MARCELO BAHUTI

EVALUATION AND MODELING OF RESPONSES OF LAYING HENS SUBJECTED TO DIFFERENT ILLUMINANCE LEVELS

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2025

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Thesis presented to the Federal University of Lavras, as part of the requirements of the Graduate Program in Agriculture Engineering, area of concentration in Constructions, Environmental Conditions, and Waste Treatment, to obtain the Ph.D. title in Agriculture Engineering.

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MARCELO BAHUTI

EVALUATION AND MODELING OF RESPONSES OF LAYING HENS SUBJECTED TO DIFFERENT ILLUMINANCE LEVELS

AVALIAÇÃO E MODELAGEM DAS RESPOSTAS DE GALINHAS POEDEIRAS SUBMETIDAS À DIFERENTES NÍVEIS DE ILUMINÂNCIA

Thesis presented to the Federal University of Lavras, as part of the requirements of the Graduate Program in Agriculture Engineering, to obtain the Ph.D. title in Agriculture Engineering.

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GENERAL ABSTRACT

This study aimed to investigate the impact of different illuminance levels and exposure times to these illuminances on laying hens during the peak production phase. The experiment was conducted in climate-controlled wind tunnels, which allowed for precise control of environmental variables such as temperature, relative humidity, air velocity, and light intensity. The treatments provided 5, 20, 50, and 100 lux illuminance levels using cold white light-emitting diode (LED) lamps. The thermal variables were adjusted to remain within the comfort ranges recommended for laying hens aged 25 to 36 weeks. Additionally, the feed provided to the hens was balanced according to the nutritional requirements for this strain at this developmental stage. 72 Hy-Line W-80 laying hens were used, divided into three experimental flocks of 24 birds per flock. Each flock was housed for 28 days, including an initial acclimation period of 7 days. During the experimental phase, data were collected on physiological responses (cloacal temperature, surface temperature, and respiration rate), productive responses (feed intake, water intake, feed conversion, body weight, egg weight, laying percentage, and percentage of viable eggs), and egg quality indicators (egg specific gravity, eggshell density, eggshell thickness, percentages of yolk, albumen, and shell, Haugh unit, and yolk index). The analyses and results were presented in Article 1 (statistical analysis of response variables) and Article 2 (comparison of modeling approaches as predictive tools to support decision-making). Regarding the responses evaluated in Article 1, the results indicated that the tested illuminance levels did not significantly impact the evaluated parameters when analyzed in isolation. However, illumination exposure times influenced variables such as cloacal and surface temperatures, feed intake, body weight, and albumen percentage. Based on these results, 28 days was recommended as the minimum acclimation period for Hy-Line W-80 laying hens during the production phase. Moreover, as no significant differences were observed among treatments, it was found that environments with 5 lux are sufficient to ensure adequate access to food and water for the birds without compromising well-being or production. These findings suggest that environments with lower illuminance can reduce production costs, as their lighting systems require lower energy power compared to systems operating at 100 lux. In Article 2, statistical and fuzzy modeling approaches were applied to accurately predict laying hens' feed intake and surface temperature subjected to different lighting challenges. The developed models demonstrated high accuracy, with a notable advantage for fuzzy inference system (FIS)-based models. The results highlight the applicability of artificial intelligence techniques for simulating complex scenarios, optimizing management, and reducing production costs. Based on expert knowledge, the FIS modeling proved to be an efficient tool for decision-making in modern poultry farming, contributing to a balance between animal well-being, productivity, and sustainability. In summary, it is concluded that LED lighting offers significant energy efficiency and environmental management benefits, as it enables energy savings and reduces electronic waste compared to traditional light sources. Moreover, these benefits were achieved without compromising the well-being or productive performance of the birds. Therefore, this study contributes to the literature by clarifying the relationship between artificial lighting and laying hens management, proposing light intensity adjustments as a viable strategy to meet the productive and environmental demands of modern poultry farming.

Keywords: poultry farming; light intensity; hen performance; artificial intelligence; fuzzy inference system; smart production; zootechnical responses predicting.

RESUMO GERAL

Objetivou-se com o presente estudo, investigar o impacto de diferentes níveis de iluminância e do tempo de exposição a essas iluminâncias em galinhas poedeiras durante o pico de postura. O experimento foi conduzido em túneis de vento climatizados, que permitiram o controle das variáveis ambientais como, temperatura, umidade relativa e velocidade do ar, além da intensidade luminosa. Assim, os tratamentos consistiram em fornecer iluminâncias de 5, 20, 50 e 100 lux, utilizando lâmpadas de diodo emissor de luz (LED) na cor branca fria. As variáveis térmicas foram ajustadas para permanecerem dentro dos intervalos de conforto recomendados para poedeiras de 25 a 36 semanas de idade. Além do mais, a ração fornecida foi balanceada conforme as exigências nutricionais da linhagem para essa fase de desenvolvimento. Um total de 72 poedeiras Hy-Line W-80 foram utilizadas, sendo divididas em três lotes experimentais (24 aves por lote). Cada lote teve duração de 28 dias, incluindo um período inicial de aclimatação de 7 dias. Assim, durante a fase experimental, foram coletados dados referentes a respostas fisiológicas (temperatura cloacal, temperatura superficial e frequência respiratória), respostas produtivas (consumo de ração, consumo de água, conversão alimentar, massa corporal, massa de ovos, porcentagem de postura e porcentagem de ovos viáveis) e indicadores de qualidade dos ovos (massa especifica dos ovos, densidade da casca, espessura da casca, porcentagens de gema, albúmen e casca, unidade Haugh e índice de gema). As análises e resultados foram apresentados em duas partes: Artigo 1 (análise estatística das variáveis respostas) e Artigo 2 (comparação entre modelagens como ferramentas preditivas para auxiliar a tomada de decisão). Em relação às respostas avaliadas no Artigo 1, os resultados indicaram que os níveis de iluminância testados não impactaram significativamente os parâmetros avaliados, quando analisados isoladamente. Contudo, o tempo de exposição à iluminação influenciou variáveis como temperaturas cloacal e superficial, consumo alimentar, massa corporal e porcentagem de albúmen. Com base nesses resultados, recomendou-se 28 dias como período mínimo de aclimatação para as poedeiras Hy-Line W-80 em fase de postura. Ademais, como não houve diferença significativa entre os tratamentos, verificou-se que ambientes com 5 lux são suficientes para garantir o acesso adequado das aves a alimentos e água, sem comprometer o bem-estar ou a produção. Desse modo, os resultados sugerem que ambientes com menor iluminância podem reduzir os custos de produção, pois demandam menor potência energética em comparação a sistemas com 100 lux. Por sua vez, no Artigo 2 foram aplicadas modelagens estatística e *fuzzy* para prever com precisão o consumo alimentar e a temperatura superficial das poedeiras submetidas aos diferentes desafios luminosos. Os modelos desenvolvidos mostraram elevada acurácia, porém, com vantagem para os modelos baseados em sistemas de inferência *fuzzy* (FISs). Os resultados ressaltam a aplicabilidade de técnicas de inteligência artificial para simular cenários complexos, otimizando o manejo e possibilitando reduzir custos de produção. Assim, a modelagem FIS, baseada em conhecimento de especialistas, demonstrou ser uma ferramenta eficiente para a tomada de decisões na avicultura moderna, contribuindo para um equilíbrio entre bem-estar animal, produtividade e sustentabilidade. Em síntese, conclui-se que a iluminação LED oferece benefícios em termos de eficiência energética e manejo ambiental, uma vez que permite economia de energia e redução de resíduos eletrônicos em comparação às fontes de luz tradicionais. Além do mais, esses benefícios ocorrem sem comprometer o bem-estar e o desempenho produtivo das aves. Portanto, este estudo contribui para a literatura ao esclarecer a relação entre iluminação artificial e o manejo de aves poedeiras, propondo ajustes na intensidade luminosa como estratégia viável para atender às demandas produtivas e ambientais da avicultura moderna.

Palavras-chave: avicultura; intensidade luminosa; desempenho de galinhas; inteligência artificial; sistema de inferência *fuzzy*; produção inteligente; previsão de respostas zootecnicas.

IMPACT INDICATORS

The results of this thesis demonstrate impacts in several aspects. Technologically, two software applications were developed and registered with the Instituto Nacional da Propriedade Industrial (INPI – Brazilian National Institute of Industrial Property). These tools incorporate artificial intelligence to predict laying hens' physiological and productive responses, enabling more precise decision-making in environmental and productive management. These systems directly benefit producers and technicians by promoting cost reduction and resource efficiency. Economically, the validation of LED lighting indicates potential energy savings and operational cost reductions. These benefits contribute directly to the financial sustainability of both small and large-scale producers. Socially, the study reinforces ethical management practices and animal well-being. These practices align with market demands and animal welfare organizations while enhancing higher productivity without compromising animal comfort. This impact also extends to final consumers by increasing the availability of affordable and high-quality animal protein. Thus, the impacts span national and international territories, offering concrete contributions to environmental and productive sustainability, as well as influencing industrial practices and public policies focused on sustainable development and animal well-being. Therefore, this study presents significant social, technological, and environmental impacts, with strong potential to contribute to sustainable development in alignment with the United Nations Sustainable Development Goals (SDGs), particularly SDGs 2, 3, 9, 10, and 12.

INDICADORES DE IMPACTO

Os resultados desta tese apresentam impactos em vários aspectos. No âmbito tecnológico, dois softwares foram desenvolvidos e registrados no Instituto Nacional da Propriedade Industrial (INPI). Eles incorporam inteligência artificial para predizer respostas fisiológicas e produtivas de galinhas poedeiras, possibilitando decisões mais precisas no manejo ambiental e produtivo. Esses sistemas promovem a redução de custos e o uso eficiente de recursos, beneficiando diretamente produtores e técnicos. Em termos econômicos, a validação do uso de iluminação LED indica possibilidade de economia de energia e redução de custos operacionais. Esses benefícios atuam diretamente para a sustentabilidade financeira de pequenos e grandes produtores. No aspecto social, o trabalho reforça práticas de manejo ético e bem-estar animal. Essas práticas, atendem às exigências do mercado e das organizações de proteção animal, além de promover maior produtividade sem comprometer o conforto dos animais. Este impacto também beneficia consumidores finais, uma vez que aumenta a oferta de proteína animal acessível e de alta qualidade. Dessa forma, os impactos alcançam territórios nacionais e internacionais, com contribuições concretas para a sustentabilidade ambiental e produtiva, além de influenciar práticas industriais e políticas públicas voltadas ao desenvolvimento sustentável e bem-estar animal. Portanto, o presente estudo apresenta impactos sociais, tecnológicos e ambientais com grande potencial de contribuir para o desenvolvimento sustentável, alinhado aos Objetivos de Desenvolvimento Sustentável (ODS) da ONU, em especial os ODS 2, 3, 9, 10 e 12.

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SUMMARY

FIRST PART

1 GENERAL INTRODUCTION

Food production and supply are essential for human subsistence and are, therefore, fundamental consumer items for society. However, population growth and the resulting demand for food exert significant pressure on the environment.

In this context, eggs stand out among animal protein sources due to their reduced water footprint. According to the Water Footprint Network, producing 1 kg of eggs, beef, pork, and chicken requires 3,300, 15,400, 6,000, and 4,300 liters of water, respectively.

Furthermore, eggs hold substantial socioeconomic importance. With a lower acquisition cost compared to meat, they represent a more accessible source of protein for populations facing socioeconomic vulnerabilities. Eggs are regarded as the second most complete food globally, second only to breast milk, as they contain various vitamins, minerals, and amino acids. Including eggs in diets, therefore, becomes a strategic option for combating malnutrition and hunger, especially considering their high protein content, which promotes a greater feeling of satiety. Additionally, eggs have a higher biological value compared to meat, with a protein absorption efficiency of 93.7% for eggs compared to 75% for meat.

These characteristics, coupled with increased access to information and adopting healthier eating habits, have driven egg consumption in Brazil and worldwide. As a result, according to Associção Brasileira de Proteina Animal (ABPA), Brazilian egg production has reached successive records, totaling 59 billion units in 2023. In this scenario, Brazilian egg exports have also grown steadily over the years.

Given this, layer poultry farming plays a crucial role in the global economy, generating direct and indirect jobs and providing a more accessible and sustainable source of animal protein for the population. Thus, eggs are a viable source of animal protein for the future, aligning with the environmental and social demands posed by population growth.

Producers adopt intensive production systems to meet market demands. However, in recent years, pressure from consumers, animal welfare organizations, and global markets has directed the poultry industry toward more ethical and sustainable practices. Consequently, the layer poultry sector has evolved, requiring compliance with animal well-being standards and the achievement of increasingly efficient productivity rates.

It is, therefore, essential to ensure adequate conditions for temperature, air quality, acoustics, and lighting within breeding environments. Lighting, in particular, is vital for laying hens, not only because it stimulates feed consumption but also due to the metabolic control that light exerts on the animal. Light, captured by the birds' receptors, influences ovarian activity and follicular development, promoting higher laying rates and more consistent egg production. Thus, lighting is an essential factor in birds' reproductive and productive management, whether natural or artificial.

Artificial lighting is more prevalent in closed-house systems, commonly used in regions with unfavorable climates. This intense use increases energy costs and affects the product's final price. In Brazil, however, most production systems use open houses, reducing the need for artificial lighting. Still, pursuing greater control over environmental variables has led to the increasing adoption of closed systems.

These facilities require numerous lamps to provide the necessary illuminance levels. In this context, light-emitting diode (LED) lamps emerged as a solution to reduce costs and environmental impacts. LED lamps offer better energy efficiency, lower energy consumption, and greater durability, generating less electronic waste.

Moreover, the use of sustainable systems must be complemented by proper management through the adjustment of ideal illuminance levels within the rearing facility. This adjustment ensures optimal laying conditions, as this variable directly relates to the birds' health and well-being.

Therefore, studies are needed to update the poultry sector by encouraging cost-containment measures and improving market competitiveness. Above all, these studies must contribute to enhancing the management of laying hens during the production phase. Analyzing productive, physiological, behavioral, and egg quality parameters is crucial to determining the effects of environmental variables on efficiency and bird well-being.

In this context, as laying hens represent complex biological systems interacting dynamically with environmental variations, modeling has been increasingly used in modern poultry farming. Using mathematical, statistical, and artificial intelligence techniques enables predicting productive performance and assessing environmental factors' impacts. Predictive models allow for simulating complex scenarios and identifying solutions to specific challenges, such as reducing energy consumption or improving egg quality. Additionally, these tools support more precise and efficient decision-making, optimizing resources to maximize productivity and bird well-being. Thus, modeling also promotes a balance between economic efficiency, well-being, and environmental responsibility.

In light of the above, this study aims to evaluate the effect of different illuminance levels and exposure durations, utilizing LED lamps for laying hens during their peak laying phase.

2 LITERATURE REVIEW

This section comprises a literature review addressing the complex relationship between lighting and the biological systems of laying hens. The aim is to emphasize the importance of lighting in poultry farming, discussing how birds perceive light, the management practices related to lighting in breeding environment, and the impacts of variations in light sources, such as lamp type and color, on productivity and well-being.

2.1 The influence of light in layer poultry farming

Lighting is a critical component of commercial poultry housing environments, given its influence on confined birds' health, productivity, and well-being.

Among the biological aspects directly influenced by light are feeding, reproductive, hormonal, and metabolic functions (Ribeiro, 2015). In laying hens, egg productivity and quality are directly tied to lighting conditions, as luminosity regulates feed intake, thereby impacting feed efficiency (Bertechini, 2012; Melo *et al.*, 2016).

Light stimulation in layers occurs via two pathways: ocular (retinal) and cranial (transcranial). In the ocular pathway, light is received by the retina and converted into nerve impulses transmitted to the hypothalamus via cones and rods (Ribeiro, 2015). In the transcranial pathway, light penetrates receptors in the cranial skin of the hens, passing through the bones to reach the hypothalamus (Ribeiro, 2015).

In response to lighting conditions (e.g., diurnal patterns, intensity, and spectrum), the hypothalamus produces gonadotropin-releasing hormones. These hormones, transported via the pituitary portal system, stimulate the secretion of follicle-stimulating hormone (FSH) and luteinizing hormone (LH) in the anterior pituitary gland (Long *et al.*, 2015).

Research suggests hypothalamic photoreceptors act as biological transducers, converting photon energy into neural impulses. These impulses are then processed by the endocrine system, regulating ovarian activity in females and influencing reproductive functions, behavioral responses, and secondary sexual characteristics (Silva *et al.*, 2010; Araújo *et al.*, 2011; Paixão, 2014; Yang *et al.*, 2016).

The avian retina is among the most sophisticated cone photoreceptor systems in vertebrates. Birds have five types of cones, including four single cones that enable tetrachromatic color vision and one double cone for achromatic motion detection (Yang *et al.*, 2016). Tetrachromatic vision in birds is mediated by four single cone types, each with maximum sensitivity to specific wavelengths: violet, blue, green, and red (Kram; Mantey; Corbo, 2010).

The transcranial pathway also effectively captures light, influencing the hypothalamus directly (Mendes *et al*., 2010). According to Jácome *et al*. (2014), transcranial light reception is the most significant pathway for reproductive stimulation in birds. This is supported by Baxter *et al*. (2014), who found no significant differences in the onset of reproduction between blind and sighted birds exposed to artificial lighting, indicating that retinal stimulation, or its absence, does not affect reproductive initiation.

Furthermore, Araújo *et al*. (2011) observed that birds respond more effectively to transcranial light stimulation when exposed to wavelengths from the end of the spectrum, such as purple and orange, which promote higher reproductive hormone production. The authors also noted that photon energy converts into neural stimuli that regulate circadian rhythms and coordinate biochemical and behavioral events, directly influencing avian performance.

In this regard, the circadian regulation of energy homeostasis is controlled by an endogenous biological clock in the hypothalamus's suprachiasmatic nuclei (SCN). The biological clock is synchronized by photic information transmitted directly from light-sensitive retinal ganglion cells to the SCN. Thus, light serves as a powerful exogenous signal for the circadian clock, although other factors, such as feed intake, also influence clock signaling (Golombek; Rosenstein, 2010).

Lighting is, therefore, a crucial factor in poultry management, contributing to improved zootechnical results by influencing animal health and development. Additionally, optimizing lighting systems can significantly enhance the economic profitability of poultry farming, emphasizing the need to understand the use and characteristics of lighting sources.

2.2 Photoperiod

Light is an electromagnetic wave observable by humans and animals through the visual sensation of brightness triggered by retinal stimulation. Photoperiod, in turn, refers to the duration of daylight relative to nighttime within a 24-hour cycle.

Egg production in hens is stimulated by long photoperiods, characterized by days with more than 12 hours of light, whether natural or artificial. These photoperiods enhance the reproductive function of layers, leading to increased egg production.

Due to Brazil's geographical position, most poultry production systems benefit from natural climatic resources such as temperature, humidity, and light, requiring only a few hours of artificial lighting to complement the photoperiod. However, to achieve better control over environmental variables in poultry houses and optimize animal productivity, there is a growing trend toward systems that rely entirely on artificial light sources.

In this context, Jácome *et al*. (2014) indicated that artificial lighting can delay or accelerate egg synthesis, as circulating levels of Luteinizing and Follicle-stimulating hormones (LH and FSH, respectively) intensify after a single day of exposure to long photoperiods.

Lighting schedules act as a means of regulating bird activity since all animals follow a circadian rhythm, representing biological activities within a 24-hour cycle. Generally, hens lay eggs shortly after the first hour of light stimulation in the day, regardless of whether the source is natural or artificial (Nunes *et al*., 2013).

According to Abreu *et al*. (2007), various lighting programs, continuous or intermittent and in different intensities, have been proposed to create optimal housing conditions. These programs aim to improve weight gain, feed conversion, and productive quality while preventing metabolic disorders.

Lighting programs for laying hens are classified as hemeral and ahemeral. Hemeral programs are composed of 24-hour periods divided into light (photoperiod or photophase) and dark phases (scotoperiod or scotophase) (Baêta; Souza, 2010; Gewehr *et al*., 2012). In contrast, ahemeral programs consist of cycles longer than 24 hours (Aguiar, 2016), where a new light cycle begins more than 24 hours after the start of the previous cycle.

Hemeral programs can include two uninterrupted daily phases, one light phase and one dark phase, termed continuous hemeral. This designation applies regardless of whether the program uses only natural light, natural light supplemented by artificial light, or solely artificial lighting. Alternatively, lighting can alternate between light and dark phases within 24 hours, constituting an intermittent hemeral program. This approach primarily aims to regulate the secretion of gonadotropins, mainly LH, which is secreted in pulses. Furthermore, hemeral programs can be symmetrical or asymmetrical, depending on whether the light and dark phases are of equal duration (Nunes *et al*., 2013).

In their review, Jácome *et al*. (2014) examined the influence of artificial lighting on egg quality and the performance of laying hens. They found that metabolic stimulation (photostimulation) occurs with more than 12 hours of light, regardless of whether the lighting program is continuous or intermittent. However, Gewehr *et al*. (2012) observed that intermittent lighting programs reduced feed intake, egg count, and egg weight compared to a continuous 16-hour program. The authors also noted that intermittent programs with 2-minute photophases (equidistant within 16 hours) or natural declining light programs were inefficient for semi-heavy layers at the start of the laying period.

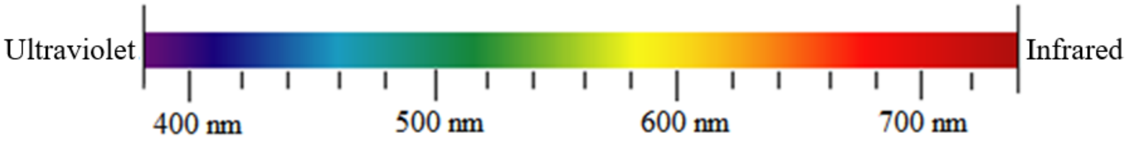
Conversely, ahemeral management is better suited for hens' production phase (Aguiar, 2016). Ahemeral cycles are used in order to increase egg size and shell quality without reducing the laying rate (Jácome *et al*., 2014; Nunes *et al*., 2013). However, the division of periods in this lighting program increases labor costs since activities must be performed outside conventional work hours (Jácome *et al*., 2014).

Thus, photoperiods, particularly when associated with light intensity, directly impact egg production by influencing weight gain during rearing and advancing or delaying reproductive maturity (Baxter *et al*., 2014; Araújo *et al*., 2011). The ideal lighting program should not only maximize production but also ensure bird comfort. Achieving these goals while minimizing feed and energy consumption requires a thorough understanding of artificial light sources and their influence on bird behavior and performance.

2.3 Artificial lighting

Artificial lighting is widely used in various poultry production systems to enhance productive performance. However, it is essential to understand how birds perceive the light environment, considering its various aspects. Beyond duration, light quality, intensity (brightness), and wavelength (color) are critical factors that significantly impact birds' development and zootechnical performance. These factors influence vision and fundamental biological processes (Benson *et al*., 2013; Borille *et al*., 2015; Mendes *et al*., 2010; Parvin *et al*., 2014). Figure 1 illustrates the visible light spectrum and its corresponding wavelengths.

Figure 1 – Wavelengths of the visible spectrum.

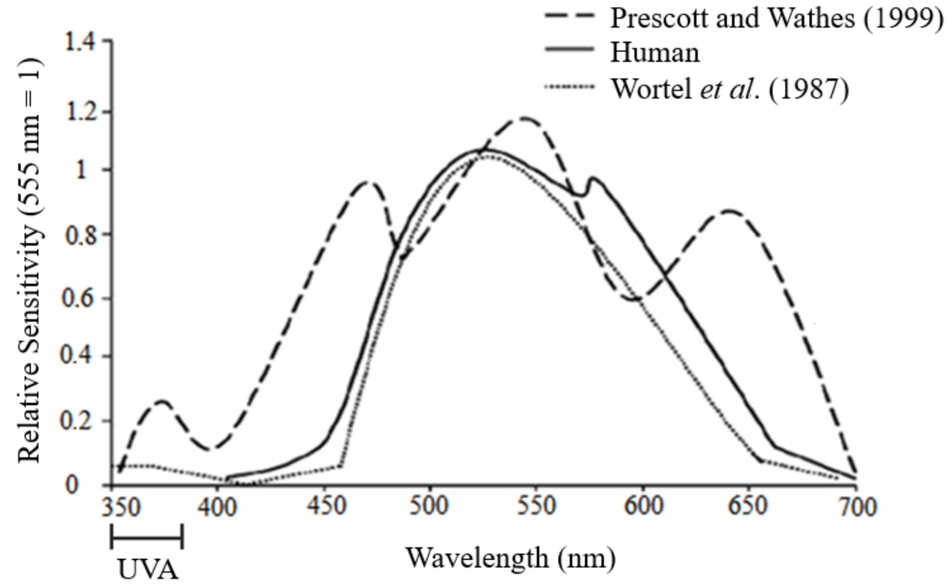


Source: Adapted from Cutnell and Cutnell (2016).

Since light comprises a broad spectrum of electromagnetic waves, the perception of these properties depends on the birds' spectral sensitivity. Using behavioral tests, Prescott and

Wathes (1999) correlated the spectral perception curves of broilers with those of humans. The authors found that birds can "see" in the ultraviolet (UVA) range (Figure 2) and that their spectral sensitivity in the visible light range differs from humans, as birds have more spectral sensitivity peaks than the human eye (Hassan *et al*., 2013). Thus, birds may behave and respond differently when exposed to the same light intensity from two sources that appear identical to human observers.

