfare of Broiler Chickens. *Ital. J. Anim. Sci.* **2009**, *8*, 161–173. [CrossRef]
29. Hocquette, J.F.; Chatellier, V. Prospects for the European Beef Sector over the next 30 Years. *Anim. Front.* **2011**, *1*, 20–28. [CrossRef]
30. Corkery, G.; Ward, S.; Kenny, C.; Hemmingway, P. Incorporating Smart Sensing Technologies into the Poultry Industry. *J. World's Poult. Res.* **2013**, *3*, 106–128.

31. Abu-Dieyeh, Z.H.M. Effect of High Temperature Per Se on Growth Performance of Broilers. *Int. J. Poult. Sci.* **2006**, *5*, 19–21.
32. Ferreira, V.M.O.S.; Francisco, N.S.; Belloni, M.; Aguirre, G.M.Z.; Caldara, F.R.; Nääs, I.A.; Garcia, R.G.; Almeida, P.I.C.L.; Polycarpo, G.v. Infrared Thermography Applied to the Evaluation of Metabolic Heat Loss of Chicks Fed with Different Energy Densities. *Rev. Bras. De Cienc. Avic.* **2011**, *13*, 113–118. [CrossRef]
33. European Commission. *The Welfare of Chickens Kept for Meat Production (Broilers)*; Report of the Scientific Comitee of Animal Health and Animal Welfare; European Comission: Brussel, Belgium, 21 March 2000.
34. Pitla, S.; Bajwa, S.; Bhusal, S.; Brumm, T.; Brown-Brandl, T.M. *Ground and Aerial Robots for Agricultural Production: Opportunities and Challenges*; Issue Paper 70; Council for Agricultural Science and Technology (CAST): Ames, IA, USA, 2020.
35. Li, N.; Ren, Z.; Li, D.; Zeng, L. Review: Automated Techniques for Monitoring the Behaviour and Welfare of Broilers and Laying Hens: Towards the Goal of Precision Livestock Farming. *Animal* **2020**, *14*, 617–625. [CrossRef]
36. Ferket, P.R.; Abel, G. Gernat Factors That Affect Feed Intake of Meat Birds: A Review. *Int. J. Poult. Sci.* **2006**, *5*, 905–911. [CrossRef]
37. Xin, H.; Liu, K. Precision Livestock Farming in Egg Production. *Anim. Front.* **2017**, *7*, 24–31. [CrossRef]
38. Linden, J. Water System Inspection Pays Off. Available online: https://www.thepoultrysite.com/articles/water-system-inspection-pays-off (accessed on 10 March 2022).
39. Kashiha, M.; Pluk, A.; Bahr, C.; Vranken, E.; Berckmans, D. Development of an Early Warning System Forabroiler House Using Computer Vision. *Biosyst. Eng.* **2013**, *116*, 36–45. [CrossRef]
40. Costa, L.S.; Pereira, D.F.; Bueno, L.G.F.; Pandorfi, H. Some Aspects of Chicken Behavior and Welfare. *Rev. Bras. De Cienc. Avic.* **2012**, *14*, 159–164. [CrossRef]
41. Alves, F.; Felix, G.; Almeida Paz, I.; Naas, I.; Souza, G.; Caldara, F.; Garcia, R. Impact of Exposure to Cold on Layer Production. *Braz. J. Poult. Sci.* **2012**, *14*, 159–232. [CrossRef]
42. Havenstein, G.B.; Ferket, P.R.; Qureshi, M.A. Carcass Composition and Yield of 1957 Versus 2001 Broilers When Fed Representative 1957 and 2001 Broiler Diets 1. *Poult. Sci.* **2003**, *82*, 1509–1518. [CrossRef]
43. Yahav, S. Alleviating Heat Stress in Domestic Fowl: Different Strategies. *World's Poult. Sci. J.* **2009**, *65*, 719–732. [CrossRef]
44. Zhou, W.T.; Yamamoto, S. Effects of Environmental Temperature and Heat Production Due to Food Intake on Abdominal Temperature, Shank Skin Temperature and Respiration Rate of Broilers. *Br. Poult. Sci.* **1997**, *38*, 107–114. [CrossRef]
45. Bloch, V.; Barchilon, N.; Halachmi, I.; Druyan, S. Automatic Broiler Temperature Measuring by Thermal Camera. *Biosyst. Eng.* **2020**, *199*, 127–134. [CrossRef]
46. Giloh, M.; Shinder, D.; Yahav, S. Skin Surface Temperature of Broiler Chickens Is Correlated to Body Core Temperature and Is Indicative of Their Thermoregulatory Status. *Poult. Sci.* **2012**, *91*, 175–188. [CrossRef]
47. Blanes-Vidal, V.; Guijarro, E.; Nadimi, E.S.; Torres, A.G. Development and Field Test of an On-Line Computerized Instrumentation System for Air Velocity, Temperature and Differential Pressure Measurements in Poultry Houses. *Span. J. Agric. Res.* **2010**, *8*, 570. [CrossRef]
48. Mutai, E.B.K.; Otieno, P.O.; Gitau, A.N.; Mbuge, D.O.; Mutuli, D.A. Simulation of the Microclimate in Poultry Structures in Kenya. *Res. J. Appl. Sci. Eng. Technol.* **2011**, *3*, 579–588.
