poultry

MDPI

Review

Rethinking Poultry Welfare—Integrating Behavioral Science and Digital Innovations for Enhanced Animal Well-Being

Suresh Neethirajan

Faculty of Agriculture and Computer Science, Dalhousie University, 6050 University Avenue, Halifax, NS B3H 1W5, Canada; sneethir@gmail.com

Abstract: The relentless drive to meet global demand for poultry products has pushed for rapid intensification in chicken farming, dramatically boosting efficiency and yield. Yet, these gains have exposed a host of complex welfare challenges that have prompted scientific scrutiny and ethical reflection. In this review, I critically evaluate recent innovations aimed at mitigating such concerns by drawing on advances in behavioral science and digital monitoring and insights into biological adaptations. Specifically, I focus on four interconnected themes: First, I spotlight the complexity of avian sensory perception—encompassing vision, auditory capabilities, olfaction, and tactile faculties—to underscore how lighting design, housing configurations, and enrichment strategies can better align with birds' unique sensory worlds. Second, I explore novel tools for gauging emotional states and cognition, ranging from cognitive bias tests to developing protocols for identifying pain or distress based on facial cues. Third, I examine the transformative potential of computer vision, bioacoustics, and sensor-based technologies for the continuous, automated tracking of behavior and physiological indicators in commercial flocks. Fourth, I assess how data-driven management platforms, underpinned by precision livestock farming, can deploy real-time insights to optimize welfare on a broad scale. Recognizing that climate change and evolving production environments intensify these challenges, I also investigate how breeds resilient to extreme conditions might open new avenues for welfare-centered genetic and management approaches. While the adoption of cutting-edge techniques has shown promise, significant hurdles persist regarding validation, standardization, and commercial acceptance. I conclude that truly sustainable progress hinges on an interdisciplinary convergence of ethology, neuroscience, engineering, data analytics, and evolutionary biology—an integrative path that not only refines welfare assessment but also reimagines poultry production in ethically and scientifically robust ways.

Keywords: poultry welfare; precision livestock farming (PLF); automated behavioral monitoring; emotional states in poultry; climate resilience in poultry; sustainable poultry production; multimodal animal welfare assessment

check for updates

Academic Editors: Temple Grandin and Kurt Vogel

Received: 8 February 2025
Revised: 21 March 2025
Accepted: 21 April 2025
Published: 29 April 2025

Citation: Neethirajan, S. Rethinking Poultry Welfare—Integrating Behavioral Science and Digital Innovations for Enhanced Animal Well-Being. *Poultry* **2025**, *4*, 20. https://doi.org/10.3390/poultry4020020

Copyright: © 2025 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The global poultry industry has undergone rapid intensification in recent decades, dramatically improving efficiency and output. Between 1961 and 2022, poultry production increased by an astounding 1456% [1], making it one of the fastest-growing sectors in animal agriculture. While this growth has significantly contributed to meeting global nutritional demands, it has also given rise to complex ethical concerns and welfare challenges that demand urgent scientific scrutiny [2,3].

Traditionally, welfare assessments in poultry production focused primarily on physical health indicators such as mortality rates, disease incidence, and growth performance. However, there is now a growing recognition that good welfare encompasses not only physical well-being but also the mental states and behavioral needs of animals [4,5]. The Five Freedoms framework—which includes freedom from hunger, discomfort, pain, fear, and the freedom to express normal behavior—highlights the importance of addressing both physical and psychological aspects of welfare [6–9].

Concurrently, the advent of digital technologies and precision livestock farming (PLF) is transforming animal agriculture, offering unprecedented capabilities for monitoring and managing animal welfare [10–12]. These technologies enable real-time data collection and analysis, facilitating proactive interventions to improve welfare outcomes. Sensor technologies can continuously monitor environmental conditions, behavioral patterns, and physiological parameters, providing insights that were previously unattainable [13].

This critical review examines how integrating behavioral science, digital technologies, and insights from biological adaptations can revolutionize approaches to poultry welfare in modern production systems. The discussion centers on four interconnected themes that represent the cutting edge of poultry welfare research:

Avian sensory perception: Recent discoveries in poultry visual, auditory, and olfactory capabilities are highlighted, emphasizing how this knowledge can inform welfare-centric housing design and management practices.

Emotional state assessment: Innovative tools for gauging affective states in poultry are explored, including cognitive bias tests and protocols for identifying pain or distress based on facial cues.

Digital monitoring technologies: The transformative potential of computer vision, bioacoustics, and sensor-based systems is examined for the continuous, automated tracking of behavior and physiological indicators in commercial flocks.

Data-driven welfare management: The role of PLF platforms is assessed, focusing on how real-time insights can be leveraged to optimize welfare outcomes on a broad scale.

Additionally, recognizing that climate change intensifies welfare challenges, I investigate how studying breeds adapted to extreme environments can open new avenues for welfare-centered genetic selection and management approaches. By synthesizing these diverse yet interconnected research streams, this review aims to chart a path toward truly sustainable progress in poultry welfare—one that hinges on the interdisciplinary convergence of ethology, neuroscience, engineering, data analytics, and evolutionary biology. This integrative approach not only refines welfare assessment but also reimagines poultry production in ethically and scientifically robust ways.

2. Systematic Literature Search and Study Selection

This critical review synthesizes findings from the peer-reviewed literature published between 2015 and 2024. To ensure rigor and comprehensiveness, we conducted a systematic literature search across three major scientific databases: Web of Science, Scopus, and PubMed. The search employed targeted keyword combinations, including “poultry welfare”, “precision livestock farming”, “automated behavioral monitoring”, “poultry cognition”, and “digital poultry production”. Studies were carefully screened based on explicit inclusion and exclusion criteria, prioritizing peer-reviewed research articles that provided direct insights into recent advancements in poultry welfare science, particularly those integrating behavioral, technological, and biological perspectives. We supplemented our database search by reviewing reference lists of selected articles and incorporating expert recommendations to identify additional relevant sources. Furthermore, each selected study underwent a quality assessment process, emphasizing empirical validation, robust

methodology, sufficient sample sizes, and demonstrable replicability, thereby ensuring the reliability and scientific rigor of the synthesis presented in this review.

3. Multifaceted Nature of Poultry Welfare

The multifaceted nature of poultry welfare encompasses a complex interplay of physical, psychological (affective states), and environmental factors that collectively shape the overall well-being of birds in modern production systems. While Table 1 summarizes the critical factors influencing poultry welfare, their impacts, and innovative approaches for assessment and improvement, it is essential to recognize the dynamic and interconnected nature of these elements.

Table 1. Multifaceted dimensions of poultry welfare: sensory aspects, welfare impacts, and technological approaches.

Welfare Aspect	Sensory System Involved	Welfare Impact	Innovative Technological Approaches
Visual perception	Visual	Affects navigation, social interactions, feeding behavior	Spectrum-specific LED lighting, computer vision for behavior monitoring
Ultraviolet sensitivity	Visual	Influences mate selection, food detection	UV-enriched lighting systems, UV-reflective enrichment materials
Color discrimination	Visual	Impacts feed preference, social recognition	Color-tunable LED systems, automated color preference testing
Motion detection	Visual	Crucial for predator avoidance, social behavior	High-speed cameras for motion analysis, dynamic visual enrichment
Light intensity perception	Visual	Affects activity levels, circadian rhythms	Adaptive lighting systems with bird-specific "clux" measurements
Auditory perception	Auditory	Influences stress levels, social communication	Bioacoustic analysis tools, noise reduction technologies
Vocalization patterns	Auditory	Indicates emotional states, flock health	Automated vocalization classification systems
Infrasound detection	Auditory	May affect stress levels, behavior	Low-frequency environmental monitoring systems
Olfactory perception	Olfactory	Impacts feed selection, social recognition	Electronic nose sensors for air quality monitoring
Pheromone detection	Olfactory	Influences social behavior, stress responses	Pheromone-based enrichment systems, stress-reducing scent diffusers
Tactile sensation	Somatosensory	Affects comfort, pain perception	Pressure-sensitive flooring, automated texture analysis of litter
Beak sensitivity	Somatosensory	Critical for feeding, exploration	Force-feedback enrichment devices, precision beak trimming technologies
Foot pad sensation	Somatosensory	Impacts mobility, perching behavior	Smart perches with pressure mapping, automated gait analysis
Thermoregulation	Thermoreceptors	Influences metabolic rate, behavior	Infrared imaging systems, smart climate control with individual monitoring
Magnetic field perception	Magnetoreceptors	May affect spatial orientation, circadian rhythms	Electromagnetic field mapping, orientation-based enrichment design
Circadian rhythm regulation	Neuroendocrine	Impacts hormone production, behavior patterns	Dynamic lighting systems mimicking natural cycles, melatonin-informed management
Pain perception	Nociceptors	Crucial for identifying health issues	Automated gait analysis, facial expression recognition for pain assessment
Hunger and satiety	Interoceptors	Affects feeding behavior, overall welfare	Precision feeding systems with individual monitoring
Vestibular sense	Vestibular system	Influences balance, spatial orientation	3D accelerometers for movement analysis, enrichments promoting balance
Proprioception	Proprioceptors	Important for movement, posture	Kinematic analysis systems, smart flooring for gait assessment

Poultry welfare is not merely the absence of negative experiences but also the presence of positive ones [14]. This holistic approach considers the birds' ability to express natural behaviors, their cognitive and emotional experiences, and their capacity to cope with environmental challenges [15]. For instance, the provision of environmental enrichment not only addresses the birds' need for exploration and foraging but also affects their stress levels, immune function, and overall health [16,17]. The concept of "behavioral needs" provides critical insights into poultry welfare, yet it represents only one component of the broader, multifactorial landscape in which physical health, environmental management, and social factors also play pivotal roles [18]. These are behaviors that birds are highly motivated to perform, such as dustbathing, perching, and nesting. When birds are unable to fulfill these needs because of environmental constraints, it can lead to frustration, stress, and the development of abnormal behaviors. Therefore, welfare assessment must examine not only physical health indicators but also the birds' capacity to engage in species-specific behaviors [19,20].

Social dynamics within poultry flocks significantly influence individual and group welfare. Factors such as stocking density, group size, and social hierarchies can impact stress levels, resource access, and the incidence of problematic behaviors like feather pecking [21]. Understanding and managing these social interactions is crucial for maintaining good welfare in commercial settings. The temporal dimension of welfare is likewise critical. Needs and challenges vary considerably across life stages, from incubation and hatching to rearing and production. For example, early life experiences can have long-lasting effects on stress resilience and behavioral development. This underscores the importance of evaluating welfare throughout the entire production cycle, rather than focusing solely on specific time points. Genetic factors also play a substantial role in shaping welfare outcomes. Different breeds and genetic lines may exhibit varied susceptibility to welfare challenges and distinct behavioral traits [22]. Breeding programs that balance production traits with welfare-related characteristics, such as robustness and adaptability, are essential for sustainably improving poultry welfare [23,24].

Environmental control and management practices are fundamental to welfare. Factors like lighting, temperature, air quality, and litter conditions not only influence physical health but also affect behavior and emotional states [17,25]. Advanced environmental control systems, coupled with PLF technologies, present new possibilities for crafting and maintaining optimal welfare conditions. Lastly, the human–animal relationship remains a crucial yet frequently overlooked element of poultry welfare [26]. The quality of interactions between caretakers and birds can substantially impact fear responses, stress levels, and overall well-being. Training programs that strengthen stockmanship skills and encourage positive human–animal engagement are vital components of comprehensive welfare management. By acknowledging and addressing these multifaceted aspects of poultry welfare, producers and researchers can create more effective, holistic strategies to improve birds' lives in commercial settings.

3.1. Poultry Sensory Capabilities and Perception

Poultry species rely extensively on sophisticated sensory systems to navigate their environment, communicate effectively, forage efficiently, and respond appropriately to threats. Unlike human sensory perception, birds have evolved highly specialized and nuanced sensory adaptations in vision, hearing, olfaction, tactile sensitivity, and thermoreception. Understanding the distinct sensory capacities of poultry is fundamental for creating optimized housing, management, and welfare strategies in commercial production systems.

3.1.1. Visual Perception

The avian visual system is exceptionally developed, presenting substantial differences from human vision in both anatomical structure and functional capability (Figure 1). Birds possess tetrachromatic color vision, which means that they have four distinct types of cone photoreceptors: violet-sensitive (VS), short-wavelength-sensitive (SWS), medium-wavelength-sensitive (MWS), and long-wavelength-sensitive (LWS) cones [27–29]. Tetrachromatic vision allows poultry to perceive an expanded color spectrum, including ultraviolet (UV) wavelengths invisible to humans. The detection of UV reflectance patterns plays a critical role in avian behavioral ecology, particularly in food selection, mate recognition, and social interactions [30,31]. For example, poultry species such as chickens utilize UV sensitivity to distinguish between ripe and unripe feed materials, enhancing their foraging efficiency and feed intake accuracy.

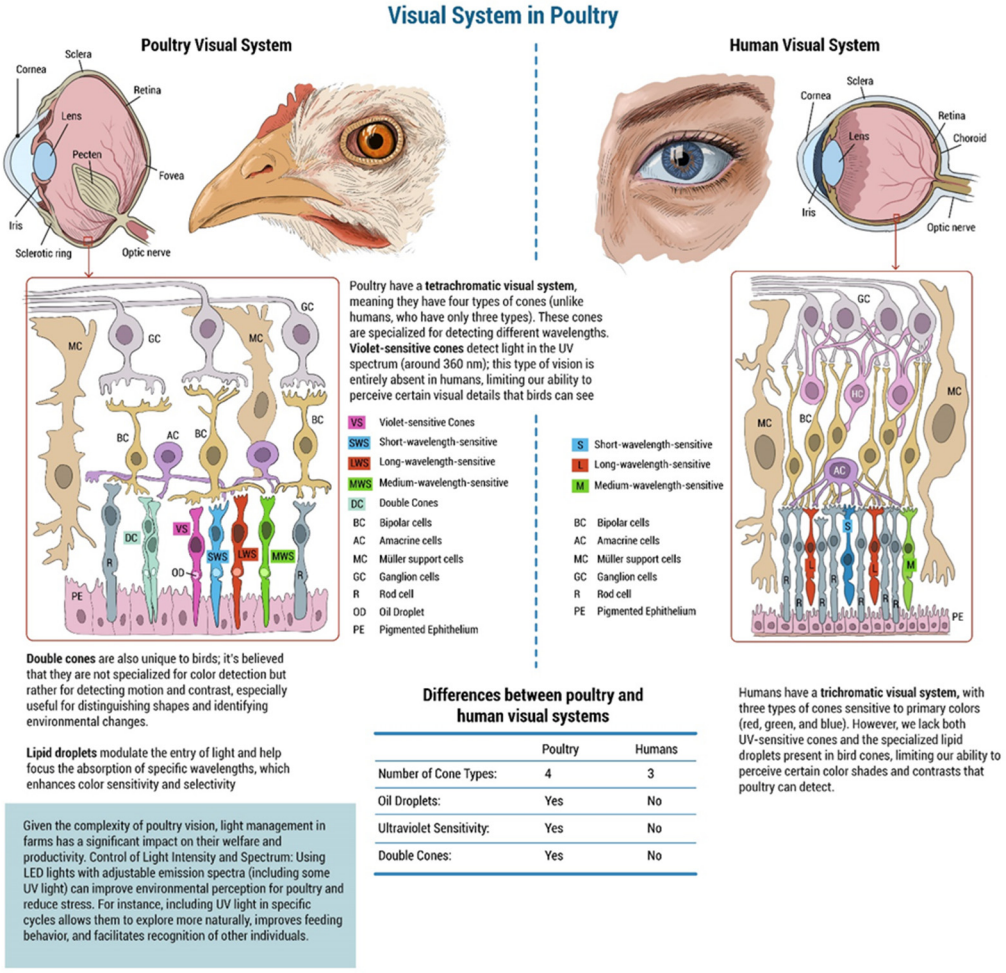


Figure 1. A comparative overview of poultry and human visual systems, highlighting differences in cone types, ultraviolet sensitivity, and the presence of oil droplets.

Birds also have specialized double cones, representing approximately 40–50% of their total cone photoreceptors. These double cones primarily enhance motion detection and brightness perception (achromatic vision), and they are critical for rapid response to predators and the accurate interpretation of social signals within flocks [32,33]. The retinal distribution of double cones varies, with higher concentrations located strategically in regions supporting forward and lateral visual fields [34]. This distribution allows poultry to maintain vigilance against predators while simultaneously engaging in complex intraspecies interactions.

Another unique avian retinal adaptation is the presence of oil droplets within cone cells. These oil droplets act as selective spectral filters, significantly narrowing the spectral sensitivity range of each cone type and thus enhancing color discrimination and contrast detection [35,36]. Differences in oil droplet composition and density between poultry breeds suggest breed-specific visual perception capabilities, potentially impacting breed responses to various lighting conditions [37]. Additionally, oil droplets serve a protective role, absorbing potentially damaging wavelengths and reducing photoreceptor damage under extended artificial lighting conditions common in commercial poultry farming [38].

Poultry visual acuity is further enhanced by retinal specializations such as the area centralis in chickens, a region of increased cone density, providing sharper visual resolution compared to surrounding retinal regions [34]. In contrast, certain predatory bird species have dual foveae, enabling simultaneous precise central and peripheral vision—an evolutionary adaptation essential for accurate prey detection [39,40]. Although chickens do not possess true dual foveae, their area centralis offers sufficiently precise visual acuity necessary for identifying fine feed details, subtle social signals, and potential threats.