Figure 2 – Spectral sensitivity of fowls and humans.



Source: Adapted from Nunes *et al*. (2013) and Prescott and Wathes (1999).

According to Jácome *et al*. (2012), transcranial penetration is a thousand times greater in birds exposed to wavelengths above 700 nm than in birds exposed to wavelengths of 400 nm. This increased penetration results in more intense metabolic and behavioral activity due to greater hypothalamic stimulation.

Therefore, lighting affects animal behavior according to the power distribution of the light sources (Silva; Tavares; Pereira, 2012), and birds have different sensitivity peaks depending on the light's wavelength. Hence, carefully selecting the lamp model for poultry houses is essential. Each lamp type has a distinct spectral profile, which can impact egg production and quality.

2.3.1 Light sources

Both photoperiod and light intensity directly influence egg production, making the management of these parameters crucial for the productive performance of poultry flocks (Borille *et al.*, 2013). Thus, lighting programs should integrate the management of laying hens, considering the light spectrum emitted by each lamp type to achieve satisfactory productive efficiency levels.

Incandescent lamps were the standard light sources used in poultry houses for decades. This type of lamp operates by passing an electric current through a thin tungsten filament to generate light.

Incandescent lamps have the advantages of providing uniform illumination and allowing the light output to be dimmed between 0% and 100% using a dimmer controller. This flexibility enables adjusting light intensity to meet the specific needs of each stage in the birds' lives. However, lamp efficiency balances illumination, effectiveness, and longevity. In this regard, incandescent lamps perform poorly since, despite their low initial cost, they require frequent replacement due to their short useful life (Benson *et al.*, 2013).

Moreover, the air temperature in housing environments is one of the most important bird comfort and performance variables, directly influencing physiological responses. In this context, incandescent lamps, which generate heat from the filament, significantly impact the thermal conditions of the rearing environment. The environmental impact of incandescent sources was demonstrated by Lima *et al.* (2014), who observed higher air and litter temperatures in poultry houses equipped with incandescent lamps compared to sodium vapor and fluorescent sources.

In turn, fluorescent lamps emit light through an electric current that ionizes the gas inside them. These characteristics can limit the applicability of such lamps in productive environments. According to Benson *et al.* (2013), energy control supplied to fluorescent lamps via dimmers is not complete, with minimum adjustments ranging from 8% to 20% of total illumination capacity. However, new electronic ballast technologies allow dimming ranges from 1% to 100% of light output.

Although fluorescent lamps are more efficient as they do not generate heat, their spectrum is not constant, and birds can perceive these light oscillations. Additionally, their luminous intensity diminishes over time, requiring regular replacement (Mendes *et al.*, 2010) or frequent verification of light intensity adjustments in the lighting program.

In view of the above, fluorescent lamps have gradually been replaced by light-emitting diode (LED) lamps. These lamps, made of semiconductor materials, emit light when subjected to a specific voltage. Furthermore, as they are composed of solid materials (semiconductors), LEDs do not contain gases potentially harmful to health or the environment, as is the case with fluorescent lamps.

Regarding the wavelengths emitted by LEDs, these vary according to the semiconductor material used (Rosa *et al.*, 2017). Additionally, LEDs can be produced to emit any monochromatic color and polychromatic temperatures, allowing the lighting program to be adapted according to the birds' preferences (Janczak; Riber, 2015). In this context, LEDs have superior luminous distribution compared to other light sources (Araújo *et al.*, 2015) and offer full dimming capability, providing greater flexibility in lighting management. However, factors such as light intensity and color influence bird activity, potentially affecting egg quality positively or negatively (Parvin *et al.*, 2014; Tsuitsui *et al.*, 2012).

2.3.1.1 Influence of light-emitting diode (LED) lamps on behavior, production, and egg quality

Egg production and quality are influenced by the visible spectrum emitted by light sources, with certain colors being more stimulating than others depending on their wavelength/color (Figure 1) and the bird's spectral sensitivity (Figure 2). Combining monochromatic LED intensities makes it possible to cover the entire range of colors in the visible spectrum (Nunes *et al.*, 2013), including white light, which results from the combination of primary colors.

In this context, Mendes *et al.* (2013) evaluated the light preference of broiler chickens exposed to white and yellow LEDs. They observed that the birds did not exhibit any behavioral preference, occupying both environments uniformly. This finding aligns with Silva, Tavares, and Pereira (2012), who also found no preference among laying hens for environments illuminated by blue, red, green, and white LEDs. However, the same authors observed the birds' behavior (eating, drinking, nesting/perching, and inactivity) and noted that light color influenced only eating behavior, with birds eating more under green light compared to blue light.

Regarding animal performance following replacing conventional artificial lighting sources with LEDs, Seber *et al.* (2018) found no differences in the productive responses of broiler chickens in environments illuminated by incandescent lamps and LEDs. Similarly, Jácome *et al*. (2012) subjected quails to 15W incandescent lamps and LEDs (blue, orange, and white) and found no significant differences in average egg weight, shell weight, or shell thickness. These results align with those reported by Borille *et al*. (2013, 2015), who found that the weight and internal quality indices of laying hen eggs were not affected by replacing incandescent lamps with LEDs, regardless of color (blue, yellow, green, red, or white). On the other hand, Mendes *et al*. (2013) reported improved production performance in broiler chickens reared under LED lighting compared to compact fluorescent lamps (CFLs).

Baxter *et al*. (2014) argue that red light is essential for adequately initiating the reproductive phase in hens, enhancing ovarian activity, maintaining high production levels, and increasing the total number of eggs. The same authors noted that hens exposed to red and white LEDs produced more eggs than those under green LEDs. These findings are supported by Hassan *et al*. (2013), who observed that hens exposed to blue LEDs experienced a 15-day delay in sexual maturity compared to layers exposed to red light. Moreover, the study found that hens under red light exhibited higher laying rates and better feed conversion compared to those exposed to green, blue, or fluorescent light.

Thus, LEDs can replace incandescent and fluorescent lamps without negatively affecting egg production and quality while offering potential for production improvements. Furthermore, in studies focusing on light colors, white light has demonstrated equally satisfactory results compared to the colors yielding the best outcomes.

2.3.1.2 Energy consumption and useful life

Light stimulation plays a crucial role in poultry behavior and productivity. Thus, optimizing and managing light programs is essential for ensuring animal well-being, alongside selecting efficient light sources. This choice is important because electricity costs directly influence egg production costs, which are ultimately passed on to the consumer.

Initially, lighting systems in poultry houses relied on incandescent bulbs. However, in Brazil, Law No. 12,350/2010 (Brasil, 2010) gradually banned these bulbs between 2012 and 2016 due to their low energy efficiency, leading to waste. Even before the ban, fluorescent lamps began to replace incandescent lamps due to their higher efficiency.

Currently, commercial poultry houses employ devices designed to adjust environmental parameters, including thermal conditions, air renewal, and lighting, to meet animal needs. These systems include misting devices, evaporative cooling pads, fans, and exhaust units, varying according to the rearing system. Among the main cost inputs in poultry production, energy ranks second in consumption, behind feed (Pereira *et al*., 2012). This high energy demand arises from the extensive number of lamps required to achieve the necessary illuminance levels and stimulate the birds' metabolism.

According to Borille *et al*. (2013), sodium lamps can reduce energy costs by 70% compared to incandescents. However, Pereira *et al*. (2012) evaluated the energy efficiency of various lamps at different intensity levels in broiler houses. Their study revealed that replacing 100 W incandescent bulbs with 28 W tubular fluorescent T5 lamps reduced energy demand by 90.62% when the illuminance level was set at 5 lux. The same study noted that replacing incandescents with compact fluorescent lamps (CFLs) resulted in up to 81.4% energy savings, regardless of whether the environment was illuminated at 5 or 20 lux.

Regarding the transition from incandescent to LED lighting, Rovaris *et al*. (2016) quantified energy consumption and assessed the economic feasibility of LED usage in dark house poultry systems. Their findings indicated that, over the production cycle, incandescent lamps (60W) consumed 1768 kWh, while LEDs (5W) consumed only 221 kWh, representing an 87.5% energy savings. Additionally, the return on investment was achieved within 21 months. Rosa *et al*. (2017) compared LEDs (5W) with fluorescent (25W) lamps in dark house systems and reported monthly energy savings of 59% and 85% relative to dimmable and non-dimmable fluorescent lamps, respectively. These results align with those of Gongruttananun and Guntapa (2012), who concluded that LED systems reduce production costs in laying hens.

Regarding lamp durability, Benson *et al*. (2013) conducted tests over 416 days, performing 6656 on-off cycles and totaling 4492 hours of use for incandescent, fluorescent, and LED lamps. Their results showed that incandescent bulbs failed after an average of 1968 hours, CFLs lasted 3986 hours on average, while LED lamps experienced no failures during the test period.

Thus, in addition to reducing energy consumption, LED lamps minimize environmental impacts, as their lower replacement frequency generates less waste than other lamp types.

Energy-efficient lighting systems, such as LEDs, combined with advanced environmental monitoring and control technologies, offer a viable solution for reducing costs in the poultry sector. These savings can either be passed on to consumers as competitive discounts or used to increase producers' profit margins.

In this way, to reduce production costs without compromising performance indices, it is essential to explore alternatives to traditional lighting sources and assess the cost-benefit ratio of their implementation. This analysis should consider not only the initial acquisition cost but also the birds' productive and physiological responses.

Furthermore, well-being represents the state in which birds experience harmony with their environment, reflecting optimal physical and mental health (Camerini *et al.*, 2016) and resulting in maximum productivity. Environmental inadequacies compromise the birds' genetic potential, leading to suboptimal physiological and productive responses, indicating a well-being imbalance. Among the main physiological indicators are cloacal and surface temperatures, which vary in response to changes in dry-bulb air temperature, relative humidity, and luminosity (solar radiation) (Costa; Saraiva; Santos, 2012; Ferreira *et al.*, 2012), signaling environmental disharmony and decreased productive responses.

2.4 Evaluation of laying hen performance

Research in genetic improvement has enabled the development of more efficient laying hens characterized by lower body weight and reduced feed intake (Ferreira *et al.*, 2014; Gewehr *et al.*, 2012). These traits promote better feed conversion rates, which in turn contribute to the industry's economic viability.

Typically, the most relevant trait for selecting laying hens is egg production throughout the cycle, a quantitative characteristic influenced by environmental factors (Michelotti, 2018). Depending on the strain, nutrition, and an adequate lighting program, a hen can produce approximately 420 eggs with an average weight of 61 g by 90 weeks of age (Hy-Line, 2019).

The environment of intensive laying hen production systems directly influences animal well-being. In order to ensure consistent production, it is essential to monitor and control the aviary's bioclimatic variables (Oliveira *et al.*, 2014). For instance, poor lighting conditions can disrupt other production variables affecting economic viability, such as feed intake, feed conversion, laying percentage, internal and external egg quality, egg mass, and others. Some productivity indicators are described below, along with their respective equations:

a) Mean feed intake (FI):

FI (Equation 1) represents the average feed consumed per hen over a specified period, generally expressed in days, weeks, or 28-day cycles.

$$\mathrm{FI} = \frac{\text{feed intake}}{\text{number of hens x number of days}} \tag{1}$$

b) Feed conversion (FC):

FC measures the efficiency of production animals. For laying hens, FC indicates the amount of feed required to produce a specific quantity of eggs, expressed either in dozens (kg · doz.$^{-1}$) or mass (kg feed · kg eggs^{-1}), as shown in Equations 2 and 3, respectively.

$$FC_{doz} = \frac{\text{FI}}{\text{dozens of eggs}} \tag{2}$$

$$FC_{mass} = \frac{\text{FI}}{\text{mean egg mass}} \tag{3}$$

c) Laying percentage (LP):

LP measures the ratio between the number of eggs produced and the number of hens in a given period. It is typically expressed as a daily percentage per hen, according to Equation 4 (Vieira Filho *et al.*, 2016). LP values of 100% indicate that each hen in the flock produced, on average, one egg per day. Values below 100% suggest that, on average, not all hens lay an egg daily, allowing the determination of the average time required for egg production.

$$\text{LP (\%)} = \frac{\text{number of eggs}}{\text{number of hens x number of days}} \text{ x } 100 \tag{4}$$

d) Percentage of viable eggs (PVE):

PVE considers only marketable eggs, excluding broken, cracked, shell-less, or soft-shell eggs. It is calculated using Equation 5, as cited by Costa *et al.* (2008). Since PVE relates to the physical characteristics of eggs, it is often used as a quality parameter. However, as viable eggs constitute the final production, PVE also serves as a productivity indicator.

$$\text{PVE} = \frac{\text{LP (\%) x number of viable eggs}}{\text{total number of eggs produced}} \tag{5}$$

Monitoring these zootechnical indicators enables the assessment of production gains and losses and the identification of correlations with environmental variables and signs of thermal stress (Loureçoni, 2017). In order to conduct an accurate productivity analysis, these indices should be compared to reference values outlined in rearing manuals. However, each strain has distinct parameters, as the productive potential is directly linked to the hens' genetic characteristics.

In this context, genetic advancements have enhanced the productive performance of hens, making industrial poultry farming more sustainable in both environmental and economic terms.

Several laying hen strains, whether purebred or hybrids, are used for egg production in Brazil, including Hisex (white and brown), Lohmann (white and brown), Isa (white and brown), Hy-Line (white and brown), Shaver (white and brown), H&N Nick Chick (white and brown), Tetra, and Harco, among others. Therefore, genetic selection is fundamental for enterprises to optimize productivity indices and achieve higher profitability (Figueiredo *et al*., 2003).

Rech *et al*. (2010) observed highly significant differences ($p < 0.01$; F-test) in productivity indicators such as egg production, egg mass, and mortality when comparing two strains reared under the same environmental conditions. This finding underscores the genetic influence on production levels. Similarly, Ferreira *et al*. (2014) identified differences in feed intake, feed conversion, laying rate, and egg mass among different strains subjected to the same management conditions.

These variations in productivity indicators suggest that different strains have specific nutritional, thermal, and lighting requirements in the rearing environment. Similarly, egg quality also varies based on factors such as the hen's health and age, diet quality and safety, and microclimatic variables of the rearing environment (Mazzuco; Bertechini, 2014). The photoperiod, in particular, can accelerate the onset of production, increase laying rates, and optimize feed efficiency.

2.5 Egg quality

Marketable eggs' quality is determined by internal and external characteristics directly influencing their market acceptance. Thus, programs ensuring egg quality standards must be implemented to meet the demands of both domestic and international markets (Stefanello, 2011). However, producers and consumers assess egg quality differently. For consumers, attributes such as size, shell appearance, yolk color, albumen consistency, and shelf life are more relevant. For producers, egg size and shell strength are the most important variables.

Eggs can be considered naturally packaged foods due to the presence of the shell, which protects against physical impacts, acts as a barrier against harmful organisms, and controls the exchange of water and gases through its pores (Barbosa *et al*., 2012). Thus, cracks in eggs intended for consumption indicate a loss of quality due to the risk of food contamination. Moreover, in hatching eggs, the shell serves as a calcium source for the embryo during development and protects it until hatching (Carvalho; Fernandes, 2013).

According to Mazzuco and Bertechini (2014), eggs with pathologies also cause economic losses to the industry, whether through disposal or additional processing needs, increasing costs.

Producing eggs with proper formation and quality depends on multiple factors. Thus, understanding aspects such as genetics, bird age, nutrition, management, and environmental variables is fundamental to the economic performance of the activity. Among the environmental variables, lighting affects egg quality based on its intensity or color (Pereira; Tavares; Mac-Lean, 2017), even altering the shell color (Navarro; Lahti, 2014). Additionally, prolonged lighting periods combined with excessive artificial light during the night may increase the occurrence of cracked eggs in the oviduct (Carvalho; Fernandes, 2013). In this context, Pereira, Tavares, and Mac-Lean (2017) concluded that the light spectrum emitted by lamps affects egg shape. They found that eggs were more elongated in environments equipped with sodium vapor lamps compared to those illuminated by incandescent or fluorescent lamps. Consequently, quality was also affected beyond the shape, as the format influences the eggs' longitudinal and transversal strength.

In this context, to assess egg quality, the following indicators are used:

a) Total egg weight (W):

According to Oliveira and Oliveira (2013), eggs are classified based on their W values as follows: jumbo (≥ 65 g), extra-large (60–64 g), large (55–59 g), medium (50–54 g), small (45–49 g), and industrial (< 45 g).

b) Percentages of yolk, albumen, and shell:

These parameters are determined as the ratio between the mass of each component and the total egg mass. Under ideal conditions, the standards range from 8.5% to 10.5% for the shell, 57% to 65% for albumen, and 23% to 33% for the yolk (Cotta, 2014; Oliveira; Oliveira, 2013). In a study by Carvalho *et al.* (2007), eggs from different laying hen strains (Babcock B 300, Hy-line W-36, Lohmann White and Hisex) showed average results of 13.2%, 62.1%, and 24.7%, respectively, for the shell, albumen, and yolk at 29 weeks of age.

c) Eggshell thickness:

It can be obtained by averaging measurements taken at the apical region (narrow end), equatorial region, and basal region (widened end containing the air cell) (Barbosa *et al.*, 2012; Vilela *et al.*, 2016).

According to Oliveira *et al.* (2017), state eggshell thickness ranges from 0.28 to 0.35 mm. These values align with the analysis conducted by Alves, Silva, and Piedade (2007), who reported a thickness of 0.34 mm in eggs from Hy-line W36 hens at 29 weeks of age. However, in addition to housing microclimate variables, factors such as age and strain also influence shell parameters due to differences in calcium metabolism.

Furthermore, Oliveira *et al.* (2014) determined that the standard shell thickness for the Dekalb White strain is between 0.41 and 0.50 mm, with a mean result of 0.45 mm at 27 weeks of age. Nonetheless, Vilela *et al.* (2016) found a thickness of 0.334 mm for the same strain when analyzed at 30 weeks of age. Such discrepancies may arise from differences in management practices and data collection methods, as thickness readings were taken in different shell zones.

d) Eggshell density:

This variable is a quality control parameter for the shell, as density is directly related to thickness, porosity, and strength. According to Nasr *et al.* (2016, 2019), shell density ($mg \cdot cm^{-2}$) can be estimated as the ratio between shell mass (mg) and egg surface area (cm^2). The egg surface area (AS) is determined using Equation 6 (Sezer, 2007).

$$AS = 3{,}9782 \cdot W^{0{,}7056} \tag{6}$$

e) Specific gravity:

Analogous to shell density, variations in specific gravity (SG) are directly related to shell quality (Rosseto *et al.*, 2019), as egg density increases or decreases according to shell density. In this regard, denser shells have greater strength and fewer pores. Furthermore, SG also correlates with internal quality, as fresher eggs (with a longer shelf life) have denser albumen and yolks.

One method to estimate SG is through Archimedes' principle, which is characterized as an adaptation of the method described by Hempe, Lauxen, and Savage (1988), as shown in Equation 7.

$$SG = \frac{W}{W_{(\text{immersed in water})} \cdot D} \quad (7)$$

where,

$W_{(\text{immersed in water})}$: total egg weight (g) measured when immersed in water;

D: is the water temperature correction which, according to Kell (1975), can be estimated by Equation 8.

$$D = \frac{\left(\begin{array}{c} 0.9998676 + 17.801161 \cdot 10^{-3} \cdot t_w - 7.942501 \cdot 10^{-6} \cdot t_w^2 - \\ 52.56328 \cdot 10^{-9} \cdot t_w^3 + 137.6891 \cdot 10^{-12} \cdot t_w^4 - 364.4647 \cdot 10^{-15} \cdot t_w^5 \end{array}\right)}{1 + 17.735441 \cdot 10^{-3} \cdot t_w} \quad (8)$$

where,

t_w: water temperature (ºC).

According to Oliveira and Oliveira (2013), regular eggs have a density of 1.080 to 1.084 $g \cdot cm^{-3}$, with higher or lower values indicating superior or inferior eggshell quality, respectively, and may range from 1.057 to 1.091 $g \cdot cm^{-3}$, as reported by Cotta (2014).

f) Haugh unit (HU):

The HU evaluates internal egg quality compared to the albumen, correlating egg weight and the height of the thick albumen (Equation 9) (Eisen; Bohren; Mckean, 1962):

$$HU = 100 \cdot \log (H + 7{,}57 - 1{,}7 \cdot W^{0{,}37}) \quad (9)$$

where,

H = height of the thick albumen (mm).

The HU is a dimensionless measurement, where higher values indicate better egg quality. According to the egg classification manual (USDA, 2000), eggs are classified as AA – excellent quality (HU ≥ 72), A – good quality (60 ≤ HU ≤ 71), and B – medium/low quality (HU ≤ 59). HU values vary depending on storage temperature, storage duration, and the hen's age. Under ideal conditions, for hens aged 27 ± 1 weeks, HU ranges from 89.5 to 92.3 (Cotta, 2014; Hy-Line, 2019).

Additionally, based on Equation 9, it can be stated that when comparing two eggs of the same weight, the one with a higher albumen height will exhibit better internal quality. Conversely, when comparing two eggs with the same albumen height, the one with the lower weight will exhibit better internal quality.

g) Yolk index (YI):

The YI assesses yolk quality based on consistency and is calculated using Equation 10. Higher YI values indicate better quality, as extended storage periods weaken the yolk membrane, reducing YI. Fresh eggs typically have YI values between 0.4 and 0.5 (Jucá *et al.*, 2011).

$$\mathrm{YI} = \frac{\text{yolk hight}}{\text{yolk diameter}} \qquad (10)$$

2.6 Modeling in applied research

Due to the complexity of laying hens as biological systems, their behavioral, physiological, and productive responses dynamically interact with variations in the rearing environment. Therefore, it is essential to develop systems and models that support decision-making for poultry farmers. These systems should optimize production management, improve husbandry practices, reduce cost, and ensure the rearing environment aligns with animal welfare principles.

Modeling refers to the simplified representation of real systems through mathematical, statistical, or computational methods. These models are designed to understand and predict the behavior of complex systems. Simulations provide a comprehensive understanding of real systems, especially when empirical data are limited (Levrault *et al.*, 2025), facilitating insights and enabling behavior prediction.

In this context, modeling improves predictability in dynamic systems and reduces uncertainties (Satpathi *et al.*, 2025). However, simplistic models may have limitations in capturing complex interactions that affect performance, resulting in less accurate predictions. Furthermore, despite its advancements, modeling has limitations, such as dependence on data quality and the risk of overfitting. Models trained with limited datasets may exhibit low generalization capacity for new scenarios (Satpathi *et al.*, 2025). Additionally, Hossein-Zadeh (2024) highlight the challenges associated with parameter adjustment in complex models, particularly in systems with high biological variability. Thus, it is possible to optimize environmental control systems and management practices by integrating expert knowledge with artificial intelligence-based methodologies.

Various artificial intelligence techniques have emerged as promising tools for addressing complex and nonlinear models. Fuzzy inference systems stand out among the approaches supporting rearing environment analysis as a decision-making aid for producers (Vargas-Rodriguez *et al*., 2022). Fuzzy logic is particularly effective in problems characterized by uncertainties, where defining a solution or mathematical model is challenging. It allows for the modeling of subjectivity through expert input (Vásquez *et al*., 2019).

Consequently, fuzzy logic has been employed to predict productive and physiological responses (Amaral *et al*., 2024; Lins *et al*., 2021; Maziero *et al*., 2022). Notably, according to Averós *et al*. (2013) and Marcone *et al*. (2022), achieving optimal animal welfare conditions is possible when animal responses are integrated with rearing environment variables. Therefore, these predictive models can be implemented in controllers to ensure efficient production and animal welfare, functioning as decision support systems (Amaral *et al*., 2023; Suseendran; Balaganesh, 2021).

3 CONSIDERATIONS

Replacing traditional lighting sources (incandescent and fluorescent lamps) with LEDs has proven to be a promising solution. LEDs can be produced to emit light at different wavelengths, enabling management practices to cater to laying hens' behavioral and reproductive preferences. Studies show that LEDs can maintain productivity or even bring benefits, both with monochromatic lights and white light.

Furthermore, this lighting technology not only promotes zootechnical gains but also contributes to environmental and economic sustainability. With greater energy efficiency, lower pollutant potential, and extended durability, LEDs reduce energy consumption and electronic waste generation, establishing themselves as a sustainable alternative for the poultry industry.

The findings discussed in this review highlight the importance of lighting in managing laying hens. Light regulates hormonal, metabolic, and behavioral aspects, directly influencing physiological responses, productivity, egg quality, and the well-being of laying hens. Therefore, efficiently managing artificial lighting in poultry farming is essential, considering that factors such as photoperiod, light intensity, and light spectrum interact intricately with the birds' biological systems.

Among the various challenges in animal housing, the impact of the lighting environment stands out. Advances in photoperiod management and using white light associated with new LED technologies are well-documented in the literature. However, gaps remain regarding the effects of different illuminance levels provided to the birds. Thus, further investigations are needed to refine management practices in lighting intensity, focusing on animal well-being during the production phase. In this regard, modeling techniques, especially those that integrate expert knowledge with artificial intelligence-based methodologies, can support advancements in poultry management.