49. Nääs, I.d.A.; Eduardo Bites Romanini, C.; Pereira Neves, D.; Rodrigues do Nascimento, G.; do Amaral Vercellino, R. Broiler Surface Temperature Distribution of 42 Day Old Chickens. *Sci. Agric.* **2010**, *67*, 497–502. [CrossRef]
50. Caslin, B.; Cirillo, M.; Finnan, J.; Forristal, D.; Gaffney, M.; McCutcheon, G.; Murphy, M.; Sproule, I.; Upton, I. *Energy Use in Agriculture*; Teagasc: Carlow, Ireland, 2011; ISBN 10 1-84170-579-9.
51. Frame, D.D. *Basics for Raising Backyard Chickens*; Paper 1295; Utah State University Extension: Logan, UT, USA, 2010.
52. Amir, N.S.; Abas, A.M.F.M.; Azmi, N.A.; Abidin, Z.Z.; Shafie, A.A. Chicken Farm Monitoring System. In Proceedings of the 6th International Conference on Computer and Communication Engineering: Innovative Technologies to Serve Humanity, ICCCE, Kuala Lumpur, Malaysia, 26–27 July 2016; pp. 132–137. [CrossRef]
53. Yahav, S.; Shinder, D.; Tanny, J.; Cohen, S. Sensible Heat Loss: The Broiler's Paradox. *World's Poult. Sci. J.* **2005**, *61*, 419–434. [CrossRef]
54. Knížatová, M.; Brouček, J.; Mihina, Š. Seasonal Differences in Levels of Carbon Dioxide and Ammonia in Broiler Housing. *Slovak. J. Anim. Sci.* **2010**, *2010*, 105–112.
55. Fairchild, B. *Environmental Factors to Control When Brooding Chicks*; Bulletin 1287; University of Georgia: Athens, GA, USA, 2009; pp. 1–5.
56. Chai, L.; Ni, J.Q.; Diehl, C.A.; Kilic, I.; Heber, A.J.; Chen, Y.; Cortus, E.L.; Bogan, B.W.; Lim, T.T.; Ramirez-Dorronsoro, J.C.; et al. Ventilation Rates in Large Commercial Layer Hen Houses with Two-Year Continuous Monitoring. *Br. Poult. Sci.* **2012**, *53*, 19–31. [CrossRef]
57. Czarick, M.; Fairchild, B. Relative Humidity . . . The Best Measure of Overall Poultry House Air Quality | UGA Poultry House Environmental Management and Energy Conservation. *Poult. Hous. Tips* **2012**, *24*, 2.
58. Grilli, G.; Borgonovo, F.; Tullo, E.; Fontana, I.; Guarino, M.; Ferrante, V. A Pilot Study to Detect Coccidiosis in Poultry Farms at Early Stage from Air Analysis. *Biosyst. Eng.* **2018**, *173*, 64–70. [CrossRef]
59. Wang, Y.M.; Meng, Q.P.; Guo, Y.M.; Wang, Y.Z.; Wang, Z.; Yao, Z.L.; Shan, T.Z. Effect of Atmospheric Ammonia on Growth Performance and Immunological Response of Broiler Chickens. *J. Anim. Vet. Adv.* **2010**, *9*, 2802–2806. [CrossRef]
60. Deep, A.; Schwean-Lardner, K.; Crowe, T.G.; Fancher, B.I.; Classen, H.L. Effect of Light Intensity on Broiler Production, Processing Characteristics, and Welfare. *Poult. Sci.* **2010**, *89*, 2326–2333. [CrossRef]

61. Kristensen, H.H.; Prescott, N.B.; Perry, G.C.; Ladewig, J.; Ersbøll, A.K.; Overvad, K.C.; Wathes, C.M. The Behaviour of Broiler Chickens in Different Light Sources and Illuminances. *Appl. Anim. Behav. Sci.* **2007**, *103*, 75–89. [CrossRef]
62. Huber-Eicher, B.; Suter, A.; Spring-Stähli, P. Effects of Colored Light-Emitting Diode Illumination on Behavior and Performance of Laying Hens. *Poult. Sci.* **2013**, *92*, 869–873. [CrossRef] [PubMed]
63. Soliman, F.N.K.; El-Sabrout, K. Light Wavelengths/Colors: Future Prospects for Broiler Behavior and Production. *J. Vet. Behav.* **2020**, *36*, 34–39. [CrossRef]
64. Cao, J.; Liu, W.; Wang, Z.; Xie, D.; Jia, L.; Chen, Y. Green and Blue Monochromatic Lights Promote Growth and Development of Broilers via Stimulating Testosterone Secretion and Myofiber Growth. *J. Appl. Poult. Res.* **2008**, *17*, 211–218. [CrossRef]
65. Mendes, A.S.; Paixão, S.J.; Restelatto, R.; Morello, G.M.; de Moura, D.J.; Possenti, J.C. Performance and Preference of Broiler Chickens Exposed to Different Lighting Sources. *J. Appl. Poult. Res.* **2013**, *22*, 62–70. [CrossRef]
66. Zhang, L.; Zhang, H.J.; Wang, J.; Wu, S.G.; Qiao, X.; Yue, H.Y.; Yao, J.H.; Qi, G.H. Stimulation with Monochromatic Green Light during Incubation Alters Satellite Cell Mitotic Activity and Gene Expression in Relation to Embryonic and Posthatch Muscle Growth of Broiler Chickens. *Animal* **2014**, *8*, 86–93. [CrossRef]
67. Lewis, P.D.; Morris, T.R. Poultry and Coloured Light. *World's Poult. Sci. J.* **2000**, *56*, 203–207. [CrossRef]