Advancements in poultry vision research are continuing to inform significant practical applications in housing design and lighting management. Traditional human-based lighting measurements such as lux fail to adequately reflect poultry visual sensitivities. Researchers developed a specialized measurement called corrected lux (clux), accurately representing avian visual perception under various lighting scenarios [25]. Implementing clux-based lighting in poultry housing has demonstrated improvements in welfare, such as reduced fearfulness, enhanced feeding behaviors, and better flock uniformity [41].

Additionally, poultry have non-visual photoreceptors located within the pineal gland and hypothalamus, and they are capable of detecting ambient light levels through the cranial bone. These receptors, sensitive primarily to blue wavelengths, profoundly influence avian circadian rhythms, reproductive cycles, and melatonin regulation [42–44]. Thus, exposure to blue-enriched lighting in commercial production systems has been associated with improved egg production rates and reduced stress-induced behaviors in laying hens [45–48].

Age-related visual decline represents another crucial factor in poultry welfare management. Older poultry exhibit diminished visual acuity, potentially affecting their ability to forage, recognize flock mates, and navigate housing environments efficiently [49–51]. Therefore, adapting lighting and housing to accommodate age-specific visual needs is increasingly recognized as necessary for sustaining welfare and productivity over the flock's lifespan.

Birds are highly adept at detecting complex shapes and distinguishing fine details, particularly in contexts such as food recognition, where shape, color, and contrast play a critical role in identifying edible particles [52,53]. This advanced visual processing ability allows poultry to assess feed granularity and distinguish nutrient-dense food items from less desirable particles [54–56]. Understanding these species-specific visual adaptations is crucial for designing poultry housing, enrichment materials, and feeding systems that align with their perceptual abilities, ensuring optimal welfare and efficiency in production environments.

The topography of photoreceptor distributions in various poultry species reveals significant variations correlating with ecological niches and behavioral traits. For instance, ground-foraging species like chickens show higher cone densities in the lower visual field, while arboreal species have adaptations for enhanced upper-field vision [57,58]. These findings highlight the importance of considering species-specific visual adaptations when designing housing and enrichment strategies.

Advancements in our understanding of avian visual perception have significant implications for poultry housing design and welfare assessment. Sophisticated models of avian visual perception allow researchers to analyze how birds perceive their environments [59]. These models have revealed that seemingly minor changes in lighting or housing materials may dramatically alter how poultry visualize their surroundings. For example, metal perches or feeders that appear distinct to humans may be difficult for birds to differentiate from backgrounds under certain lighting conditions. The spectral reflectance of metal surfaces can make them blend into backgrounds when viewed through an avian visual system, even though they appear clearly distinct to humans [60,61]. By employing these visual models in the design of husbandry systems, researchers have realized increased perch use and improved foot health in laying hens [62]. By selecting materials and colors that provide better contrast from the birds' perspective, they created perching options that are more visually accessible and appealing.

The importance of light spectrum in poultry housing design was underscored by Osadcha et al. [63], who examined how different monochromatic wavelengths affect various biochemical parameters in hens. They found that shorter wavelengths (460 nm) significantly elevated glucose, creatinine, total protein, urea, total bilirubin, and phosphorus levels, often exceeding physiological norms, while also increasing the activities of alkaline phosphatase, aspartate aminotransferase, lactate dehydrogenase, and gamma-glutamyltransferase. These effects were less pronounced yet still notable under 600 nm light; by contrast, 630 nm and 650 nm generally maintained parameters within normal ranges. The study suggests that shorter wavelengths may induce greater metabolic or stress responses in hens. Complementing these findings, Olanrewaju et al. [64] investigated how high-frequency LED lighting influences biochemical, enzymatic, and electrolyte variables in laying hens, revealing age-dependent variations in responses. Collectively, these results emphasize the need to consider both light quality and the age of the flock in designing poultry lighting systems. Tailoring spectral composition to specific life stages can potentially optimize welfare and productivity throughout the production cycle.

Research also suggests that different chicken breeds may exhibit variations in photoreceptor density and spectral sensitivity, potentially leading to differences in how they perceive their environments. Although direct evidence is limited, it is hypothesized that brown and white chicken breeds might differ in photoreceptor density and wavelength absorption characteristics. Such variations could influence behaviors related to mate selection, aggression, and stress responses. Moreover, the visual systems of chickens can be affected by environmental factors, and different breeds may show variations in sensory perception and responses due to both genetic and environmental influences. Understanding breed-specific visual capabilities is crucial for tailoring housing and management practices to different genetic lines. Future research should focus on characterizing visual traits across a wider range of commercial and heritage poultry breeds to inform breed-specific welfare strategies.

Building on insights into avian visual perception, researchers have developed models to analyze how birds perceive elements of their housing environment. These avian vision models examine the chromatic (color) and achromatic (brightness) contrasts of objects and surfaces in commercial layer housing. For instance, brown eggs on a litter floor exhibit low chromatic contrast under most lighting conditions, suggesting that hens may struggle to visually distinguish eggs from the litter background, potentially impacting nesting behavior and egg collection efforts.

Prescott and Wathes [56] investigated the spectral sensitivity of domestic fowl (Gallus gallus domesticus), providing valuable insights into their visual perception. Their study established foundational knowledge on how chickens perceive different wavelengths of light,

which is crucial for designing housing elements like perches and nesting areas. Seifert [65] explored how chickens process chromatic and achromatic information at the level of retinal ganglion cells, offering deeper insights into the neural mechanisms underlying avian visual perception. Incorporating these neural processing insights can further refine visual models, ensuring that they accurately reflect how chickens process visual information at both the photoreceptor and neural levels.

These findings highlight the complexity of avian visual perception in production environments and underscore the potential for the evidence-based design of housing elements to optimize visibility and functionality for the birds. Future research should continue to refine these models and validate their predictions through behavioral studies.

As our understanding of avian visual capabilities advances, several key areas warrant further investigation:

- Developing species-appropriate lighting standards that account for avian spectral sensitivities and non-visual photoreceptors.
- Investigating the effects of UV-enriched lighting on poultry behavior, welfare, and production outcomes to optimize lighting conditions.
- Exploring dynamic lighting systems that mimic natural daylight cycles, potentially benefiting circadian rhythms and physiological processes.
- Validating visual perception models through behavioral studies to inform evidence-based housing design.
- Characterizing age-related changes in visual capabilities and developing compensatory strategies for older birds to address welfare concerns in aging flocks.
- Examining the interaction between visual perception and other sensory modalities in shaping poultry behavior and welfare.

3.1.2. Auditory Perception

While vision is often considered the primary sensory modality in birds, auditory perception plays an equally crucial role in their behavior and welfare. Birds, including domestic chickens, perceive a wider range of frequencies than humans, extending into infrasonic (<20 Hz) and ultrasonic (>20 kHz) ranges [66]. Chickens can hear frequencies from about 2 Hz up to 9 kHz [67–69], enabling them to communicate and interpret a rich tapestry of sounds within their environment.

Recent studies have highlighted the communicative complexity of chicken vocalizations. Multiple distinct call types have been identified in adult chickens, each associated with specific contexts or emotional states [49,70–72]. These include alarm calls signaling predators, food calls indicating discoveries, contact calls maintaining flock cohesion, and distress calls expressing pain or discomfort.

Chicks begin vocalizing even before hatching, producing prenatal calls that influence the incubation behavior of hens. Post-hatching, chicks utilize a variety of calls crucial for survival and social development [73–75]. Advances in machine learning and natural language processing have enabled the automatic classification of these vocalizations [76]. Changes in the acoustic characteristics of flock vocalizations can predict welfare issues, such as feather pecking outbreaks, up to three days before visible signs appear, highlighting the potential of acoustic monitoring as an early warning system. Understanding auditory perception and communication is particularly relevant in the context of environmental noise within commercial poultry facilities. Chronic exposure to mechanical noise impairs production and elevates stress markers in laying hens [77,78]. For instance, constant exposure to ventilation fan noise above 80 dB is associated with reduced egg production [79,80] and increased plasma corticosterone levels, leading to immunosuppression and heightened disease susceptibility.

High noise levels during transportation induce acute stress responses in poultry, affecting meat quality through physiological changes. Elevated transport noise correlates with increased heterophil/lymphocyte ratios, a common stress indicator in birds [81,82]. While excessive noise is detrimental, appropriate auditory stimulation can positively influence welfare. Studies demonstrate that playing classical music or natural sounds reduces stress indicators and enhances welfare in broilers and laying hens [83,84]. Gao et al. [85] found that exposure to classical music improved growth rates and feed conversion efficiency in broiler chickens.

The playback of species-specific contact calls or maternal vocalizations exerts calming effects, particularly in young birds. Peixoto et al. [86] and Semrov et al. [87] showed that chicks exposed to hen vocalizations exhibited reduced fear responses and improved cognitive performance. Additionally, constant low-level white noise can mask sudden, startling sounds, potentially reducing stress responses [88]. The effectiveness of auditory enrichment depends on acoustic features like tempo, frequency range, and rhythmic patterns; slow-tempo music (60–80 beats per minute) is more effective at reducing stress than fast-tempo music [89–93].

The impact of auditory enrichment may hinge on birds' early auditory experiences. Exposure to complex auditory stimuli during incubation and early life can have lasting effects on behavior and cognition [94]. Chicks exposed to species-specific calls during the last week of incubation show enhanced social recognition and reduced fearfulness post-hatching [95,96]. Early auditory stimulation is associated with improved spatial learning and memory in adult chickens [97–99]. Birds raised in acoustically enriched environments demonstrate greater resilience to stressors, evidenced by lower corticosterone responses to acute stress [100,101]. These findings suggest that appropriate auditory stimulation throughout the production cycle could yield long-term welfare and productivity benefits, though care must be taken to ensure enrichment is species-appropriate and not a source of stress.

Advancements in bioacoustic technology have unlocked new possibilities for automated welfare assessment through vocalization analysis (Figure 2). Changes in the acoustic properties of vocalizations can indicate stress or discomfort. Van den Heuvel et al. [102] developed an automated system detecting stress-induced vocalizations in broiler chickens with 85% accuracy.

Certain vocalizations may signal respiratory diseases or other health issues. Ginovart-Panisello et al. [103] used vocal analysis to detect early signs of infectious bronchitis in broilers. Moreover, the frequency and type of vocalizations can provide insights into emotional states. McGrath et al. [104] and Papageorgiou et al. [19] found that the acoustic features of "food calls" varied with the quality of the food reward, potentially indicating levels of positive affect. Analyzing the overall acoustic environment can reveal valuable information about flock welfare. Ginovart-Panisello et al. [105] and Coutant et al. [106] developed systems using multiple microphones to characterize the soundscape and detect anomalies indicating welfare issues.

Bioacoustic monitoring offers several advantages: It is non-invasive, provides continuous real-time data, allows early problem detection, and is scalable to large commercial flocks. However, challenges remain in commercial implementation, such as filtering environmental noise, isolating individual vocalizations, interpreting acoustic data into meaningful welfare indicators, accounting for breed and age differences in vocalization patterns, and integrating these systems with existing farm management infrastructures.

To advance our understanding of auditory perception and its welfare implications, several key areas warrant further investigation. Characterizing breed-specific auditory capabilities is crucial for tailored management strategies. Investigating how auditory

perception and vocal production evolve throughout poultry lifespans can inform welfare assessments at different production stages. Longitudinal studies are essential to comprehend the long-term effects of various types and levels of environmental noise on health, productivity, and welfare.

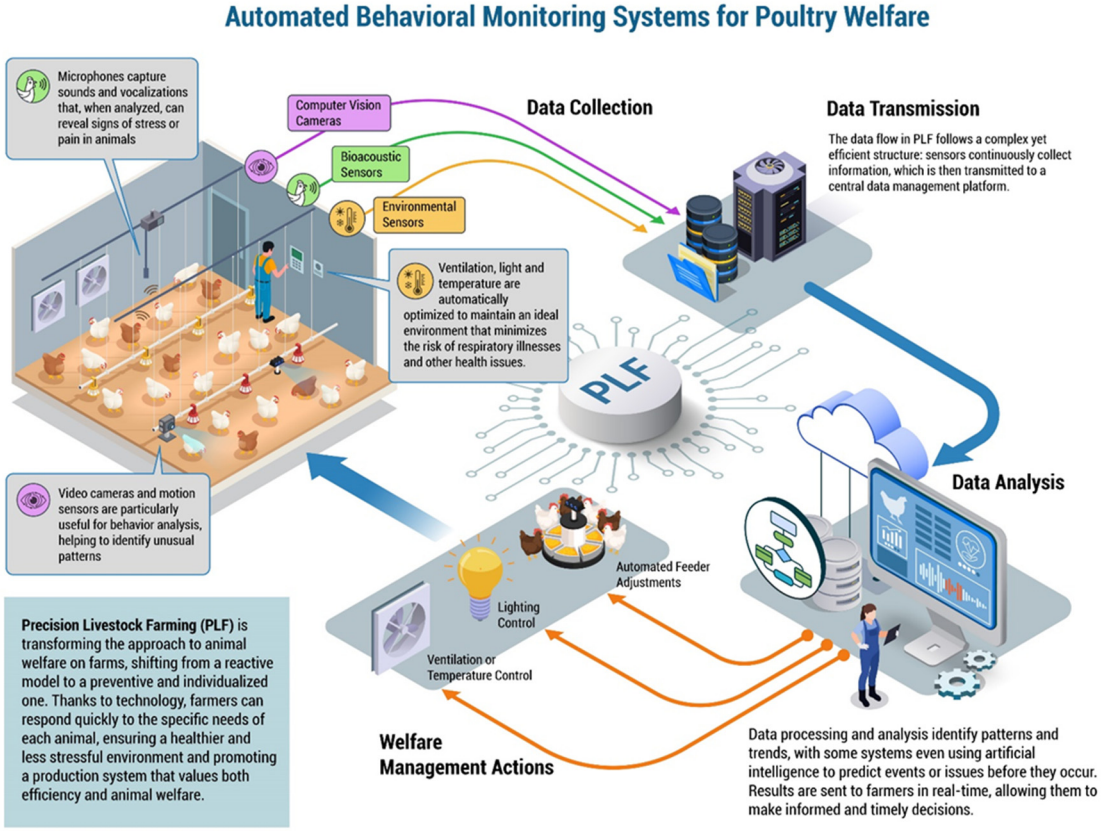


Figure 2. Automated behavioral monitoring systems for poultry welfare, illustrating how microphone arrays capture and analyze flock vocalizations within a broader precision livestock farming (PLF) framework. In addition to highlighting computer vision, environmental sensors, and data analytics, the figure underscores the critical role of bioacoustic monitoring for detecting early indicators of stress, discomfort, or disease. By integrating vocal, visual, and environmental data, these systems enable responsive interventions—such as adjustments to lighting, ventilation, or feeding routines—ultimately promoting a healthier and more humane production environment.

Determining ideal acoustic environments for different production systems—considering housing type, flock size, and production purpose—can guide welfare improvements. Developing and validating species-specific auditory enrichment protocols practical for commercial settings is also vital. Exploring how auditory stimuli interact with other sensory modalities to influence behavior and welfare can provide a more comprehensive understanding.

Enhancing bioacoustics monitoring requires the development of sophisticated machine learning algorithms for the real-time analysis of vocalizations and acoustic environments in commercial settings. Investigating designed soundscapes that mask aversive noises while providing beneficial auditory stimulation can improve welfare. The further exploration of prenatal auditory stimulation's potential to enhance post-hatch welfare and cognitive development is promising. Establishing industry-wide standards for using acoustic data in welfare assessment and certification schemes can facilitate the widespread adoption of these technologies.

3.1.3. Other Sensory Modalities

Beyond vision and hearing, other sensory faculties substantially influence poultry behavior and welfare. Understanding these modalities is vital for establishing genuinely welfare-focused production environments.

Recent findings underscore how the olfactory system shapes poultry behavior, informing social recognition, environmental assessment, and feeding. Chickens possess around 229 functional olfactory receptor genes [107]. Odor cues guide feed choice, helping birds distinguish between different feeds and avoid harmful substances [108–111]. These cues also factor in feeding neophobia, dietary preferences, and social hierarchies [112,113]. Chicks can even detect and favor their mother hen's odor, facilitating imprinting and social bonding. Additionally, chickens display aversion to certain predator odors, highlighting a role for olfaction in threat detection [114]. Olfactory perception lets them gauge environmental safety, avoiding ammonia-rich areas [115,116]. The provision of varied, species-appropriate odors can enhance environmental complexity and natural behaviors [117]. Managing aversive odors like ammonia is likewise critical, and olfactory cues may serve as early indicators of poor air quality.

Tactile inputs—particularly via the beak and feet—are central to poultry welfare yet often overlooked in housing and management. The beak, densely innervated for tactile exploration, thermoregulation, and precision handling [118,119], contains numerous mechanoreceptors and thermoreceptors. Beak trimming, common for curbing feather pecking and cannibalism, has profound welfare implications; it causes acute pain and can lead to chronic pain via neuroma formation [120]. This procedure reduces the beak's sensory function, influencing feeding and environmental interactions [121], and may alter feeding patterns alongside diminished preening [122]. Chickens' feet likewise possess mechanoreceptors that convey key substrate information. Foot pad dermatitis causes pain and reduces normal behavior [123]. Perch texture affects foot health and roosting; offering suitable perch surfaces is crucial [62,124]. Ensuring diverse substrate textures can support dustbathing and foraging, benefiting foot health and overall welfare [125]. Tactile enrichment, such as objects with varied textures, promotes exploratory needs and may mitigate harmful pecking [126,127]. A significant goal is to develop housing systems that remove the necessity for beak trimming while preventing injurious pecking. In many European countries, beak trimming is banned; Canada and the USA also regulate it.