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SECOND PART – ARTICLES

ARTICLE 1 - EVALUATION OF DIFFERENT LIGHT INTENSITIES ON THE WELL-BEING, PRODUCTIVITY, AND EGGS QUALITY OF LAYING HENS

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Highlights

- Light intensities between 5 and 100 lx were not harmful to laying hens;
- Environments with illuminance of 5 lx are sufficient for the correct handling of hens;
- Egg quality is not affected by light intensity in the rearing environment;
- Illumination exposure time influences some responses of hens;
- An acclimatization period of 28 days is recommended for light related studies in laying hens.

EVALUATION OF DIFFERENT LIGHT INTENSITIES ON THE WELL-BEING, PRODUCTIVITY, AND EGGS QUALITY OF LAYING HENS

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Abstract: Light sources and light intensity are factors that can elicit different responses in laying hens. Investigations carried out on this subject show divergent results or are scarce, particularly for light emitting diode (LED) sources and for more recent strains. Therefore, the goal of the present study was to evaluate the effects of different illuminances (5, 20, 50 and 100 lux), from linear LED lighting on the physiological responses, productive performance and egg quality of 25–36-week-old Hy-line W-80 laying hens. The experiment was conducted in climate-controlled wind tunnels and the birds were divided into three experimental flocks, each lasting 28 days. Initially, the birds underwent seven days of acclimatization, and the evaluations of all parameters were performed on Days 10, 14, 17, 21, 24 and 28 of each flock. The results demonstrated that the tested illuminances did not influence the responses of the birds and the quality of the eggs when their effect was evaluated separately ($p>0.05$, F test). However, the illuminance exposure time influenced cloacal and surface temperatures, feed intake, body mass and albumen percentage. Therefore, an acclimatization period of 28 days is recommended for Hy-line W-80 laying hens at the peak laying period. The illuminances of 5, 20, 50 and 100 lux were not harmful for the laying hens, since the changes in the physiological responses remained within the thresholds recommended as comfort. Thus, environments with 5 lux were sufficient to guarantee access to feeders and drinkers by the birds and avoid discomfort and production and egg quality losses.

Keywords: Illuminance, hen performance, light emitting diode (LED), egg quality, physiological responses.

1 Introduction

Eggs are increasingly consumed by humans because they are one of the main natural sources of essential nutrients such as antioxidants, proteins, minerals, and various vitamins. Among the raised laying species, hens are the most used and are ubiquitous worldwide. Thus, animal welfare is one of the greatest challenges for poultry production because chickens are commonly reared in intensive systems.

Among the various variables related to the breeding environment, light exerts stimuli that affect the growth, reproduction, behaviors, productivity, egg quality, physiological processes, and immunological health of chickens (Erensoy *et al*., 2021; Kim *et al*., 2021). Thus, light is a key factor affecting the ability to achieve the maximum genetic potential of a bird (Soliman and El-Sabrout, 2020). In terms of light, the influence of illumination varies according to the source, photoperiod (duration), wavelength (color/color temperature), uniformity of distribution, and illuminance (brightness/intensity) (Barros *et al*., 2020a; England and Ruhnke, 2020; Oso *et al*., 2022)

Therefore, the performance of laying hens is highly dependent on the lighting settings used during housing. In poultry houses, the light intensity is adjusted to provide maximum egg production with minimal energy costs (Shi *et al*., 2021). However, it is necessary to understand the spectral sensitivity of birds so that lighting adjustments meet the biological or physiological needs of the birds rather than the adjustments being based on human perception (Ma *et al*., 2016; Li *et al*., 2019). While humans have 3 cones (a type of photoreceptor cell that allows us to recognize colors) in their retinas, birds have 4, allowing the detection of ultraviolet radiation. The peak spectral sensitivity of birds occurs, similar to humans, between 545 and 575 nm (Pescott and Wathes, 1999), however, the spectral sensitivity of birds between 400 and 480 nm and between 580 and 700 nm is greater than that of humans. In this way, birds perceive light brighter than humans, but the degree of extra brightness varies according to the type of lamp (Lewis and Morris, 2006). It is noteworthy that the perception of light by birds at illuminances greater than 4 lux also occurs transcranially (Morgan *et al*., 1995), stimulating specific photoreceptors of the hypothalamus.

Thus, by providing illuminance specifically adapted to bird vision, the social interactions of the animals and their ability to locate feeders and drinkers can be improved, and consequently, the welfare, efficiency, and quality of production can be improved as well (Purswell *et al*., 2018; Olanrewaju *et al*., 2019).

To achieve these goals, poultry producers have adopted recent technologies such as light emitting diode (LED) sources (Liu *et al*., 2018, Li *et al*., 2019), which in addition to meeting the physiological demands of birds, reduce energy consumption. Notably, among the production costs of producing eggs from laying hens, the lighting system cost constitutes the second or third highest cost after the cost of feed and/or climatization of the poultry house (Pereira *et al*., 2012; Ribeiro *et al*., 2016).

In addition, LED lighting allows the use of small elements that can be placed in cages, providing greater uniformity than the bulbs usually employed. Relatedly, Barros *et al*. (2020a, 2020b) found that linear LED lighting inserted in cages led to better bird performance because it provided better light distribution, in addition to energy consumption savings and decreased heat dissipation into the environment. However, few studies have investigated the implications of the variation in illuminance for bird well-being.

Ma *et al*. (2016) investigated the behavior of Hy-Line W-36 hens in response to a fluorescent light source with illuminances of less than 1, 5, 15, 30, and 100 lux. However, the authors investigated only the preference for occupying an environment with different levels of illuminance and did not evaluate egg quality. In turn, Erensoy *et al*. (2021) subjected Lohmann-Brown laying hens to 12, 57, and 122 lux from a fluorescent source and verified egg performance and quality. However, bird physiological characteristics are also affected by light intensity (Erensoy *et al*., 2021), and neither Ma *et al*. (2016) nor Erensoy *et al*. (2021) evaluated the physiological responses of birds in their studies. In addition, the responses to light stimuli do not change only according to light parameters but also according to hen strain (England and Ruhnke, 2020; Chew *et al*., 2021) and age.

Thus, for recently developed genetic varieties, such as Hy-Line W-80, scientific studies on the effect of illuminance on bird performance, especially with the use of LED technology, are scarce or insufficient. In addition, there are divergences among the research results, indicating the need for further investigation. Notably, studies of this nature will assist in supporting decisions to implement lighting systems for poultry houses that address bird welfare, in addition to egg production efficiency and quality.

Thus, the objective of this study was to determine the effects of different illuminance levels of linear LED lighting on laying hen physiological responses, productive performance, and egg quality in the peak laying period.

2 Material and methods

A total of 72 Hy-Line W-80 laying hens ranging in age from 26 to 36 weeks, divided into three flocks of 24 birds, were subjected to four levels of illuminance in a thermoneutral environment to quantify the illuminance effect on the bird physiological and productive responses and egg quality.

Furthermore, this study was conducted after approval by the Animal Ethics Committee of Federal University of Lavras under protocol no. 079/2017.

2.1 Experimental installation, instrumentation, and control

The experiment was conducted in four climate-controlled wind tunnels. A cage was placed inside each tunnel (62 x 52 x 40 cm in length, width and height, respectively), in which 6 birds were housed at 537 cm^2 $bird^{-1}$. This adopted housing density is consistent with that recommended by the strain’s manual (Hy-Line, 2019), whose minimum value is 490 cm^2 $bird^{-1}$.

The thermal environment inside each climate-controlled wind tunnel was controlled by two heaters and two air humidifiers, with the aid of a datalogger (CR1000, Campbell Scientific), a relay controller (SDM-CD16AC, Campbell Scientific), a channel multiplexer (AM16/32B, Campbell Scientific), and temperature (t_{air}), and air relative humidity (RH) sensors (HMP45c, Vaisala, accuracy of ± 0,3ºC for t_{air} and ± 2% for RH), which performed readings every 10 seconds. The air velocity in the bird occupation zone in each climate-controlled wind tunnel was maintained by controlling the exhaust fans via a potentiometer and measured using a hot wire anemometer (Extech, 407123, ± 3% + 0,1 m s^{-1}).

Regarding illuminance, a set of linear white LEDs (Chew *et al*., 2021; Sadvakassova *et al*., 2022) illuminated the interior of each cage. The power of the LED lamps was controlled by a dimmer to provide the desired illuminance at the bird's eye level. Luminescent LEDs were used to promote broad-spectrum white light, aiming to obtain stimuli at all peaks of the birds' sensitivity to visible light (between 470 and 490nm, 555 and 580nm, and 620 and 640nm). Furthermore, the materials used in luminescent LEDs have properties to maintain a relatively stable spectral distribution, regardless of the adjusted light intensity (5, 20, 50 or 100 lux).

A programmable timer relay module (COEL, model RTST-20) was used to turn the lamps on and off according to the lighting program adopted. The illuminances were adjusted with the aid of a digital lux meter (SKLD-400, SKILL-TEC, accuracy of ± 3%) and checked weekly at nine points homogeneously distributed along a horizontal plane elevated at 32 cm above the cage floor (bird’s eye level). To obtain uniformity in the adjusted illuminances, the lighting system was distributed over the top of the cage. The Fig. 1 illustrates the wind tunnel.

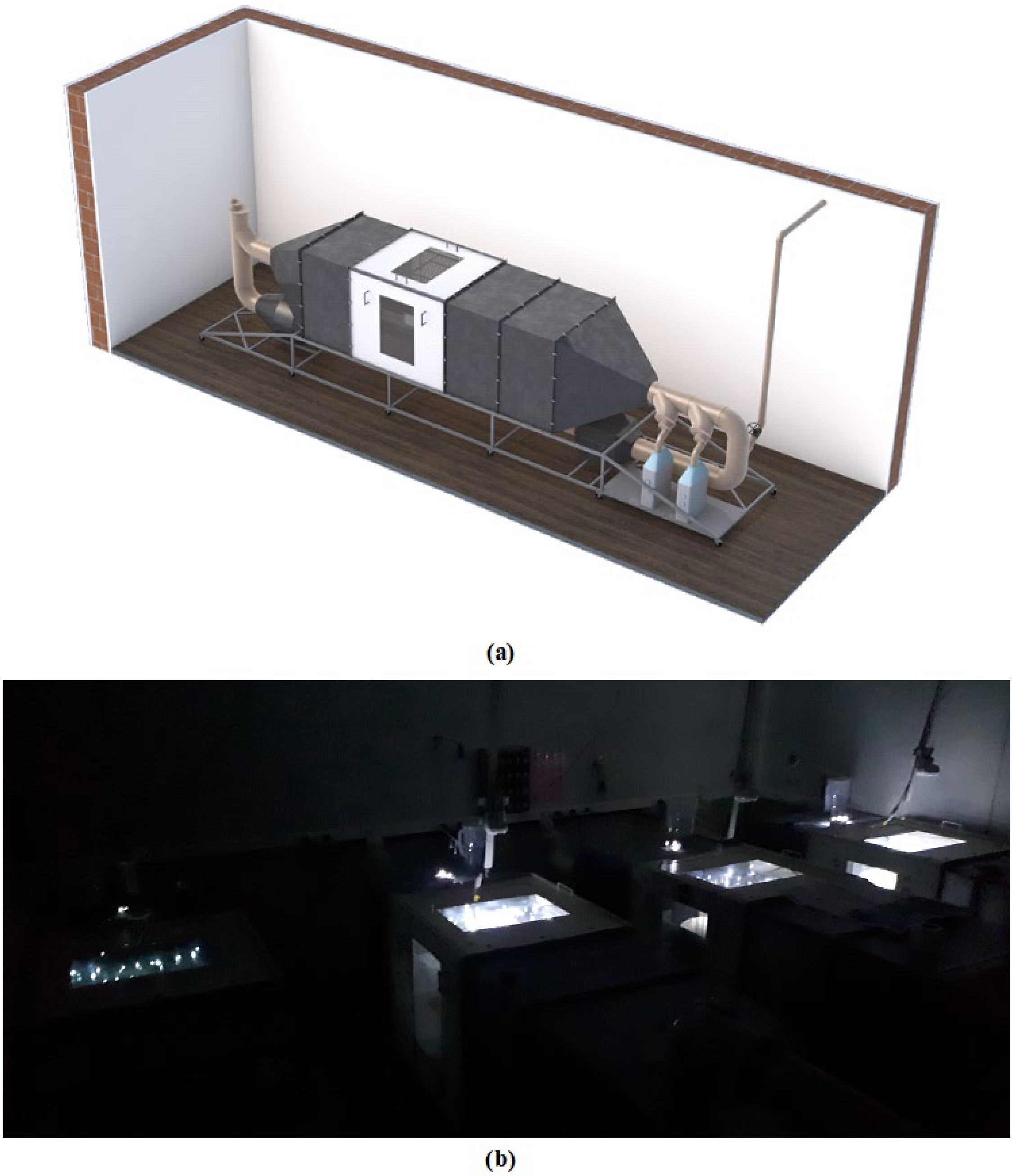

Fig 1. (a) 3D illustration of the wind tunnel in perspective, and (b) picture of experimental room with the four wind tunnels during the experimental period (illuminance levels, from left to right: 5, 50, 20 and 100 lux).

2.2. Bird management

The 72 hens were transferred to the experimental facility in three flocks of 24 birds each, and 6 birds were randomly housed in each of the four climate-controlled wind tunnels. Each flock was housed for 28 days; thus, the age range of the birds in each flock was 25 to 28, 29 to 32, and 33 to 36 weeks.

For each flock of birds, the first 7 days were used as the acclimation period (Qu *et al.*, 2018). The conditions during this period were similar to those of the experimental phase, in which the birds were subjected to illuminations of 5, 20, 50, or 100 lux in each climate-controlled wind tunnel. Therefore, the experiment was conducted in three periods of 28 days (three blocks), with birds from 25 to 36 weeks of age, and in each flock, the four treatments (5, 20, 50, and 100 lux) were randomly allocated to the four tunnels. In addition, animal response evaluations (Sections 2.3 to 2.5) were performed twice a week, thus consisting of six exposures to illumination in each flock (Days 10, 14, 17, 21, 24, and 28). Fig. 2 illustrates the schedule and division of the experimental flocks. It should be noted that the light inputs into the experimental room were properly obstructed, thus, the illuminance observed in the environment around each wind tunnel was ≤ 1 lux.

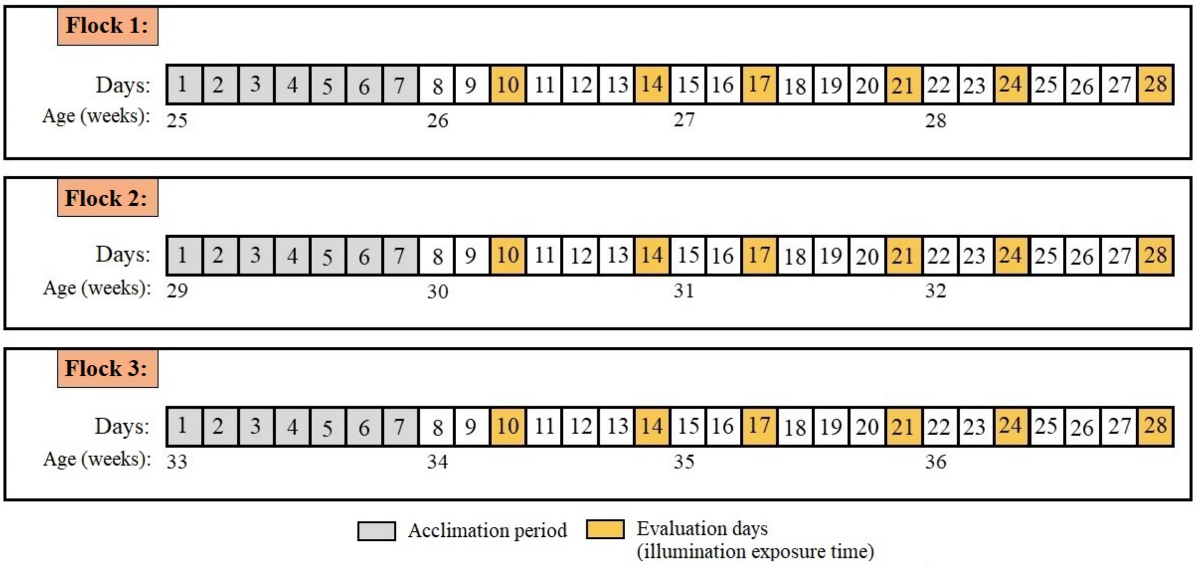

Fig 2. Representation of the experimental schedule performed for all treatments (5, 20, 50 and 100 lux) for each flock of hens.

Throughout the 28 days, the birds were kept under thermoneutral conditions, characterized by a temperature and RH of 23°C and 60%, respectively (Ribeiro *et al.*, 2020). To promote sanitary ventilation conditions, the air inside each tunnel was renewed, and the air velocity was fixed at 0.2 ms^{-1} (Abreu *et al.*, 2017; Bahuti *et al.*, 2018).

Water and feed were offered to the birds *ad libitum*. Feed was provided once a day and balanced according to the recommendations of the strain's manual (Hy-Line, 2019) and diet composition in Rostagno *et al.* (2017) (Table 1). In addition, the tunnels were cleaned daily to mitigate the formation of gases. The lighting program established was 16 h of light and 8 h of dark (Hy-Line, 2019; Ribeiro *et al.*, 2020) throughout the experimental period.

Table 1. Percentage of ingredients and calculated composition of the diet supplied to laying hens throughout the experimental phase.

Ingredient	**Composition (%)**
Ground corn	59.79
Soybean meal	25.72
Soybean oil	2.36
Dicalcium phosphate	1.87
Calcitic limestone[1]	9.20
Common salt	0.29
Micromineral premix[2]	0.05
Vitamin premix[3]	0.10
DL-methionine (99%)	0.21
Choline chloride (70%)	0.10
Sodium bicarbonate	0.20
Mycotoxin adsorbent	0.10
Phytase	0.005
Total	100
Calculated composition:	
Metabolizable energy (kcal/kg)	2850
Crude protein (%)	16.50
Calcium (%)	4.00
Phosphorus availability (%)	0.45
Sodium (%)	0.18
Methionine + Cysteine, digestible (%)	0.67
Lysine, digestible (%)	0.77
Threonine, digestible (%)	0.57
Tryptophan, digestible (%)	0.18

[1] Used ½ in powder and ½ in granulated form.

[2] Product composition (kg): copper – 20 g; iron – 100 g; iodine – 2.4 g; manganese – 160g; selenium – 0.56g; zinc – 120g.

[3] Product composition (kg): vit. A – 8,100,000 IU; vit. D3 – 2,500,00 IU; vit. E – 7,000 IU; vit. K3 – 2g; vit. B1 – 1g; vit. B2 – 3.5g; vit. B6 – 1g; vit. B12 – 10mg; niacin – 21g; pantothenic acid – 6.6g; folic acid – 0.4g; biotin – 15mg; butylated hydroxy toluene (B.H.T.) – 15g.

2.3. Physiological responses

According to Fig. 2, the physiological responses were evaluated on Days 10, 14, 17, 21, 24, and 28. Cloacal and surface temperatures were quantified using a digital thermometer (OMRON, model MC-245, ± 0.2ºC precision) and a thermographic camera (Fluke, model Ti55, 0.05°C accuracy), respectively. The thermographic camera was positioned at a height sufficient to cover the entire area of the cage and fit all the animals housed in each tunnel. In turn, the respiration rate (RR, mov. $\cdot$ min^{-1}) was determined from direct visual observation for 15 seconds and then extrapolated to 1 minute.

2.4. Productive responses

The following productive responses were also determined on Days 10, 14, 17, 21, 24, and 28 in each flock: mean feed intake (FI, g), mean water intake (WI, mL), mean body weight (BW, g), mean egg weight (EW, g), feed conversion (FC, kg of feed $\cdot$ kg of eggs^{-1}), laying percentage (LP, %, calculated according to Vieira Filho *et al.* (2016)), and percentage of viable eggs (PVE, %, ratio between marketable eggs and total produced).

Each day, all eggs produced were identified, weighed, and classified. Broken, cracked, shelled, or soft shell eggs were classified as undesirable, while the others were classified as marketable.

The weight of eggs and chickens was measured using a digital scale (Mark L 8001 Class II, BEL Engineering, ± 0.05 g accuracy).

2.5. Egg quality

In all treatments, the quality of the eggs laid on Days 10, 14, 17, 21, 24, and 28 of each experimental flock was evaluated. The eggs were collected and stored in the experimental room at a temperature of 20.2 ± 1.7°C. All analyses were performed on the day after laying (Damaziak *et al.*, 2021).

First, the specific gravity (SG) was obtained based on Archimedes' principle and characterized by an adaptation of the method described by Hempe *et al.* (1988), according to Eq. (1).

$$SG = \frac{EW_{(in\ air)}}{EW_{(immersed\ in\ water)} \cdot D} \quad (1)$$

where,

$EW_{(in\ air)}$ = mean egg weight (g) measured in air;

$EW_{(immersed\ in\ water)}$: mean egg weight (g) measured when immersed in water;

D: is the water temperature correction which, according to Kell (1975), can be estimated by Eq. (2).

$$D = \frac{\left(\begin{array}{c} 0.9998676 + 17.801161 \cdot 10^{-3} \cdot t_w - 7.942501 \cdot 10^{-6} \cdot t_w^2 - \\ 52.56328 \cdot 10^{-9} \cdot t_w^3 + 137.6891 \cdot 10^{-12} \cdot t_w^4 - 364.4647 \cdot 10^{-15} \cdot t_w^5 \end{array}\right)}{1 + 17.735441 \cdot 10^{-3} \cdot t_w} \quad (2)$$

where,

t_w: water temperature (ºC).

Subsequently, the eggs were cracked, and the Haugh unit (HU) was estimated by Eq. (3) from the albumen height (H) and total egg weight (TEW) (Eisen *et al.*, 1962).

$$HU = 100 \cdot \log \left(H + 7.57 - 1.7 \cdot TEW^{0.37}\right) \quad (3)$$

The yolk index (YI) was calculated by dividing the height of the yolk by its diameter. The eggshell weight and thickness (EST, mm) were determined after washing and air-drying for two days (Poudel *et al.*, 2022a). The EST was measured by the mean between observations in the apical, equatorial, and basal zones of the egg. The percentages of yolk (PY), albumen (PA) and shell (PS) were calculated by dividing the respective weights by the TEW. The albumen weight was estimated by subtracting the yolk and shell weights from the TEW. Finally, the eggshell density ($mg \cdot cm^{-2}$) was determined according to Nasr *et al.* (2019).

All measurements were performed using a digital caliper (Digimess ± 0.02 mm accuracy) or digital micrometer (Caliper, ± 0.001 mm accuracy) and a digital scale (Mark L 8001 Class II, BEL Engineering, ± 0.05 g accuracy).

2.6. Experimental design and statistical analysis

Due to the limitation in the number of birds housed in each wind tunnel (6 birds were housed per tunnel in order to respect the housing density), the experiment had to be divided into blocks. Thus, the statistical model was also defined with a block design, aiming to minimize the possible effects that the different hens' ages in each flock could cause on the evaluated responses. Thus, the experiment was carried out in a randomized block design, in a split-plot arrangement, with treatments in the plot (5, 20, 50 and 100 lux) and illumination exposure times (t_{illu}) in the subplot (10, 14, 17, 21, 24 and 28 days). The statistical model considered was as follows:

$$y_{ijk} = \mu + \tau_i + \beta_j + \epsilon_{ij} + \gamma_k + \beta\gamma_{jk} + \tau\gamma_{ik} + \varepsilon_{ijk}$$

where y_{ijk} is the value observed in the portion of block j, which received treatment i and which was evaluated at time k, with i=1,2,3,4, j=1,2,3 and k=1,2,3 ,4,5,6; μ is a constant associated with each observation, τ_i is the effect of treatment i, β_j is the effect of block j, which corresponds to the flock effect, ϵ_{ij} is the experimental error at the plot level, γ_k is the effect of t_{illu} k, $\beta\gamma_{jk}$ is the effect of the interaction between flock and t_{illu}, $\tau\gamma_{ik}$ is the effect of the interaction between treatment and t_{illu}, and ε_{ijk} is the experimental error at the subplot level, where $\varepsilon_{ijk}{\sim}N(\mu,\sigma^2)$.

After verifying the normality and homogeneity of the variances in the collected data (Shapiro-Wilk and Bartlett tests, respectively), the productive variables, egg quality and physiological responses were subjected to analysis of variance. Thus, the response variables (which are quantitative data) were analyzed using regression when they were significant. The effect of the block (which is qualitative) was analyzed using the Scott-Knott test when it was significant.

3 Results and discussion

3.1 Thermal and luminescent control

The values of the variables related to the thermal and luminescent environments monitored inside the wind tunnels are listed in Table 2. From the averages of t_{air} and RH, it was observed that the thermal environment remained within the thermoneutral range (Castilho *et* *al*., 2015; Ferreira 2016; Ribeiro *et al*., 2020) and close to the desired values (23°C and 60%, respectively). The low standard deviation values indicated the efficiency of the control system, corroborating Abreu *et al*. (2019).

Generally, conventional lighting systems installed inside poultry houses provide low uniformity in light distribution, which can compromise productive performance and egg quality (Barros *et al*., 2020a). In this experiment, the observed illuminance values showed low standard deviations from the desired values ($\leq$ 2.9 lux), and the means of each treatment showed no significant differences (p>0,05, F test) when compared between the experimental flocks. Similarly, Barros *et al*. (2020a) found that linear LED lighting inside cages promotes uniformity in illuminance value distribution, increasing productivity compared to the conventional system, in which lamps are installed outside the cages.