68. Riber, A.B. Effects of Color of Light on Preferences, Performance, and Welfare in Broilers. *Poult. Sci.* **2015**, *94*, 1767–1775. [CrossRef]
69. James, C.; Wiseman, J.; Asher, L. The Effect of Supplementary Ultraviolet Wavelengths on the Performance of Broiler Chickens. *Poult. Sci.* **2020**, *99*, 5517–5525. [CrossRef]
70. Prayitno, D.S.; Phillips, C.J.C.; Omed, H. The Effects of Color of Lighting on the Behavior and Production of Meat Chickens. *Poult. Sci.* **1997**, *76*, 452–457. [CrossRef]
71. Zhang, Z.; Cao, J.; Wang, Z.; Dong, Y.; Chen, Y. Effect of a Combination of Green and Blue Monochromatic Light on Broiler Immune Response. *J. Photochem. Photobiol. B: Biol.* **2014**, *138*, 118–123. [CrossRef] [PubMed]
72. Olanrewaju, H.A.; Miller, W.W.; Maslin, W.R.; Collier, S.D.; Purswell, J.L.; Branton, S.L. Interactive Effects of Light-Sources, Photoperiod, and Strains on Growth Performance, Carcass Characteristics, and Health Indices of Broilers Grown to Heavy Weights. *Poult. Sci.* **2019**, *98*, 6232–6240. [CrossRef] [PubMed]
73. Averós, X.; Estevez, I. Meta-Analysis of the Effects of Intensive Rearing Environments on the Performance and Welfare of Broiler Chickens. *Poult. Sci.* **2018**, *97*, 3767–3785. [CrossRef] [PubMed]
74. Alvino, G.M.; Archer, G.S.; Mench, J.A. Behavioural Time Budgets of Broiler Chickens Reared in Varying Light Intensities. *Appl. Anim. Behav. Sci.* **2009**, *118*, 54–61. [CrossRef]
75. Alvino, G.M.; Blatchford, R.A.; Archer, G.S.; Mench, J.A. Light Intensity during Rearing Affects the Behavioural Synchrony and Resting Patterns of Broiler Chickens. *Br. Poult. Sci.* **2009**, *50*, 275–283. [CrossRef]
76. Blatchford, R.A.; Klasing, K.C.; Shivaprasad, H.L.; Wakenell, P.S.; Archer, G.S.; Mench, J.A. The Effect of Light Intensity on the Behavior, Eye and Leg Health, and Immune Function of Broiler Chickens. *Poult. Sci.* **2009**, *88*, 20–28. [CrossRef]
77. Sanotra, G.S.; Lund, J.D.; Vestergaard, K.S. Influence of Light-Dark Schedules and Stocking Density on Behaviour, Risk of Leg Problems and Occurrence of Chronic Fear in Broilers. *British Poult. Sci.* **2002**, *43*, 344–354. [CrossRef]
78. Bayram, A.; Özkan, S. Effects of a 16-Hour Light, 8-Hour Dark Lighting Schedule on Behavioral Traits and Performance in Male Broiler Chickens. *J. Appl. Poult. Res.* **2010**, *19*, 263–273. [CrossRef]
79. Schwean-Lardner, K.; Fancher, B.I.; Classen, H.L. Impact of Daylength on Behavioural Output in Commercial Broilers. *Appl. Anim. Behav. Sci.* **2012**, *137*, 43–52. [CrossRef]
80. Meyer, M.M.; Johnson, A.K.; Bobeck, E.A. A Novel Environmental Enrichment Device Increased Physical Activity and Walking Distance in Broilers. *Poult. Sci.* **2020**, *99*, 48–60. [CrossRef]
81. Lasagabaster, A.; Arboleya, J.C.; de Marañón, I.M. Pulsed Light Technology for Surface Decontamination of Eggs: Impact on Salmonella Inactivation and Egg Quality. *Innov. Food Sci. Emerg. Technol.* **2011**, *12*, 124–128. [CrossRef]
82. Fontana, I.; Tullo, E.; Butterworth, A.; Guarino, M. An Innovative Approach to Predict the Growth in Intensive Poultry Farming. *Comput. Electron. Agric.* **2015**, *119*, 178–183. [CrossRef]
83. Chedad, A.; Vranken, E.; Aerts, J.-M.; Berckmans, D. Behaviour of Chickens Towards Automatic Weighing Systems. *IFAC Proc. Vol.* **2000**, *33*, 207–212. [CrossRef]
84. Larios, D.F.; Rodrguez, C.; Barbancho, J.; Baena, M.; Leal, M.Á.; Marn, J.; León, C.; Bustamante, J. An Automatic Weighting System for Wild Animals Based in an Artificial Neural Network: How to Weigh Wild Animals without Causing Stress. *Sensors* **2013**, *13*, 2862–2883. [CrossRef] [PubMed]
85. Wang, K.; Pan, J.; Rao, X.; Yang, Y.; Wang, F.; Zheng, R.; Ying, Y. An Image-Assisted Rod-Platform Weighing System for Weight Information Sampling of Broilers. *Trans. ASABE* **2018**, *61*, 631–640. [CrossRef]
86. Lee, C.C.; Adom, A.H.; Markom, M.A.; Tan, E.S.M.M. Automated Chicken Weighing System Using Wireless Sensor Network for Poultry Farmers. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Atlanta, GA, USA, 28 June 2019; Institute of Physics Publishing: Bristol, UK, 2019; Volume 557.