Although less researched in domestic poultry, evidence shows that chickens possess magnetoreception, allowing them to sense Earth's magnetic field and possibly aiding spatial navigation and orientation [128–130]. Cryptochrome proteins, linked to magnetoreception, have been identified in chicken retinas [131–133]. Artificial magnetic fields during incubation can alter embryonic development and subsequent behavior [134]. Though the welfare implications remain unclear, potential effects include shifts in spatial orientation, circadian rhythms, and sensitivity to electromagnetic fields in housing.

3.2. Integrating Multiple Sensory Modalities

Poultry does not rely on individual sensory modalities in isolation but instead integrate visual, auditory, olfactory, tactile, and thermoreceptive cues to navigate their environment, assess threats, and make behavioral decisions. Sensory integration plays a crucial role in shaping their perception, influencing everything from foraging and nesting behaviors to social interactions and stress responses. As a result, cross-modal interactions—where multiple sensory inputs are processed simultaneously—can significantly impact poultry welfare and management strategies. Recent research in poultry sensory biology highlights the importance of designing multi-sensory enrichment strategies that align with birds' natural perception, ensuring that environmental conditions optimize welfare and productivity.

Chickens, like other birds, combine visual and auditory information to assess danger, demonstrating how sensory integration amplifies behavioral responses. Studies indicate that predator silhouettes paired with alarm calls elicit stronger avoidance responses than visual cues alone, confirming that auditory warnings heighten the perception of danger [135,136]. Similarly, social cohesion within flocks relies on a combination of vocalizations and visual recognition, where distress calls trigger increased vigilance and escape behaviors. This interplay between sensory modalities suggests that managing auditory and visual stimuli in poultry environments—such as reducing loud mechanical noise or optimizing lighting conditions—can help reduce stress and support natural behaviors.

Olfactory cues also interact with visual and tactile inputs to influence poultry feeding behavior. Bertin et al. [137] demonstrated that early exposure to specific odors fosters long-term preferences for certain foods, suggesting that poultry form associative links between smell, taste, and the visual presentation of feed. These findings have direct implications for feed formulation and presentation in commercial systems, where odor-enhanced feeds or specific visual contrasts could improve palatability and feed efficiency. Additionally, poultry rely on tactile and visual cues when selecting foraging substrates, with birds showing a preference for surfaces that mimic natural ground textures [138,139]. Integrating these sensory elements into environmental enrichment strategies, such as providing varied textures for pecking and scratching, can encourage natural foraging behaviors and reduce feather pecking incidents.

Sensory integration is also evident in poultry nesting and perching behaviors. Studies show that nesting success improves when lighting, substrate texture, and olfactory cues are adjusted in combination rather than in isolation. For instance, laying hens prefer nesting materials with specific tactile properties, but these preferences are enhanced when accompanied by appropriate light levels and familiar scents [110,140]. Furthermore, perching behavior is influenced by a combination of visual contrast, stability, and tactile feedback, with poorly designed perches leading to balance difficulties, reduced usage, and increased stress levels [17,141]. By optimizing multiple sensory inputs, poultry housing can be designed to enhance comfort and engagement, leading to improved welfare outcomes.

Research also suggests that cross-modal stimulation can modulate stress responses in poultry. Neethirajan et al. [142] introduced a "sensory welfare index" that evaluates multiple sensory domains to create a comprehensive welfare assessment framework. This research revealed that poultry reacts less intensely to stressful stimuli when ambient noise levels are reduced and lighting conditions are optimized, suggesting that combining environmental modifications may mitigate negative stress responses more effectively than single-factor interventions. Similarly, Rubene et al. [143] reported that individual birds have varying sensory thresholds, meaning that a one-size-fits-all approach to environmental management may not be effective. Instead, individualized welfare adjustments based on specific sensory sensitivities could enhance stress resilience and behavioral engagement.

The rise of PLF technologies has enabled real-time multisensory monitoring and adaptive management strategies. Intelligent control systems can now adjust multiple environmental factors dynamically based on sensory data and behavioral patterns [144]. These technologies integrate computer vision, bioacoustics analysis, and sensor-based monitoring, offering a comprehensive assessment of poultry well-being. For example, multimodal AI systems can analyze vocalizations, movement patterns, and environmental variables simultaneously to detect early signs of distress, disease, or behavioral abnormalities. This capability allows farm managers to implement targeted interventions, such as modifying light intensity, adjusting ventilation, or playing calming auditory stimuli to reduce anxiety.

Understanding the neural mechanisms underlying sensory integration in poultry is an area of ongoing research. Zidar et al. [145] emphasized the need for studies examining

how environmental information is processed in the avian brain, particularly in relation to decision-making, memory, and stress regulation. Research spanning embryonic development to adulthood may identify critical windows where sensory experiences shape long-term behavior and welfare [146]. Additionally, crossbreed comparisons could provide insights into how genetic factors influence sensory integration, guiding breed-specific management strategies [147]. Given that poultry sensitivity to sensory complexity varies, further research could explore the development of virtual reality-based environments to simulate different multisensory conditions and assess behavioral responses in controlled experimental settings [3].

Another key aspect of multisensory integration in poultry welfare is preventing sensory overload or deprivation. Birds exposed to excessive, unstructured stimuli may exhibit heightened stress responses, reduced cognitive performance, and increased aggressive behaviors [8]. Conversely, environments that lack sufficient sensory stimulation may lead to behavioral stagnation and boredom-related welfare issues. Understanding the balance between sensory engagement and overstimulation is essential for designing optimal rearing conditions in poultry farming.

By developing welfare strategies that integrate multiple sensory modalities, poultry environments can be designed to match birds' innate perceptual needs, ensuring improved health, stress resilience, and overall well-being. Advances in sensor technology, machine learning, and environmental enrichment will continue to refine evidence-based management practices, benefiting both poultry welfare and production efficiency. The integration of sensory science into poultry welfare frameworks represents a promising avenue for future research and industry application.

3.3. The Challenge of Measuring Affective States in Poultry

Recent trends in animal welfare research have shifted from simply preventing negative experiences to actively promoting positive emotional states [2,148]. This new emphasis aligns with a broader recognition that animals, including poultry, can experience a range of affective states, from fear and frustration to curiosity and contentment. However, measuring these emotional states reliably in commercial poultry settings remains a formidable challenge. Many conventional methods were pioneered in controlled laboratory environments and have proven difficult to scale for large, diverse flocks. Here, I critically examine current and emerging strategies for assessing poultry affective states, highlighting the need to integrate automated behavioral monitoring technologies so as to avoid rehashing known information and uncover new insights into how chickens experience their environments.

3.4. Cognitive Bias Testing: From Laboratory to Farm

Cognitive bias testing has grown into one of the key frameworks for measuring affective states in animals, based on the notion that an individual's emotional state can color its interpretation of ambiguous stimuli [149]. In essence, animals in a positive affective state interpret neutral or ambiguous cues more optimistically, while those experiencing negative states respond more pessimistically. These tests have yielded revealing insights under controlled research conditions, showcasing how the environment, stressors, and even group size can shift interpretative biases. Despite their promise, traditional cognitive bias tests are constrained by logistical difficulties when applied to large commercial flocks. Poultry production sites often house thousands of birds, making repeated individual trials time-consuming and resource intensive. Moreover, training animals to discriminate between positive and negative reference cues can be impractical in large-scale farm environments. Consequently, researchers have begun developing faster and more automated versions of cognitive bias tests to reduce labor needs and minimize disturbances to the birds.

Zidar et al. [145] provided an important breakthrough by devising a single-session judgment bias test for broilers, revealing that even short-term stressors can skew birds toward a more pessimistic interpretation of neutral cues. This underscores the sensitivity of cognitive bias tests to subtle welfare changes. Building on these advancements, Neethirajan et al. [3] developed an AI-powered system that employs machine vision to track individual birds during cognitive bias trials, thus eliminating the need for continual human observation. The system relies on algorithms capable of distinguishing subtle variations in approach or avoidance behavior, enabling researchers to conduct high-throughput assessments without interfering extensively in the birds' daily routines.

3.5. Attention Bias Testing

An additional technique related to cognitive bias is attention bias testing, which evaluates how quickly an animal redirects its focus from a positive stimulus when a perceived threat is introduced [150,151]. Animals that are more anxious are prone to switch attention rapidly to possible dangers, whereas calmer individuals may be slower to abandon a rewarding or neutral stimulus. Until recently, these tests also required meticulous observation, limiting their scalability. Lourenço da Silva et al. [152] developed and validated an attention bias test (ABT) for assessing anxiety-like states in broiler chickens. Their experimental setup utilized two square testing arenas equipped with multiple cameras to record behavioral responses. An overhead camera provided a top-down view for live recording, while a side-view camera captured footage for later analysis. This dual-camera system allowed for comprehensive behavioral observations without disturbing the birds. The cameras were connected to an external network video recorder and monitors in a separate room, enabling undisturbed live behavioral coding. The test involved exposing groups of three birds to positive stimuli (feed and mealworms) and a negative stimulus (conspecific alarm call). By measuring latencies to begin feeding, first vocalization, and first step, as well as vigilance behaviors, the researchers were able to quantify anxiety levels in the birds. This method offers a promising approach for assessing affective states in poultry, with potential applications in commercial settings for welfare assessment and management.

Although promising, both cognitive and attention bias tests risk oversimplification if not contextualized within each flock's unique environment. Lighting regimes, feed availability, stocking density, and a host of other factors might modify how ambiguous cues are perceived. Consequently, these methods could best be employed within integrated frameworks that also track behaviors like feather pecking or dustbathing, thereby capturing a more comprehensive welfare profile.

3.6. Anticipatory Behavior: Leveraging Automated Monitoring

Anticipatory behavior—heightened activity, vocalization, or other behavioral changes preceding a known reward or event—has emerged as a valuable indicator of emotional valence and motivational states. For instance, Baciadonna et al. [153] demonstrated that hens increase their activity and vocalizations in anticipation of highly valued rewards. The intensity of these changes often correlates with how the bird perceives the forthcoming event, offering a window into its internal emotional landscape.

Paradoxically, birds experiencing poorer welfare sometimes display heightened anticipation for rewards because their environments are relatively barren or stressful [154,155]. Under such conditions, even minor positive events can become disproportionately salient. For example, broiler breeders on restricted feeding schedules often show conspicuous excitement just before meals—an observation that might appear to represent positive anticipation but could also signal frustration born of chronic hunger. This dual interpretation

underscores the importance of situating behavioral data within the broader environmental and physiological context.

To detect these anticipatory behaviors at scale, researchers like Neethirajan and Kemp [12] have developed multi-sensor systems combining accelerometers, acoustic recordings, and machine vision. By continuously logging the movement speed, vocalization frequency, and spatial distribution of birds in the hours prior to feeding or other scheduled events, these platforms can flag anomalies or acute changes in anticipatory response. Machine learning algorithms analyze patterns in real time, allowing farm managers to assess whether a sudden increase in anticipatory behavior reflects healthy excitement or signals a potential welfare issue—such as feed restriction-induced stress.

3.7. Play Behavior: Automated Detection and Analysis

Although the notion of play in poultry remains relatively novel, growing evidence suggests that chickens exhibit play-like behaviors indicative of positive welfare states. These behaviors can include spontaneous running, "flapping runs", object manipulation, and social frolicking, especially among younger birds [19]. Unlike other behaviors with clearer adaptive functions—such as foraging or predator evasion—playing lacks an immediate survival benefit, implying that it could be an expression of surplus energy and psychological well-being. Studies like Campbell et al. [156] highlight the value of monitoring play over time. Early exposure to environmental enrichments—such as perches, dustbathing areas, or novel objects—may not instantly change overt behaviors. However, these changes can manifest in the long term as increased foraging, dustbathing, or reduced fear responses. By combining automated play detection with other welfare indicators, researchers can better understand how enrichment strategies impact positive welfare states over a bird's lifespan.

3.8. Facial Expression and Body Language: AI-Powered Analysis

Recent advancements in poultry welfare assessment have focused on decoding subtle visual cues in facial expressions and body language to gain insights into birds' emotional states. This approach, inspired by mammalian studies, offers promising non-invasive methods for detecting pain, discomfort, and stress in chickens. Schlegel et al. [157] developed a pioneering "chicken grimace scale" that reliably distinguishes birds experiencing pain from those given analgesics by analyzing eye aperture, beak position, and head posture. Despite the challenges posed by the unfamiliar appearance of avian faces, this work lays a crucial foundation for more nuanced welfare assessment tools. Complementing these efforts, Ma et al. [158] proposed a highly accurate and efficient chicken face detection network using GAN-MAE-based data augmentation suitable for farm applications. Neethirajan [11] further advanced this field with the ChickTrack model, employing deep learning to monitor individual behaviors like perching and foraging.

Beyond welfare-related applications, recent research has illustrated how facial image analysis can serve other practical needs in the poultry industry. Rodriguez et al. [159] introduced a novel "facial chick sexing" system inspired by human facial gender classification techniques. Their method avoids reliance on breed-specific traits and minimizes chick manipulation, thereby improving animal welfare. By collecting and processing two sets of facial images—Cropped Full Face and Cropped Middle Face—this system preserved key visual features necessary for accurate classification, achieving an overall accuracy of 81.89%. Such an approach not only holds potential for broader commercial adoption but also underscores the versatility of AI-driven facial analysis for critical tasks like sex determination in day-old chicks.

In welfare research, Pijpers et al. [160] made significant strides in understanding stress responses in young chickens, finding that decreased eye temperatures and blinking

rates (especially full blinks), coupled with increased temperatures in the head and beak regions, reflect a sophisticated physiological stress response. This nuanced pattern—where eye temperature drops may indicate peripheral vasoconstriction and heightened head and beak temperatures could point to increased metabolic activity—suggests a complex interplay of thermoregulation and vigilance. The reduction in blinking rate likely signifies an adaptive strategy to maintain heightened awareness. Such age-sensitive variations highlight the importance of calibrated protocols for welfare assessment across different growth stages. Infrared thermography is proving to be invaluable in this regard (Figure 3), as it enables the non-invasive measurement of surface temperatures in the eye, beak, head, and comb regions. Decreases in eye temperature may hint at acute stress, while elevated head or beak temperatures can flag underlying circulatory or emotional changes. The comb, being highly vascularized, stands out as a particularly sensitive region for gauging overall physiological arousal.

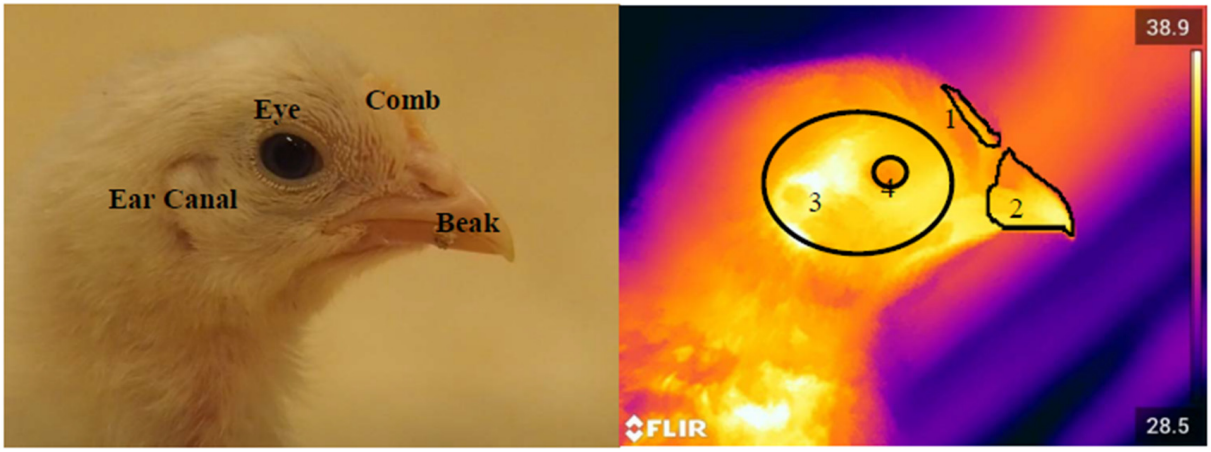


Figure 3. Infrared thermography of a chick's head, featuring a regular photograph (**left**) and a corresponding thermal image (**right**) with numbered regions, (1) comb, (2) beak, (3) head, and (4) eye, identified for temperature measurement. Although these surface temperature readings can act as proxies for assessing physiological state and potential stress, they do not directly equate to definitive welfare indicators. Instead, they offer complementary data points that, in conjunction with behavioral and environmental assessments, can help build a more comprehensive picture of a bird's overall well-being. Source: Pijpers et al. [160].

Taken together, these developments in facial and body language analysis—spanning both welfare-focused assessments and emerging practical applications like chick sexing—demonstrate the growing potential of computer vision and AI to revolutionize poultry management. By refining facial expression scales, automating sexing protocols, and incorporating real-time thermal imaging, researchers and producers can gain deeper, more precise insights into the well-being and needs of chickens in modern production systems.

3.9. Neuroendocrine Relationships with Affective States

Neuroendocrine research highlights the complex hormonal and neurological underpinnings that mold an animal's emotional life. In birds, dopamine and serotonin pathways govern motivation, reward, and stress responses, mirroring their roles in mammalian physiology. These neurotransmitters dynamically interact with environmental factors, making them pivotal in shaping welfare outcomes.

Avoiding Redundancy: Integrating Automated Measures for Fresh Perspectives.