3.2 Physiological responses

Understanding bird physiological responses is important for verifying their well-being, and changes in their responses that go beyond the established values of comfort indicate that the birds are being exposed to stressors. Cloacal and surface temperatures and RR stand out among the main physiological responses commonly evaluated in laying hens.

The ANOVA results for the physiological responses are listed in Table 3, whereas, Table 4 lists the mean and standard deviation of respiration rate for each illuminance level.

Table 2. Mean, standard deviation and median values of temperature and relative humidity of the air, and illuminance, observed in each wind tunnel, throughout the three experimental flocks.

Stage		**Air temperature (ºC)**				**Relative air humidity (%)**				**Illuminance (lux)**			
		tunnel 1	**tunnel 2**	**tunnel 3**	**tunnel 4**	**tunnel 1**	**tunnel 2**	**tunnel 3**	**tunnel 4**	**5**	**20**	**50**	**100**
Flock 1	**Mean**	23.5	23.4	23.4	23.5	59.7	60.1	60.1	59.9	5.3	20.3	50	100.3
	Standard deviation	0.4	0.3	0.3	0.4	1.6	0.9	0.7	1.1	0.6	1.3	2.9	2.6
	Median	23.5	23.3	23.4	23.5	60.0	60.2	60.1	60.1	5.3	20.0	49.9	100.9
Flock 2	**Mean**	23.4	23.3	23.5	23.5	59.5	60.0	59.1	59.8	5.0	20.0	49.9	100.8
	Standard deviation	0.4	0.3	0.4	0.4	1.7	0.8	2.0	1.2	0.5	0.9	1.4	2.2
	Median	23.4	23.3	23.4	23.4	60.0	60.1	59.9	60.0	5.0	20.2	50.0	100.9
Flock 3	**Mean**	23.3	23.3	23.4	23.3	59.1	60.0	59.7	60.0	5.1	20.3	50.1	100.8
	Standard deviation	0.3	0.2	0.3	0.3	1.5	0.4	1.2	0.8	0.5	1.3	2.2	2.3
	Median	23.2	23.2	23.3	23.2	59.8	60.0	60.0	60.1	5.1	20.0	50.0	100.8

Table 3. Variance analysis results for birds' physiological responses, according to the statistical model adopted.

Response variable	Sources of variation in ANOVA			
	Flock (age group)	**Illuminance**	**t_{illu}**	**Interaction (illuminance x t_{illu})**
Cloacal temperature (°C)	p=0.0083 *	p=0.0545 ^{NS}	p=0.8286 ^{NS}	p=0.0365 *
Surface temperature (°C)	p=0.0006 *	p=0.0088 *	p=0.1629 ^{NS}	p=0.0173 *
Respiration rate (mov.min^{-1})	p=0.4094 ^{NS}	p=0.5364 ^{NS}	p=0.1626 ^{NS}	p=0.8107 ^{NS}

ANOVA = analysis of variance, * = significant ($p<0.05$, F test), NS = not significant ($p>0.05$, F test).

Table 4. Means and standard deviations of respiration rate for each treatment, regardless of flock and illumination exposure times.

Response variable	Illuminance level (lux)			
	5	**20**	**50**	**100**
Respiration rate (mov.min^{-1})	23.8 ± 1.3	23.1 ± 1.8	23.6 ± 1.7	22.9 ± 1.3

It is observed in Table 3 that for the cloacal temperature, the flock factor and the interaction between the lighting intensity and t_{illu} factors were significant ($p<0.01$ and $p<0.05$ – F test, respectively). Thus, Fig. 3 illustrates the mean cloacal temperatures obtained over the three experimental flocks, regardless of the illuminances to which the birds were subjected and the t_{illu}.

In turn, Fig. 4 illustrates only the interaction effect between the intensity of 50 lux ($p<0.05$, F test) and t_{illu}, due to the fact of interaction effects for the others illuminance were not significant ($p>0.05$, F test). Thus, the maximum cloacal temperature occurred at 18.8 days of evaluation for birds subjected to 50 lux illuminance, and this maximum point was obtained by mathematical derivation.

When observing the data from both figures, it was found that although the mean cloacal temperatures were significantly different, they were within the range considered for thermal comfort for the birds, which in the study by Cândido *et al.* (2020) ranged from 40.8 to 42.2°C. Furthermore, the differences between the mean values (Fig. 3) were within the margin of error of the temperature sensor used in the measurement (accuracy of ± 0.2°C). In addition, the minimum and maximum values are also shown in Fig. 4.

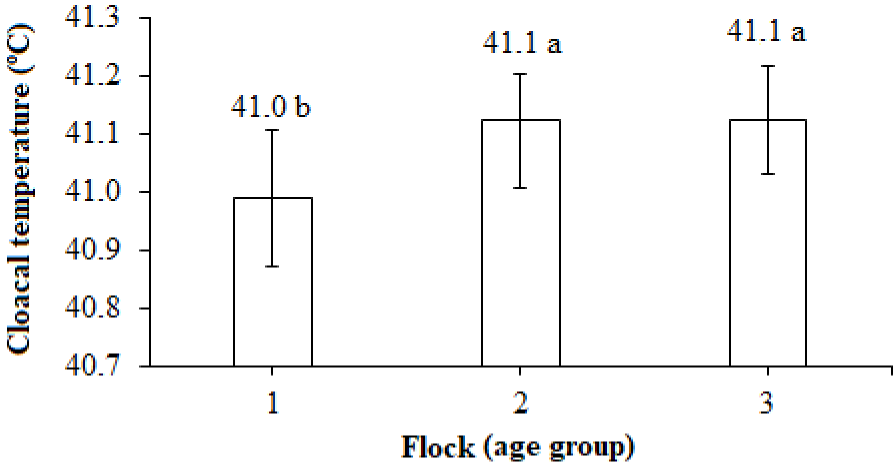

Fig 3. Means and standard deviations of cloacal temperatures observed for the flocks of laying hens regardless of the illuminances to which the birds were subjected and the time of exposure to illumination.

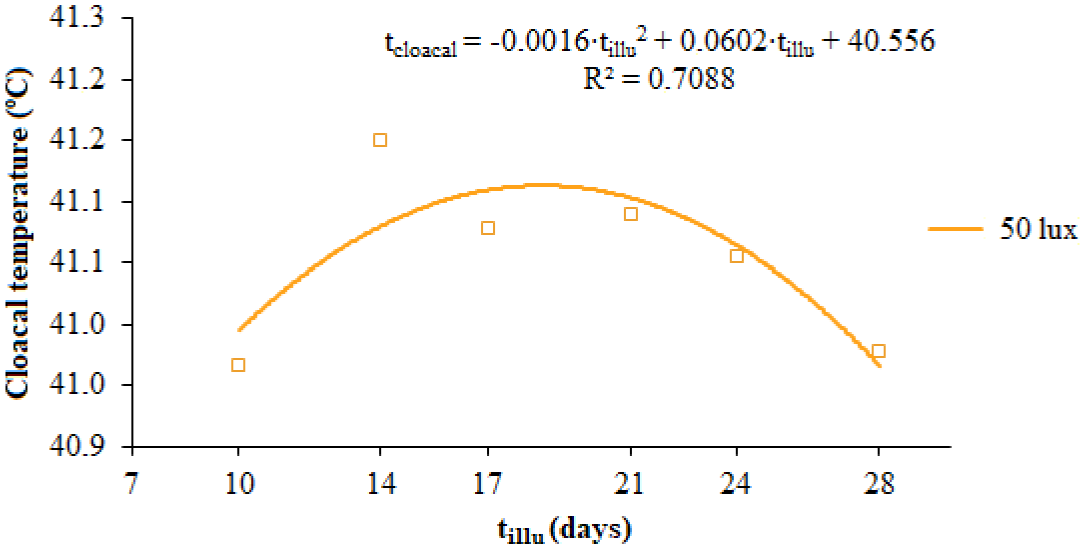

Fig 4. Variation in cloacal temperature ($t_{cloacal}$) of laying hens as a function of illumination exposure time (t_{illu}) when subjected to an illuminance of 50 lux.

Analyzing the surface temperature variable in Table 3, the flock factor and the interaction between the lighting intensity and t_{illu} factors were also significant ($p<0.01$ and $p<0.05$ – F test, respectively). Thus, Fig. 5 illustrates the magnitudes of the mean surface temperatures of the three experimental flocks, regardless of the illuminances to which the birds were subjected. Although the means were significantly different ($p<0.05$, Scott-Knott test), in all flocks, the values were within the range recommended as comfortable for laying hens at peak laying, which, according to Ribeiro *et al.* (2020), is between 26.5 and 29.9°C. This behavior of the data can also be observed in Fig. 6, which illustrates the variation in the surface temperature as a function of the illuminance level and t_{illu}. The rates of surface temperature reduction for birds subjected to illuminances of 5, 20, 50, and 100 lux were 0.0629, 0.0602, 0.0563 and 0.0677°C per day of exposure, respectively, which varied from 10 to 28 days.

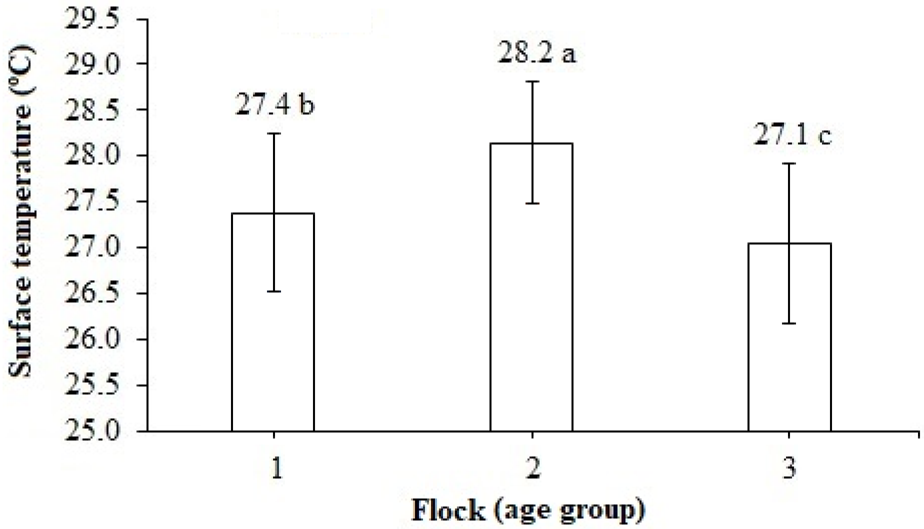

Fig 5. Surface temperatures (means and standard deviations) of laying hens as a function of flocks and regardless of the illuminance to which the birds were subjected.

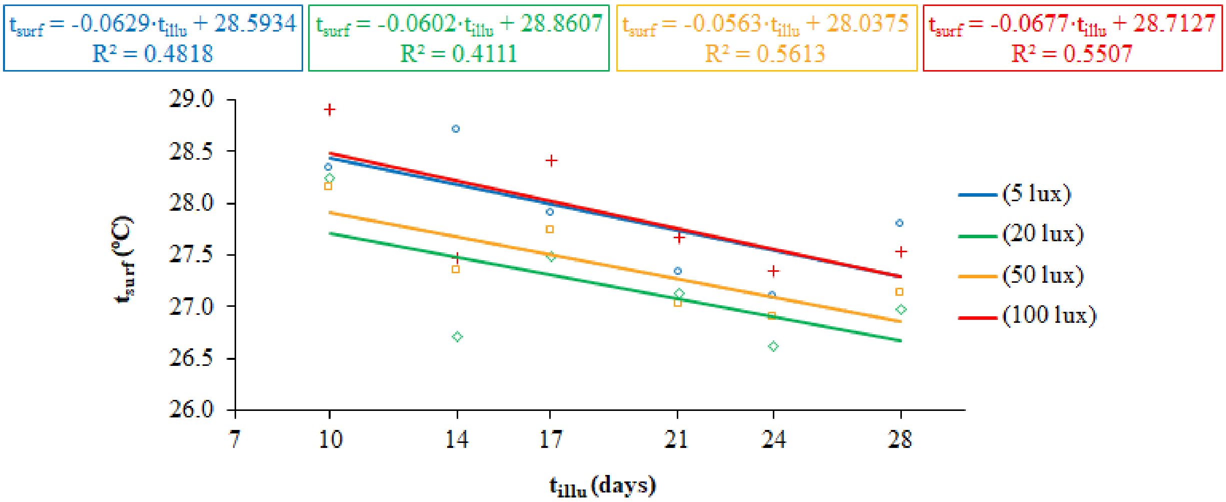

Fig 6. Surface temperature (t_{surf}) of laying hens as a function of illumination exposure time (t_{illu}) when subjected to different illuminances.

A bird in its rearing environment is subjected to body temperature gradients related its internal temperature (cloacal temperature) and external temperature (surface temperature), as well as the temperature of the air and the surrounding surfaces, promoting sensitive heat exchanges (Bahuti *et al*., 2022). The effects of LED lamps on surrounding surfaces should also be considered because although they do not emit heat in the form of radiation, they dissipate heat to the environment by conduction and convection, which can change rearing facility microclimates and negatively affect the homeostasis of birds (Barros *et al*., 2020b). Given this information, Li and Zhang (2022) investigated lighting heat dissipation to the environment and found that 50% of the heat dissipation from an LED lamp to the environment occurs by convection.

In this study, the surface temperatures of the lamps were not evaluated, but one of the possible reasons for the difference between the surface temperatures occurred may have been the temperature emitted by the LEDs at different light intensities.

The respiration rate is related to the thermal and/or psychological comfort of animals, and its alteration precedes other physiological responses.

Thus, the effects of the treatments were not significant for RR (Table 3) in relation to the different illuminances evaluated, t_{illu}, and age groups (flock) ($p>0.05$, F test). It is observed in Table 4 the variability in the data for each treatment, regardless of the other factors studied, and the maximum variation observed between the means was 0.9 mov min^{-1}. The mean RR of the birds for all the illuminances tested was close to the value recommended as comfortable for laying hens, as reported by Kassim and Sykes (1982), which is 23 mov. min^{-1}. In turn, Ribeiro *et al*. (2020) reported that values between 30 and 67 mov. min^{-1} indicate that the birds are experiencing comfortable thermal conditions.

3.3 Productive responses

The ANOVA results and descriptive analysis (average and standard deviation) for productive responses are listed in Tables 5 and 6, respectively.

Regarding the FI, there was no difference among the flocks ($p>0.05$, F test); however, the interaction between illuminance and t_{illu} (Table 5) was significant ($p<0.02$, F test). Fig. 7 illustrates the range of the lighting levels within the tunnel, regardless of the flock (age group) to which the birds belonged, as well as the equations that best describe the behavior of the data for each illuminance level.

Table 5. Variance analysis results for birds' productive responses, according to the statistical model adopted.

Response variable	Sources of variation in ANOVA			
	Flock (age group)	**Illuminance**	**t_{illu}**	**Interaction (illuminance x t_{illu})**
Feed intake (g)	p=0.7418 ^{NS}	p=0.3688 ^{NS}	p=0.0057 *	p=0.0176 *
Body weight (g)	p=0.0081 *	p=0.1028 ^{NS}	p=0.0000 *	p=0.5958 ^{NS}
Egg weight (g)	p=0.0798 ^{NS}	p=0.6906 ^{NS}	p=0.0958 ^{NS}	p=0.8804 ^{NS}
Feed conversion	p=0.8910 ^{NS}	p=0.1533 ^{NS}	p=0.7977 ^{NS}	p=0.7911 ^{NS}
Laying percentage (% bird^{-1} day^{-1})	p=0.3401 ^{NS}	p=0.1111 ^{NS}	p=0.6583 ^{NS}	p=0.1393 ^{NS}
Water intake (mL bird^{-1} day^{-1})	p=0.2977 ^{NS}	p=0.4905 ^{NS}	p=0.5688 ^{NS}	p=0.4422 ^{NS}

ANOVA = analysis of variance, * = significant ($p<0.05$, F test), NS = not significant ($p>0.05$, F test).

Table 6. Means and standard deviations of productive responses for each treatment, regardless of flock and illumination exposure times.

Response variable	Illuminance level (lux)			
	5	**20**	**50**	**100**
Body weight (g)	1602.2 ± 41.0	1566.7 ± 42.0	1589.6 ± 35.3	1556.9 ± 34.9
Egg weight (g)	61.3 ± 1.9	62.1 ± 1.8	60.1 ± 1.5	61.7 ± 3.1
Feed conversion	1.9 ± 0.2	1.8 ± 0.1	2.0 ± 0.2	1.8 ± 0.1
Laying percentage (% bird^{-1} day^{-1})	94.8 ± 5.7	95.4 ± 5.6	91.1 ± 6.7	98.3 ± 3.1
Water intake (mL bird^{-1} day^{-1})	196.5 ± 12.5	214.8 ± 17.9	235.2 ± 36.7	213.2 ± 26.5

According to Ma *et al.* (2016), light intensity can influence the behavior and performance of chickens. Thus, when analyzing the behavior of Hy-Line W-36 chickens at 5 and 100 lux from a fluorescent source, the aforementioned authors found that the birds preferred to feed in environments with 5 lux rather than with 100 lux. However, when using incandescent sources, Prescott and Wathes (2002) observed that chickens preferred to spend more time feeding in an environment with more light (200 lux) than in an environment with less light (20, 6, and <1 lux). In contrast, when Rozenboim *et al.* (1998) subjected chickens to 1.3 lux, they found an approximately 8 g reduction in the FI compared to that when subjected to 13 lux. However, a negative relationship between light intensity and FI was unexpected (Lewis and Morris, 1999).

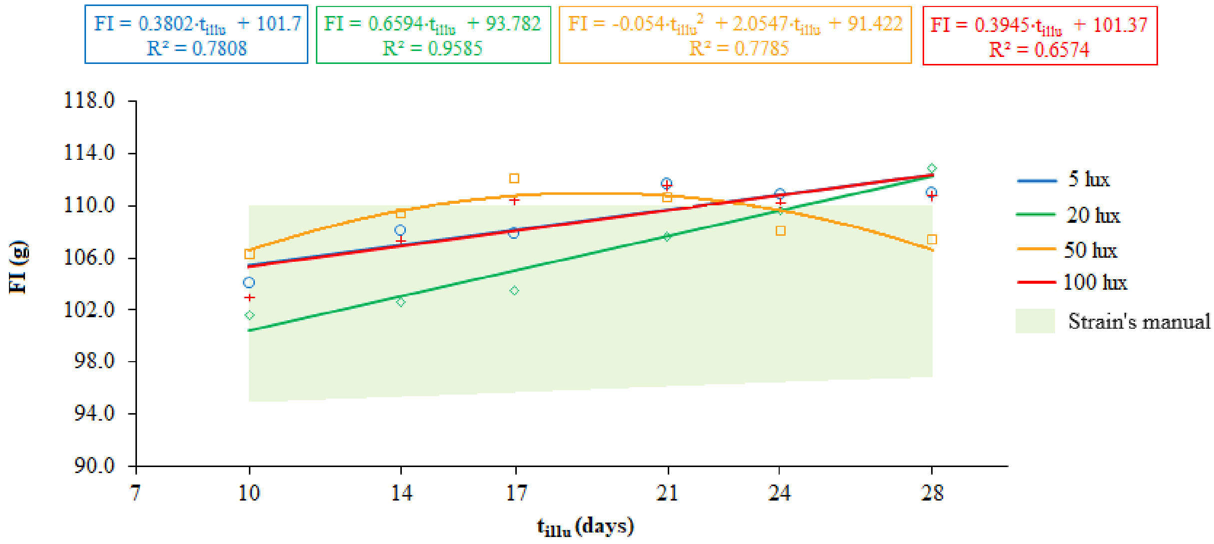

Fig 7. Mean feed intake (FI, g) of laying hens as a function of illumination exposure time (t_{illu}) when subjected to different illuminances.

In this study, except for the illuminance of 50 lux, which was not significant ($p>0.05$, F test), there was an increase in the FI from 10 to 28 days of age, regardless of the flock. Notably, although the FI values tended to be lower for the illuminance of 20 lux compared to the values observed for the illuminances of 5 and 100 lux, which behaved similarly, these FI values were all similar when close to 28 days. While the rate of increase in the FI was 0.6594 g day^{-1} for 20 lux, these values were 0.3802 and 0.3945 g day^{-1} for illuminances of 5 and 100 lux, respectively.

The variation in the FI with t_{illu} was close to that indicated by the strain's manual (Hy-Line, 2019), which predicts an increase in FI between 94 and 110 g with the variation in bird age from 25 to 36 weeks.

The convergence of the FI values at 28 days for illuminances of 5, 20, and 100 lux indicates that the birds needed this time to adapt to the illuminances, and the adopted acclimation time should be at least 28 days rather than the 7 days generally adopted in poultry experiments (Qu *et al.*, 2018; Ribeiro *et al.*, 2020). Furthermore, according to Borille *et al.* (2013), the absence of changes in feed consumption indicates that the birds had similar visual sensitivities for all illuminance intensity levels tested. Thus, clearly, none of the applied illuminance levels resulted in increased or decreased FI levels for the birds, as there was no significant difference ($p>0.05$, Scott-Knott test) between the means of the treatments at 28 days.

As a result of the ANOVA for the BW variable (Table 5), the sources of the flock and t_{illu} variation were significant ($p<0.01$, F test). Thus, Fig. 8 illustrates the BW for each of the three experimental lots, regardless of the applied illuminance levels and t_{illu}. Fig. 9 illustrates the variation in the BW along the t_{illu}, regardless of the illuminance levels and flocks. Based on the age groups of flocks 1, 2, and 3, the BW values indicated in the manual are 1590 ± 70, 1640 ± 70, and 1650 ± 60 g, respectively (Hy-Line, 2019). Thus, since the equation fitted in Fig. 9 indicates a linear increase rate in the BW for all flocks, the significant difference ($p<0.05$, Scott-Knott test) between the means of the flocks (Fig. 8) possibly occurred due to the lower bird BW at the beginning of the second experimental flock. In addition, given the age groups of the experimental period, an increase in the bird BW was expected, indicating that there was correct management during the experiment.

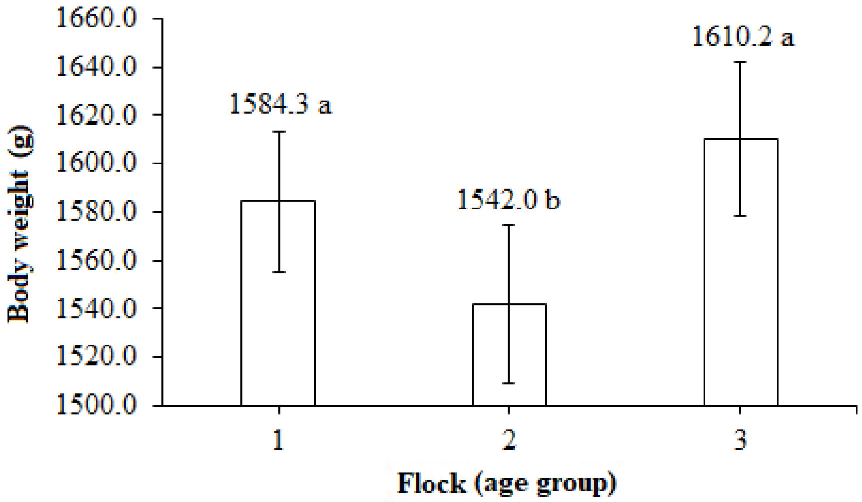

Fig 8. Means and standard deviations of body weight (g) of laying hen flocks regardless of illuminances levels.

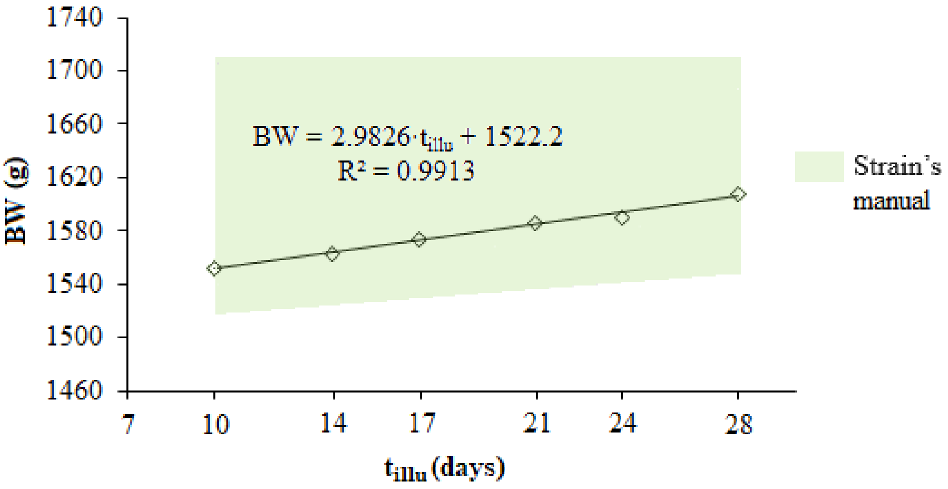

Fig 9. Mean body weight (BW, g) of laying hens as a function of illumination exposure time (t_{illu}) when subjected to different illuminances.

The EW (Table 5) showed no differences in relation to the flocks, illuminance levels, t_{illu}, or their interactions (p>0.05, F test). However, regardless of the light intensity to which the birds were exposed, all averages (Table 6) were higher than the overall average expected for the age of the birds during the experimental period (58.4 g). This result reiterates the effectiveness of the thermal control and food management performed during the experiment. However, it is notable that this condition is difficult to obtain under commercial conditions.