87. Lacy, M.P. Broiler Management. In *Commercial Chicken Meat and Egg Production*; Springer Science+Business Media: New York, NY, USA, 2002; pp. 829–868.
88. Chedad, A.; Aerts, J.M.; Vranken, E.; Lippens, M.; Zoons, J.; Berckmans, D. Do Heavy Broiler Chickens Visit Automatic Weighing Systems Less than Lighter Birds? *British Poult. Sci.* **2003**, *44*, 663–668. [CrossRef]

89. Bowling, D.L.; Garcia, M.; Dunn, J.C.; Ruprecht, R.; Stewart, A.; Frommolt, K.H.; Fitch, W.T. Body Size and Vocalization in Primates and Carnivores. *Sci. Rep.* **2017**, *7*, 41070. [CrossRef]
90. Fontana, I.; Tullo, E.; Carpentier, L.; Berckmans, D.; Butterworth, A.; Vranken, E.; Norton, T.; Berckmans, D.; Guarino, M. Sound Analysis to Model Weight of Broiler Chickens. *Poult. Sci.* **2017**, *96*, 3938–3943. [CrossRef]
91. Aydin, A.; Bahr, C.; Berckmans, D. A Real-Time Monitoring Tool to Automatically Measure the Feed Intakes of Multiple Broiler Chickens by Sound Analysis. *Comput. Electron. Agric.* **2015**, *114*, 1–6. [CrossRef]
92. Aydin, A.; Bahr, C.; Viazzi, S.; Exadaktylos, V.; Buyse, J.; Berckmans, D. A novel method to automatically measure the fed intake of broiler chickens by sound technology. *Comput. Electron. Agric.* **2014**, *101*, 17–23. [CrossRef]
93. Curtin, R.R.; Daley, W.; Anderson, D.v. Classifying Broiler Chicken Condition Using Audio Data. In Proceedings of the 2014 IEEE Global Conference on Signal and Information Processing, GlobalSIP 2014, Atlanta, GA, USA, 3–5 December 2014; pp. 1141–1144. [CrossRef]
94. Jahns, G. Call Recognition to Identify Cow Conditions-A Call-Recogniser Translating Calls to Text. *Comput. Electron. Agric.* **2008**, *62*, 54–58. [CrossRef]
95. Sheng, H.; Zhang, S.; Zuo, L.; Duan, G.; Zhang, H.; Okinda, C.; Shen, M.; Chen, K.; Lu, M.; Norton, T. Construction of Sheep Forage Intake Estimation Models Based on Sound Analysis. *Biosyst. Eng.* **2020**, *192*, 144–158. [CrossRef]
96. Ikeda, Y.; Ishii, Y. Recognition of Two Psychological Conditions of a Single Cow by Her Voice. *Comput. Electron. Agric.* **2008**, *62*, 67–72. [CrossRef]
97. Manteuffel, G.; Puppe, B.; Schön, P.C. Vocalization of Farm Animals as a Measure of Welfare. *Appl. Anim. Behav. Sci.* **2004**, *88*, 163–182. [CrossRef]
98. Steen, K.A.; Therkildsen, O.R.; Karstoft, H.; Green, O. A Vocal-Based Analytical Method for Goose Behaviour Recognition. *Sensors* **2012**, *12*, 3773–3788. [CrossRef] [PubMed]
99. Ren, Y.; Johnson, M.T.; Clemins, P.J.; Darre, M.; Glaeser, S.S.; Osiejuk, T.S.; Out-Nyarko, E. A Framework for Bioacoustic Vocalization Analysis Using Hidden Markov Models. *Algorithms* **2009**, *2*, 1410–1428. [CrossRef]
100. de Moura, D.J.; Vale, M.M.; Nääs, D.A.; Rodrigues, L.H.A.; Oliveira, S.R.D.M. Estimating Poultry Production Mortality Exposed to Heat Wave Using Data Mining. In Proceedings of the Livestock Environment VIII—Proceedings of the Eighth International Symposium, Iguassu Falls, Brazil, 31 August–4 September 2008; pp. 865–872. [CrossRef]
101. de Moura, D.J.; Nääs, I.D.A.; Alves, E.C.D.S.; de Carvalho, T.M.R.; do Vale, M.M.; de Lima, K.A.O. Noise Analysis to Evaluate Chick Thermal Comfort. *Sci. Agric.* **2008**, *65*, 438–443. [CrossRef]
102. Bright, A. Vocalisations and Acoustic Parameters of Flock Noise from Feather Pecking and Non-Feather Pecking Laying Flocks. *Br. Poult. Sci.* **2008**, *49*, 241–249. [CrossRef]
103. Exadaktylos, V.; Silva, M.; Berckmans, D. Real-Time Analysis of Chicken Embryo Sounds to Monitor Different Incubation Stages. *Comput. Electron. Agric.* **2011**, *75*, 321–326. [CrossRef]