While significant research has investigated each affective-state measure (cognitive bias, anticipatory behavior, play, facial expressions, and neuroendocrine markers), these strands risk reiterating existing findings without further advancing the field if they remain

siloed. One solution is to merge these methodologies via automated, sensor-driven ecosystems. For instance, a single farm-level platform might combine an AI-based "grimace scale" for pain detection, an accelerometer-based system tracking play behaviors, and an attention bias camera module. This holistic approach not only avoids duplication but also captures interdependencies among various indicators, improving the reliability of welfare judgments.

Moreover, many existing studies conduct short-term trials, assessing stress or positive affect at isolated time points. However, welfare in commercial poultry often evolves over weeks or months as birds pass through different growth or laying phases, face variable housing conditions, or endure transport events. Longitudinal designs, potentially combined with wearable sensors or frequent sensor-based "checkpoints", could reveal how early-life stressors reverberate into adult behavior and physiology or how repeated mild stressors accumulate to degrade welfare.

Bridging contextual information with technical innovations is equally crucial. For example, data gleaned from facial expression analysis should be correlated with details about the flock's stocking density, feeding regime, or recent human intrusions. In so carrying this out, one can discriminate between ephemeral disturbances and deeper, systemic welfare problems. In addition, applying advanced machine-learning models that account for environmental confounders—like daily temperature fluctuations or automated lighting cycles—reduces the likelihood of misattributing changes in behavior to emotional states alone.

Blending established welfare assessment techniques with advanced sensor technologies stands to revolutionize our understanding of poultry affective states. However, effectively implementing these integrative approaches requires addressing several priorities: High-throughput versions of these tests must be tested in real-world farm contexts, where consistency in lighting, noise levels, and handling can be difficult to maintain. Multi-year trials across different housing systems would determine their robustness.

Behavioral classification algorithms—especially for nuanced emotional cues—need calibration and cross-validation across breeds, ages, and housing types. Ensuring that an algorithm trained on one flock (e.g., a slow-growing genotype in a free-range environment) performs reliably for a different flock (e.g., fast-growing broilers in a closed barn) remains an ongoing challenge. Future innovations should strive toward real-time biosensing that detects hormone or metabolite changes without invasive sampling. Wearable sensors or contact-free imaging (e.g., thermal or spectral) might reveal short-term stress events that more invasive methods cannot capture at scale. A truly holistic welfare model would converge multiple forms of data: biometric signals, environmental readings (e.g., ammonia, temperature), and behavioral markers (e.g., dustbathing frequency). Machine learning techniques like data fusion or ensemble modeling could produce an overarching "welfare index" that adapts to dynamic conditions.

Monitoring affective states from hatching through different growth or laying phases would reveal how early interventions (e.g., enrichments, reduced stocking density, feed type adjustments) shape long-term welfare. Researchers might discover critical developmental windows during which targeted changes yield enduring welfare improvements. As these methods become more sophisticated, it is essential to weigh associated costs, the required expertise, and the potential for overreliance on technology at the expense of skilled human observation. Additionally, ethical discussions must address data privacy, particularly if such monitoring extends to tracking massive numbers of animals at the individual level.

3.10. Dopamine and Serotonin Systems

The dopaminergic and serotonergic systems are central to regulating emotional states across vertebrates, including birds. Recent studies have illuminated how these neurotransmitter pathways influence both positive and negative affective states in poultry.

Kang et al. [161] explored the impact of environmental enrichment on welfare and neurological responses in broiler chickens, focusing on dopamine-related pathways. They discovered that broilers exhibited a preference for environmental huts (EHs) over other enrichment types like boards and ramps. EHs provided areas of lower light intensity conducive to resting, potentially enhancing feelings of safety and positive affective states. The combination of variable light intensity (VL) and EHs led to improved emotional states and neurological responses, making birds more responsive to environmental light variations. Neurologically, the VL_Hut treatment reduced the expression of tyrosine hydroxylase (TH), a key enzyme in dopamine biosynthesis, indicating the modulation of the dopaminergic system. Additionally, markers such as TPH2, GR, and BDNF were expressed at lower levels, suggesting reduced stress and improved serotonergic balance, which likely interacts with dopamine pathways. The study concluded that the synergistic use of VL lighting and EHs not only promoted voluntary activity and enhanced positive affective states but also altered dopamine signaling, contributing to improved welfare and behavior in broiler chickens. These findings underscore the significance of thoughtfully designed environmental enrichments in influencing neurotransmitter systems and enhancing poultry welfare.

Chen et al. [162] explored how domestication level and feed restriction influence organ indices, dopamine levels, and transcriptome profiles in slow- versus fast-growing chicken breeds. Their findings revealed a robust dopamine surge in both breeds under feed restriction compared to ad libitum feeding, underscoring a pronounced dopaminergic response to nutritional limitation. However, gene expression patterns diverged markedly between the two breed types. Slow-growing chickens showed minimal alterations under feed restriction, with only 84 upregulated and 62 downregulated genes, and no significantly enriched Gene Ontology (GO) terms or KEGG pathways. By contrast, fast-growing chickens exhibited a much larger shift, with 701 upregulated and 521 downregulated genes. GO enrichment revealed notable changes in mitochondrial function, respiratory electron transport chains, and energy metabolism, while KEGG pathway analysis indicated the upregulation of genes linked to cardiovascular and neurodegenerative diseases. Notably, feed restriction also affected the brain organ index, with slow-growing chickens displaying higher values than their fast-growing counterparts. Collectively, these results suggest that slow-growing chickens possess greater resilience to feed limitation, manifesting fewer transcriptomic disruptions and more stable physiological responses. In contrast, fast-growing chickens undergo profound metabolic and cellular changes, reflecting their intensified genetic background shaped by rigorous selection for rapid growth. This breed-specific disparity underlines the importance of considering both genotype and environmental stressors—such as feed restriction—when evaluating welfare outcomes in commercial poultry. By highlighting distinct adaptive pathways in slow- versus fast-growing chickens, Chen et al. [162] underscore how domestication and breeding practices continue to influence the capacity of birds to cope with management interventions, ultimately informing strategies for more targeted, welfare-oriented practices.

Ahmed-Farid et al. [163] demonstrated that chronic thermal stress in broiler chickens significantly reduced brain serotonin levels, leading to various physiological and metabolic changes. Heat-stressed broilers exhibited reduced average daily feed intake, a higher feed conversion ratio, and altered blood biochemistry, including increased serum cholesterol and liver enzymes. Metabolically, thermal stress disrupted the antioxidant defense system,

with lower superoxide dismutase and catalase levels in heart tissues and reduced ATP levels in the liver. These changes culminated in poorer growth performance compared to broilers maintained under thermoneutral conditions. Although the study did not focus on fearfulness or cognitive performance, it clearly links reduced serotonin levels to altered stress responses, emphasizing the necessity of considering both neurochemical and physiological factors when evaluating the effects of environmental stressors on broiler welfare and performance.

Dudde et al. [164] investigated the impact of serotonin transporter (5-HTT) polymorphism on cognitive performance and fearfulness in domestic hens. The study involved 52 adult laying hens with different 5-HTT genotypes (W/W, W/D, and D/D) tested in an operant learning paradigm across initial learning, reversal learning, and extinction phases. The key findings indicated that the 5-HTT polymorphism affected learning, with homozygous wild-type (W/W) hens being the slowest learners, requiring significantly more choices to complete the initial task. In terms of fearfulness, W/W hens also exhibited the highest latencies in the tonic immobility test, indicating greater fearfulness. Interestingly, the most fearful genotype (W/W) had the slowest learning performance, contrasting with findings in human studies where more fearful individuals often perform better in learning tasks. These results suggest that genetic variations in 5-HTT play a significant role in both cognitive performance and fearfulness in chickens. The study highlights the complex interaction between genetics, behavior, and cognition in poultry, suggesting that the 5-HTT gene could be a target for future breeding strategies and research.

Collectively, these studies suggest that measuring neurotransmitter levels or receptor expression could provide objective indicators of emotional states in poultry. However, the invasive nature of such measurements currently limits their practical application in commercial settings.

3.11. Stress Response Pathways

The hypothalamic–pituitary–adrenal (HPA) axis is a central component of the stress response in birds, mirroring its role in mammals. Corticosterone, the primary glucocorticoid in birds, is widely used as a physiological indicator of stress. Yet, recent research has unveiled the complexity of interpreting corticosterone levels.

Austin et al. [165] conducted a groundbreaking study investigating the specific role of corticosterone (CORT) in hypothalamic–pituitary–gonadal (HPG)-axis transcriptomic stress responses using male and female rock doves (Columba livia). By administering exogenous CORT to mimic stress-induced circulating levels, they compared transcriptional changes across the HPG axis with those observed in restraint-stressed birds and vehicle-injected controls. Their findings revealed the distinct and sex-specific effects of CORT on gene expression. Notably, restraint stress induced differential expression in 1567 genes, while elevated CORT alone affected 304 genes. The study identified five genes (KCNJ5, CISH, PTGER3, CEBPD, and ZBTB16) in the pituitary that were differentially expressed in both sexes in response to elevated CORT and restraint stress, potentially influencing immune function and prolactin synthesis. Interestingly, females exhibited a more pronounced transcriptional response to elevated CORT than males. This pioneering research provides valuable insights into the complex interplay between stress hormones and reproductive physiology, offering a comprehensive view of CORT's role in the HPG transcriptomic stress response and potentially informing future therapeutic strategies for reproductive dysregulation across vertebrate species.

Yang et al. [166] examined the effects of chronic corticosterone exposure on circadian rhythms of corticotropin-releasing hormone (CRH) expression and N6-methyladenosine (m6A) RNA methylation in the chicken hypothalamus. Their key findings showed that

chronic corticosterone exposure eliminated the diurnal patterns of plasma corticosterone and melatonin levels. This disruption extended to circadian rhythms of clock genes in the hippocampus, hypothalamus, and pituitary. The normal diurnal fluctuation of CRH mRNA in the hypothalamus was flattened, along with other feeding-related neuropeptides. Interestingly, hypothalamic m6A levels oscillated inversely to CRH mRNA, with the lowest m6A levels after midnight coinciding with peak CRH mRNA before dawn. Chronic corticosterone treatment diminished the circadian rhythm of m6A methylation, significantly increasing m6A levels at night. The site-specific analysis of the 3′UTR of CRH mRNA revealed that higher m6A levels corresponded to lower CRH mRNA levels at night. This study provides insights into how chronic stress disrupts circadian rhythms in chickens and highlights the role of m6A RNA modification in regulating these rhythms under both normal and stress conditions.

3.12. Neuroplasticity and Environmental Enrichment

Recent studies have delved into the intricate relationship between environmental enrichment, neuroplasticity, and welfare in poultry, with a particular focus on laying hens. Kliphuis et al. [167] conducted a comprehensive investigation into how lighted incubation and foraging enrichment during rearing affect fear behavior, corticosterone levels, and neuroplasticity in laying hen pullets.

The researchers examined neuroplasticity markers—including calbindin D28k (calbindin1), doublecortin (DCX), and neuronal nuclein protein (NeuN)—which play crucial roles in neuronal development, migration, and maturation. Although they found no significant effects of light during incubation on these neuroplasticity markers, the study represents a pivotal step toward understanding the neurobiological foundations of poultry welfare.

Intriguingly, pullets incubated under light conditions demonstrated reduced fearfulness toward humans in a voluntary approach test, suggesting that early-life environmental conditions can have lasting impacts on behavioral outcomes. This finding aligns with the principle that early sensory experiences shape neural circuits and influence subsequent behavior—a fundamental aspect of neuroplasticity. By integrating neurobiological, physiological, and behavioral measures, the study offers a holistic perspective on how environmental factors may influence poultry welfare. Despite the minor effects observed—possibly due to the generally enriched rearing conditions for all birds—the research underscores the importance of considering multiple variables when assessing welfare outcomes.

Future research should continue exploring environmental enrichment strategies that promote positive neuroplasticity and enhance poultry welfare. This includes investigating various enrichment types, durations, and timings to assess their effects on neuroplasticity markers and their correlation with long-term behavioral and physiological outcomes. Additionally, examining the interplay between genetic factors and environmental enrichment could provide valuable insights into individual differences in neuroplasticity and stress responsiveness among poultry. Armstrong et al. [168] provided valuable insights into the relationship between hippocampal neuroplasticity and individual behavioral differences in laying hens. Their study revealed that cell proliferation in the adult chicken hippocampus correlates with time spent in outdoor areas and tonic immobility responses. Specifically, greater time spent outdoors was associated with higher proliferation in the rostral hippocampal subregion, while longer durations of tonic immobility positively correlated with proliferation across the entire hippocampal formation. Interestingly, neuronal differentiation in the caudal hippocampus negatively covaried with time spent on the grassy range, suggesting that outdoor access may be both stimulating and potentially stressful for hens. These findings highlight the complex interplay between environmental experiences, individual coping styles, and hippocampal plasticity, emphasizing the need to

consider both beneficial and potentially stressful aspects of environmental enrichment in welfare assessments.

Emerging research underscores the profound impact of early-life environmental enrichment on brain development and adult behavior in poultry. Exposure to complex environments during critical developmental periods has been shown to enhance neuroplasticity, improve cognitive function, and reduce stress reactivity in adult birds. Lourenco-Silva et al. [21] investigated the effects of environmental complexity on affective states in slow-growing broiler chickens using a novel social-pair judgment bias test (JBT). They housed Hubbard Redbro broilers in either low-complexity (commercial-like) or high-complexity (with permanent and temporary enrichments) environments. Employing a multimodal approach, chicken pairs were trained to discriminate between reward and neutral cues and then tested with ambiguous cues. Surprisingly, chickens from low-complexity environments approached the middle ambiguous cue faster than those from high-complexity environments, suggesting a more positive affective state. This unexpected result challenges the assumption that increased environmental complexity invariably leads to improved welfare. The study also demonstrated the effectiveness of the social-pair JBT, with 83% of chickens successfully trained in 13 days and no impact of personality or chronic stress on test performance. These findings highlight the complexity of assessing affective states in poultry and underscore the need for further research to understand the nuanced effects of environmental enrichment on the welfare of slow-growing broilers.

3.13. Integrating Behavioral and Physiological Measures

While significant progress has been made in developing the behavioral and physiological indicators of welfare, integrating these measures to provide a holistic assessment remains challenging. Future research should focus on developing and validating multimodal assessment techniques that combine behavioral, physiological, and cognitive measures. I propose a welfare assessment protocol that integrates automated behavioral analysis, thermal imaging, and cognitive bias testing. Such comprehensive approaches could offer a more accurate and nuanced picture of overall welfare status.

3.14. Machine Learning for Data Integration and Transformative Insights

Integrating and interpreting multimodal datasets through advanced machine learning (ML) represent pivotal steps toward truly comprehensive welfare assessment in poultry. Far from being a mere incremental improvement, these methods have the potential to revolutionize how farmers and researchers identify and address welfare issues. Deep learning algorithms, for example, can detect correlations across behavioral, vocalization, and physiological data streams, enabling the earlier and more accurate detection of problems such as feather pecking outbreaks. Moreover, this high-resolution approach offers critical insights into the underlying interactions among multiple welfare indicators, illustrating how environmental and biological factors converge to influence flock health.

Traditional animal science approaches often struggle to address the multifaceted nature of livestock systems, where complex interactions between genetics, environment, and management practices can yield unpredictable outcomes. Sundrum [169] argues that truly effective animal health and welfare (AHW) solutions demand transdisciplinary research that integrates diverse sources of knowledge, extends beyond purely internal validations, and remains sensitive to local economic and ecological constraints. Machine learning excels in this role by identifying nuanced patterns that may be overlooked in reductionist methodologies, thus helping tailor farm-specific recommendations.

Importantly, ML's role in welfare assessment goes well beyond predictive modeling. Ojo et al. [170] proposes a scalable framework fusing deep learning, digital twin technology,

cloud-edge computing, and blockchain-based security to enable real-time PLF. Such an integrated system could coordinate the autonomous monitoring of flock behavior, environmental conditions, and biosecurity measures. However, achieving widespread adoption requires robust external validation and a clear demonstration of economic benefits to ensure feasibility in diverse farm contexts.

Emphasizing the transformative potential of ML, Merenda et al. [171] validated a suite of machine learning models (YOLOv5l, osnet_x0_25_msmt17, and Gradient Boosting) to monitor individual behaviors in group-housed broilers, achieving high accuracies in detecting feeding (89.5%) and drinking (90%) behaviors. Although classifying active (54.5%) and inactive (50.5%) states posed challenges—particularly in maintaining bird identities over time—this study illustrates the remarkable promise of advanced analytics for automated poultry behavior tracking. Future directions should concentrate on improving model robustness across varying environments, refining individual identification systems, and expanding the scope of recognized behaviors (e.g., play, aggression). By combining real-time data streams, advanced ML algorithms, and context-aware management interventions, researchers and producers can move from incremental improvements to genuinely transformative changes in poultry welfare science and practice.

3.15. Longitudinal Studies

Conducting long-term studies to understand how welfare indicators change over time and across different production stages is essential for developing more nuanced assessment protocols. Longitudinal studies can reveal temporal patterns and critical periods that cross-sectional assessments might miss.

In the Mullan et al. [172] study, the authors found that a higher proportion of broiler farms remained consistently in the best welfare quartile (16.4%) compared to the worst welfare quartile (6.6%). This finding was not specific to a particular type of farm in terms of welfare standards or management practices. Rather, it was based on analyzing data from a large national dataset of 438,155 batches of chickens between 2010 and 2014 and 228,795 batches between 2016 and 2018, representing over 3.1 billion chickens from broiler farms across England and Wales. The study looked at various welfare outcome measures collected at slaughterhouses, such as mortality rates, footpad dermatitis scores, and other health conditions. The consistency in performance was determined by tracking individual farm performance over time across multiple batches. While the study did not specify characteristics of the consistently better or worse performing farms, it suggests there are inherent differences between farms that allow some to maintain higher welfare standards more consistently than others regardless of specific management practices or welfare scheme participation. This highlights the potential to identify and learn from consistently high-performing farms to improve broiler welfare across the industry.