When subjecting Lohmann-Brown laying hens to fluorescent lamps with 12, 57, and 122 lux, Erensoy *et al*. (2021) observed a significant reduction of 2 and 1.4 g in the EW in the 122 lux treatment compared to those in the 12 and 57 lux treatments, respectively. This result may indicate that birds react differently to LED and fluorescent light sources, corroborating Long *et al*. (2016a, 2016b), and Tünaydin and Yilmaz Dikmen (2019). However, this conclusion is not consistent across studies, as there are several studies reporting results that are different from this conclusion (Borille *et al*., 2013; Ribeiro *et al*., 2021; Oso *et al*., 2022).

In turn, Nasr *et al*. (2019) found that the EW of quails also decreased at high light intensities (250 lux); however, the increase from 10 to 50 lux was sufficient to promote a significant reduction in EW. This scenario did not occur with chicken eggs in this study. In contrast, Lewis and Morris (1999), when reviewing data from several studies, found similar EW reduction behavior at higher illuminance levels. However, the authors emphasized that the ratio of egg weight decreasing with increasing light intensity was not confirmed. Therefore, there is still a need for more research under commercial conditions to evaluate the actual production conditions and the use of LED lighting technology, as most experiments are performed in the laboratory (Ma *et al*., 2016; Archer, 2019; Nasr *et al*., 2019).

Because there was no treatment effect on the EW and given the influence of the t_{illu} on both the FI (Fig. 7) and the BW (Fig. 9), a reduction in bird production efficiency was expected. Therefore, the energy used to increase the FI also increased the BW rather than egg production. In addition, according to Boshouwers and Nicaise (1987), reducing the illuminance level from 120 to 1 lux can reduce the total metabolic energy expenditure of chickens by 18%. However, the FC (Table 5) was not significantly different among the flocks, illuminance levels, and t_{illu} (p>0.05, F test). This result indicates that the observed behaviors were not sufficient to promote changes in FC. Regarding the results reported by Boshouwers and Nicaise (1987), in addition to the higher illuminance variation, a lower illuminance value (1 lux) suggests a penumbra, which differs substantially from the lower illuminance value tested in this study (5 lux).

For the flock age groups, a FC between 1.8 and 1.9 was expected (Hy-Line 2019). Thus, although the result was not significant, only the 50 lux treatment (Table 6) had a higher mean

FC than expected (2.0 kg kg^{-1}). This behavior may have been due to the lower mean EW obtained by the same treatment (Table 6).

Nasr *et al.* (2019), when subjecting Japanese quails to illuminances of 50 and 250 lux from incandescent lamps, found an increase in FC of 0.51 and 0.60, respectively, compared to that at 10 lux. In contrast, when conducting a study with Hy-Line Brown under white LEDs with 20 lux from 18 to 40 weeks of age, Min *et al.* (2012) found a mean FC of 1.94. This value is consistent with that in the strain's manual (Hy-Line, 2018). Additionally, when Long *et al.* (2016b) subjected Dekalb White laying hens to LEDs with intensities between 5 and 9 lux, they found that the mean FC value was 2.03, resulting in a 3% increase compared to the expected value according to the strain's manual. Thus, some studies show that increasing the light intensity decreases the efficiency of birds, suggesting that the 100 lux applied in this study was not sufficient to promote discomfort. However, the sensitive of laying hens to the light spectrum is similar to all strains, once they came from the same specie (Gallus). Thus, when different strains of laying hens are subjected to a specific light intensity from the same light source, the differences among the responses are due to genetic characteristics as well as the attendance to the well-being requirements.

The illuminance levels evaluated throughout the experimental period did not have a significant effect on the LP ($p>0.05$, F test; Table 5), with means of 94.8, 95.4, 91.1, and 98.3% for 5, 20, 50, and 100 lux, respectively (Table 6). The mean LP values observed were consistent with or very close to those indicated in the strain manual for birds at peak production (95 to 97%) (Hy-Line, 2019).

Poudel *et al.* (2022a) subjected Hy-Line W-36 hens ranging from 26 to 31 weeks of age to 30 lux from LED lamps and verified mean LP of 92.4 ± 4.6. This result obtained is also close to that indicated by the manual for W-36 hens (Hy-Line, 2020). In turn, Barros *et al.* (2020b) subjected Hy-Line Brown hens ranging from 25 to 36 weeks of age to 20 lux from LED lamps. Based on their published data, it was possible to estimate a mean LP value of 89.6%. The observed value was below that indicated in the strain's manual, which is 94.8 ± 0.6 (Hy-Line, 2018). However, this loss of productivity compared to that in the manual possibly occurred because the experiment was not conducted in a controlled environment; thus, favorable conditions were not present throughout the experimental period.

However, there is no consensus in the literature on the effect of illuminance on egg production. Renema *et al.* (2001) found no significant differences in egg production among ISA-White, Shaver 2000, ISA-Brown, and Shaver 579 laying hens subjected to 5, 50, and 500 lux. However, when subjected to 1 lux, there was a significant decrease in egg production (mean of 4.6%). In contrast, Tucker and Charles (1993) did not observe differences in egg production with light intensities ranging from 0.75 to 12.4 lux in a study conducted with ISA Brown, Hisex Brown, Shaver Brown, and Hisex White laying hens. Despite this result, the authors suggested maintaining the recommended light intensity (10 to 20 lux) for the epoch to provide comfortable conditions for the birds.

Finally, it is known that changes in bird WI are commonly related to heat stress, as birds can increase their WI to assist in dissipating body heat. However, according to the results for the physiological responses (cloacal and surface temperatures and RR) in this study, the birds were within the comfort range.

In addition, the WI results were not significant ($p>0.05$, F test) for the different illuminance levels, evaluation times, or age groups (flock) (Table 5). The variability in the WI throughout the experiment for each light intensity level is listed in Table 6.

Illuminance can impact the identification of drinking troughs by birds (Olanrewaju *et al.*, 2019); thus, the lack of significant differences among treatments suggests that environments with 5 lux are sufficient to meet this visual need of laying hens, as found in this research. However, as transcranial stimulation occurs above 4 lux (Morgan *et al.*, 1995), ocular perception is not essential for light stimulation of the avian hypothalamus (Sopes and Wilson, 1980). Research with blind chickens corroborates this finding (Baxter *et al.*, 2014). In addition, this result also corroborates Chew *et al.* (2021), who found that 10 lux is enough for pullets to navigate their environment safely, when reared in floor pens containing a perchery system.

Nasr *et al.* (2019) found that quails increased their drinking behavior when subjected to high light intensity (250 lux) because high light intensity levels increase bird activity. However, when also evaluating Japanese quails, Khalil *et al.* (2016) found no significant difference in bird drinking behavior between naturally lit (mean of 375 lux) and artificially lit (10, 50, 250, and 500 lux) environments.

For the age groups in this experiment, the expected WI is between 143 and 220 mL bird^{-1} day^{-1}, with a mean of 181.5 ± 38.5 mL bird^{-1} day^{-1}. Thus, although the illuminance levels did not have a significant effect on the WI, the 50 lux treatment resulted in a WI of 235.2 mL bird^{-1} day^{-1} (Table 6), which was 6.91% higher than the upper limit of the expected range. For this treatment, no anomalies, such as bird stress or inadequate functioning of drinking troughs, were detected that could have caused this highest level of consumption. Notably, excess water consumption can be detrimental to egg quality because it compromises the formation of shells and leads to the production of thin-shelled and/or brittle eggs (Santana *et al.*, 2018).

3.4 Egg quality

The ANOVA results for the egg quality responses are listed in Table 7. Table 8 lists the means and standard deviations of egg quality variables for each illuminance level, independent of flocks and illumination exposure times.

Table 7. Results of the analysis of variance for egg quality, according to the statistical model adopted.

Response variable	Sources of variation in ANOVA			
	Flock (age group)	**Illuminance**	**t_{illu}**	**Interaction (illuminance x t_{illu})**
Eggshell thickness (mm)	p=0.0021 *	p=0.8309 ^{NS}	p=0.6932 ^{NS}	p=0.1206 ^{NS}
Percentage of viable eggs (%)	p=0.9047 ^{NS}	p=0.0539 ^{NS}	p=0.6137 ^{NS}	p=0.4046 ^{NS}
Egg specific gravity (g cm^{-3})	p=0.0755 ^{NS}	p=0.3965 ^{NS}	p=0.9969 ^{NS}	p=0.3206 ^{NS}
Eggshell density (mg cm^{-2})	p=0.6178 ^{NS}	p=0.7850 ^{NS}	p=0.3025 ^{NS}	p=0.9421 ^{NS}
Haugh unit	p=0.5891 ^{NS}	p=0.5943 ^{NS}	p=0.1934 ^{NS}	p=0.2858 ^{NS}
Yolk index	p=0.2016 ^{NS}	p=0.6159 ^{NS}	p=0.2760 ^{NS}	p=0.4352 ^{NS}
Percentage of yolk (%)	p=0.0808 ^{NS}	p=0.8554 ^{NS}	p=0.0820 ^{NS}	p=0.4989 ^{NS}
Percentage of shell (%)	p=0.4273 ^{NS}	p=0.7881 ^{NS}	p=0.4326 ^{NS}	p=0.9657 ^{NS}
Percentage of albumen (%)	p=0.1368 ^{NS}	p=0.7628 ^{NS}	p=0.0162 *	p=0.8825 ^{NS}

ANOVA = analysis of variance, * = significant ($p<0.05$, F test), NS = not significant ($p>0.05$, F test).

Table 8. Means and standard deviations of egg quality variables for each treatment, regardless of flock and illumination exposure times.

Response variable	Illuminance level (lux)			
	5	**20**	**50**	**100**
Eggshell thickness (mm)	0.471 ± 0.015	0.473 ± 0.017	0.470 ± 0.011	0.474 ± 0.018
Percentage of viable eggs (%)	95.8 ± 5.1	96.9 ± 4.2	93.7 ± 4.9	99.2 ± 2.7
Egg specific gravity (g cm^{-3})	1.097 ± 0.002	1.095 ± 0.003	1.097 ± 0.002	1.095 ± 0.003
Eggshell density (mg cm^{-2})	87.1 ± 3.4	85.4 ± 5.3	86.4 ± 3.0	85.6 ± 1.5
Haugh unit	91.3 ± 1.3	92.3 ± 1.3	92.4 ± 1.3	93.0 ± 2.1
Yolk index	0.44 ± 0.01	0.45 ± 0.01	0.45 ± 0.01	0.45 ± 0.01
Percentage of yolk (%)	25.5 ± 1.0	24.9 ± 1.5	25.4 ± 1.1	25.5 ± 0.6
Percentage of shell (%)	10.3 ± 0.4	10.1 ± 0.7	10.3 ± 0.4	10.1 ± 0.2
Percentage of albumen (%)	64.3 ± 1.1	65.0 ± 1.2	64.3 ± 1.3	64.4 ± 0.7

Regarding eggshell thickness (Table 7), only the flock factor was significant ($p<0.01$, F test). Thus, Fig. 10 illustrates the average thicknesses obtained in each flock ($p<0.05$, Scott-Knott test), regardless of the illuminances and t_{illu}.

Alves *et al*. (2007) found an eggshell thickness of 0.34 mm for Hy-Line W-36 hens at 29 weeks of age, while Liu *et al*. (2018) found an average shell thickness of 0.43 mm for the same strain from 23 to 41 weeks. Additionally, according to Oliveira *et al*. (2014), the standard eggshell thickness for the Dekalb White strain is between 0.41 and 0.50 mm, so the authors obtained an average result of 0.45 mm at 27 weeks of age. However, Vilela *et al*. (2016) found a thickness of 0.334 mm for the same strain when analyzed at 30 weeks of age. Thus, eggshell thickness may vary according to bird strain and age, in addition to the evaluation method, management, and feeding. In addition, regarding the effect of illuminance, Erensoy *et al*. (2021) found that there were no differences in eggshell thickness among treatments with 12, 57 and 122 lux, with Lohmann-Brown hens with ages ranging from 20 to 40 weeks having an average thickness of 0.40 mm.

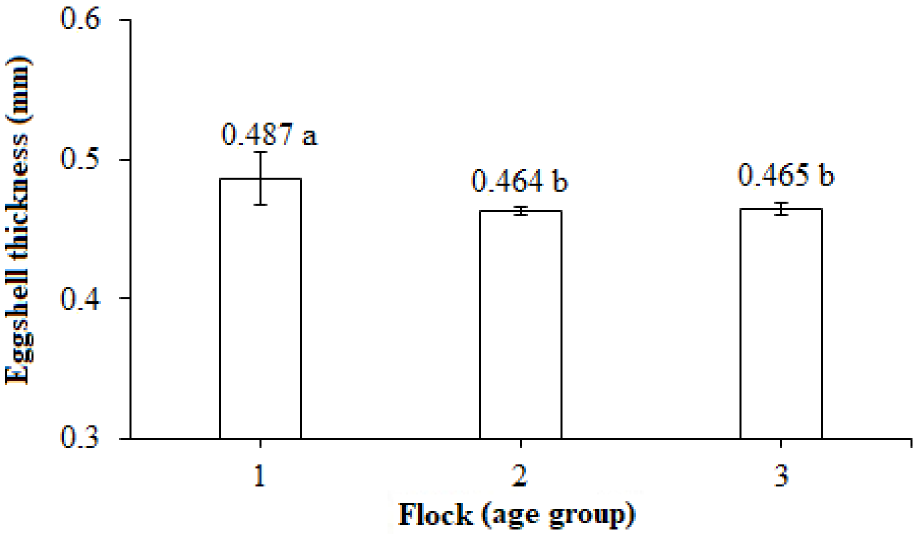

Fig 10. Means and standard deviations of eggshell thickness according to the experimental flock, regardless of illuminance and exposure time to lighting.

Due to the lack of significance for the results of the light intensities on the EST in this study, it was found that the higher WI observed in the 50 lux treatment was not sufficient to impair shell formation. Furthermore, RR can also influence the quality of the shell; however, high RR values were not observed in this study (Table 4). In addition, according to the data in Fig. 10, there was a decrease in shell thickness as the birds aged. According to Poudel *et al*.

(2022b), the percentage of calcium in an eggshell decrease with increasing bird age, which affects the formation of the shell. Additionally, egg size also increases with advancing age (Sirri *et al*., 2018; Hy-Line, 2019; England and Ruhnke, 2020).

Eggs can be considered naturally packaged foods because their shells protect them from mechanical shocks; thus, poor shell quality can cause substantial economic losses (Barbosa *et al*., 2012). Therefore, PVE is directly related to the quality of the shell. However, although shell thickness underwent a change according to the experimental flock (Table 7), the PVE was not significantly different among any of the factors levels ($p>0.05$, F test).

Regarding the external quality of the eggs, neither the SG of the eggs nor the shell density were significantly ($p>0.05$, F test) related to the flocks, illuminance levels, and t_{illu} (Table 7). Table 8 lists the behavior of the variables SG and shell density. According to Rosseto *et al.* (2019) and Ribeiro *et al.* (2021), variations in SG are directly related to shell quality; thus, thicker shells increase egg SG. However, although the average shell thickness decreased as the bird age increased (Fig. 10), the shells possibly became less porous and compensated for possible variations in egg SG and shell density, with no significant differences observed among the flocks.

In this regard, the porosity of the shell is directly related to its internal quality, and the shell controls the exchange of water and gases through the pores (Barbosa *et al*., 2012). However, the HU was not significantly different ($p>0.05$, F test) among the different illuminance levels, t_{illu}, and flocks evaluated (Table 7).

High HU values indicate higher egg quality and, according to the USDA Egg-Grading Manual (2000), can be classified as type AA - excellent quality ($HU \geq 72$), A - good quality (HU 60 to 71), and B - medium/low quality ($HU \leq 59$). Thus, regardless of the illuminance level used, all eggs were classified as having AA quality (Table 8). When laying hens were exposed to fluorescent sources with 12, 57, and 122 lux, Erensoy *et al.* (2021) found no significant difference in HU among the treatments, and the eggs in all treatments were also classified as AA. Additionally, when Long *et al.* (2016a), Borille *et al.* (2015), Poudel *et al.* (2022a) and Archer (2019) subjected chickens to LED illuminations with intensities of 5 to 9, 20, 30 and 40 lux, respectively, they also obtained eggs with excellent HU values (≥ 82.5).

Therefore, the assumption that egg shells have distinct porosities did not affect the internal quality of the eggs. Notably, the variables related to egg quality were evaluated at intervals less than 24 hours after laying, minimizing possible exchanges of water and gases through the shell. Thus, it was found that this evaluation interval was not sufficient to change the HU classification and that HU is mainly altered by egg storage time and temperature (Lana *et al.*, 2017).

The freshness of eggs is also related to the quality of the yolk; thus, another index for evaluating the internal quality of eggs is YI. The YI determines the quality of the yolk based on its consistency so that the higher its value is, the better the egg quality. With the aging of the eggs, the yolk membrane loses its strength (Spada *et al.*, 2012). In this study, the YI was not significantly ($p>0.05$, F test) among the different illuminance levels, t_{illu}, and flocks evaluated (Table 7).

When studying the effect of storage time and conditions on the internal egg quality of Isa Brown laying hens, Jucá *et al.* (2011) found that values considered normal for the YI were between 0.3 and 0.5. In addition, for Hy-Line W-36, values between 0.4 and 0.45 have been reported (Kazempoura and Jahanianb, 2017; Zang *et al.*, 2019). Considering these limits for YI, despite the differences between the strains, all treatments obtained a distribution of values (Table 8) within the normal range, and the lack of significant differences between the means indicated that the different illuminance levels did not affect the useful life of the eggs produced. Moreover, such results were expected because the yolk and albumen height are directly related to the egg weight (Sekeroglu and Altuntas, 2009), and both the HU and the EW were not significant among the light intensity variations. Erensoy *et al.* (2021) also found no significantly different difference in the YI for chicken eggs (Lohmann-Brown with age ranging from 20 to 40 weeks) subjected to treatments of 12, 57, and 122 lux, with values between 0.447 and 0.464. The thermal conditions to which the birds were subjected were 16.4°C of t_{air} and 63.4% RH, which were considered thermally comfortable by the authors.

In turn, PY and PS showed no differences in relation to flocks, illuminance levels, t_{illu}, and their interactions ($p>0.05$, F test). However, the effect of t_{illu} on PA was significant (Table 7). Thus, the Fig. 11 illustrates the PA variation throughout the t_{illu}, independent of the illuminance levels and flocks.

The PA had a negative correlation with the t_{illu} and it showed a decrease of 0.0522% for each day, regardless of the illuminance level provided, totaling a reduction of 1.46%. Tunaydin and Yilmaz Dikmen (2019) also observed a significant decrease in PA when exposing Nick Chick White laying hens to LED lamps with 12 lux. The reduction reported by the authors was 3.23% over a period of 20 weeks (between the 25th and 45th weeks of life). Such data resulted in a decrease rate of approximately 0.0231% per day of exposure. However, in the same study, there was also a significant increase of 3.94% in PY and a reduction of 0.7% in PS.

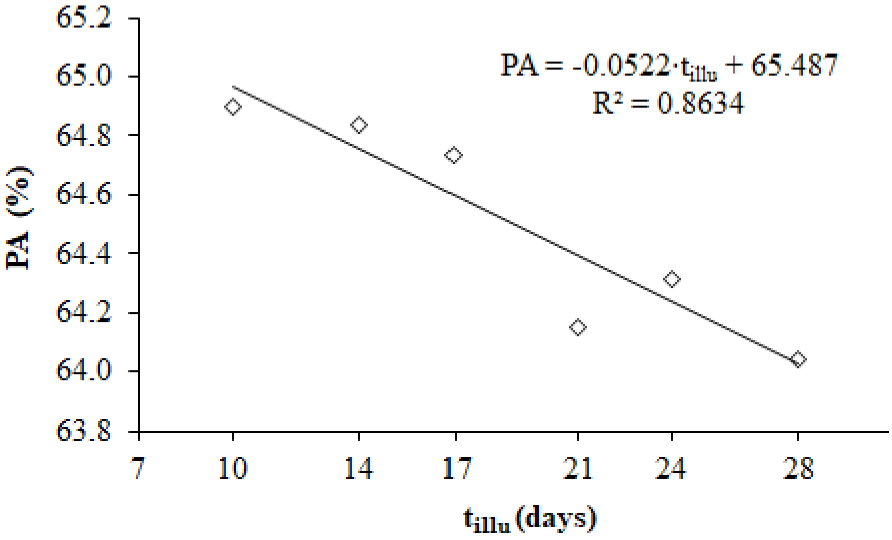

Fig 11. Percentage of albumen (PA) in eggs from laying hens as a function of illumination exposure time (t_{illu}), regardless of illuminances.

Therefore, because the illuminance treatments did not directly influence the hen physiological responses, production performance, and egg quality, it is understood that the modern Hy-Line W-80 hybrid laying hens are more tolerant to changes in environmental illuminance during rearing. This result is consistent with the results of Nasr *et al.* (2019), when evaluating Japanese quails. However, it should be noted that to define the complete state of well-being of hens with higher precision, additional analyses to evaluate whether the birds were in health is required, such as the serum biochemistry parameters, liver and kidney antioxidant ability. Furthermore, research on the influence of different light intensities on laying hens still lacks investigations into the biochemical characteristics of eggs. Wei *et al.* (2019) found that LEDs with B-wave ultraviolet can influence the vitamin D (1,25-dihydroxyvitamin D3) and cholesterol (7-dehydrocholesterol) content of egg yolks. However, the authors did not evaluate the effect of different illuminances.

It is also important to highlight, further research is needed in commercial facilities to evaluate production conditions using LED lighting technology, which is often offered in a complementary manner. Moreover, as the different light intensities did not result in significant differences in the results and 5 lux was sufficient for the birds to identify the feeders and drinkers, it is clear that lower illuminance levels can promote energy consumption savings. However, in addition to evaluating energy consumption, it is also necessary to evaluate whether some of the light intensities promote adequate lighting for the human work environment inside poultry houses without requiring supplementary lighting.

4 Conclusions

The results of this study showed that illuminance levels between 5 and 100 lux from LED light did not influence the physiological responses, production, or egg quality of Hy-Line W-80 laying hens. However, the illumination exposure time can influence some variables, such as cloacal and surface temperatures, feed intake, body weight, and albumen percentage. However, variations in these responses occurred very close to or within the expected limits. In addition, there was no evidence that the illuminance levels used in this study harmed the birds because the changes in their physiological responses remained within the recommended comfort ranges.

Egg quality variables, such as HU, YI, shell thickness, SG, and egg density, were not affected by the different illuminance levels from the tested LEDs, suggesting that these variables are more correlated with the thermal conditions of the rearing environment or egg house.

In a light environment, 28 days of acclimation is recommended for chickens during the laying period. Thus, environments with 5 lux of illuminance are sufficient to ensure bird access to the feeder and drinker and avoid discomfort and losses in production and egg quality.

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ARTICLE 2 - STATISTICAL AND FUZZY MODELING FOR ACCURATE PREDICTION OF FEED INTAKE AND SURFACE TEMPERATURE OF LAYING HENS SUBJECTED TO LIGHT CHALLENGES

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Highlights

- White LED light intensities were evaluated for rearing modern laying hens;
- Feed intake and surface temperature of laying hens are dependent on the interaction between the level of illuminance and the exposure time;
- FIS models tended to perform better than statistical models;
- The prediction models developed can help in making decisions about bird management.

STATISTICAL AND FUZZY MODELING FOR ACCURATE PREDICTION OF FEED INTAKE AND SURFACE TEMPERATURE OF LAYING HENS SUBJECTED TO LIGHT CHALLENGES

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Abstract: The use of artificial lighting for laying hens in poultry houses allows production optimization. However, the effect of recent lighting technologies needs to be investigated, as their use can affect the welfare of hens, causing biological rhythm, behavior, health, productive and reproductive performance and egg quality changes. Therefore, the objective of this study was to evaluate the physiological responses, productive performance and egg quality of hens under different light intensities. If a significant difference between treatments was found, statistical models and fuzzy inference systems (FISs) to predict such responses were developed and compared. Thus, 76 Hy-Line W-80 laying hens were housed in a controlled environment with temperature, relative humidity and air speed adjusted for bird comfort. The hens were exposed to illuminances of 5, 20, 50 and 100 lux for a period of 21 days. Among the evaluated response variables, only the mean feed intake (FI) and surface temperature (t_{surf}) of the hens had a significant interaction and interaction sliced by main factors ($p<0.05$), allowing statistical model adjustment. For these two variables, FISs were also developed so that the illuminance and the time of exposure to illumination (t_{illu}) were defined as input variables of the systems. As a result, the statistical models and FISs presented significant high-accuracy indexes when predicting the FI and the t_{surf} (except for R^2 values related to the statistical models), yet with an advantage for the FISs models, in which greater generalization capabilities were obtained in the validation step. Therefore, the developed models can be used to support decisions related to the management of hens, supporting the smart production, with emphasis on FISs based on expert knowledge, since they can be used to obtain predicted responses in different scenarios in addition to those evaluated experimentally with high accuracy.

Keywords: laying poultry, light intensity, mathematical modeling, fuzzy inference systems, support smart production, zootechnical responses predicting.

1 Introduction

In poultry sector, egg production from laying hens stands out (Mehlhorn and Petow, 2020). Thus, since enterprises have the potential to increase their profitability (Omomule *et al.*, 2020) and increasingly seek to promote bird welfare, constant improvements in production systems have been implemented through the adoption of recent technologies and improved management.