104. Aydin, A.; Cangar, O.; Ozcan, S.E.; Bahr, C.; Berckmans, D. Application of a Fully Automatic Analysis Tool to Assess the Activity of Broiler Chickens with Different Gait Scores. *Comput. Electron. Agric.* **2010**, *73*, 194–199. [CrossRef]
105. Renema, R.A.; Rustad, M.E.; Robinson, F.E. Implications of Changes to Commercial Broiler and Broiler Breeder Body Weight Targets over the Past 30 Years. *World's Poult. Sci. J.* **2007**, *63*, 457–472. [CrossRef]
106. Kapell, D.N.R.G.; Hill, W.G.; Neeteson, A.M.; McAdam, J.; Koerhuis, A.N.M.; Avendaño, S. Twenty-Five Years of Selection for Improved Leg Health in Purebred Broiler Lines and Underlying Genetic Parameters. *Poult. Sci.* **2012**, *91*, 3032–3043. [CrossRef] [PubMed]
107. Jacob, F.G.; Baracho, M.D.S.; Nääs, I.D.A.; Souza, R.; Salgado, D.D. The Use of Infrared Thermography in the Identification of Pododermatitis in Broilers. *J. Braz. Assoc. Agric. Eng.* **2016**, *36*, 253–259. [CrossRef]
108. Bessei, W. Welfare of Broilers: A Review. *World's Poult. Sci. J.* **2006**, *62*, 455–466. [CrossRef]
109. Knowles, T.G.; Kestin, S.C.; Haslam, S.M.; Brown, S.N.; Green, L.E.; Butterworth, A.; Pope, S.J.; Pfeiffer, D.; Nicol, C.J. Leg Disorders in Broiler Chickens: Prevalence, Risk Factors and Prevention. *PLoS ONE* **2008**, *3*, e1545. [CrossRef]
110. Ben Sassi, N.; Averós, X.; Estevez, I. Technology and Poultry Welfare. *Animals* **2016**, *6*, 62. [CrossRef]
111. Haslam, S.M.; Knowles, T.G.; Brown, S.N.; Wilkins, L.J.; Kestin, S.C.; Warriss, P.D.; Nicol, C.J. Factors Affecting the Prevalence of Foot Pad Dermatitis, Hock Burn and Breast Burn in Broiler Chicken. *Br. Poult. Sci.* **2007**, *48*, 264–275. [CrossRef]
112. De Jong, I.C.; van Harn, J.; Gunnink, H.; Lourens, A.; van Riel, J.W. Measuring Foot-Pad Lesions in Commercial Broiler Houses. Some Aspects of Methodology. *Anim. Welf.* **2012**, *21*, 325–330. [CrossRef]
113. Kyvsgaard, N.C.; Jensen, H.B.; Ambrosen, T.; Toft, N. Temporal Changes and Risk Factors for Foot-Pad Dermatitis in Danish Broilers. *Poult. Sci.* **2013**, *92*, 26–32. [CrossRef]
114. Dawkins, M.S.; Roberts, S.J.; Cain, R.J.; Nickson, T.; Donnelly, C.A. Early Warning of Footpad Dermatitis and Hockburn in Broiler Chicken Flocks Using Optical Flow, Bodyweight and Water Consumption. *Vet. Rec.* **2017**, *180*, 499. [CrossRef]
115. Shepherd, E.M.; Fairchild, B.D. Footpad Dermatitis in Poultry. *Poult. Sci.* **2010**, *89*, 2043–2051. [CrossRef] [PubMed]
116. Elson, H.A. Poultry Welfare in Intensive and Extensive Production Systems. *World's Poult. Sci. J.* **2015**, *71*, 449–459. [CrossRef]
117. Bilgili, S.F.; Hess, J.B.; Blake, J.P.; Macklin, K.S.; Saenmahayak, B.; Sibley, J.L. Influence of Bedding Material on Footpad Dermatitis in Broiler Chickens. *J. Appl. Poult. Res.* **2009**, *18*, 583–589. [CrossRef]
118. Hoffmann, G.; Ammon, C.; Volkamer, L.; Sürie, C.; Radko, D. Sensor-Based Monitoring of the Prevalence and Severity of Foot Pad Dermatitis in Broiler Chickens. *Br. Poult. Sci.* **2013**, *54*, 553–561. [CrossRef] [PubMed]

119. Siegford, J.M.; Berezowski, J.; Biswas, S.K.; Daigle, C.L.; Gebhardt-Henrich, S.G.; Hernandez, C.E.; Thurner, S.; Toscano, M.J. Assessing Activity and Location of Individual Laying Hens in Large Groups Using Modern Technology. *Animals* **2016**, *6*, 10. [CrossRef] [PubMed]