Longitudinal studies also provide valuable insights into the lasting impacts of early-life experiences on animal welfare. Ross et al. [173] demonstrated that environmental enrichment during the early weeks of life significantly influenced stress resilience and cognitive performance in laying hens, with effects persisting even after the enrichment was removed. Chickens housed in enriched environments for 5–6 weeks exhibited notably reduced stress responses compared to controls in less stimulating conditions. Specifically, enriched hens showed reduced startle reflex amplitudes, lowered autonomic stress responses—as evidenced by the decreased and faster recovery of comb temperature following stress—and reduced baseline comb temperatures, indicating a less stressed physiological state. These findings mirror the effects observed in laboratory rodents and suggest that environmental enrichment enhances stress resilience across different species. The study highlights the potential of using baseline comb temperature as a non-invasive welfare indicator and

encourages further research into the mechanisms underlying enhanced stress resilience and its broader application for assessing chronic stress in poultry.

By integrating machine learning techniques and longitudinal study designs, researchers can gain a deeper understanding of welfare dynamics in poultry production. These approaches enable the identification of critical welfare indicators and the development of targeted interventions, ultimately contributing to improved animal well-being and sustainable farming practices.

3.16. Individual Differences—Genetic Background, Management, and Welfare Implications

Recent research has highlighted the importance of considering individual variability among birds when developing welfare management approaches in poultry production. While traditionally focused on flock-level assessments, there is growing recognition that individual differences significantly influence welfare outcomes. Studies underscore how breed-specific traits, ethical considerations in breeding, and diverse production systems jointly shape the welfare outcomes of individual hens. Underwood et al. [174] provided a comprehensive overview of genetic advancements in commercial layer hen breeding, tracing the evolution from ancient domestication to modern selection techniques. Hybrid vigor, quantitative trait loci mapping, and single-nucleotide polymorphism assessments have all improved production traits while allowing greater focus on behavioral characteristics. These innovations have enabled layer strains to adapt to different housing systems, climates, and feed types, thereby enhancing welfare. Additionally, the industry's ability to respond rapidly to changing welfare policies, such as those concerning stocking density or beak trimming, highlights the interplay between targeted genetic selection and adaptive management practices.

Fernyhough et al. [175] critically examined the ethical and practical dilemmas faced by breeding companies, for which their decisions affect billions of hens worldwide. Issues like injurious pecking, bone health, induced molting, and chick culling often intersect with genetic selection goals. The authors stressed that moral responsibility extends beyond improving productivity to encompassing welfare. They argued for a more holistic approach—one that balances efficiency with ethical and societal expectations—thus acknowledging that differences in birds' welfare outcomes can be shaped by corporate breeding objectives as much as by genetic lineage itself.

Bonnefous et al. [176] shifted the focus to free-range and organic production, where variations in environment and management interact with genetic predispositions. While these systems permit more natural behaviors (e.g., foraging, dust bathing, perching), they also expose hens to pathogens, predators, and weather extremes. Proposed solutions include biosecurity enhancements, insect-derived feeds, and strategic enrichments to mitigate stress and disease risk. Bone health and feather pecking, for instance, hinge partly on nutritional and activity considerations—again illustrating how management choices and genetic factors converge to create individualized welfare outcomes.

To effectively improve poultry welfare, the industry must integrate genetic advancements, ethical considerations, and targeted management practices. This approach allows for the development of personalized strategies that address individual variability, enhancing both animal welfare and productivity while meeting societal expectations and regulatory standards.

3.17. Microbiome–Gut–Brain Axis in Poultry Welfare

An intriguing frontier in poultry welfare research is the exploration of the gut microbiome's role in modulating behavior and stress responses. The microbiome–gut–brain axis constitutes a bidirectional communication network that profoundly influences both

physical health and mental well-being in birds. Understanding this intricate system offers promising avenues for enhancing welfare and productivity in poultry.

Cao et al. [177] provided a comprehensive review of the complex microbiota–gut–brain axis in chickens under heat stress, a global challenge that triggers a cascade of physiological and behavioral changes. Heat stress not only provokes hyperthermia and oxidative damage in the gut epithelium—raising permeability and infection risk—but also alters gut microbiome composition and abundance. The authors underscored the bidirectional gut–brain dialogue, wherein shifts in microbial communities can modify intestinal health and affect central nervous system pathways. In proposing mitigation strategies, they highlighted the utility of probiotics (e.g., *Bacillus subtilis*) and prebiotics, either separately or as synergistic synbiotics, to stabilize the gut microbiota. Nutritional interventions, from targeted nutrient supplementation to diet adjustments, and environmental enrichments—such as huts—can lessen stress while improving welfare. Genetic selection for heat-tolerant traits emerged as a promising long-term tactic, alongside practical housing modifications like optimized ventilation, stocking density, and climate control. Taken together, these approaches underscore the importance of supporting the microbiota–gut–brain axis to bolster chicken health, welfare, and resilience in the face of rising temperatures.

Similarly, Beldowska et al. [178] delve into the gut–liver–brain axis in poultry, highlighting the intricate interrelationships among the intestines, microbiota, liver, and neuronal system. They underscore the crucial role of gut microbiota in poultry performance, feed utilization, and product quality. The correct composition of intestinal microbiota influences essential metabolic pathways and biological processes, affecting internal organs like the liver and brain. The authors explore the symbiotic relationship between the liver and gut microbiota based on immune, metabolic, and neuroendocrine regulation. Additionally, they examine the bidirectional interaction of the gut–brain axis, facilitating information transfer between the gastrointestinal tract and the central nervous system. This comprehensive review provides valuable insights into the current understanding of the gut–liver–brain axis in poultry and discusses factors that may influence this complex relationship, laying a foundation for future research in this emerging field.

Recent studies have demonstrated that stress-induced alterations in the gut microbiome can significantly affect immune function and behavior in chickens. Acute heat stress has been shown to lead to substantial shifts in gut microbial composition, correlating with increased inflammatory markers and altered feeding behavior. Probiotic supplementation emerges as a promising strategy, and it is capable of modulating stress responses and reducing fearfulness in broilers. Furthermore, early-life microbial colonization patterns may have enduring effects on behavior and stress resilience. Manipulating the early-life microbiome through targeted probiotic administration has been found to enhance social behavior and reduce feather pecking in adult laying hens.

Jiang et al. [179] investigated the potential of the probiotic Bacillus subtilis in reducing injurious behavior in laying hens. Recognizing that social stress often triggers such behaviors—leading to negative impacts on production, survivability, and gut microbiota balance—the authors propose that probiotics may serve as therapeutic psychobiotics. Their research suggests that Bacillus subtilis can regulate the microbiota–gut–brain axis, potentially mitigating stress-induced injurious behaviors. This approach offers a promising alternative to practices like beak trimming in poultry egg production, addressing both welfare concerns and production challenges. The study underscores the interconnectedness of gut microbiota, stress responses, and behavior in poultry, opening new avenues for managing injurious behaviors through probiotic supplementation.

In a groundbreaking study, Fu et al. [180] explored the impact of early-life cecal microbiota transplantation on social stress and injurious behaviors in egg-laying chickens.

The researchers transplanted cecal bacterial profiles from two divergently selected inbred genetic lines into newly hatched male chicks of a commercial layer strain. Their findings demonstrate that modifying gut microbiota composition can reduce social stress and stress-related injurious behaviors through alterations in brain serotonergic activities via the gut–brain axis. This study provides the first evidence that such behavioral modifications can be achieved through microbiota transplantation without donor–recipient genetic effects. The research offers novel insights into the cellular mechanisms underlying the gut microbiota's role in regulating stress-induced abnormal behaviors and presents a new strategy for improving health and welfare in laying hens. These findings have significant implications for addressing critical issues in the egg industry, such as aggressive pecking, feather pecking, and cannibalism, which are associated with increased social stress and economic losses.

Collectively, these studies suggest that the microbiome is a promising target for welfare interventions in poultry. However, more research is needed to fully comprehend the complex interactions between the gut microbiome, the immune system, and the brain. Future research directions in this area should include characterizing the "healthy" microbiome across different poultry breeds and production systems to establish baselines for comparison. Investigating the impact of common stressors—such as heat stress and transportation—on the gut microbiome will help identify protective or resilience-promoting microbial communities. Developing microbiome-based interventions to enhance welfare and resilience, such as targeted probiotic formulations or prebiotic dietary supplements, could be highly beneficial. Exploring the potential of the microbiome as a biomarker for welfare assessment, possibly through non-invasive sampling methods like fecal metabolomics, offers another promising avenue. Additionally, examining the interaction between the microbiome and other physiological systems, such as the hypothalamic–pituitary–adrenal (HPA) axis, will contribute to a more integrated understanding of stress responses in poultry.

Recent technological advances have revolutionized our ability to monitor and assess poultry welfare in real time. Table 2 presents an overview of cutting-edge technologies being applied in poultry welfare research and commercial settings, including computer vision systems, bioacoustics analysis tools, and multimodal sensor networks. These innovations enable the non-invasive, continuous monitoring of individual and flock-level welfare indicators, facilitating early intervention and data-driven management decisions.

Table 2. Cutting-edge welfare assessment techniques: challenges and opportunities in commercial poultry production.

Assessment Technique	Key Advantages	Implementation Challenges	Future Opportunities
Automated Vocalization Analysis	- Real-time stress and health monitoring - Non-invasive, continuous assessment - Potential for early disease detection	- Background noise interference - Need for breed and age-specific calibration - Complexity in interpreting diverse vocalizations	- Integration with farm management systems - Development of stress-predictive algorithms - Application in assessing positive emotional states
Infrared Thermography	- Non-contact physiological assessment - Applicable to large flocks - Potential for automated, continuous monitoring	- Influenced by environmental factors - Requires standardized imaging protocols - Limited to surface temperature measurement	- Integration with other health parameters - Development of AI-driven image analysis - Early detection of subclinical infections

Table 2. *Cont.*

Assessment Technique	Key Advantages	Implementation Challenges	Future Opportunities
Wearable Sensor Technology	- Individual-level physiological monitoring - Continuous data collection - Potential for early health issue detection	- Attachment methods may affect behavior - Data overload and interpretation challenges - Battery life and durability concerns	- Development of less invasive, longer-lasting sensors - AI-driven data interpretation systems - Integration with automated farm management
Automated Gait Analysis	- Objective lameness assessment - High-throughput capability - Early detection of mobility issues	- Requires sophisticated image processing - Sensitive to environmental variables - High initial investment costs	- Integration with weight monitoring systems - Development of early intervention protocols - Breed-specific gait analysis algorithms
3D Cameras for Body Condition Scoring	- Objective assessment of body condition - Automated and rapid - Non-invasive and stress-free for birds	- Requires advanced software and calibration - Accuracy affected by feather cover - High initial setup costs	- Integration with feeding systems - Predictive health modeling - Development of breed-specific body condition algorithms
Facial Expression Analysis for Pain Assessment	- Non-invasive pain evaluation - Potential for automated monitoring - Applicable to various welfare issues	- Limited research base in poultry - Requires high-resolution imaging - Breed and individual variations in expression	- Development of standardized “pain scales” for poultry - Integration with veterinary care systems - Application in assessing positive emotional states
Automated Feather Condition Scoring	- Objective and consistent assessment - Rapid processing of entire flocks - Non-invasive welfare indicator	- Requires high-quality imaging setup - Algorithm training for different breeds/ages - Distinguishing between causes of feather damage	- Real-time monitoring and alert systems - Integration with environmental control systems - Predictive modeling of feather pecking outbreaks
Heart Rate Variability (HRV) Analysis	- Non-invasive stress assessment - Insights into autonomic nervous system function - Potential for long-term monitoring	- Sensitive to movement artifacts - Requires specialized sensors - Complex data interpretation	- Development of poultry-specific HRV metrics - Integration with other physiological measures - Use in assessing positive welfare states
Microbiome Analysis	- Insights into gut health and stress - Potential for early disease detection - Holistic approach to health assessment	- Complex sample processing requirements - Expensive analysis procedures - Challenges in data interpretation	- Development of rapid, on-farm testing methods - Integration with nutrition management systems - Personalized health interventions based on microbiome profiles
Environmental DNA (eDNA) Analysis	- Non-invasive pathogen detection - Potential for early disease warning - Simultaneous monitoring of flock and environment	- Requires specialized laboratory equipment - High risk of contamination - Complex data interpretation	- Development of on-site testing capabilities - Integration with biosecurity protocols - Tracking of antimicrobial resistance patterns

Table 2. *Cont.*

Assessment Technique	Key Advantages	Implementation Challenges	Future Opportunities
Automated Feed and Water Intake Monitoring	- Early detection of health issues - Individual-level consumption data - Optimization of nutrition strategies	- Requires specialized feeding equipment - High initial implementation costs - Data management and interpretation challenges	- Predictive health modeling based on intake patterns - Integration with precision feeding systems - Early detection of flock-wide health issues
Optical Flow Analysis for Flock Behavior	- Non-invasive group behavior assessment - Covers large areas efficiently - Potential for early detection of distress or disease spread	- Affected by lighting and environmental conditions - Requires multiple camera setups - Complex algorithm development needs	- Integration with automated climate control systems - Development of flock-wide welfare indices - Early warning system for disease outbreaks
Automated Egg Quality Assessment	- Rapid, objective egg quality measures - Detection of internal and external defects - Insights into hen health and welfare	- High initial equipment costs - Requires regular calibration and maintenance - Limited to egg-laying production systems	- Integration with hen health monitoring systems - Predictive modeling of flock health issues - Development of egg-based welfare indicators
Spectral Analysis of Feathers and Skin	- Non-invasive health assessment - Potential for nutritional status evaluation - Early detection of skin conditions	- Requires specialized spectral equipment - Affected by environmental factors - Limited research in commercial settings	- Development of portable spectral devices - Integration with automated health monitoring systems - Assessment of feed additive efficacy
Automated Assessment of Dustbathing Behavior	- Monitors important natural behavior - Indicator of good welfare - Non-invasive, continuous monitoring	- Requires specialized arena design - Video processing challenges in complex environments - Limited to specific areas in housing	- Integration with litter management systems - Development of welfare scoring based on dustbathing patterns - Automated provision of suitable substrates
Feather Corticosterone Analysis	- Non-invasive stress assessment - Provides long-term stress information - Potential for automation in large flocks	- Requires specialized laboratory analysis - Affected by molting cycles - Challenges in result interpretation	- Development of on-farm testing methods - Integration with other welfare measures - Assessment of long-term management changes
Social Network Analysis via RFID	- Insights into flock social dynamics - Individual-level behavioral data - Detection of hierarchy changes	- Requires individual bird tagging - Large data processing and storage needs - Setup complexity and cost	- Integration with other behavioral measures - Development of social welfare indicators - Use in breeding programs for social adaptability
Automated Mortality Detection and Analysis	- Rapid identification of dead birds - Improved biosecurity management - Data for health trend analysis	- Requires sophisticated imaging systems - Challenges in complex housing environments - Potential for false positives	- Integration with predictive health models - Development of AI for cause-of-death analysis - Real-time alerts for unusual mortality patterns

Table 2. *Cont.*

Assessment Technique	Key Advantages	Implementation Challenges	Future Opportunities
Cognitive Bias Testing	- Measures emotional states - Insights into subjective experiences - Assessment of positive welfare	- Time-consuming implementation - Difficult to scale in commercial settings - Potential subjectivity in interpretation	- Development of quick, automated tests - Standardization across breeds and age groups - Integration with other welfare measures

4. Future Research Directions

The rapidly evolving field of poultry welfare science presents substantial opportunities for impactful research that can significantly enhance our understanding and improve the well-being of billions of birds. To achieve meaningful advancements, future investigations should integrate cutting-edge technologies, genetic insights, and ethical frameworks in a cohesive manner.

Building comprehensive welfare phenotypes that incorporate physical, behavioral, and environmental indicators remains crucial. Existing sensor systems can collect data on temperature, humidity, and flock movement in real time, while automated data collection platforms (e.g., accelerometers, cameras, bioacoustics sensors) provide initial analytics. Combining these methods offers a holistic view of positive affective states and resilience to stressors, but current approaches often only scratch the surface of what is possible. Within these existing applications, exploring the genetic basis of positive welfare can reveal key genes linked to traits such as play behavior, stress resilience, and social adaptability. Genome-wide association studies (GWASs) and functional genomics have begun pinpointing candidates for selective breeding, including robust bone health in broilers or lower feather pecking in layers. Moreover, precision gene editing techniques, like CRISPR-Cas9, offer a potentially powerful avenue to address specific welfare problems—provided that rigorous ethical guidelines are enforced.

Emerging fields, such as multimodal data fusion, digital twin technologies, and forecast modeling for predictive welfare management, showcase how machine learning and computer vision can move beyond incremental gains. Rather than detecting lameness or feather damage in isolation, integrated systems can leverage audio analysis, thermal imaging, and environmental metrics to identify problems before they escalate. These platforms promise real-time, individualized monitoring, which may radically reshape how farmers manage feeding, housing, and environmental conditions.

Conducting longitudinal welfare assessments over multiple generations enables the simultaneous optimization of productivity and welfare, shedding light on potential trade-offs. Coupled with biodiversity-driven breeding strategies, which incorporate genetics from heritage lines or wild relatives, producers can cultivate flocks with improved disease resistance and adaptability under changing climates. This synergy of biology and tech-driven monitoring holds the potential to make welfare a central, rather than secondary, breeding goal.