Among the factors of the rearing environment, light exerts physiological stimuli that influence the behavior, biological rhythm, health, well-being, productive performance and egg quality of hens (Li *et al.*, 2019; Wei *et al.*, 2020; Zaguri *et al.*, 2020; Poudel *et al.*, 2022a). Therefore, artificial lighting has become a resource to optimize egg production (Barros *et al.*, 2020; Sobotik *et al.*, 2020). However, the influence of lighting on hens varies according to the light source, duration of the exposure period, wavelength and illuminance (Fernandes *et al.*, 2021; Xin *et al.*, 2021).

In this regard, among the various variables related to lighting, the light intensity has not yet been fully adapted to the needs of hens (Raccoursier *et al.*, 2019; Chew *et al.*, 2021; Sadvakassova *et al.*, 2022). Thus, the laying performance of modern laying hens is highly dependent on the lighting used during housing (England and Ruhnke, 2020), and under controlled conditions, the appropriate lighting parameters can be obtained (Li *et al.*, 2018).

In this context, according to Erensoy *et al.* (2021), there is a hypothesis that from the beginning of laying, excessive light intensity is increasingly harmful to the responses of hens. Thus, for laying hens, intensities below 5 and above 50 lux are not appropriate (Hy-Line, 2017). The aforementioned thresholds are in agreement with those observed by Chew *et al.* (2021), in which found no body mass decrease of Lohmann laying hens (white and brown) subjected to 10-50 lux light intensity. Therefore, the economic and welfare implications related to laying hens as a function of lighting need to be investigated.

Laying hens express their levels of comfort or discomfort through their physiological and productive responses, thus enabling these responses to be used to evaluate the efficiency of the management and the status related to welfare (Ponciano *et al.*, 2012). Due to the complexity of the interactions involved, decision support systems can be used to aid actions (Omomule *et al.*, 2020). In this context, mathematical and computational modeling has been successfully used as a methodology to describe the behavior of response variables in animals (Damasceno *et al.*, 2019; Hernández-Julio *et al.*, 2020; Lins *et al.*, 2021a; Ribeiro *et al.*, 2020). However, it should be noted that classical mathematical methods may not produce satisfactory results due to the subjectivity of the information and the presence of environmental factors in the systems (Akilli and Gorgulu, 2020). In addition, the application of methodologies based on artificial intelligence, such as fuzzy logic, is important in the resolution of complex problems that are not well defined and for which it is difficult to determine a solution or mathematical model (Singh and Gill 2010; Vargas-Rodriguez *et al*., 2022), such as zootechnical issues (Maziero *et al*., 2022).

Thus, several studies have obtained good performances when using fuzzy modeling applied to the simulations of productive and physiological responses of animals (Hernández-Julio *et al*., 2020; Omomule *et al*., 2020; Lins *et al*., 2021a, 2021b; Maziero *et al*., 2022). However, according to Klotz *et al*. (2022), considering adaptations over time is a fundamental feature for updating and implementing daily action plans, since the production conditions present dynamic scenarios. Moreover, due to the way the models are validated, the vast majority of developed fuzzy systems have not been tested for their ability to generalize to unknown scenarios, as in the cases presented in (Damasceno *et al*., 2019; Martínez *et al*., 2020; Lins *et al*., 2021b; Gabriel Filho *et al*., 2022). In addition, there is a lack of fuzzy studies on the influence of light intensity on laying hens.

Therefore, the objective of the present study was to verify the existence of the effects of different illuminances on the physiological responses, productive performance and egg quality of laying hens in the peak laying phase. If statistically significant effects were observed, empirical statistical models and fuzzy systems that describe these effects on the responses were developed, validated and compared.

2 Material and methods

This study was conducted in two stages, the experimental stage and the development of empirical statistical models and fuzzy systems stage. All management procedures applied during the experimental period were conducted after approval, under protocol no. 079/2017, by the Ethics Committee on Animal Use of the Federal University of Lavras.

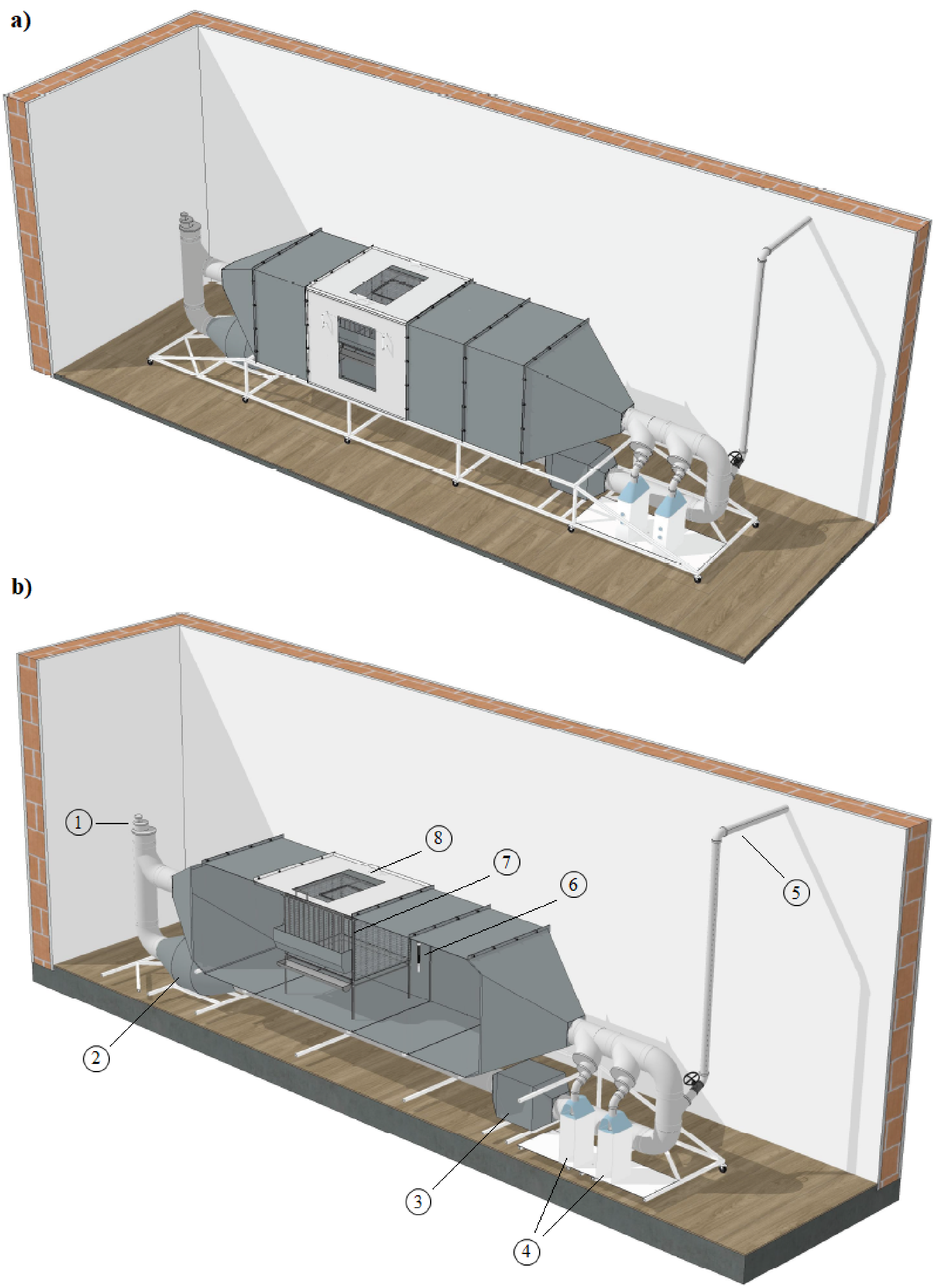
2.1 Experimental design

The experiment was conducted in an experimental laboratory, where 72 Hy-Line W-80 laying hens were housed in four climate-controlled wind tunnels. The hens were divided into three groups with 24 laying hens in each group (6 hens per tunnel), and the duration was 28 days. The execution of the experiment for groups 2 and 3 occurred consecutively after the end of the previous group (group 1). For each group, the hens were initially subjected to 7 days of acclimation (Qu *et al.*, 2018). Thus, during the experimental evaluation period of 21 days, the age groups of the chickens in groups 1, 2 and 3 were 26 to 28, 30 to 32 and 34 to 36 weeks, respectively. These age groups represent the peak production stages for this strain (Hy-Line, 2019).

The experimental treatments consisted of evaluating different light intensities from a white light-emitting diode (LED) source. Thus, in each wind tunnel, the hens were subjected to illuminances of 5, 20, 50 or 100 lux. The light program established was 16 hours of light and 8 hours of dark (Hassan *et al.*, 2013; Hy-Line, 2019; Wen *et al.*, 2019; Ribeiro *et al.*, 2020). Throughout the experimental period, the hens were kept in thermoneutral conditions, characterized by a temperature and relative humidity of 23°C and 60%, respectively (Barrett *et al.*, 2019; Philippe *et al.*, 2020; Ribeiro *et al.*, 2020). The air velocity inside each wind tunnel was set at 0.2 ms^{-1} to promote hygienic ventilation and air renewal (Sousa *et al.*, 2016; Abreu *et al.*, 2017; Bahuti *et al.*, 2018). Throughout the experimental period, water and feed were offered daily to the hens *ad libitum*, following the recommendations for experiments of this nature (Rana *et al.*, 2021; Poudel *et al.* 2022a; Sadvakassova *et al.*, 2022).

Each wind tunnel (Fig. 1) was equipped with a set of electrical resistances (totaling 2400 W), air humidifiers (total flow of 600 mL of water h^{-1}), an exhaust fan (40 cm in diameter and flow of 4200 m^3 h^{-1}) and a lighting system. Thus, it was possible to control the thermolumen environment independently in each tunnel. In addition, inside the tunnels, there was a cage (62 x 52 x 40 cm in length, width and height, respectively) equipped with a feeder, drinker and trough for collecting eggs.

The monitoring and control system of the hygrothermal environment inside the wind tunnels consisted of a datalogger (CR1000, Campbell Scientific®), a relay controller (SDM-CD16AC, Campbell Scientific®) and a channel multiplexer (AM16/32B, Campbell Scientific®). The thermal variables were measured using temperature and relative humidity sensors (HMP45C, Vaisala®) with accuracies of 0.3 °C and 2.0%, respectively. In turn, the illuminances were adjusted using a digital lux meter (SKLD-400, SKILL-TEC, accuracy of ± 3%) and were checked weekly.



1 – Air intake piping
2 – Exhaust fan
3 – Electric heaters compartment
4 – Set of air humidifiers
5 – Air outlet piping (for air renewal)
6 – Temperature and relative humidity sensor (HMP45C)
7 – Cage
8 – Inspection window (transparent material)

Note: To obtain uniformity in the adjusted illuminances, a prototype of a linear lighting system with white LEDs was distributed over the top of the cage, however, it is not represented.

Fig 1. Perspective (a) and perspective section (b) of the wind tunnel.

2.2. *Collection of response variables*

Throughout each of the experimental groups, physiological and productive variables and egg quality of all treatments were collected.

The physiological responses of cloacal temperature (t_{clo}, °C), surface temperature (t_{surf}, °C) and respiratory rate (RR, mov min^{-1}) were evaluated. Regarding the productive responses, the mean feed intake (FI, g), mean water intake (WI, mL), mean body weight (BW, g), mean egg weight (EW, g), feed conversion (FC, g of feed · g of egg^{-1}), laying percentage (LP, % $bird^{-1}$ day^{-1}) and percentage of viable eggs (PVE, %) were quantified. In turn, the external and internal characteristics of the eggs, such as shell density (ESD, mg cm^{-2}), specific gravity (SG, g cm^{-3}) of the eggs, eggshell thickness (EST, mm), and percentages of eggs shell, albumen and yolk (PS, PA and PY, respectively, %), Haugh unit (HU) and yolk index (YI), were measured.

All physiological responses and egg quality were evaluated on days 10, 14, 17, 21, 24 and 28 for each experimental group as well as the BW. The productive responses were collected daily. It should be noted that the number of days to evaluate the physiological responses and BW was defined to avoid stress to the animals due to the complexity of obtaining the variables. Thus, the same pattern was followed for egg quality to maintain the same statistical model.

2.3. *Experimental design and statistical modeling*

A completely randomized block experimental design was adopted in a plot scheme subdivided by the treatments in the plot (illuminances of 5, 20, 50 and 100 lux) and times of exposure to illumination (t_{illu}) in the subplot (10, 14, 17, 21, 24 and 28 days). The statistical model considered was:

$$y_{ijk} = \mu + \tau_i + \beta_j + \epsilon_{ij} + \gamma_k + \beta\gamma_{jk} + \tau\gamma_{ik} + \varepsilon_{ijk}$$

where y_{ijk} is the value observed in the portion of block j that received treatment i evaluated at time k, with $i = 1, 2, 3, 4$, $j = 1, 2, 3$ and $k = 1, 2, 3, 4, 5, 6$; μ is a constant associated with each observation; τ_i is the effect of treatment *i;* β_j is the effect of block j, which corresponds to the effect of the group; ϵ_{ij} is the whole-plot error; γ_k is the t_{illu} effect on *k*; $\beta\gamma_{jk}$ is the effect of the interaction between the block and t_{illu}; $\tau\gamma_{ik}$ is the effect of the interaction between the treatment and t_{illu}; and ε_{ijk} is the subplot error, where $\varepsilon_{ijk} \sim N(\mu, \sigma^2)$.

The productive variables, egg quality and physiological responses, were subjected to the Kolmogorov–Smirnov normality test and analyzed by analysis of variance (ANOVA) and regression analysis. All statistical analyses were performed using SISVAR (Ferreira, 2019).

2.4. Fuzzy modeling

After data collection, Mamdani fuzzy inference systems (FISs) were developed for those variables from which a statistic difference in the interaction between the illuminance and t_{illu} was determined when evaluating t_{illu} at a given intensity. The Mamdani inference was selected because it has a history of efficient results with different types of membership functions (Hernández-Julio *et al*., 2020; Lins *et al*., 2021a; Amorim *et al*., 2022).

Thus, first, the illuminance values and t_{illu} were defined as inputs of the fuzzy system. Subsequently, fuzzification was performed, in which the pertinence functions of these variables were delimited (Figs. 2 and 3). Thus, for the physiological responses, egg quality and BW, the variable t_{illu} had 6 membership functions (Fig. 3a), referring to the days on which collections were performed (days 10, 14, 17, 21, 24 and 28). In turn, for the productive responses, the same input variable t_{illu} was defined with 19 membership functions (Fig. 3b), referring to the frequency of daily collection of experimental data. In this model, days 8 and 9 were not considered to maintain the same domain for both FIS and adjusted statistical models.

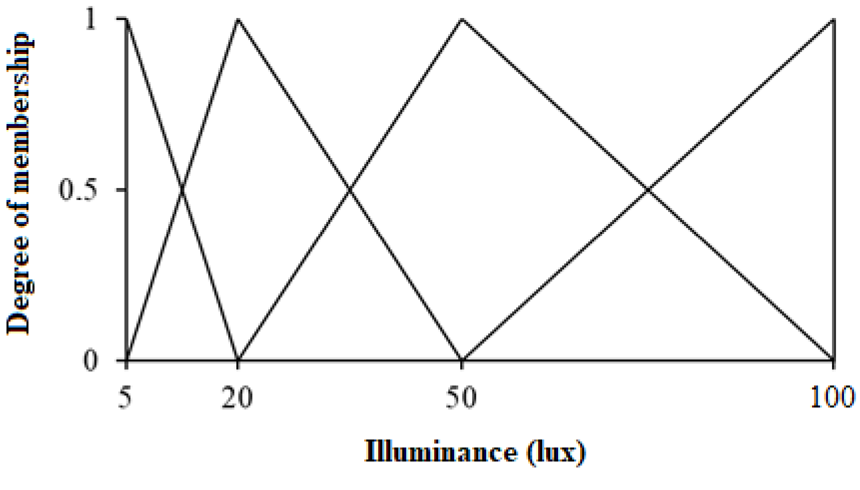
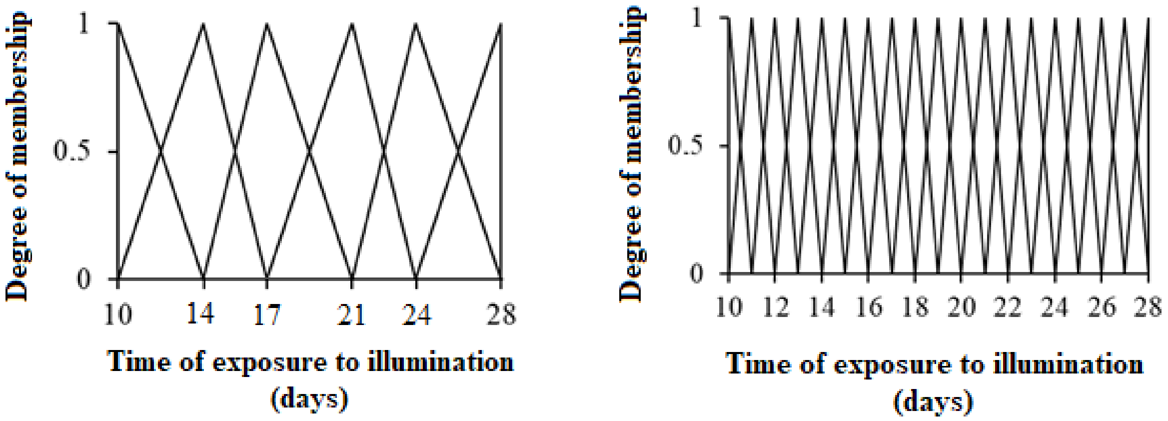


Fig 2. Membership functions of the fuzzy input set for the illuminance variable.



(a) (b)

Fig 3. Membership functions of the input fuzzy sets for the variable time of exposure to illumination defined for (a) physiological responses, egg quality and mean body weight and (b) productive responses.

For both the fuzzification of the inputs and the definition of the rules system, three experts were consulted according to the expert selection methodology (Cornelissen *et al.*, 2003), a procedure that has been used by several authors (Hernádez-Julio *et al.*, 2020; Lins *et al.*, 2021a; Amorim *et al.*, 2022). Thus, the rules were developed based on the combinations of the inputs; a total of 24 rules were developed for the FIS of the physiological responses, egg quality and BW and 76 rules were developed for the FIS of the productive responses. In addition, a weighting factor of 1 was adopted for all rules (Hernández-Julio *et al.*, 2020; Omomule *et al.*, 2020; Maziero *et al.*, 2022), regardless of the output.

Finally, in relation to defuzzification, all the methods available in the MATLAB ® Fuzzy Logic Designer for Mamdani inference were evaluated, namely, center of gravity of the area (COG or centroid), bisector of area (BOA or bisector), largest of maximum (LOM), mean of maximum (MOM) and smallest of maximum (SOM) (Wang and Chen, 2014; Amindoust and Saghafinia, 2017). This procedure allowed the verification of the best fuzzy system configuration to obtain the smallest simulation errors (Bahuti *et al.*, 2018; Alamroshan *et al.*, 2022; Çalmaz,and Neslihan, 2022).

2.5. Model performance

According to Tedeschi (2006), the verification of the performance of the models is an important step to increase the confidence in the developed model or allow the selection of alternative models.

Therefore, to evaluate the performance of fuzzy systems and statistical models, the simulated data from a validation set (containing 30% of the total data) were compared to those obtained experimentally using Student's t-test and statistical indices such as bias, mean absolute error (MAE), mean absolute percentage error (MAPE), coefficient of determination (R^2) and root mean square error (RMSE), calculated by Eqs. (1) - (5), respectively.

$$\text{Bias} = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \tag{1}$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|P_i - O_i| \tag{2}$$

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n} \left|\frac{P_i - O_i}{O_i}\right| \cdot 100 \tag{3}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(P_i - \bar{P}) \cdot (O_i - \bar{O})}{\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2 \cdot \sum_{i=1}^{n}(O_i - \bar{O})^2}}\right]^2 \tag{4}$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{5}$$

where

n = total number of samples; P_i = i-th predicted values; O_i = i-th value observed; $\overline{P}$ = mean of the predicted values and $\overline{O}$ = mean of the observed values.

3 Results and discussion

3.1 Analysis of variance

All the response variables evaluated showed normal distribution (p>0.05, Kolmogorov–Smirnov test). Thus, the ANOVA results for the physiological, productive and egg quality responses are listed in Table 1. It can be seen that the variables t_{clo}, t_{surf}, BW and EST were the only variables influenced by the age of the hens (experimental groups). These results were expected for EST and BW because, in the period between 25 and 36 weeks of age, there is a natural increase in the BW of the hens under correct management (Hy-Line, 2019). In addition, advancing hen age can also affect shell formation (Sirri *et al.*, 2018; Poudel *et al.*, 2022b).

In turn, the illuminance or t_{illu} factors were significant for t_{surf}, FI, BW and PA. However, the interest for this study is in the interaction between illuminance and t_{illu}, since for the development of fuzzy systems, it is interesting to use at least two variables with a correlation. Thus, the illuminance and t_{illu} were the factors defined as inputs of the fuzzy systems (Figs. 2 and 3).

Table 1. Results of the analysis of variance, according to the statistical model adopted, for all response variables evaluated.

Category	Response variable	Sources of variation in ANOVA			
		Group (age group)	**Illuminance**	**t_{illu}**	**Interaction (illuminance x t_{illu})**
Physiological	t_{clo}	p=0.0083 *	p=0.0545 ^{NS}	p=0.8286 ^{NS}	p=0.0365 *
	t_{surf}	p=0.0006 *	p=0.0088 *	p=0.1629 ^{NS}	p=0.0173 *
	RR	p=0.4094 ^{NS}	p=0.5364 ^{NS}	p=0.1626 ^{NS}	p=0.8107 ^{NS}
Productive performance	FI	p=0.7418 ^{NS}	p=0.3688 ^{NS}	p=0.0057 *	p=0.0176 *
	WI	p=0.2977 ^{NS}	p=0.4905 ^{NS}	p=0.5688 ^{NS}	p=0.4422 ^{NS}
	EW	p=0.0798 ^{NS}	p=0.6906 ^{NS}	p=0.0958 ^{NS}	p=0.8804 ^{NS}
	FC	p=0.8910 ^{NS}	p=0.1533 ^{NS}	p=0.7977 ^{NS}	p=0.7911 ^{NS}
	BW	p=0.0081 *	p=0.1028 ^{NS}	p=0.0000 *	p=0.5958 ^{NS}
	LP	p=0.3401 ^{NS}	p=0.1111 ^{NS}	p=0.6583 ^{NS}	p=0.1393 ^{NS}
	PVE	p=0.9047 ^{NS}	p=0.0539 ^{NS}	p=0.6137 ^{NS}	p=0.4046 ^{NS}
Egg quality	EST	p=0.0021 *	p=0.8309 ^{NS}	p=0.6932 ^{NS}	p=0.1206 ^{NS}
	ESD	p=0.6178 ^{NS}	p=0.7850 ^{NS}	p=0.3025 ^{NS}	p=0.9421 ^{NS}
	SG	p=0.0755 ^{NS}	p=0.3965 ^{NS}	p=0.9969 ^{NS}	p=0.3206 ^{NS}
	PS	p=0.4273 ^{NS}	p=0.7881 ^{NS}	p=0.4326 ^{NS}	p=0.9657 ^{NS}
	PA	p=0.1368 ^{NS}	p=0.7628 ^{NS}	p=0.0162 *	p=0.8825 ^{NS}
	PY	p=0.0808 ^{NS}	p=0.8554 ^{NS}	p=0.0820 ^{NS}	p=0.4989 ^{NS}
	HU	p=0.5891 ^{NS}	p=0.5943 ^{NS}	p=0.1934 ^{NS}	p=0.2858 ^{NS}
	YI	p=0.2016 ^{NS}	p=0.6159 ^{NS}	p=0.2760 ^{NS}	p=0.4352 ^{NS}

ANOVA = analysis of variance, t_{illu} = times of exposure to illumination (days), t_{clo} = cloacal temperature (°C), t_{surf} = surface temperature (°C), RR= respiratory rate (mov. min^{-1}), FI = mean feed intake (g bird^{-1}), WI = mean water intake (mL bird^{-1}), EW = mean egg weight (g), FC = feed conversion (g of feed · g of egg^{-1}), BW = mean body weight (g), LP = laying percentage (% bird^{-1} day^{-1}), PVE = percentage of viable eggs (%), EST = eggshell thickness (mm), ESD = eggshell density (mg cm^{-2}), SG = specific gravity of eggs (g cm^{-3}), PS = percentage of shell (%), PA = percentage of albumen (%), PY = percentage of yolk (%), HU = Haugh unit, YI = yolk index, * = significant ($p<0.05$, F test), NS = not significant ($p>0.05$, F test).

Thus, the interaction was significant for the t_{clo}, t_{surf} and FI responses. For the variable t_{clo}, the effect of the t_{illu} levels when it was fixed the illuminance levels were not significant

($p>0.05$). However, for FI and t_{surf}, effect of the t_{illu} levels were significant ($p<0.05$) when all levels of illuminance were fixed. In view of this, empirical statistical models and FISs were developed to describe the behaviors of FI and t_{surf}.