120. Stadig, L.M.; Rodenburg, T.B.; Ampe, B.; Reubens, B.; Tuyttens, F.A.M. An Automated Positioning System for Monitoring Chickens' Location: Effects of Wearing a Backpack on Behaviour, Leg Health and Production. *Appl. Anim. Behav. Sci.* **2018**, *198*, 83–88. [CrossRef]
121. Rodenburg, T.B.; van der Eijk, J.A.J.; Pichova, K.; van Mil, B.; de Haas, E.N. PhenLab: Automatic Recording of Location, Activity and Proximity in Group-Based Laying Hens. In Proceedings of the 8th European Conference on Precision Livestock Farming, Nantes, France, 12–14 September 2017; pp. 275–276.
122. Fleet, D.; Weiss, Y. Optical Flow Estimation. In *Mathematical Models for Computer Vision*; Springer: Boston, MA, USA, 2005; pp. 239–258.
123. Dawkins, M.S.; Lee, H.J.; Waitt, C.D.; Roberts, S.J. Optical Flow Patterns in Broiler Chicken Flocks as Automated Measures of Behaviour and Gait. *Appl. Anim. Behav. Sci.* **2009**, *119*, 203–209. [CrossRef]
124. Dawkins, M.S.; Cain, R.; Roberts, S.J. Optical Flow, Flock Behaviour and Chicken Welfare. *Anim. Behav.* **2012**, *84*, 219–223. [CrossRef]
125. Roberts, S.J.; Cain, R.; Dawkins, M.S. Prediction of Welfare Outcomes for Broiler Chickens Using Bayesian Regression on Continuous Optical Flow Data. *J. R. Soc. Interface* **2012**, *9*, 3436–3443. [CrossRef]
126. Peña Fernández, A.; Norton, T.; Tullo, E.; van Hertem, T.; Youssef, A.; Exadaktylos, V.; Vranken, E.; Guarino, M.; Berckmans, D. Real-Time Monitoring of Broiler Flock's Welfare Status Using Camera-Based Technology. *Biosyst. Eng.* **2018**, *173*, 103–114. [CrossRef]
127. Altera. *White Paper A Flexible Architecture for Fisheye Correction in Automotive Rear-View Cameras Version 1.2 1*; Altera Corporation: San Jose, CA, USA, 2008.
128. Baracho, M.; Naas, I.; Nascimento, G.; Cassiano, J.; Oliveira, K. Surface Temperature Distribution in Broiler Houses. *Braz. J. Poult. Sci.* **2011**, *13*, 177–182. [CrossRef]
129. Van Hertem, T.; Norton, T.; Berckmans, D.; Vranken, E. Predicting Broiler Gait Scores from Activity Monitoring and Flock Data. *Biosyst. Eng.* **2018**, *173*, 93–102. [CrossRef]
130. Winckler, C. Assessing Animal Welfare at the Farm Level: Do We Care Sufficiently about the Individual? *Anim. Welf.* **2019**, *28*, 77–82. [CrossRef]
131. Dawkins, M.S.; Wang, L.; Ellwood, S.A.; Roberts, S.J.; Gebhardt-Henrich, S.G. Optical Flow, Behaviour and Broiler Chicken Welfare in the UK and Switzerland. *Appl. Anim. Behav. Sci.* **2021**, *234*, 105180. [CrossRef]
132. Rowe, E.; Dawkins, M.S.; Gebhardt-Henrich, S.G. A Systematic Review of Precision Livestock Farming in the Poultry Sector: Is Technology Focussed on Improving Bird Welfare? *Animals* **2019**, *9*, 614. [CrossRef] [PubMed]
133. Kristensen, H.H.; Cornou, C. Automatic Detection of Deviations in Activity Levels in Groups of Broiler Chickens–A Pilot Study. *Biosyst. Eng.* **2011**, *109*, 369–376. [CrossRef]
134. Silvera, A.M.; Knowles, T.G.; Butterworth, A.; Berckmans, D.; Vranken, E.; Blokhuis, H.J. Lameness Assessment with Automatic Monitoring of Activity in Commercial Broiler Flocks. *Poult. Sci.* **2017**, *96*, 2013–2017. [CrossRef]
135. Nääs, I.d.A.; Paz, I.C.d.L.A.; Baracho, M.d.S.; de Menezes, A.G.; de Lima, K.A.O.; Bueno, L.G.d.F.; Mollo Neto, M.; de Carvalho, V.C.; Almeida, I.C.d.L.; de Souza, A.L. Assessing Locomotion Deficiency in Broiler Chicken. *Sci. Agric.* **2010**, *67*, 129–135. [CrossRef]
136. Epp, M. Poultry Technology—Rise of the Robots. *Can. Poult.* **2019**. Available online: https://www.canadianpoultrymag.com/rise-of-the-robots-30876/ (accessed on 10 March 2022).