Building on our growing comprehension of avian perception, sensory environment design could utilize dynamic lighting, targeted olfactory stimuli, and acoustic modifications. This goes well beyond static enrichment strategies. As artificial intelligence for welfare monitoring matures, automated systems may adapt to environmental conditions like light intensity or airflow—instantaneously, minimizing stress and enhancing birds' natural behaviors. The investigation of the microbiome–gut–brain axis offers an innovative dimension for welfare improvements. Probiotics and prebiotic supplements may

enhance immune function and stress resilience, but transdisciplinary research is necessary to integrate microbiological, genetic, and ecological perspectives.

Global climate change intensifies the importance of heat tolerance and environmental adaptability. Identifying genetic markers for thermal regulation and combining them with AI-based early warning systems can help flocks cope with extreme conditions. Ethical and economic considerations remain vital for large-scale adoption. While AI-driven dashboards and autonomous management systems can significantly reduce labor and improve precision, they also raise concerns about data ownership, privacy, and the need for specialized training. Cost barriers and farmers' willingness to adapt may hinder the uptake of new technologies, necessitating user-friendly designs, transparent governance, and clear demonstrations of return on investment.

Despite promising results in research settings, translating AI-based digital technologies, such as automated pain recognition systems and real-time bioacoustics analysis, into large-scale commercial poultry operations remains challenging. Key scalability considerations include significant infrastructure and data-processing requirements, ongoing costs for specialized hardware, and the critical need for extensive, accurately annotated datasets to train reliable AI models. Economic feasibility studies and pilot programs indicate substantial potential benefits, such as the early detection of welfare issues, reduced labor costs, and improved productivity, yet initial investment remains a barrier for many producers. Successful adoption will likely require targeted training programs to enhance farmer readiness, seamless integration with existing farm management systems, and the demonstration of clear cost–benefit outcomes through industry-based pilot studies. Addressing these practical barriers through interdisciplinary collaboration among researchers, technology developers, and farmers is essential to realize the full welfare and productivity benefits offered by digital innovations.

To illustrate truly transformative possibilities, researchers must delve further into multimodal sensing and predictive modeling. Rather than stopping at single-dimensional indicators—such as gait scoring or vocalization analysis, new projects should combine voiceprints, real-time video feeds, and microclimate records. Such high-frequency data streams can be aggregated into AI-driven platforms capable of making autonomous or semi-autonomous management decisions. These near-term pilots, once validated, offer a roadmap for broader adoption in the longer term. Bridging theoretical advances with on-farm realities is vital. Ongoing pilot studies that integrate high-resolution sensors and machine learning—capable of adjusting feeding regimes or ventilation in real time—demonstrate how incremental steps can evolve into genuinely transformative solutions. Moreover, longitudinal welfare assessments provide crucial insights into how early-life stressors or enrichments impact birds' later development, adding depth to both research outcomes and commercial viability.

Finally, alongside technological innovation, frameworks that address concerns around data governance and animal autonomy must be established. Transparent guidelines on data privacy, system reliability, and social acceptance will be pivotal in ensuring that transformative tools align with societal values. By actively engaging stakeholders—from farmers and veterinarians to consumers and policymakers—researchers can build solutions that balance productivity, sustainability, and the ethical imperative of improving poultry welfare.

The future of poultry welfare science hinges on harmonizing advanced technologies (e.g., integrated sensors, AI, genomic tools) with robust ethical safeguards and commercial practicality. If effectively orchestrated, these approaches can shift welfare from a reactive, problem-solving paradigm toward a proactive, evidence-driven strategy that maximizes both bird well-being and industry viability.

5. Conclusions

The integration of behavioral science, digital technologies, and biological adaptations is continuing to advance poultry welfare research and management. However, this transformation presents both unprecedented opportunities and complex challenges that require careful scrutiny. While our understanding of avian sensory capabilities has expanded significantly, we must critically assess whether current housing designs truly align with the sensory world of poultry or merely represent incremental improvements to fundamentally flawed systems. The gap between scientific knowledge and practical implementation remains substantial, and it is often constrained by economic realities, producer needs, and the logistical challenges of large-scale adoption.

The emerging field of poultry emotional state assessment raises profound ethical questions. As we develop more sophisticated tools to measure subjective experiences in birds, we must confront the moral implications of continuing intensive production practices in light of this knowledge. The potential for cognitive bias testing and anticipatory behavior analysis to reveal negative emotional states on a large scale could force a fundamental reassessment of current production models. Yet, ethical tensions in poultry production extend beyond the welfare of individual birds—they also encompass balancing welfare advancements with the economic sustainability of poultry farming. Welfare improvements must be contextualized within real-world production challenges, recognizing that producers operate within a competitive market shaped by consumer demand, regulatory requirements, and financial constraints.

Digital livestock farming technologies offer exciting possibilities for real-time welfare monitoring, but they also risk reducing animals to mere data points, potentially overlooking crucial welfare aspects that resist quantification. Overreliance on technology may lead to the erosion of human observation and empathy, shifting the focus from holistic animal well-being to automated compliance metrics. Additionally, the vast amounts of data generated by these systems present significant challenges in interpretation, integration, and practical application, necessitating the careful consideration of how these insights translate into tangible welfare improvements.

The exploration of the microbiome–gut–brain axis offers promising avenues for enhancing welfare, yet it also exposes the reductionist tendency in animal science—the inclination to seek single-variable solutions to complex, multifaceted welfare issues. While physiological indicators provide valuable insights, welfare must not be oversimplified into a checklist of biological markers at the expense of broader behavioral and environmental considerations. Similarly, as genetic selection continues to shape commercial poultry lines, we face a critical ethical dilemma: How do we balance productivity traits with welfare-related characteristics? While incorporating insights from heritage breeds is valuable, it underscores how far modern breeds have diverged from their ancestors, raising deeper questions about domestication and our responsibilities to the animals we have selectively shaped for economic efficiency.

The development of comprehensive, multimodal welfare assessment protocols is crucial, but even the most sophisticated tools have inherent limitations. Welfare is subjective, dynamic, and context-dependent, making it impossible for any single metric—or combination of metrics—to fully capture the complexity of an animal's lived experience. There is an ongoing risk of conflating measurability with significance, potentially neglecting less quantifiable yet equally crucial aspects of well-being, such as social interactions, cognitive engagement, and emotional fulfillment.

While cognitive enrichment strategies hold promise, they also highlight the ethical tensions embedded in poultry production. Providing mental stimulation to animals in highly structured, intensive systems raises difficult questions about whether meaningful

welfare improvements can ever be fully reconciled with large-scale, high-density production. Additionally, the ethical implications of advanced digital welfare technologies extend beyond immediate concerns for poultry well-being. Issues of data ownership, privacy, and the potential for technology to further consolidate power within large agribusiness entities warrant serious consideration, particularly as small and mid-sized producers may struggle to afford or implement these innovations.

In conclusion, while significant strides have been made in poultry welfare, we must remain vigilant against complacency and oversimplified solutions. The challenges ahead demand not only technological innovation but also a fundamental reevaluation of our relationship with food animals. As we work toward truly welfare-centric production systems, we must be willing to challenge long-standing assumptions about efficiency, economic viability, and ethical responsibilities in poultry farming. Only through this critical self-examination and open dialogue between scientists, producers, and policymakers can we hope to harmonize welfare, sustainability, and industry realities, ensuring a more balanced and ethically sound future for poultry production.

Funding: This research was funded by the Natural Sciences and Engineering Research Council of Canada (R37424) and the Department of Agriculture, Fisheries and Forestry of New Brunswick (54254).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Ritchie, H.; Rosado, P.; Roser, M. Meat and Dairy Production. *Our World in Data*. 2024. Available online: https://ourworldindata.org/meat-production (accessed on 2 September 2024).
2. Dawkins, M.S. *The Science of Animal Welfare: Understanding What Animals Want*; Oxford University Press: Oxford, UK, 2021.
3. Neethirajan, S. *Metaverse for Modern Animal Farming*; Amazon: Seattle, WA, USA, 2023.
4. Broom, D.M. Welfare, sentience and pain: Concepts, ethics and attitudes. In *Animal Suffering: The Ethics and Politics of Animal Lives*; John Wiley & Sons: Hoboken, NJ, USA, 2023; p. 211.
5. Colditz, I.G. A biological integrity framework for describing animal welfare and wellbeing. *Anim. Prod. Sci.* **2023**, *63*, 423–440. [CrossRef]
6. Voogt, A.M.; Ursinus, W.W.; Sijm, D.T.; Bongers, J.H. From the Five Freedoms to a more holistic perspective on animal welfare in the Dutch Animals Act. *Front. Anim. Sci.* **2023**, *4*, 1026224. [CrossRef]
7. Beausoleil, N.J.; Swanson, J.C.; McKeegan, D.E.F.; Croney, C.C. Application of the five domains model to food chain management of animal welfare: Opportunities and constraints. *Front. Anim. Sci.* **2023**, *4*, 1042733. [CrossRef]
8. Arndt, S.S.; Goerlich, V.C.; van der Staay, F.J. A dynamic concept of animal welfare: The role of appetitive and adverse internal and external factors and the animal's ability to adapt to them. *Front. Anim. Sci.* **2022**, *3*, 908513. [CrossRef]
9. Robertson, I.; Goldsworthy, D. Recognising and defining animal sentience in legislation: A framework for importing positive animal welfare through the five domains model. *Monash Univ. Law Rev.* **2022**, *48*, 244.
10. Berckmans, D. Smart farming for Europe: Value creation through precision livestock farming. In *Precision Livestock Farming Applications*; Wageningen Academic: Wageningen, The Netherlands, 2015; pp. 25–36.
11. Neethirajan, S. Artificial intelligence and sensor innovations: Enhancing livestock welfare with a human-centric approach. *Hum.-Cent. Intell. Syst.* **2024**, *4*, 77–92. [CrossRef]
12. Neethirajan, S.; Kemp, B. Digital livestock farming. *Sens. Bio-Sens. Res.* **2021**, *32*, 100408. [CrossRef]
13. Neethirajan, S. Automated tracking systems for the assessment of farmed poultry. *Animals* **2022**, *12*, 232. [CrossRef] [PubMed]
14. Rowe, E.; Mullan, S. Advancing a "good life" for farm animals: Development of resource tier frameworks for on-farm assessment of positive welfare for beef cattle, broiler chicken and pigs. *Animals* **2022**, *12*, 565. [CrossRef]
15. Ferreira, V.H.B.; Guesdon, V.; Calandreau, L. How can the research on chicken cognition improve chicken welfare: A perspective review. *World's Poult. Sci. J.* **2021**, *77*, 679–698. [CrossRef]
16. El-Sabrout, K.; Landolfi, S.; Ciani, F. Feed additives and enrichment materials to reduce chicken stress, maximize productivity, and improve welfare. *Vet. World* **2024**, *17*, 2044. [CrossRef]

17. Jacobs, L.; Blatchford, R.A.; De Jong, I.C.; Erasmus, M.A.; Levengood, M.; Newberry, R.C.; Regmi, P.; Riber, A.B.; Weimer, S.L. Enhancing their quality of life: Environmental enrichment for poultry. *Poult. Sci.* **2023**, *102*, 102233. [CrossRef] [PubMed]
18. Dawkins, M.S. Farm animal welfare: Beyond "natural" behavior. *Science* **2023**, *379*, 326–328. [CrossRef]
19. Papageorgiou, M.; Goliomytis, M.; Tzamaloukas, O.; Miltiadou, D.; Simitzis, P. Positive welfare indicators and their association with sustainable management systems in poultry. *Sustainability* **2023**, *15*, 10890. [CrossRef]
20. Rose, P.; Freeman, M.; Hickey, I.; Kelly, R.; Greenwell, P. Considering what animals "need to do" in enclosure design: Questions on bird flight and aviaries. *Birds* **2024**, *5*, 586–603. [CrossRef]
21. Lourenco-Silva, M.I.; Ulans, A.; Campbell, A.M.; Paz, I.A.; Jacobs, L. Social-pair judgment bias testing in slow-growing broiler chickens raised in low- or high-complexity environments. *Sci. Rep.* **2023**, *13*, 9393. [CrossRef]
22. Underwood, G.; Andrews, D.; Phung, T. Advances in genetic selection and breeder practice improve commercial layer hen welfare. *Anim. Prod. Sci.* **2021**, *61*, 856–866. [CrossRef]
23. Castro, F.L.S.; Chai, L.; Arango, J.; Owens, C.M.; Smith, P.A.; Reichelt, S.; DuBois, C.; Menconi, A. Poultry industry paradigms: Connecting the dots. *J. Appl. Poult. Res.* **2023**, *32*, 100310. [CrossRef]
24. Nicol, C.J.; Abeyesinghe, S.M.; Chang, Y.M. An analysis of the welfare of fast-growing and slower-growing strains of broiler chicken. *Front. Anim. Sci.* **2024**, *5*, 1374609. [CrossRef]
25. Franco, B.R.; Shynkaruk, T.; Crowe, T.; Fancher, B.; French, N.; Gillingham, S.; Schwean-Lardner, K. Light color and the commercial broiler: Effect on behavior, fear, and stress. *Poult. Sci.* **2022**, *101*, 102052. [CrossRef]
26. Neethirajan, S.; Scott, S.; Mancini, C.; Boivin, X.; Strand, E. Human-computer interactions with farm animals—Enhancing welfare through precision livestock farming and artificial intelligence. *Front. Vet. Sci.* **2024**, *11*, 1490851. [CrossRef] [PubMed]
27. Günther, A.; Dedek, K.; Haverkamp, S.; Irsen, S.; Briggman, K.L.; Mouritsen, H. Double cones and the diverse connectivity of photoreceptors and bipolar cells in an avian retina. *J. Neurosci.* **2021**, *41*, 5015–5028. [CrossRef] [PubMed]
28. Seifert, M.; Baden, T.; Osorio, D. The retinal basis of vision in chicken. In *Seminars in Cell & Developmental Biology*; Academic Press: Cambridge, MA, USA, 2020; Volume 106, pp. 106–115.
29. Tanaka, K.D. A colour to birds and to humans: Why is it so different? *J. Ornithol.* **2015**, *156* (Suppl. S1), 433–440. [CrossRef]
30. Tedore, C.; Nilsson, D.E. Ultraviolet vision aids the detection of nutrient-dense non-signaling plant foods. *Vis. Res.* **2021**, *183*, 16–29. [CrossRef] [PubMed]
31. Tedore, C.; Tedore, K.; Westcott, D.; Suttner, C.; Nilsson, D.E. The role of detectability in the evolution of avian-dispersed fruit color. *Vis. Res.* **2022**, *196*, 108046. [CrossRef]
32. Baden, T. Ancestral photoreceptor diversity as the basis of visual behaviour. *Nat. Ecol. Evol.* **2024**, *8*, 374–386. [CrossRef]
33. Baden, T.; Euler, T.; Berens, P. Understanding the retinal basis of vision across species. *Nat. Rev. Neurosci.* **2020**, *21*, 5–20. [CrossRef]
34. Ekesten, B.; Ofri, R. Fundamentals of animal vision. *Vet. Ophthalmol.* **2021**, *1*, 225–259.
35. Victory, N.; Segovia, Y.; García, M. Cone distribution and visual resolution of the yellow-legged gull, *Larus michahellis* (Naumann, 1840). *Anat. Histol. Embryol.* **2022**, *51*, 197–214. [CrossRef]
36. Günther, A.; Haverkamp, S.; Irsen, S.; Watkins, P.V.; Dedek, K.; Mouritsen, H.; Briggman, K.L. Species-specific circuitry of double cone photoreceptors in two avian retinas. *Commun. Biol.* **2024**, *7*, 992. [CrossRef]
37. Toomey, M.B.; Ronald, K.L. Avian color expression and perception: Is there a carotenoid link? *J. Exp. Biol.* **2021**, *224*, jeb203844. [CrossRef] [PubMed]
38. Hanna, J.; David, L.A.; Touahri, Y.; Fleming, T.; Screaton, R.A.; Schuurmans, C. Beyond genetics: The role of metabolism in photoreceptor survival, development and repair. *Front. Cell Dev. Biol.* **2022**, *10*, 887764. [CrossRef]
39. Potier, S.; Mitkus, M.; Kelber, A. Visual adaptations of diurnal and nocturnal raptors. *Semin. Cell Dev. Biol.* **2020**, *106*, 116–126. [CrossRef] [PubMed]
40. Moore, B.A.; Fernandez-Juricic, E.; Hawkins, M.G.; Montiani-Ferreira, F.; Lange, R.R. Introduction to ophthalmology of Aves. In *Wild and Exotic Animal Ophthalmology: Volume 1: Invertebrates, Fishes, Amphibians, Reptiles, and Birds*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 321–348.
41. Wilcox, C.H.; Sandilands, V.; Mayasari, N.; Asmara, I.Y.; Anang, A. A literature review of broiler chicken welfare, husbandry, and assessment. *World's Poult. Sci. J.* **2024**, *80*, 3–32. [CrossRef]
42. Horodincu, L.; Solcan, C. Influence of different light spectra on melatonin synthesis by the pineal gland and influence on the immune system in chickens. *Animals* **2023**, *13*, 2095. [CrossRef]
43. Hanlon, C.; Ramachandran, R.; Zuidhof, M.J.; Bédécarrats, G.Y. Should I lay or should I grow: Photoperiodic versus metabolic cues in chickens. *Front. Physiol.* **2020**, *11*, 707. [CrossRef]
44. Cassone, V.M.; Kumar, V. Circadian rhythms. In *Sturkie's Avian Physiology*; Academic Press: Cambridge, MA, USA, 2022; pp. 1163–1181.
45. Shi, H.; Li, B.; Tong, Q.; Zheng, W.; Zeng, D.; Feng, G. Effects of LED light color and intensity on feather pecking and fear responses of layer breeders in natural mating colony cages. *Animals* **2019**, *9*, 814. [CrossRef]