3.2 Statistical models

After slicing the interaction between the treatment and t_{illu}, Eqs. (6-9) and (10-13) were fitted to estimate FI and t_{surf}, respectively, as a function of t_{illu}. All fitted models were statistically significant (F test, $p<0.05$), and their coefficients were also significant (t test, $p<0.05$). The standard error values of each coefficient are specified in parentheses and must be disregarded when applying the equations. The models fitted for FI and t_{surf} are valid for the t_{illu} range from 10 to 28 days.

$$FI_{(5lux)} = 0.3802\ (\pm 0.110) \cdot t_{illu} + 101.6974\ (\pm 2.1926) \tag{6}$$
$$R^2 = 0.7808$$

$$FI_{(20lux)} = 0.6594\ (\pm 0.110) \cdot t_{illu} + 93.7821\ (\pm 2.1926) \tag{7}$$
$$R^2 = 0.9585$$

$$FI_{(50lux)} = -0.0541(\pm 0.0205) \cdot t_{illu}^2 + 2.0566(\pm 0.7862) \cdot t_{illu} + 91.4205(\pm 6.9968) \tag{8}$$
$$R^2 = 0.7787$$

$$FI_{(100lux)} = 0.3945\ (\pm 0.110) \cdot t_{illu} + 101.3758\ (\pm 2.1926) \tag{9}$$
$$R^2 = 0.6574$$

$$t_{surf(5lux)} = -0.0629\ (\pm 0.0247) \cdot t_{illu} + 28.5934\ (\pm 0.3316) \tag{10}$$
$$R^2 = 0.4818$$

$$t_{surf(20lux)} = -0.0602\ (\pm 0.0247) \cdot t_{illu} + 28.8607\ (\pm 0.3316) \tag{11}$$
$$R^2 = 0.4111$$

$$t_{surf(50lux)} = -0.0563\ (\pm 0.0247) \cdot t_{illu} + 28.0375\ (\pm 0.3316) \tag{12}$$
$$R^2 = 0.5941$$

$$t_{surf(100lux)} = -0.0677\ (\pm0.0247) \cdot t_{illu} + 28.7127\ (\pm0,.316) \qquad (13)$$

$R^2 = 0.6015$

In general, it is observed that the statistical models achieved better adjustments for FI when compared to t_{surf}, regardless of the illuminance evaluated. This result occurs because t_{illu} is not significant ($p>0.05$) for t_{surf} when evaluated alone (Table 1). Thus, as the regressions are adjusted for the t_{illu} by fixing the illuminance levels, the models for FI have higher R^2 values.

In this regard, based on data from several authors, Lewis and Morris (1999) developed a model that describes the behavior of FI as a function of illuminance (for the range of 1 to 100 lux) and obtained an R^2 of 0.938. However, the model has a negative relationship between light intensity and FI, which is contrary to the models developed in this study. It is noteworthy that such behavior was considered unexpected by the aforementioned authors. Prescott and Wathes (2002) found a preference for chickens to spend more time feeding in a lighter environment (200 lux) rather than darker environments (20, 6 and <1 lux). In turn, Erensoy *et al.* (2021) did not find an increase in the FI of chickens subjected to 12, 57 and 122 lux.

However, Eqs. (6-13), derived from the adopted statistical model, were developed using all information (100%) from the database, which is a characteristic procedure in ANOVA. Moreover, they have the limitation of estimating the variables only for a given illuminance (5, 20, 50 or 100 lux). Thus, to broaden the scope of use of the equations to enable the estimation of FI and t_{surf} for different values of illuminance and t_{illu}, multiple regression models were adjusted for FI and t_{surf} as a function of the illuminance levels (illu) and of t_{illu}, both using 70% of the information in the database.

The best fit, i.e., the models were significant (F test, $p<0.05$) as well as all their coefficients (t test, $p<0.05$), was obtained using Eqs. (14) and (15). Again, the standard error values of each coefficient are specified in parentheses to indicate the magnitude of the error associated with the constant fit but should be disregarded in the application of the equations. In addition, the equations are valid for the intervals of $5 \leq illu \leq 100$ lux and $10 \leq t_{illu} \leq 28$ days.

$$FI = 102.0463\ (\pm2.1226) - 0.2031\ (\pm0.0813) \cdot illu + 0.3388\ (\pm0.1064) \cdot t_{illu} + 0.0252\ (\pm0.0087) \cdot (illu \cdot t_{illu}) - 0.0007\ (\pm0.0002) \cdot (illu \cdot t_{illu}^2) \qquad (14)$$

$R^2 = 0.5915$

$$t_{surf} = 31.8025\ (\pm 1.0200) - 0.0267\ (\pm 0.0113) \cdot illu - 0.3761\ (\pm 0.1126) \cdot t_{illu} + 0.0003\ (\pm 0.0001) \cdot illu^2 + 0.0079\ (\pm 0.0029) \cdot t_{illu}^2 \quad (15)$$

$R^2 = 0.6334$

When comparing the R^2 value of 0.5915 with the values using Eqs. (6-9), a lower performance is observed for the multiple regression model adjusted for FI. However, this model has greater practical application capacity because it allows simulations of light intensities different from those experimentally tested (5, 20, 50 and 100 lux). In turn, the highest R^2 value was obtained with the multiple regression model for t_{surf} than all the simple regression models (Eqs. (7-13)), indicating that the exclusion of 30% of the information decreased the variability of the database and favored the fit of the model. This result supports the work by the authors in Cecchin *et al.* (2016), who mentioned that the variability of t_{surf} is a factor that reduces the efficiency of models, even those based on expert knowledge.

Thus, the remaining 30% of the data were used to validate Eqs. (14) and (15). As a result of the multiple regression model adjusted for FI, the bias, MAE, MAPE and RMSE performance indicators were -0.448, 1.708, 1.571 and 2.216, respectively. For the prediction of t_{surf}, values equal to 0.030, 0.491, 1.784 and 0.671, respectively, were obtained for the same indices.

Fig. 4 illustrates the functional relationship between the values observed experimentally and those predicted in the validation using Eqs. (14) and (15). It is observed that the R^2 values obtained do not refer to high precision models. However, this result does not indicate that the values observed and predicted by the model are not correlated because the data may have a curvilinear rather than linear relationship (Tedeschi, 2006).

Furthermore, when comparing the means of the predicted and experimentally observed values, for both multiple regression models, the Student's t-test result was not significant ($p>0.05$). Lewis and Morris (1999) obtained a mean standard deviation of 1.79 g for the FI model as a function of illuminance, while the mean deviation of Eq. (14) was 1.4 g.

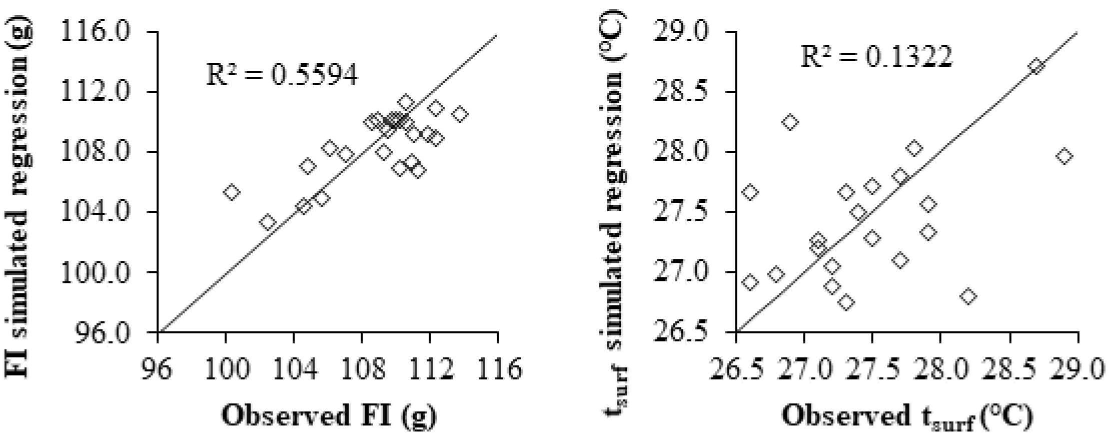


Fig 4. Functional relationship between the values of feed intake (observed FI) and surface temperature (observed t_{surf}) experimentally observed and predicted by multiple linear regressions (FI and t_{surf} simulated regression) during validation.

3.3 Fuzzy systems

3.3.1 Feed intake

As in the fuzzification stage, the definition of the fuzzy sets for the FI output variable was also performed based on expert knowledge. Thus, two FISs were initially generated, one with outputs represented by triangular membership functions and the other with trapezoidal functions. Thus, both systems were validated with a set of 30% of the data using all defuzzification methods.

Fig. 5 illustrates the fuzzy set of outputs that best fit the model (trapezoidal membership functions), and Fig. 6 illustrates the summary of the developed Mamdani FIS.

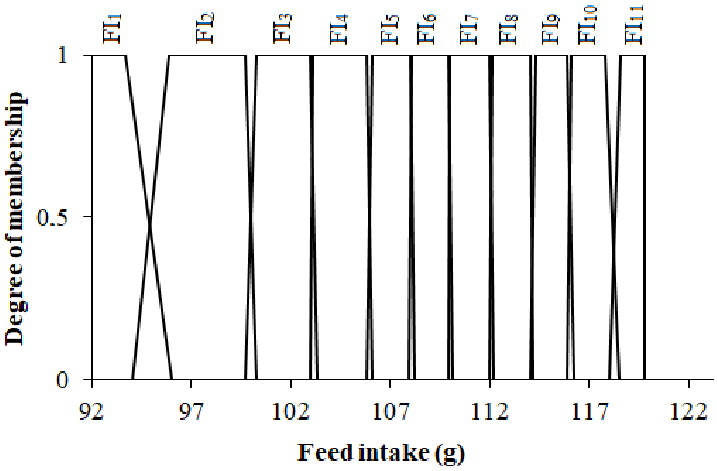


Fig 5. Fuzzy set with the best suitability for output variable mean feed intake.

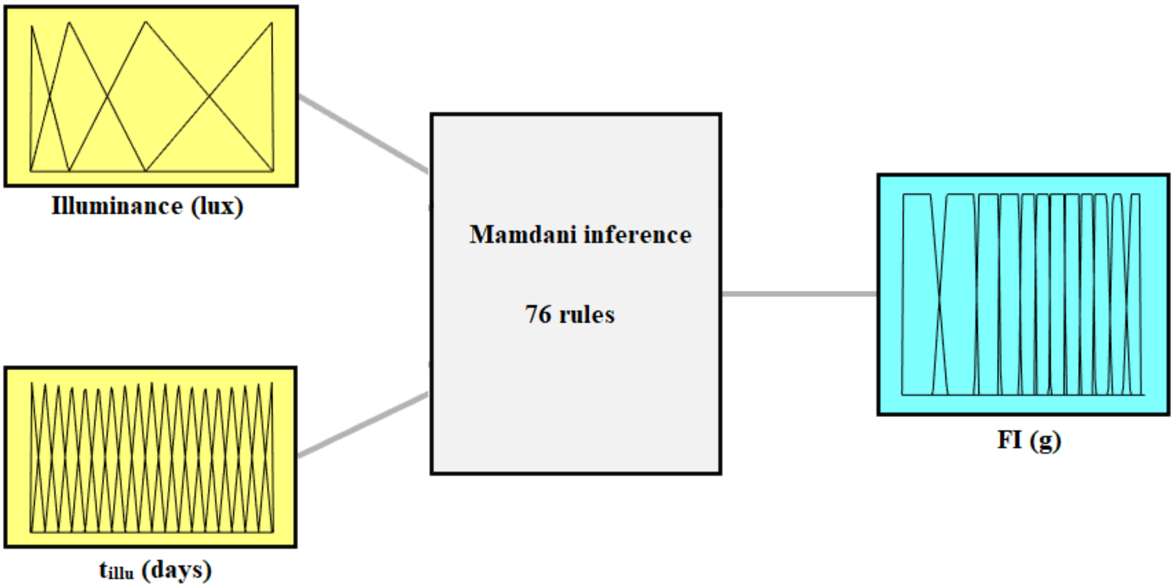


Fig 6. Summarized representation scheme of the fuzzy inference system developed to predict the mean feed intake (FI) as a function of illuminance and time of exposure to illumination (t_{illu}).

The best results were obtained by the bisector defuzzification method, and the bias, MAE, MAPE and RMSE performance indicators were 0.010, 1.335, 1.218 and 1.585, respectively. These values are lower than those of models considered accurate and with good generalization capacity (for example, MAPE = 1.43) (Amini *et al*., 2020; Omomule *et al*., 2020), indicating the efficiency of the proposed FIS model in simulating the response variable.

In Lourençoni *et al*. (2019), when a fuzzy model was used to predict the FI of broiler chickens based on enthalpy values, an MAPE of 5.05 was obtained. However, the aforementioned study was conducted from commercial environment data, which increases their variability. In turn, Castro *et al*. (2019) developed FIS to predict the FI of Japanese quails raised in an experimental facility or wind tunnels under different thermal conditions and obtained an MAPE equivalent to 2.26.

Furthermore, in the age group that comprises the experimental period, the lineage manual (Hy-Line, 2019) specifies the estimate for the FI with an MAPE equivalent to 4.4. Thus, the FIS developed in this study is also accurate within the limits established by the poultry supplier.

According to Tedeschi (2006), R^2 is a good indicator of accuracy, and the validation of the model resulted in an overall R^2 of 79.55%. In this regard, Castro *et al*. (2019) obtained a R^2 of 93% when estimating the FI of quails also reared in a controlled environment. However, when performing the validation and comparing the observed data with those estimated by the fuzzy model, the authors took advantage of the dataset used for the development of the FIS. In addition, according to Campos *et al.* (2013), an FIS model with R^2 of 75.45% can be considered efficient. In this regard, the result of Student's t-test comparing the means of the values observed and predicted by the FIS was not significant ($p>0.05$), indicating the suitability of the FIS developed in this study.

Thus, to analyze more than the overall performance of the model, Fig. 7 illustrates the functional relationship between the predicted and observed data, in addition to the bias, in the different illuminance ranges evaluated.

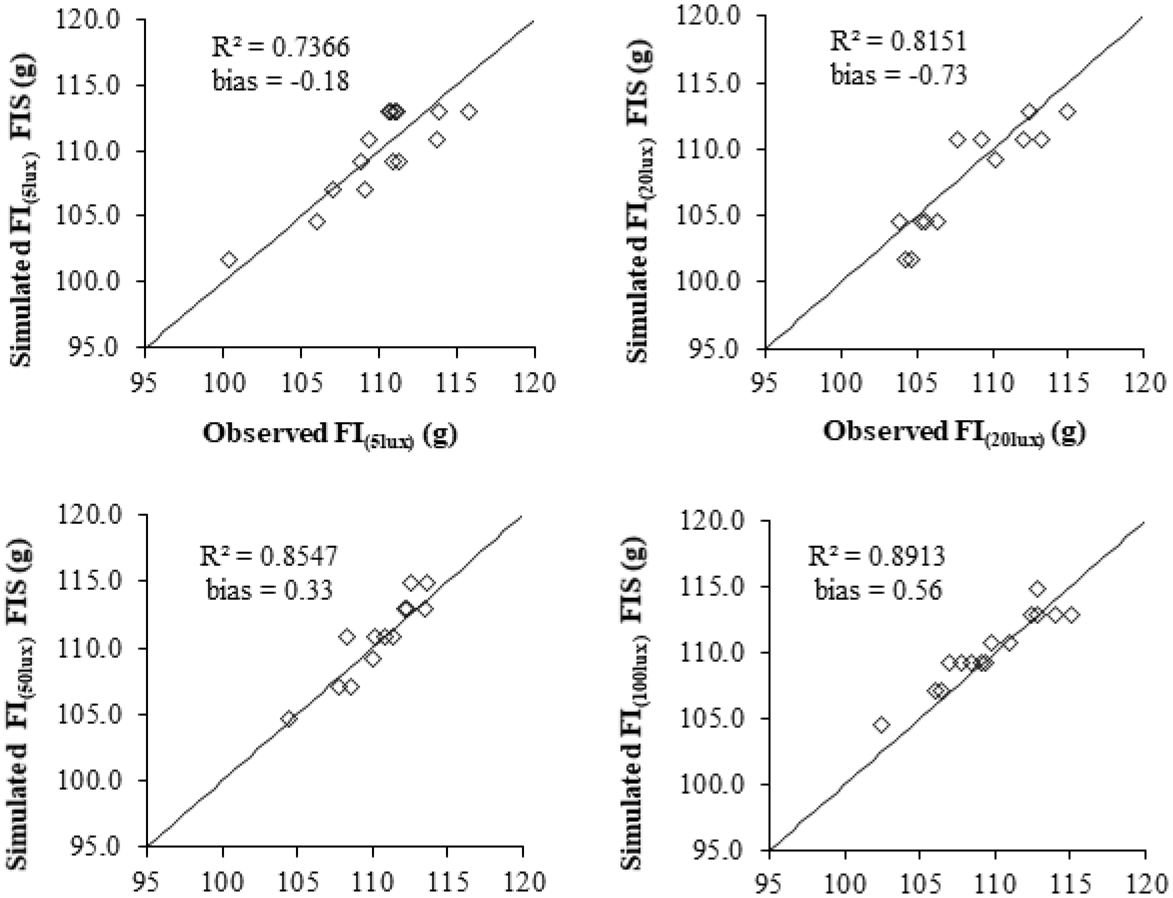


Fig 7. Functional relationship between the feed intake values obtained experimentally (observed FI) and predicted by the fuzzy inference systems (simulated FI FIS) during validation for the conditions of 5, 20, 50 and 100 lux.

The graphs show that at all intensities evaluated, the model results in outputs above and below the x = y line. However, the bias values indicate that, in general, the model underestimates FI for 5 and 20 lux and overestimates FI for 50 and 100 lux. In this context, Omomule *et al.* (2020) developed a model for predicting egg productivity using centroid defuzzification and obtained all overestimated outputs. This result of Omomule *et al.* (2020) indicates that tests with other defuzzification methods could be used to improve the overall accuracy of the model and cause some underestimated or exact outputs, as occurred in this study when using bisector defuzzification.

3.3.2 Surface temperature

Similarly, all the processes performed for the development of the FIS to predict the FI were also applied to develop the FIS that describes the behavior of t_{surf}. Thus, during the validation process, all defuzzification methods were tested. In addition, output sets were also generated from triangular and trapezoidal membership functions. The fuzzy sets for the output t_{surf} that obtained the best results are shown in Fig. 8. Fig. 9 illustrates the summary of the FIS developed to describe the behavior of t_{surf}.

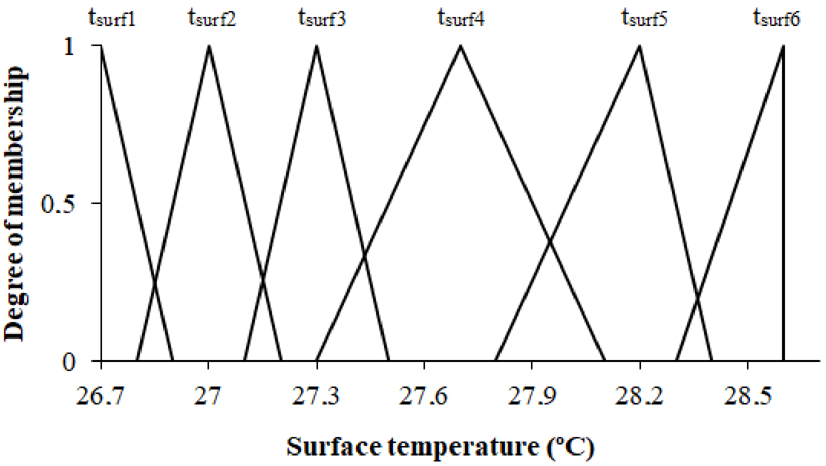


Fig 8. Fuzzy set with the best suitability for output variable surface temperature.

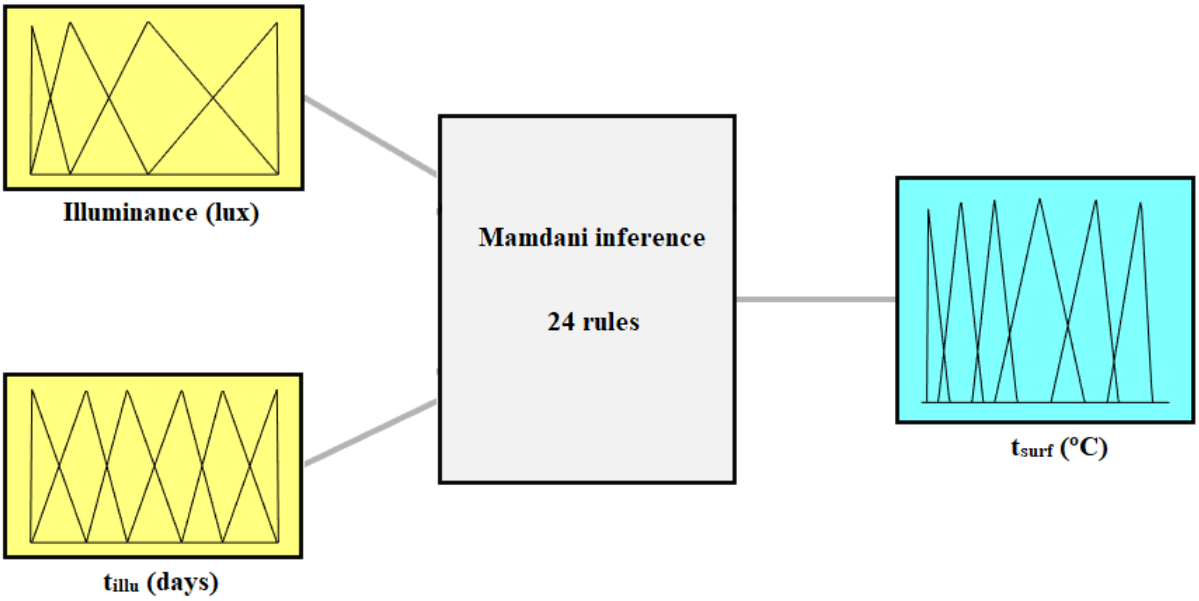


Fig 9. Summarized representation scheme of the fuzzy inference system developed to predict the surface temperature (t_{surf}) as a function of illuminance and time of exposure to illumination (t_{illu}).

The best results were obtained using the MOM, LOM and SOM defuzzification methods, which showed identical results, with the bias, MAE, MAPE, RMSE and R^2 indicators equal to -0.080, 0.199, 0.717, 0.270 and 0.8383, respectively. These results are better than those reported in other models that were considered adequate (Marques *et al.*, 2016; Omomule *et al.*, 2020; Lins *et al.*, 2021b; Amorim *et al.*, 2022).

Cecchin *et al.* (2016), when developing FISs to predict the t_{surf} of growing and finishing pigs as a function of age and temperature-humidity index (THI), obtained a R^2 value of 0.5872. Thus, the authors classified the model as unsatisfactory, justifying that the t_{surf} of animals has high variation, requiring a model with a higher R^2 value. It is noteworthy that a R^2 value with superior performance was obtained in the system developed in this study. In this context, the model obtained adequate performance because, similar to the FI result, the t-test was not significant ($p>0.05$) when comparing the means of the values predicted by the FIS and those observed experimentally.

Thus, Fig. 10 shows the correlation graphs between the t_{surf} experimentally obtained and those predicted by the FIS in the four illuminance conditions evaluated. Based on these graphs, it is observed that the prediction of the values occurs with lower efficiency ($R^2 = 0.6674$) only for the illuminance of 20 lux. However, similar to the R^2 values obtained using Eqs. (14) and (15) (Fig. 4), the value does not indicate the absence of correlation.

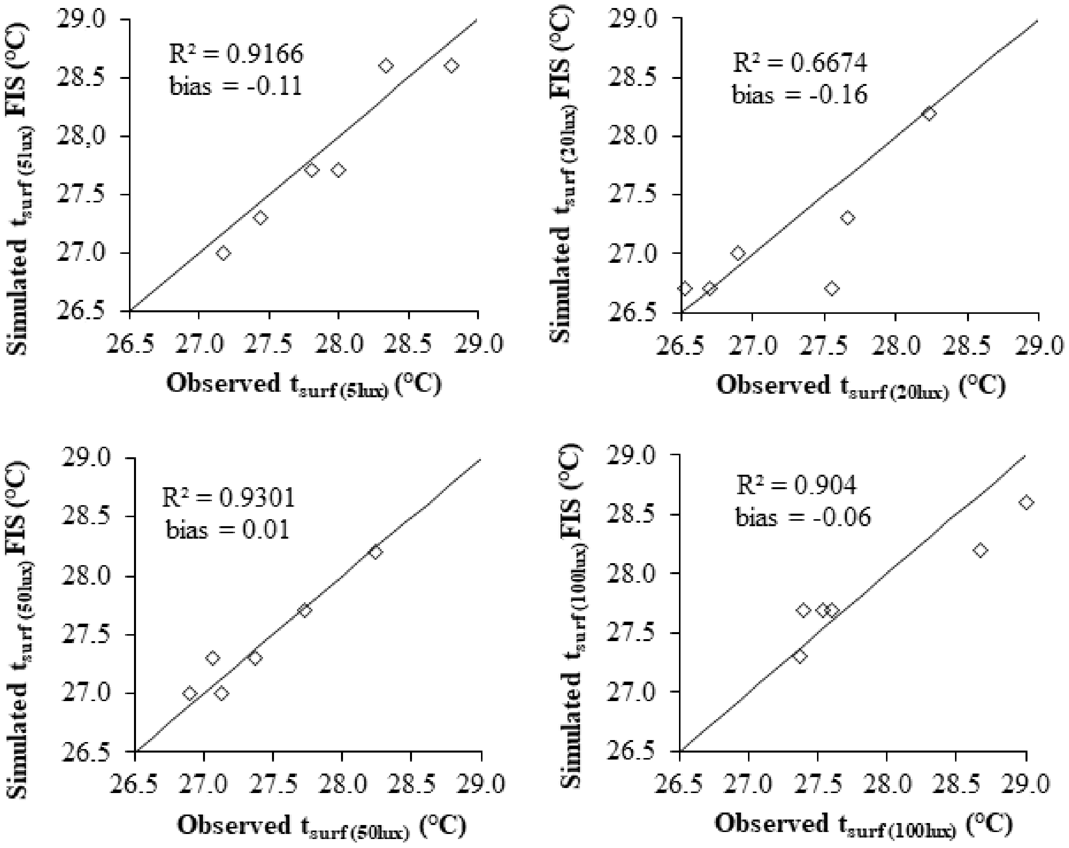


Fig 10. Functional relationship between the surface temperature values obtained experimentally (observed t_{surf}) and predicted by the fuzzy inference systems (simulated t_{surf} FIS) during validation for the conditions of 5, 20, 50 and 100 lux.