137. Quwaider, M.Q.; Daigle, C.L.; Biswas, S.K.; Siegford, J.M.; Swanson, J.C. Development of a Wireless Body–Mounted Sensor to Monitor Location and Activity of Laying Hens in a Non-Cage Housing System. *Am. Soc. Agric. Biol. Eng.* **2010**, *53*, 1705–1713. [CrossRef]
138. Kozak, M.; Tobalske, B.; Springthorpe, D.; Szkotnicki, B.; Harlander-Matauschek, A. Development of Physical Activity Levels in Laying Hens in Three-Dimensional Aviaries. *Appl. Anim. Behav. Sci.* **2016**, *185*, 66–72. [CrossRef]
139. Leroy, T.; Vranken, E.; van Brecht, A.; Struelens, E.; Sonck, B.; Berckmans, D. A computer vision method for on-line behavioral quantification of individually caged poultry. *Trans. ASABE* **2006**, *49*, 795–802. [CrossRef]
140. Zaninelli, M.; Redaelli, V.; Luzi, F.; Mitchell, M.; Bontempo, V.; Cattaneo, D.; Dell'Orto, V.; Savoini, G. Development of a Machine Vision Method for the Monitoring of Laying Hens and Detection of Multiple Nest Occupations. *Sensors* **2018**, *18*, 132. [CrossRef] [PubMed]
141. Chien, Y.R.; Chen, Y.X. An RFID-Based Smart Nest Box: An Experimental Study of Laying Performance and Behavior of Individual Hens. *Sensors* **2018**, *18*, 859. [CrossRef] [PubMed]
142. Pickel, T.; Schrader, L.; Scholz, B. Pressure Load on Keel Bone and Foot Pads in Perching Laying Hens in Relation to Perch Design. *Poult. Sci.* **2011**, *90*, 715–724. [CrossRef]
143. Bailie, C.L.; O'Connell, N.E. The Influence of Providing Perches and String on Activity Levels, Fearfulness and Leg Health in Commercial Broiler Chickens. *Animal* **2015**, *9*, 660–668. [CrossRef]
144. Bailie, C.L.; Baxter, M.; O'Connell, N.E. Exploring Perch Provision Options for Commercial Broiler Chickens. *Appl. Anim. Behav. Sci.* **2018**, *200*, 114–122. [CrossRef]

145. Bokkers, E.A.M.; Zimmerman, P.H.; Bas Rodenburg, T.; Koene, P. Walking Behaviour of Heavy and Light Broilers in an Operant Runway Test with Varying Durations of Feed Deprivation and Feed Access. *Appl. Anim. Behav. Sci.* **2007**, *108*, 129–142. [CrossRef]
146. Bizeray, D.; Estevez, I.; Leterrier, C.; Faure, J.M. Effects of Increasing Environmental Complexity on the Physical Activity of Broiler Chickens. *Appl. Anim. Behav. Science* **2002**, *79*, 27–41. [CrossRef]
147. Guo, Y.; Aggrey, S.E.; Oladeinde, A.; Johnson, J.; Zock, G.; Chai, L. A Machine Vision-Based Method Optimized for Restoring Broiler Chicken Images Occluded by Feeding and Drinking Equipment. *Animals* **2021**, *11*, 123. [CrossRef]
148. Welfare Quality. *Welfare Quality®Assessment Protocol for Poultry (Broilers, Laying Hens)*; ASG Veehouderij BV: Lelystad, The Netherlands, 2009; pp. 1–142.
149. Ferrante, V.; Watanabe, T.T.N.; Marchewka, J.; Estevez, I. AWIN Animal Welfare Indicators AWIN Welfare Assessment Protocol for Turkeys, March 2015, Uppsala, Sweden. Available online: https://air.unimi.it/handle/2434/269107 (accessed on 23 March 2022).
150. Carpentier, L.; Vranken, E.; Berckmans, D.; Paeshuyse, J.; Norton, T. Development of Sound-Based Poultry Health Monitoring Tool for Automated Sneeze Detection. *Comput. Electron. Agric.* **2019**, *162*, 573–581. [CrossRef]
151. Okada, H.; Suzuki, K.; Kenji, T.; Itoh, T. Avian Influenza Surveillance System in Poultry Farms Using Wireless Sensor Network. In Proceedings of the Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS, Seville, Spain, 5–7 May 2010; pp. 253–258.