46. Poudel, I.; Beck, M.M.; Kiess, A.S.; Adhikari, P. The effect of blue and red LED light on the growth, egg production, egg quality, behavior, and hormone concentration of Hy-Line W-36 laying hens. *J. Appl. Poult. Res.* **2022**, *31*, 100248. [CrossRef]
47. Wichman, A.; De Groot, R.; Håstad, O.; Wall, H.; Rubene, D. Influence of different light spectrums on behaviour and welfare in laying hens. *Animals* **2021**, *11*, 924. [CrossRef]
48. Fernandes, A.M.; de Lucca Sartori, D.; de Oliveira Morais, F.J.; Salgado, D.D.A.; Pereira, D.F. Analysis of cluster and unrest behaviors of laying hens housed under different thermal conditions and light wave length. *Animals* **2021**, *11*, 2017. [CrossRef]
49. Ferreira, V.H.B.; Seressia, J.; Même, N.; Bernard, J.; Pinard-van der Laan, M.H.; Calenge, F.; Lecoeur, A.; Hedlund, L.; Jensen, P.; Guesdon, V.; et al. Early and late cognitive and behavioral aspects associated with range use in free-range laying hens (*Gallus gallus domesticus*). *Poult. Sci.* **2024**, *103*, 103813. [CrossRef] [PubMed]
50. Calder, C.; Albright, J. Chicken behavior. In *Backyard Poultry Medicine and Surgery: A Guide for Veterinary Practitioners*; John Wiley & Sons: Hoboken, NJ, USA, 2021; pp. 434–454.
51. Dereli Fidan, E.; Yaygıngül, R.; Kaya, M. Effects of intermittent lighting program and light colour on ocular health variables as welfare indicators in broiler chickens. *Br. Poult. Sci.* **2024**, *66*, 10–18. [CrossRef] [PubMed]
52. Hurnik, J.F.; Jerome, F.N.; Reinhart, B.S.; Summers, J.D. Colour as a stimulus for the choice of the nesting site by laying hens. *Br. Poult. Sci.* **1973**, *14*, 1–8. [CrossRef]
53. Appleby, M.C.; Mench, J.A.; Hughes, B.O. *Poultry Behaviour and Welfare*; Cabi: Wallingford, UK, 2004.
54. Adamczyk, K.; Górecka-Bruzda, A.; Nowicki, J.; Gumulka, M.; Molik, E.; Schwarz, T.; Earley, B.; Klocek, C. Perception of environment in farm animals-A review. *Ann. Anim. Sci.* **2015**, *15*, 565. [CrossRef]
55. Jones, E.K.M.; Prescott, N.B. Visual cues used in the choice of mate by fowl and their potential importance for the breeder industry. *World's Poult. Sci. J.* **2000**, *56*, 127–138. [CrossRef]
56. Prescott, N.B.; Wathes, C.M. Spectral sensitivity of the domestic fowl (*Gallus g. domesticus*). *Br. Poult. Sci.* **1999**, *40*, 332–339. [CrossRef]
57. Gisbert, S.; Schaeffel, F. M to L cone ratios determine eye sizes and baseline refractions in chickens. *Exp. Eye Res.* **2018**, *172*, 104–111. [CrossRef]
58. Nilsson, D.E.; Smolka, J.; Bok, M. The vertical light-gradient and its potential impact on animal distribution and behavior. *Front. Ecol. Evol.* **2022**, *10*, 951328. [CrossRef]
59. Trapp, R.; Fernández-Juricic, E. How visual system configuration can play a role in individual recognition: A visual modeling study. *Anim. Cogn.* **2022**, *25*, 205–216. [CrossRef]
60. Caves, E.M.; Fernández-Juricic, E.; Kelley, L.A. Ecological and morphological correlates of visual acuity in birds. *J. Exp. Biol.* **2024**, *227*, jeb246063. [CrossRef]
61. Sans, E.C.D.O.; Tuyttens, F.A.M.; Taconeli, C.A.; Pedrazzani, A.S.; Vale, M.M.; Molento, C.F.M. From the point of view of the chickens: What difference does a window make? *Animals* **2021**, *11*, 3397. [CrossRef] [PubMed]
62. Xu, D.; Shu, G.; Liu, Y.; Qin, P.; Zheng, Y.; Tian, Y.; Zhao, X.; Du, X. Farm environmental enrichments improve the welfare of layer chicks and pullets: A comprehensive review. *Animals* **2022**, *12*, 2610. [CrossRef] [PubMed]
63. Osadcha, Y.; Sakhatsky, M.; Dzhus, P. Effect of monochrome light with different wavelengths on biochemical parameters of hens. *J. Anim. Behav. Biometeorol.* **2023**, *11*, 2023014. [CrossRef]
64. Olanrewaju, H.A.; Evans, J.D.; Collier, S.D.; Purswell, J.L.; Branton, S.L. Age-related effect of high-frequency LED lighting in laying hens on biochemical, enzymatical, and electrolytes variables. *J. Appl. Poult. Res.* **2023**, *32*, 100351. [CrossRef]
65. Seifert, M. What the Avian Eye Tells Its Brain: Processing of Chromatic and Achromatic Information at the Level of Chicken Retinal Ganglion Cells. Ph.D. Dissertation, University of Sussex, Brighton, UK, 2022.
66. Milinusic, C. The inaudible world: Measuring sounds perceived by non-human life. In Proceedings of the Audio Engineering Society Convention 152, Online, 16 May 2022.
67. Hill, E.M.; Koay, G.; Heffner, R.S.; Heffner, H.E. Audiogram of the chicken (*Gallus gallus domesticus*) from 2 Hz to 9 kHz. *J. Comp. Physiol. A* **2014**, *200*, 863–870. [CrossRef]
68. Zeyl, J.N.; den Ouden, O.; Köppl, C.; Assink, J.; Christensen-Dalsgaard, J.; Patrick, S.C.; Clusella-Trullas, S. Infrasonic hearing in birds: A review of audiometry and hypothesized structure–function relationships. *Biol. Rev.* **2020**, *95*, 1036–1054. [CrossRef]
69. Olczak, K.; Penar, W.; Nowicki, J.; Magiera, A.; Klocek, C. The role of sound in livestock farming—Selected aspects. *Animals* **2023**, *13*, 2307. [CrossRef]
70. Collins, S.A.; Herborn, K.; Sufka, K.J.; Asher, L.; Brilot, B. Do I sound anxious? Emotional arousal is linked to changes in vocalisations in domestic chicks (*Gallus gallus dom.*). *Appl. Anim. Behav. Sci.* **2024**, *277*, 106359. [CrossRef]
71. Herborn, K.A.; McElligott, A.G.; Mitchell, M.A.; Sandilands, V.; Bradshaw, B.; Asher, L. Spectral entropy of early-life distress calls as an iceberg indicator of chicken welfare. *J. R. Soc. Interface* **2020**, *17*, 20200086. [CrossRef]
72. Laurijs, K.A.; Briefer, E.F.; Reimert, I.; Webb, L.E. Vocalisations in farm animals: A step towards positive welfare assessment. *Appl. Anim. Behav. Sci.* **2021**, *236*, 105264. [CrossRef]

73. McGrath, N.; Phillips, C.J.; Burman, O.H.; Dwyer, C.M.; Henning, J. Humans can identify reward-related call types of chickens. *R. Soc. Open Sci.* **2024**, *11*, 231284. [CrossRef]
74. Liu, J.; Liang, W. Free-range domestic chickens can distinguish between different alarm calls of Japanese tits. *Anim. Cogn.* **2023**, *26*, 715–720. [CrossRef]
75. Zhang, L.; Zhang, Z.; Liang, W. Domestic chicken hens can eavesdrop on the alarm calls of wild tits. *Ethol. Ecol. Evol.* **2024**, *36*, 355–366. [CrossRef]
76. Neethirajan, S. Decoding the language of chickens—An innovative NLP approach to enhance poultry welfare. *bioRxiv* **2024**. [CrossRef]
77. Manikandan, V.; Neethirajan, S. Decoding poultry vocalizations-natural language processing and transformer models for semantic and emotional analysis. *bioRxiv* **2024**, *2024*, 629057. [CrossRef]
78. Ncho, C.M.; Berdos, J.I.; Gupta, V.; Rahman, A.; Mekonnen, K.T.; Bakhsh, A. Abiotic stressors in poultry production: A comprehensive review. *J. Anim. Physiol. Anim. Nutr.* **2024**, *109*, 30–50. [CrossRef]
79. Chang, Q.; Li, C.; Zhao, S.; Wang, H.; Li, J.; Zhang, R.; Bao, J. Research Note: Effects of environmental sound stimulus on behavioral responses, cortisol levels, and horizontal immunity of transferred pullets. *Poult. Sci.* **2024**, *103*, 103689. [CrossRef]
80. Zhao, S.; Xu, C.; Zhang, R.; Li, X.; Li, J.; Bao, J. Effect of prenatal different auditory environment on learning ability and fearfulness in chicks. *Anim. Biosci.* **2022**, *35*, 1454. [CrossRef]
81. Mitchell, M.A.; Kettlewell, P.J.; Maxwell, M.H. Indicators of physiological stress in broiler chickens during road transportation. *Anim. Welf.* **1992**, *1*, 91–103. [CrossRef]
82. Nwaigwe, C.U.; Ihedioha, J.I.; Shoyinka, S.V.; Nwaigwe, C.O. Evaluation of the hematological and clinical biochemical markers of stress in broiler chickens. *Vet. World* **2020**, *13*, 2294. [CrossRef]
83. Ciborowska, P.; Michalczuk, M.; Bień, D. The effect of music on livestock: Cattle, poultry and pigs. *Animals* **2021**, *11*, 3572. [CrossRef] [PubMed]
84. Jacob, F.G.; Nääs, I.D.A.; Salgado, D.D.A.; Baracho, M.D.S.; Lima, N.D.D.S.; Pereira, D.F. Does environmental enrichment with music and strobe light affect broilers' welfare? analyzing their on-farm reaction. *AgriEngineering* **2022**, *4*, 707–718. [CrossRef]
85. Gao, X.; Gong, J.; Yang, B.; Liu, Y.; Xu, H.; Hao, Y.; Jing, J.; Feng, Z.; Li, L. Effect of classical music on growth performance, stress level, antioxidant index, immune function and meat quality in broilers at different stocking densities. *Front. Vet. Sci.* **2023**, *10*, 1227654. [CrossRef]
86. Peixoto, M.R.; Karrow, N.A.; Newman, A.; Widowski, T.M. Effects of maternal stress on measures of anxiety and fearfulness in different strains of laying hens. *Front. Vet. Sci.* **2020**, *7*, 128. [CrossRef] [PubMed]
87. Šemrov, M.Z.; Terčič, D.; Gobbo, E. Assessment of positive experiences using associative learning in chickens. *Poult. Sci.* **2024**, *103*, 104282. [CrossRef]
88. Campo, J.L.; Gil, M.G.; Davila, S.G. Effects of specific noise and music stimuli on stress and fear levels of laying hens of several breeds. *Appl. Anim. Behav. Sci.* **2005**, *91*, 75–84. [CrossRef]
89. Ubiema, G.; Siwiaszczyk, M.; Parias, C.; Bresso, R.; Hay, C.; Mulot, B.; Love, S.A.; Chaillou, E. The use and impact of auditory stimulation in animals. *J. Interdiscip. Methodol. Issues Sci.* **2022**, *9*, 1–23. [CrossRef]
90. Snowdon, C.T. Animal signals, music and emotional well-being. *Animals* **2021**, *11*, 2670. [CrossRef]
91. McArdie, T.M.; Foster, T.M.; Temple, W.; Matthews, L.R. A method for measuring the aversiveness of sounds to domestic hens. *Appl. Anim. Behav. Sci.* **1993**, *37*, 223–238. [CrossRef]
92. Chiandetti, C.; Vallortigara, G. Chicks like consonant music. *Psychol. Sci.* **2011**, *22*, 1270–1273. [CrossRef]
93. Tamagi, H.M.; Idrus, Z.; Farjam, A.S.; Awad, E.A.; Hussein, A.N. Effects of auditory enrichment and regular human contact on stress response, underlying fearfulness, and growth performance in broiler chickens. *Eur. Poult. Sci./Arch. Geflügelkd.* **2024**, *88*, 1–10. [CrossRef]
94. De Haas, E.N.; Newberry, R.C.; Edgar, J.; Riber, A.B.; Estevez, I.; Ferrante, V.; Hernandez, C.E.; Kjaer, J.B.; Ozkan, S.; Dimitrov, I.; et al. Prenatal and early postnatal behavioural programming in laying hens, with possible implications for the development of injurious pecking. *Front. Vet. Sci.* **2021**, *8*, 678500. [CrossRef]
95. Edgar, J.; Held, S.; Jones, C.; Troisi, C. Influences of maternal care on chicken welfare. *Animals* **2016**, *6*, 2. [CrossRef] [PubMed]
96. Hedlund, L.; Jensen, P. Incubation and hatching conditions of laying hen chicks explain a large part of the stress effects from commercial large-scale hatcheries. *Poult. Sci.* **2021**, *100*, 1–8. [CrossRef]
97. Narinç, D.; Aygun, A. Effects of species-specific auditory stimulation on broiler embryos on hatchability, developmental stability, behavior, and performance characteristics. *Animals* **2023**, *13*, 3739. [CrossRef]
98. Gall, G.E.; Letherbarrow, M.; Strandburg-Peshkin, A.; Radford, A.N.; Madden, J.R. Exposure to calls before hatching affects the post-hatching behaviour of domestic chickens. *R. Soc. Open Sci.* **2024**, *11*, 240114. [CrossRef]
99. Campbell, D.L.M.; De Haas, E.N.; Lee, C. A review of environmental enrichment for laying hens during rearing in relation to their behavioral and physiological development. *Poult. Sci.* **2019**, *98*, 9–28. [CrossRef] [PubMed]

100. Corbani, T.L.; Martin, J.E.; Healy, S.D. The impact of acute loud noise on the behavior of laboratory birds. *Front. Vet. Sci.* **2021**, *7*, 607632. [CrossRef] [PubMed]
101. von Holdt, B.M.; Kartzinel, R.Y.; van Oers, K.; Verhoeven, K.J.; Ouyang, J.Q. Changes in the rearing environment cause reorganization of molecular networks associated with DNA methylation. *J. Anim. Ecol.* **2023**, *92*, 648–664. [CrossRef]
102. van den Heuvel, H.; Youssef, A.; Grat, L.M.; Neethirajan, S. Quantifying the effect of an acute stressor in laying hens using thermographic imaging and vocalisations. *bioRxiv* **2022**. [CrossRef]
103. Ginovart-Panisello, G.J.; Iriondo, I.; Panisello Monjo, T.; Riva, S.; Cancer, J.C.; Alsina-Pagès, R.M. Acoustic detection of vaccine reactions in hens for assessing anti-inflammatory product efficacy. *Appl. Sci.* **2024**, *14*, 2156. [CrossRef]
104. McGrath, N.; Dunlop, R.; Dwyer, C.; Burman, O.; Phillips, C.J. Hens vary their vocal repertoire and structure when anticipating different types of reward. *Anim. Behav.* **2017**, *130*, 79–96. [CrossRef]
105. Ginovart-Panisello, G.J.; Alsina-Pagès, R.M.; Sanz, I.I.; Monjo, T.P.; Prat, M.C. Acoustic description of the soundscape of a real-life intensive farm and its impact on animal welfare: A preliminary analysis of farm sounds and bird vocalisations. *Sensors* **2020**, *20*, 4732. [CrossRef]
106. Coutant, M.; Villain, A.S.; Briefer, E.F. A scoping review of the use of bioacoustics to assess various components of farm animal welfare. *Appl. Anim. Behav. Sci.* **2024**, *275*, 106286. [CrossRef]
107. Steiger, S.S.; Fidler, A.E.; Valcu, M.; Kempenaers, B. Avian olfactory receptor gene repertoires: Evidence for a well-developed sense of smell in birds? *Proc. R. Soc. B* **2008**, *275*, 2309–2317. [CrossRef]
108. Krause, E.T.; Schrader, L.; Caspers, B.A. Olfaction in chicken (*Gallus gallus*): A neglected mode of social communication? *Front. Ecol. Evol.* **2016**, *4*, 94. [CrossRef]
109. Jones, R.B.; Roper, T.J. Olfaction in the domestic fowl: A critical review. *Physiol. Behav.* **1997**, *62*, 1009–1018. [CrossRef]
110. Nielsen, B.L. Understanding the sensory perception of chickens. In *Understanding the Behaviour and Improving the Welfare of Chickens*; Burleigh Dodds Science Publishing: Cambridge, UK, 2020; pp. 37–58.
111. Clark, L.; Smeraski, C.A. Chemesthesis and olfaction. In *Sturkie's Avian Physiology*; Academic Press: Cambridge, MA, USA, 2022; pp. 179–203.
112. Whittaker, D.J.; Hagelin, J.C. Female-based patterns and social function in avian chemical communication. *J. Chem. Ecol.* **2021**, *47*, 43–62. [CrossRef] [PubMed]
113. Brecht, K.F.; Nieder, A. Parting self from others: Individual and self-recognition in birds. *Neurosci. Biobehav. Rev.* **2020**, *116*, 99–108. [CrossRef]
114. Abankwah, V.; Deeming, D.C.; Pike, T.W. Avian olfaction: A review of the recent literature. *Comp. Cogn. Behav. Rev.* **2020**, *15*, 1–13. [CrossRef]
115. Lu, D.; Mi, J.; Wu, Y.; Liang, J.; Liao, X.; Wang, Y. Effects of different laying hen species on odour emissions. *Animals* **2020**, *10*, 2172. [CrossRef] [PubMed]
116. Pokharel, B.B.; Dos Santos, V.M.; Wood, D.; Van Heyst, B.; Harlander-Matauschek, A. Laying hens behave differently in artificially and naturally sourced ammoniated environments. *Poult. Sci.* **2017**, *96*, 4151–4157. [CrossRef] [PubMed]
117. Makinde, T.O.; Adewole, D.I. Can feed additives be used to promote positive behaviour in laying hens? A review. *World's Poult. Sci. J.* **2022**, *78*, 21–40. [CrossRef]
118. Ziolkowski, L.H.; Gracheva, E.O.; Bagriantsev, S.N. Tactile sensation in birds: Physiological insights from avian mechanoreceptors. *Curr. Opin. Neurobiol.* **2022**, *74*, 102548. [CrossRef]
119. Soroko, M.; Zaborski, D. Beak temperature change in response to acute stress in laying hens measured using infrared thermography. *Vet. Arhiv.* **2021**, *91*, 647–654. [CrossRef]
120. Glatz, P.C.; Underwood, G. Current methods and techniques of beak trimming laying hens, welfare issues and alternative approaches. *Anim. Prod. Sci.* **2020**, *61*, 968–989. [CrossRef]
121. Baker, P.E.; Nicol, C.J.; Weeks, C.A. The effect of hard pecking enrichment during rear on feather cover, feather pecking behaviour and beak length in beak-trimmed and intact-beak laying hen pullets. *Animals* **2022**, *12*, 674. [CrossRef]
122. Kliphuis, S.; Manet, M.W.; Goerlich, V.C.; Nordquist, R.E.; Vernooij, H.; van den Brand, H.; Tuyttens, F.A.; Rodenburg, T.B. Early-life interventions to prevent feather pecking and reduce fearfulness in laying hens. *Poult. Sci.* **2023**, *102*, 102801. [CrossRef]
123. Sans, E.C.D.O.; Tuyttens, F.A.M.; Taconeli, C.A.; Rueda, P.M.; Ciocca, J.R.; Molento, C.F.M. Welfare of broiler chickens reared in two different industrial house types during the winter season in Southern Brazil. *Br. Poult. Sci.* **2021**, *62*, 621–631. [CrossRef]
124. Skånberg, L.; Nielsen, C.B.K.; Keeling, L.J. Litter and perch type matter already from the start: Exploring preferences and perch balance in laying hen chicks. *Poult. Sci.* **2021**, *100*, 431–440. [CrossRef]
125. Schrader, L.; Malchow, J. The role of perches in chicken welfare. In *Understanding the Behaviour and Improving the Welfare of Chickens*; Burleigh Dodds Science Publishing: Cambridge, UK, 2020; pp. 375–416.
126. Anderson, M.G.; Campbell, A.M.; Crump, A.; Arnott, G.; Jacobs, L. Environmental complexity positively impacts affective states of broiler chickens. *Sci. Rep.* **2021**, *11*, 16966. [CrossRef] [PubMed]