3.4 Comparison between prediction methodologies

The analysis of the model's suitability is an essential step in the modeling process because it indicates the level of efficiency of the model's predictions (Tedeschi, 2006). In this context, to compare the statistical models and fuzzy systems developed, the predicted and observed data were compared at 10, 14, 17, 21, 24 and 28 days. Thus, Fig. 11 illustrates the differences between the FI values observed experimentally (considering 100% of the database) and those predicted by the FIS and statistical models (Eq. (14)) for illuminances of 5, 20, 50 and 100 lux.

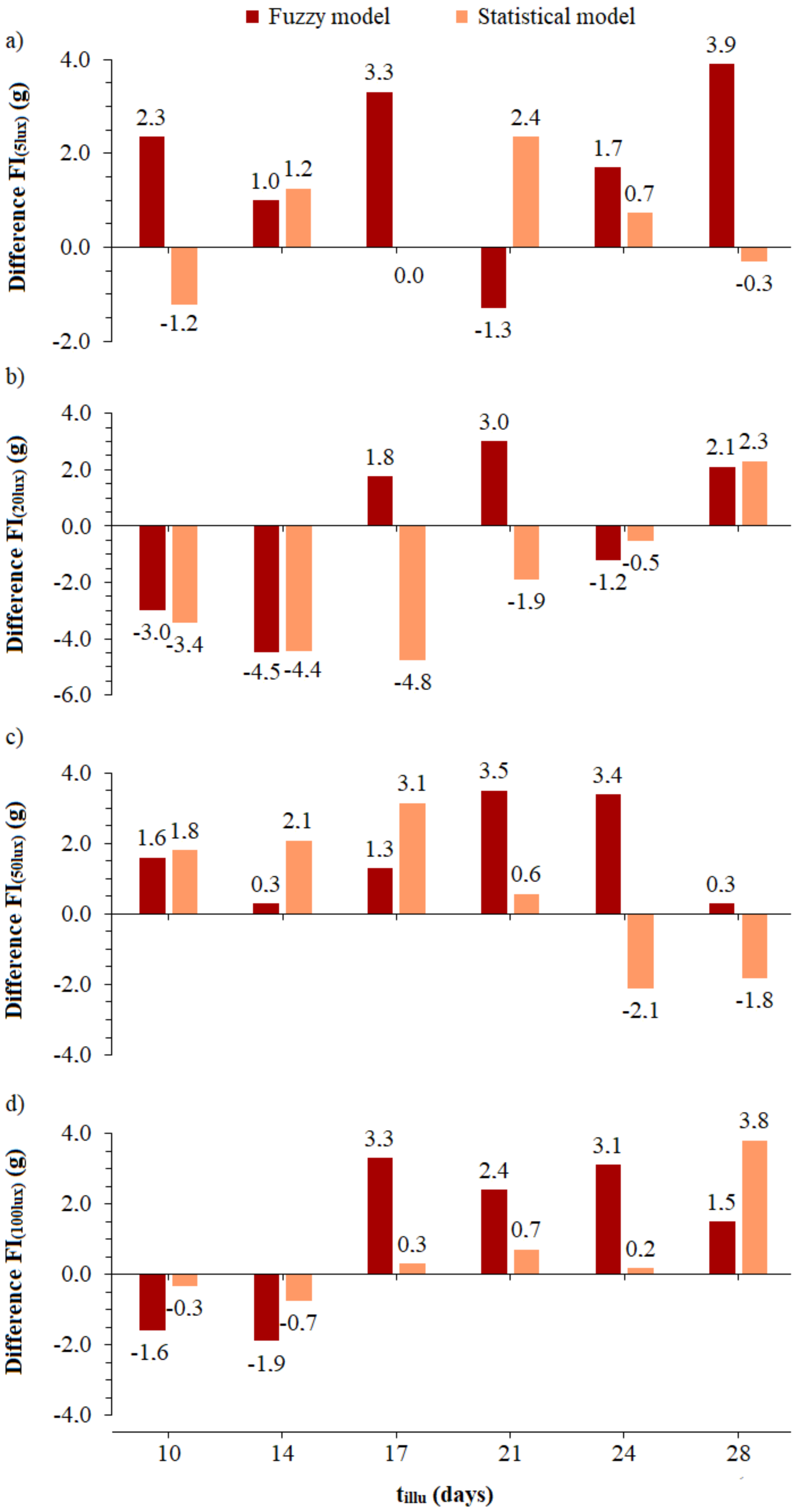


Fig 11. Differences in estimates of mean feed intake (FI, g), compared to the experimentally obtained, using the fuzzy and multiple statistical models, for the illuminances of a) 5 lux, b) 20 lux, c) 50 lux and d) 100 lux, in the times of exposure to illumination (t_{illu}) evaluated.

In Fig. 11, it is observed that in certain circumstances, the models alternate the underestimation and overestimation conditions of the FI. Generally, the output values of the FIS have greater divergence in relation to the observed data because in 58% of the scenarios evaluated, a difference greater than that of the statistical model (Eq. (14)) was obtained using the FIS. In addition, the largest discrepancy between the sum of the moduli of the values presented by the statistical and FIS models occurred for the 100 lux condition, although the highest R^2 value was obtained for this condition during validation (Fig. 7). However, when analyzing the data in Fig. 11, the values simulated by the FIS and statistical models were compared to the set of 100% of experimentally observed data, instead of 30% as in the validation step. Thus, the statistical model obtained outputs close to the means of the total experimentally observed data. However, when comparing the statistical indicators (bias, MAE, MAPE, RMSE and R^2) with those of the FIS model, it was found that the FIS has a greater generalization capacity.

Therefore, simulations were performed to represent the difference between the models and to analyze the ability to generalize in a practical manner. For this purpose, the FI accumulated over 19 days (from days 10 to 28) was estimated using the two methodologies. Table 2 lists the accumulated FI values obtained experimentally and simulated by the models under each lighting condition. The total FIs of medium- and large-sized poultry houses are also listed based on the cumulative FIs per hen that were observed and predicted by the models.

Table 2 shows the FI values for the different illuminances. The exception between the observed values was for the illuminance of 20 lux, in which the accumulation per hen showed a reduction of 50 g in relation to the other treatments. However, despite the low difference, the reduction in FI is 1750 and 2700 kg when considering poultry houses of 35 and 54 thousand hens, respectively. These results refer to a period of 19 days. However, when considering that the hens are kept in production until they reach 90 weeks (mean slaughter age of W-80 laying hens in Brazil, without the performance of forced molting), the difference of the FI for the other treatments is approximately 38.7 and 59.7 thousand kg of feed, respectively.

Table 2. Cumulative feed intake (FI) per hen and by medium- and large-sized poultry houses over a period of 19 days, according to the experimentally obtained data and data estimated by statistical and fuzzy models for different illuminance (Illu) conditions.

	Illu (lux)	**Cumulative FI (1) (kg bird^{-1})**	**FI (kg) of 35,000 birds (2)**	**FI (kg) of 54,000 birds (3)**	**Difference (4) (kg)**	**Difference (5) (kg)**
Observed	5	2.08	72,800	112,320	- -	- -
	20	2.03	71,050	109,620	- -	- -
	50	2.08	72,800	112,320	- -	- -
	100	2.08	72,800	112,320	- -	- -
Statistical model (Eq. (14))	5	2.06	72,100	111,240	-700	-1,080
	20	2.06	72,100	111,240	1,050	1,620
	50	2.06	72,100	111,240	-700	-1,080
	100	2.07	72,450	111,780	-350	-540
Fuzzy model	5	2.08	72,800	112,320	0	0
	20	2.05	71,750	110,700	700	1,080
	50	2.08	72,800	112,320	0	0
	100	2.09	73,150	112,860	350	540

(1) Mean feed intake observed per hen (accumulated in the period from day 10 to day 28). Number of hens in a (2) medium- and (3) large-sized poultry houses, defined based on the capacity of poultry houses with vertical cage systems. Differences in the values predicted by the statistical and fuzzy models in relation to those estimated based on the experimental data for housing of (4) 35,000 hens and (5) 54,000 hens.

Thus, there is an indication that environments with 20 lux provide savings in the production process with an input that contributes significantly to the total cost of animal production, since, according to Ribeiro *et al.* (2016), the feed is the highest cost in the supply chain. However, behavioral responses, electricity consumption and minimum illuminance for labor activities should be evaluated but are not addressed in this study.

Regarding the predicted values (Table 2), the statistical model underestimates the FI accumulated under the conditions of 5, 50 and 100 lux, while the FIS overestimates the FI accumulated for the illuminances of 20 and 100 lux. In addition, the greatest difference between the observed and predicted FI values occurs in the estimation performed by the statistical model for illuminance of 20 lux; for a flock of 54,000 hens, this value is overestimated by 1620 kg. The lower performance of Eq. (14) at an illuminance of 20 lux supports the result illustrated in Fig. 11, which shows that when performing the sum, in modulus, of the FI differences determined by the models in each condition, a higher value is obtained for the statistical model considering the illuminance of 20 lux (Fig. 11b) compared with the other values (Figs. 11a, 11c and 11d).

In addition, the values in Table 2 contrast the results shown in Fig. 11, as it is possible to observe a tendency of the FIS to overestimate the results at 50 lux (Fig. 11c) and Eq. (14) to underestimate the results at the 20 lux (Fig. 11b). However, the cumulative analysis of the FI over 19 days did not confirm this behavior and indicated greater accuracy and generalizability of the FIS compared to the statistical model.

However, in general, both the statistical models and the FIS obtained satisfactory results, since when comparing the predicted values to the observed values, the largest variations in the FI were 0.5% (for both models) at 100 lux, 1.0% (for the statistical model) at 5 and 50 lux, and 1.5% (for the statistical model) at 20 lux.

In turn, the difference between the values of t_{surf} observed (considering 100% of the database) and predicted by the statistical models, Eq. (15), and fuzzy system for illuminances of 5, 20, 50 and 100 lux are illustrated in Fig. 12. Similar to the results observed for FI, the FIS model for t_{surf} showed higher accuracy than the statistical model, both in the validation and in the comparison with the mean of the total data. Thus, in addition to the statistical parameters that indicated greater generalization capacity, Fig. 12 shows that the FIS has a deviation less than or equal to the statistical model in 96% of the scenarios evaluated and that in 33% of these, the simulated value was accurate compared with the observed value.

Thus, the suitability of all developed models was verified through the statistical indicators; however, the results obtained when using Eqs. (14) and (15) had lower statistical performance than the FIS models for both FI and t_{surf}.

Therefore, the superior performances of the FISs support those results obtained in Ahmad (2011) and Maziero *et al.* (2022), who stated that modeling based on expert knowledge and opinion may yield perform predictions that are superior to those obtained using traditional mathematical and statistical models. This behavior was also observed by other authors (Sousa *et al.*, 2006; Akilli and Gorgulu, 2020; Boso *et al.*, 2021a; 2021b; Góes *et al.*, 2022; Putti *et al.*, 2021; Gabriel Filho *et al.*, 2022). However, the performance of fuzzy models is conditioned not only on the level of knowledge of the experts (regarding fuzzification, membership functions, rules and defuzzification methods) but also on the variability of the response variable and the database that composes it (amount of data and variance of the replicates). In addition, the applicability of accurate modeling to predict the responses of laying hens, be they behavioral, physiological, productive or based on egg quality, helps to support the decision on which management strategies should be implemented in poultry farming, enabling the improvement of the health and well-being of the hens and mitigating or eliminating economic losses.

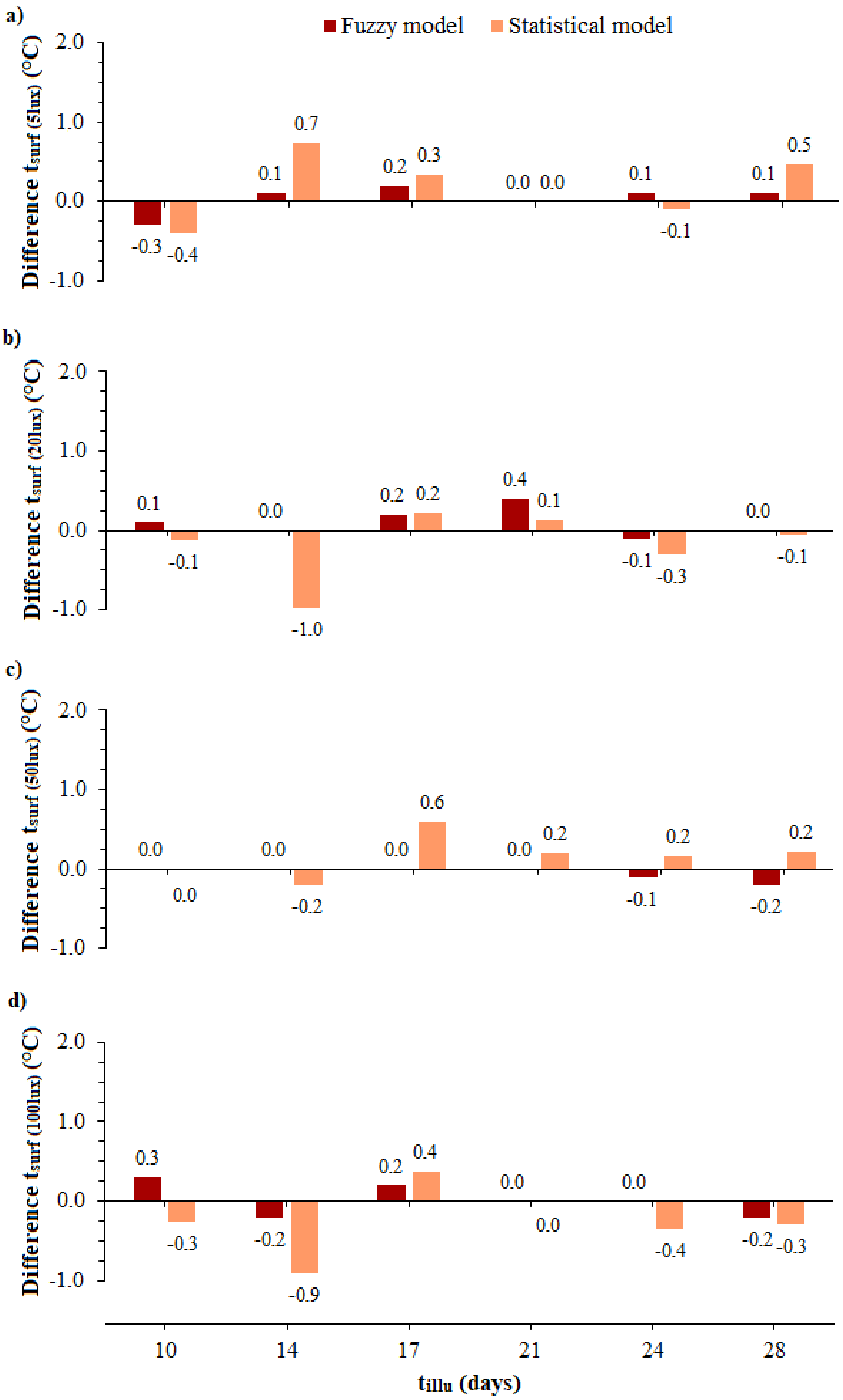


Fig 12. Differences in estimates of mean surface temperature (t_{surf}, °C), compared to the experimentally obtained, using the fuzzy and multiple statistical models, for the illuminances of a) 5 lux, b) 20 lux, c) 50 lux and d) 100 lux, in the times of exposure to illumination (t_{illu}) evaluated.

4 Conclusions

When evaluating the models that utilize illu and t_{illu} levels as input variables, the FIS obtained better indices (bias, MAE, MAPE, RMSE and R^2) compared to the statistical models for both FI and t_{surf}. Such statistical performances were obtained in the validation stage, in which there was a greater ability to generalize the FISs and, therefore, a greater ability to generate accurate responses to unknown conditions. Furthermore, these models have greater application and simulation potential for management systems that support smart production, since they have the ability to predict responses in different scenarios in addition to those evaluated experimentally.

Thus, fuzzy modeling based on expert knowledge and opinion yielded a better prediction performance than the statistical models tested. However, such performance is conditioned by the database, the variability of the response variable, the previous experience of the experts and the FIS configurations (membership functions, rules and defuzzification methods).

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THIRD PART – INNOVATIVE COMPUTATIONAL TOOLS DEVELOPED

REGISTERED SOFTWARE

In addition to the articles developed in this thesis, two computer programs were also produced as final outputs. This software comprises the fuzzy inference systems (FIS) models developed in Article 2. Both computer programs were registered with the *Instituto Nacional da Propriedade Industrial* (INPI – Brazilian National Institute of Industrial Property).

The registration certificates for both computer programs are available in Annexes A and B. They are as follows:

a) Software 1 (Annexe A):
Registration name: *Preditor* fuzzy *da temperatura superficial de galinhas poedeiras*.
INPI registration number: BR512024004565-1

b) Software 2 (Annexe B):
Registration name: *Preditor* fuzzy *do consumo de ração de galinhas poedeiras*.
INPI registration number: BR512024004564-3

FOURTH PART

FINAL REMARKS AND FUTURE PERSPECTIVES

Among the main results discussed in both articles, the following stand out:

a) Illuminances between 5 and 100 lux did not demonstrate harmful effects on hens;
b) A light intensity of 5 lux was sufficient for the hens to locate feeders and drinkers;
c) The cumulative exposure time to lighting influences some responses in hens;
d) The intensity of 20 lux suggests a reduction in feed consumption without compromising productivity, indicating potential cost savings, as feed is the primary input in layer production;
e) Feed intake and the surface temperature of laying hens depend on the interaction between illuminance levels and exposure time;
f) The absence of significant differences between treatments for some variables suggests that environments with lower illuminance may reduce production costs;
g) FIS models developed based on expert knowledge outperformed statistical models;
h) FIS models demonstrated a greater ability to respond accurately to unknown conditions (generalization capacity) than statistical models.

Given the above, the research presented in this thesis contributes to developing more sustainable and efficient practices in layer poultry farming, encouraging the adoption of modern technologies and evidence-based practices. However, implementing new technologies requires careful planning that considers cost-benefit analyses and the specific needs of each production system.

In this sense, further studies are still necessary to understand better the interactions between different lighting parameters and their impact on the behavior and well-being of hens. Among the research possibilities that require further investigation, the following stand out:

a) Evaluation in commercial facilities: Lighting was entirely artificial in this research. However, in many farming systems, artificial lighting is only used as a supplement. Thus, it is necessary to evaluate production, quality, and welfare parameters in commercial facilities. One hypothesis is that the acclimatization period may exceed the 28 days observed in this study. Furthermore, the light intensities were adjusted to the hens' eye level. Therefore, evaluating whether some intensities provide adequate lighting for human work is necessary. Otherwise, supplemental lighting may be required inside the facilities, potentially resulting in uneven distribution within the cages;

b) **Energy consumption analysis:** Lower light intensities can be provided by systems requiring less power, promoting energy savings. This evaluation is justified since the outcomes of the different light intensities tested did not significantly differ;

c) **Analysis of biochemical and antioxidant blood parameters:** Investigating markers such as serum biochemistry and the antioxidant capacity of the liver and kidneys will allow for a more accurate assessment of the hens' complete well-being;

d) **Biochemical analysis of eggs:** Some blood biochemical analyses can indicate whether illuminance altered the hens' ability to absorb calcium and phosphorus from the diet. Thus, evaluations of egg characteristics such as albumen pH, lipid oxidation, and vitamin D, calcium, and phosphorus concentrations will complement the findings;

e) **Novel decision support models:** The models developed in Manuscript 2 showed good predictive performance and can aid in decision-making regarding hen management. However, the results in this thesis do not eliminate the need for continued research on the same focus. While the models were suitable under comfortable conditions for the birds, simulations in different thermal conditions and other external stimuli may produce greater errors. Additionally, detecting production and well-being issues in poultry houses is crucial to avoid and correct long-term effects. However, the non-stationarity of data in a flock poses challenges to anomaly detection. Artificial intelligence (AI) based modeling techniques improve as data increases. Continued research will expand the available big data for AI model development and learning. Thus, databases will enable the creation of self-adaptive systems with greater accuracy and predictive power.

In summary, lighting management must be integrated with other practices like nutrition and climate control to achieve the best productive and economic results. The presented results and future perspectives underscore the importance of ongoing studies that bridge science and practice. In this way, the poultry sector can meet the growing market demands efficiently, ethically, and environmentally responsible.

ANNEXE A – Certificate of Computer Program Registration (software 1)

REPÚBLICA FEDERATIVA DO BRASIL
MINISTÉRIO DO DESENVOLVIMENTO, INDÚSTRIA, COMÉRCIO E SERVIÇOS
INSTITUTO NACIONAL DA PROPRIEDADE INDUSTRIAL
DIRETORIA DE PATENTES, PROGRAMAS DE COMPUTADOR E TOPOGRAFIAS DE CIRCUITOS

Certificado de Registro de Programa de Computador

Processo Nº: **BR512024004565-1**

O Instituto Nacional da Propriedade Industrial expede o presente certificado de registro de programa de computador, válido por 50 anos a partir de 1° de janeiro subsequente à data de 12/10/2023, em conformidade com o §2°, art. 2° da Lei 9.609, de 19 de Fevereiro de 1998.

Título: Preditor fuzzy da temperatura superficial de galinhas poedeiras

Data de criação: 12/10/2023

Titular(es): UNIVERSIDADE FEDERAL DE LAVRAS

Autor(es): MARCELO BAHUTI; TADAYUKI YANAGI JUNIOR; RENATO RIBEIRO DE LIMA; ÉDISON JOSÉ FASSANI; BRUNA PONTARA VILAS BOAS RIBEIRO; ALESSANDRO TORRES CAMPOS; LUCAS HENRIQUE PEDROSO ABREU; ANA CAROLINA DE SÁ SILVA LINS

Linguagem: PYTHON

Campo de aplicação: AG-10

Tipo de programa: IA-01

Algoritmo hash: SHA-512

Resumo digital hash:
b95a89c82b6e9a3c8721ff84fd14b5ae9f053d0e077bdbc248b3a661855ed1c58cfef4f9c388a8962071b56b6751b6b22eb
b0579c5a86027290a1f6d7c17bde9

Expedido em: 03/12/2024

Aprovado por:
Carlos Alexandre Fernandes Silva
Chefe da DIPTO

ANNEXE B – Certificate of Computer Program Registration (software 2)

REPÚBLICA FEDERATIVA DO BRASIL
MINISTÉRIO DO DESENVOLVIMENTO, INDÚSTRIA, COMÉRCIO E SERVIÇOS
INSTITUTO NACIONAL DA PROPRIEDADE INDUSTRIAL
DIRETORIA DE PATENTES, PROGRAMAS DE COMPUTADOR E TOPOGRAFIAS DE CIRCUITOS

Certificado de Registro de Programa de Computador

Processo Nº: **BR512024004564-3**

O Instituto Nacional da Propriedade Industrial expede o presente certificado de registro de programa de computador, válido por 50 anos a partir de 1° de janeiro subsequente à data de 12/10/2023, em conformidade com o §2°, art. 2° da Lei 9.609, de 19 de Fevereiro de 1998.

Título: Preditor fuzzy do consumo de ração de galinhas poedeiras

Data de criação: 12/10/2023

Titular(es): UNIVERSIDADE FEDERAL DE LAVRAS

Autor(es): MARCELO BAHUTI; TADAYUKI YANAGI JUNIOR; RENATO RIBEIRO DE LIMA; ÉDISON JOSÉ FASSANI; BRUNA PONTARA VILAS BOAS RIBEIRO; ALESSANDRO TORRES CAMPOS; LUCAS HENRIQUE PEDROSO ABREU; ANA CAROLINA DE SÁ SILVA LINS

Linguagem: PYTHON

Campo de aplicação: AG-10

Tipo de programa: IA-01

Algoritmo hash: SHA-512

Resumo digital hash:
735a45257cfc61d3148cb838ba6abac518ce48effbdbbab926b9e267980da60ea60a71775ff79c34eb56f4c82b851c2d8c6e096947e96d08dbc0ba08dca1048f

Expedido em: 03/12/2024

Aprovado por:
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