152. Mitchell, M.A.; Kettlewell, P.J.; Lowe, J.C.; Hunter, R.R.; King, T.; Ritchie, M.; Bracken, J. Remote Physiological Monitoring of Livestock–An Implantable Radio-Telemetry System. In *Proceedings of the Livestock Environment VI: Proceedings of the 6th International Symposium*; Loisville, KY, USA, 21–23 May 2001, pp. 535–541.
153. Yang, H.H.; Bae, Y.H.; Min, W. Implantable Wireless Sensor Network to Monitor the Deep Body Temperature of Broilers. In Proceedings of the Proceedings–SERA 2007: Fifth ACIS International Conference on Software Engineering Research, Management, and Applications, Busan, Korea, 20–22 August 2007; pp. 569–576.
154. Schaefer, A.L.; Cook, N.; Tessaro, S.v.; Deregt, D.; Desroches, G.; Dubeski, P.L.; Tong, A.K.W.; Godson, D.L. Early Detection and Prediction of Infection Using Infrared Thermography. *Can. J. Anim. Sci.* **2004**, *84*, 73–80. [CrossRef]
155. Noh, J.Y.; Kim, K.J.; Lee, S.H.; Kim, J.B.; Kim, D.H.; Youk, S.; Song, C.S.; Nahm, S.S. Thermal Image Scanning for the Early Detection of Fever Induced by Highly Pathogenic Avian Influenza Virus Infection in Chickens and Ducks and Its Application in Farms. *Front. Vet. Sci.* **2021**, *8*, 616755. [CrossRef] [PubMed]
156. Tessier, M.; du Tremblay, D.; Klopfenstein, C.; Beauchamp, G.; Boulianne, M. Abdominal Skin Temperature Variation in Healthy Broiler Chickens as Determined by Thermography. *Poult. Sci.* **2003**, *82*, 846–849. [CrossRef]
157. Weschenfelder, A.V.; Saucier, L.; Maldague, X.; Rocha, L.M.; Schaefer, A.L.; Faucitano, L. Use of Infrared Ocular Thermography to Assess Physiological Conditions of Pigs Prior to Slaughter and Predict Pork Quality Variation. *Meat Sci.* **2013**, *95*, 616–620. [CrossRef] [PubMed]
158. Lovarelli, D.; Bacenetti, J.; Guarino, M. A Review on Dairy Cattle Farming: Is Precision Livestock Farming the Compromise for an Environmental, Economic and Social Sustainable Production? *J. Clean. Prod.* **2020**, *262*, 121409. [CrossRef]
159. McFadden, J.; Casalini, F.; Griffin, T.; Anton, J. *The Digitalisation of Agriculture: A Literature Review and Emerging Policy Issues*; OECD Food, Agriculture and Fisheries Papers, No. 176; OECD Publishing: Paris, France, 2022. [CrossRef]
160. Baylis, K.; Coppers, J.; Gramig, B.M.; Sachdeva, P. Agri-Environmental Programs in the United States and Canada. *Rev. Environ. Econ. Policy* **2022**, *16*, 83–104. [CrossRef]
161. Panell, D.; Rogers, A. Agriculture and the Environment: Policy Approaches in Australia and New Zealand. *Rev. Environ. Econ. Policy* **2022**, *16*, 126–145. [CrossRef]
162. Hasler, B.; Termansen, M.; Nielsen, H.O.; Daugbjerg, C.; Wunder, S.; Latacz-Lochmann, U. European Agi-Environmental Policy: Evolution, Effectiveness and Challenges. *Rev. Environ. Econ. Policy* **2022**, *16*, 105–125. [CrossRef]
163. Werkheiser, I. Precision Livestock Farming and Farmers' Duties to Livestock. *J. Agric. Environ. Ethics* **2018**, *31*, 181–195. [CrossRef]
164. Banhazi, T.M.; Lehr, H.; Black, J.L.; Crabtree, H.; Schofield, P.; Tscharke, M.; Berckmans, D. Precision Livestock Farming: An International Review of Scientific and Commercial Aspects. *Artic. Int. J. Agric. Biol. Eng.* **2012**, *5*, 1. [CrossRef]
165. Bahlo, C.; Dahlhaus, P.; Thompson, H.; Trotter, M. The Role of Interoperable Data Standards in Precision Livestock Farming in Extensive Livestock Systems: A Review. *Comput. Electron. Agric.* **2019**, *156*, 459–466. [CrossRef]
166. McFadden, J.; Casalini, F.; Antón, J. *Policies to Bolster Trust in Agricultural Digitalisation: Issues Note*; OECD Food, Agriculture and Fisheries Papers, No. 175; OECD Publishing: Paris, France, 2022. [CrossRef]
167. Werkheiser, I. Technology and Responsibility: A Discussion of Underexamined Risks and Concerns in Precision Livestock Farming. *Anim. Front.* **2020**, *10*, 51–57. [CrossRef] [PubMed]