127. Taylor, P.S.; Hemsworth, P.H.; Rault, J.L. Environmental complexity: Additional human visual contact reduced meat chickens' fear of humans and physical items altered pecking behavior. *Animals* **2022**, *12*, 310. [CrossRef]
128. Mouritsen, H. Magnetoreception in birds and its use for long-distance migration. In *Sturkie's Avian Physiology*; Academic Press: Cambridge, MA, USA, 2022; pp. 233–256.
129. Morandi-Raikova, A.; Vallortigara, G.; Mayer, U. The use of spatial and local cues for orientation in domestic chicks (*Gallus gallus*). *Anim. Cogn.* **2020**, *23*, 367–387. [CrossRef] [PubMed]
130. Weir, E. Animals and their ability to sense magnetic fields. *J. Agric. Food Inf.* **2020**, *21*, 90–94. [CrossRef]
131. Einwich, A.; Seth, P.K.; Bartölke, R.; Bolte, P.; Feederle, R.; Dedek, K.; Mouritsen, H. Localisation of cryptochrome 2 in the avian retina. *J. Comp. Physiol. A* **2022**, *208*, 69–81. [CrossRef]
132. Kavet, R.; Brain, J. Cryptochromes in mammals and birds: Clock or magnetic compass? *Physiology* **2021**, *36*, 72–85. [CrossRef]
133. Wiltschko, R.; Nießner, C.; Wiltschko, W. The magnetic compass of birds: The role of cryptochrome. *Front. Physiol.* **2021**, *12*, 667000. [CrossRef]
134. Siddiqi, N.A.; Shalaby, A.; Al Kindi, M.; Al Ghafri, F. Mobile phone electromagnetic fields affected the hepatocytes in the White Leghorn chicken embryo: An ultra-structural study. *Biomed. Pharmacol. J.* **2020**, *13*, 245–252. [CrossRef]
135. Paul, E.S.; Edgar, J.L.; Caplen, G.; Nicol, C.J. Examining affective structure in chickens: Valence, intensity, persistence and generalization measured using a conditioned place preference test. *Appl. Anim. Behav. Sci.* **2018**, *207*, 39–48. [CrossRef]
136. Gill, S.A.; Bierema, A.M.K. On the meaning of alarm calls: A review of functional reference in avian alarm calling. *Ethology* **2013**, *119*, 449–461. [CrossRef]
137. Bertin, A.; Calandreau, L.; Arnould, C.; Lévy, F. The developmental stage of chicken embryos modulates the impact of olfactory stimulation on food preferences. *Chem. Senses* **2012**, *37*, 253–261. [CrossRef] [PubMed]
138. Moroki, Y. Impact of flooring type on the sham dustbathing behaviour of caged laying hens. *Appl. Anim. Behav. Sci.* **2020**, *230*, 105066. [CrossRef]
139. Cronin, G.M.; Glatz, P.C. Causes of feather pecking and subsequent welfare issues for the laying hen: A review. *Anim. Prod. Sci.* **2020**, *61*, 990–1005. [CrossRef]
140. Rincón-Atuesta, A.J.; Roso-Molina, M.A.; Batista-Bayona, P.A. The HEN Gallus gallus domesticus, A Sentient and Productive Being. *A Sentient and Productive Being* **2023**. [CrossRef]
141. Zeiträg, C.; Jensen, P. The effects of play stimulation on cognitive capacities of chickens. *Front. Ethol.* **2024**, *3*, 1403082. [CrossRef]
142. Neethirajan, S.; Reimert, I.; Kemp, B. Measuring farm animal emotions—Sensor-based approaches. *Sensors* **2021**, *21*, 553. [CrossRef]
143. Rubene, D.; Low, M.; Brodin, A. Birds differentially prioritize visual and olfactory foraging cues depending on habitat of origin and sex. *Royal Soc. Open Sci.* **2023**, *10*, 221336. [CrossRef]
144. Neethirajan, S. ChickTrack–A quantitative tracking tool for measuring chicken activity. *Measurement* **2022**, *191*, 110819. [CrossRef]
145. Zidar, J.; Campderrich, I.; Jansson, E.; Wichman, A.; Winberg, S.; Keeling, L.; Løvlie, H. Environmental complexity buffers against stress-induced negative judgement bias in female chickens. *Sci. Rep.* **2018**, *8*, 5404. [CrossRef]
146. Colditz, I.G.; Campbell, D.L.M.; Ingham, A.B.; Lee, C. Environmental enrichment builds functional capacity and improves resilience as an aspect of positive welfare in production animals. *Animal* **2024**, *18*, 101173. [CrossRef]
147. Kochish, I.I.; Titov, V.Y.; Nikonov, I.N.; Brazhnik, E.A.; Vorobyov, N.I.; Korenyuga, M.V.; Myasnikova, O.V.; Dolgorukova, A.M.; Griffin, D.K.; Romanov, M.N. Unraveling signatures of chicken genetic diversity and divergent selection in breed-specific patterns of early myogenesis, nitric oxide metabolism and post-hatch growth. *Front. Genet.* **2023**, *13*, 1092242. [CrossRef] [PubMed]
148. Rault, J.L.; Waiblinger, S.; Boivin, X.; Hemsworth, P. The power of a positive human–animal relationship for animal welfare. *Front. Vet. Sci.* **2020**, *7*, 590867. [CrossRef] [PubMed]
149. Lagisz, M.; Zidar, J.; Nakagawa, S.; Neville, V.; Sorato, E.; Paul, E.S.; Bateson, M.; Mendl, M.; Løvlie, H. Optimism, pessimism and judgement bias in animals: A systematic review and meta-analysis. *Neurosci. Biobehav. Rev.* **2020**, *118*, 3–17. [CrossRef]
150. Košťál, Ľ.; Skalná, Z.; Pichová, K. Use of cognitive bias as a welfare tool in poultry. *J. Anim. Sci.* **2020**, *98* (Suppl. S1), S63–S79. [CrossRef] [PubMed]
151. Deakin, A.; Browne, W.J.; Hodge, J.J.; Paul, E.S.; Mendl, M. A screen-peck task for investigating cognitive bias in laying hens. *PLoS ONE* **2016**, *11*, e0158222. [CrossRef]
152. Lourenço da Silva, M.I.; Ulans, A.; Jacobs, L. Pharmacological validation of an attention bias test for conventional broiler chickens. *PLoS ONE* **2024**, *19*, e0297715. [CrossRef]
153. Baciadonna, L.; Briefer, E.F.; McElligott, A.G. Investigation of reward quality-related behaviour as a tool to assess emotions. *Appl. Anim. Behav. Sci.* **2020**, *225*, 104968. [CrossRef]
154. Taylor, P.S.; Hamlin, A.S.; Crowley, T.M. Anticipatory behavior for a mealworm reward in laying hens is reduced by opioid receptor antagonism but not standard feed intake. *Front. Behav. Neurosci.* **2020**, *13*, 290. [CrossRef] [PubMed]
155. van Emous, R.A.; Mens, A.J.W. Effects of breeder feed restriction on behavior, welfare, reproduction and health. In *Breeder Management and Nutrition*; Novus International, Inc.: St. Louis, MO, USA, 2022; pp. 35–60.

156. Campbell, D.L.; Belson, S.; Dyall, T.R.; Lea, J.M.; Lee, C. Impacts of rearing enrichments on pullets' and free-range hens' positive behaviors across the flock cycle. *Animals* **2022**, *12*, 280. [CrossRef]
157. Schlegel, L.; Kleine, A.S.; Doherr, M.G.; Fischer-Tenhagen, C. How to see stress in chickens: On the way to a stressed chicken scale. *Poult. Sci.* **2024**, *103*, 103875. [CrossRef]
158. Ma, X.; Lu, X.; Huang, Y.; Yang, X.; Xu, Z.; Mo, G.; Ren, Y.; Li, L. An advanced chicken face detection network based on GAN and MAE. *Animals* **2022**, *12*, 3055. [CrossRef]
159. Rodriguez, M.V.; Phan, T.; Fernandes, A.F.; Breen, V.; Arango, J.; Kidd, M.T.; Le, N. Facial chick sexing: An automated chick sexing system from chick facial image. *arXiv* **2024**, arXiv:2410.09155. [CrossRef]
160. Pijpers, N.; van den Heuvel, H.; Duncan, I.H.; Yorzinski, J.; Neethirajan, S. Understanding chicks' emotions: Are eye blinks & facial temperatures reliable indicators? *bioRxiv* 2022. [CrossRef]
161. Kang, S.W.; Christensen, K.D.; Kidd, M.T., Jr.; Orlowski, S.K. Effects of environmental enrichments on welfare and hepatic metabolic regulation of broiler chickens. *Animals* **2024**, *14*, 557. [CrossRef]
162. Chen, S.; Yan, C.; Xiao, J.; Liu, W.; Li, Z.; Liu, H.; Liu, J.; Zhang, X.; Ou, M.; Chen, Z.; et al. Domestication and feed restriction programming organ index, dopamine, and hippocampal transcriptome profile in chickens. *Front. Vet. Sci.* **2021**, *8*, 701850. [CrossRef] [PubMed]
163. Ahmed-Farid, O.; Salah, A.S.; Nassan, M.A.; El-Tarabany, M.S. Effects of chronic thermal stress on performance, energy metabolism, antioxidant activity, brain serotonin, and blood biochemical indices of broiler chickens. *Animals* **2021**, *11*, 2554. [CrossRef] [PubMed]
164. Dudde, A.; Phi Van, L.; Schrader, L.; Obert, A.J.; Krause, E.T. Brain gain—Is the cognitive performance of domestic hens affected by a functional polymorphism in the serotonin transporter gene? *Front. Psychol.* **2022**, *13*, 901022. [CrossRef]
165. Austin, S.H.; Harris, R.M.; Booth, A.M.; Lang, A.S.; Farrar, V.S.; Krause, J.S.; Hallman, T.A.; MacManes, M.; Calisi, R.M. Isolating the role of corticosterone in the hypothalamic–pituitary–gonadal transcriptomic stress response. *Front. Endocrinol.* **2021**, *12*, 632060. [CrossRef]
166. Yang, Y.; Han, W.; Zhang, A.; Zhao, M.; Cong, W.; Jia, Y.; Wang, D.; Zhao, R. Chronic corticosterone disrupts the circadian rhythm of CRH expression and m6A RNA methylation in the chicken hypothalamus. *J. Anim. Sci. Biotechnol.* **2022**, *13*, 29. [CrossRef]
167. Kliphuis, S.; Manet, M.W.; Goerlich, V.C.; Nordquist, R.E.; Vernooij, H.; Tuyttens, F.A.; Rodenburg, T.B. Effects of lighted incubation and foraging enrichment during rearing on individual fear behavior, corticosterone, and neuroplasticity in laying hen pullets. *Poult. Sci.* **2024**, *103*, 103665. [CrossRef]
168. Armstrong, E.A.; Voelkl, B.; Voegeli, S.; Gebhardt-Henrich, S.G.; Guy, J.H.; Sandilands, V.; Boswell, T.; Toscano, M.J.; Smulders, T.V. Cell proliferation in the adult chicken hippocampus correlates with individual differences in time spent in outdoor areas and tonic immobility. *Front. Vet. Sci.* **2020**, *7*, 587. [CrossRef] [PubMed]
169. Sundrum, A. Why has animal science not led to improved farm animal health and welfare? *Front. Anim. Sci.* **2024**, *4*, 1214889. [CrossRef]
170. Ojo, R.O.; Ajayi, A.O.; Owolabi, H.A.; Oyedele, L.O.; Akanbi, L.A. Internet of Things and machine learning techniques in poultry health and welfare management: A systematic literature review. *Comput. Electron. Agric.* **2022**, *200*, 107266. [CrossRef]
171. Merenda, V.R.; Bodempudi, V.U.; Pairis-Garcia, M.D.; Li, G. Development and validation of machine-learning models for monitoring individual behaviors in group-housed broilers. *Poult. Sci.* **2024**, *103*, 104374. [CrossRef] [PubMed]
172. Mullan, S.; Stuijfzand, B.; Butterworth, A. Longitudinal national-level monitoring of on-farm broiler welfare identifies consistently poorly performing farms. *Sci. Rep.* **2021**, *11*, 11928. [CrossRef]
173. Ross, M.; Rausch, Q.; Vandenberg, B.; Mason, G. Hens with benefits: Can environmental enrichment make chickens more resilient to stress? *Physiol. & Behav.* **2020**, *226*, 113077. [CrossRef]
174. Underwood, G.; Andrews, D.; Phung, T.; Edwards, L.E. Incubation, hatchery practice and the welfare of layer hens. *Anim. Prod. Sci.* **2021**, *61*, 867–875. [CrossRef]
175. Fernyhough, M.; Nicol, C.J.; van de Braak, T.; Toscano, M.J.; Tønnessen, M. The ethics of laying hen genetics. *J. Agric. Environ. Ethics* **2020**, *33*, 15–36. [CrossRef]
176. Bonnefous, C.; Collin, A.; Guilloteau, L.A.; Guesdon, V.; Filliat, C.; Réhault-Godbert, S.; Rodenburg, T.B.; Tuyttens, F.A.; Warin, L.; Steenfeldt, S.; et al. Welfare issues and potential solutions for laying hens in free-range and organic production systems: A review based on literature and interviews. *Front. Vet. Sci.* **2022**, *9*, 952922. [CrossRef]
177. Cao, C.; Chowdhury, V.S.; Cline, M.A.; Gilbert, E.R. The microbiota–gut–brain axis during heat stress in chickens: A review. *Front. Physiol.* **2021**, *12*, 752265. [CrossRef]
178. Beldowska, A.; Barszcz, M.; Dunislawska, A. State of the art in research on the gut–liver and gut–brain axis in poultry. *J. Anim. Sci. Biotechnol.* **2023**, *14*, 37. [CrossRef] [PubMed]
179. Jiang, S.; Hu, J.Y.; Cheng, H.W. The impact of probiotic *Bacillus subtilis* on injurious behavior in laying hens. *Animals* **2022**, *12*, 870. [CrossRef] [PubMed]

180. Fu, Y.; Hu, J.; Zhang, H.; Erasmus, M.A.; Johnson, T.A.; Cheng, H.W. The impact of early-life cecal microbiota transplantation on social stress and injurious behaviors in egg-laying chickens. *Microorganisms* **2024**, *12*, 471. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.