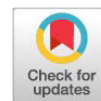


Review Article



Lighted Incubation in Poultry: Current Insights and Prospects for Enhancing Embryonic and Post-Hatch Development

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Abstract | Light exposure during avian incubation has emerged as a key environmental factor capable of modulating embryonic development, hatching traits, and post-hatch performance. This review synthesizes current knowledge on the mechanisms of embryonic photoreception, including the roles of retinal and deep-brain photoreceptors, melatonin rhythms, and downstream endocrine pathways involved in growth, stress regulation, and circadian entrainment. A comprehensive literature search was conducted via several databases, such as Google Scholar and Scopus. Studies were selected based on experimental manipulation of light wavelength, photoperiod, or intensity during incubation and reported embryonic, hatching, physiological, behavioral, or post-hatch outcomes. Across species, green and blue wavelengths consistently stimulate somatotrophic axis activation and myogenic proliferation, leading to accelerated post-hatch growth. However, their influence on hatchability remains inconsistent across studies, with outcomes ranging from positive to neutral or even negative depending on experimental parameters. In contrast, red and white light predominantly modulate melatonin secretion, immune function, and stress physiology. Lighted incubation not only modulates embryo development, organogenesis, and hatch window dynamics but also shapes post-hatch traits such as feed efficiency, carcass yield, bone development, behavior, and fear responses. However, substantial variation exists among studies due to differences in light regimens, strain-specific sensitivity, and interactions with temperature and humidity. Despite promising evidence, commercial adoption remains limited owing to uncertainties regarding optimal lighting protocols, potential thermal interactions, and cost-benefit considerations in large-scale hatcheries. Overall, light should be considered not merely an external physical parameter but a powerful biological cue capable of programming avian development. Standardization of lighting protocols, integration with precision incubation systems, and multidisciplinary industry-research collaboration are essential to fully exploit lighted incubation as a tool for sustainable improvement of poultry welfare, productivity, and robustness.

Keywords | Avian embryogenesis, Chick quality, Hatchability, LED photostimulation, Lighted incubation, Photoreceptors

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Poultry productivity is closely tied to embryonic and post-hatch development, making optimal incubation conditions fundamental for achieving desirable performance outcomes. Post-hatch growth, skeletal muscle development, and meat quality depend significantly on both egg storage conditions and incubation parameters, such as relative humidity, temperature, ventilation, lighting, egg turning, delayed access to feed, *in ovo* feeding, and oxygen density (Tona *et al.*, 2022; Wang *et al.*, 2022). Egg fertility and management of both setters and hatcheries can also affect hatchability (Araújo *et al.*, 2016).

In addition to specific incubation conditions, hatchery type has a considerable impact on hatchability and post-hatch outcomes. Multistage and single-stage incubators are commonly used in commercial settings. Multistage systems tend to exhibit higher embryo mortality, more live and dead pipped chicks, and a greater number of cracked eggs, partly due to transportation-related stress (Mesquita *et al.*, 2021). The increased mortality in multistage incubators is often attributed to elevated temperatures caused by heat transfer from older to younger embryos as the system attempts to maintain thermal balance (Araújo *et al.*, 2016). Despite these drawbacks, multistage machines reduce overall incubation energy consumption because they rely on embryo-derived heat, making them relatively cost-efficient. Conversely, single-stage incubators typically provide higher hatchability, a more uniform hatch window, and better chick physical quality (Araújo *et al.*, 2016; Mesquita *et al.*, 2021). Because all eggs are at the same developmental stage, incubation conditions can be precisely adjusted to the embryo's requirements (Araújo *et al.*, 2016). In addition, single-stage units can be completely emptied after each hatch, allowing for thorough cleaning and disinfection and thus improving sanitation (Mesquita *et al.*, 2021).

Achieving optimal hatchability requires meeting all critical incubation conditions, particularly temperature and lighting, regardless of hatchery type. Incubation temperature and lighting play central roles in embryonic development and post-hatch physiology. For example, pineal aralkylamine N-acetyltransferase, the rate-limiting enzyme in melatonin synthesis, is regulated by both light exposure and temperature (Yalcin *et al.*, 2022). The optimal incubation temperature for maximizing hatchability is 37.5–37.8 °C. Wijnen *et al.* (2020) reported that an eggshell temperature of 38.9 °C during week 2 increased post-hatch chick length and lowered blood glucose compared to 37.8 °C, whereas an eggshell temperature of 36.7 °C during the third week reduced post-hatch chick length, body weight, average daily gain, and feed intake, and increased blood

glucose, heart, and stomach weight.

Lighting during incubation influences the intra-egg environment and shapes post-natal physiological responses. Permanent darkness acts as a stressor, reducing hatchability and impairing post-hatch performance (Riaz *et al.*, 2024). Photostimulation can affect hatchability, the hatch window, the percentage of fertile eggs that hatch, post-hatch growth, chick quality, stress susceptibility, welfare indicators, and economic outcomes (Seremet and Bayraktar, 2021; Riaz *et al.*, 2024).

Incubation lighting also modulates embryonic development, physiological traits, stress responses, fear-related behavior, spatial abilities, and cognitive performance (Yalcin *et al.*, 2022; Riaz *et al.*, 2024). Furthermore, embryonic hemispheric lateralization, circadian entrainment, and establishment of melatonin rhythm (key factors influencing thermoregulation) are all dependent on light exposure (Yalcin *et al.*, 2022). Intermittent light for 12 hours per day improves hatching traits, meat quality, and blood biochemical parameters (Yameen *et al.*, 2020). White light-emitting diodes (LED; 5000K; 250 lux) provided for 12 or 24 h during incubation enhances hatchability, narrows the hatch window, increases the hatch-to-fertile percentage, and improves carcass yield (Riaz *et al.*, 2021). Similarly, 12 hours of LED light at 250 lux reduces embryonic mortality, the incidence of dead germs and dead-in-shell embryos, as well as improving feed conversion ratio (FCR) and stress susceptibility indicators such as physical asymmetry and heterophil-to-lymphocyte (H/L) ratio (Riaz *et al.*, 2024).

Light wavelength also affects hatching and post-hatching performance, as avian embryos respond sensitively to spectral differences. Approximately 98.2% of incident light is absorbed by the eggshell, and only a small fraction reaches the embryo (Yameen *et al.*, 2020). In avian species, stimulation of the light-sensitive pineal gland enhances embryonic growth and shortens incubation time when exposed to certain wavelengths and intensities. Embryonic exposure to light promotes post-hatch performance and welfare, although high light intensity may decrease chick weight (Tainika and Bayraktar, 2022). Green light during incubation enhances muscle development and weight gain, whereas red and white light generally improve hatchability (Tainika and Bayraktar, 2022). Incubation light wavelengths significantly shape development. Red light exposure during the dark phase (scotophase) enhances immune health lowering air cell temperature while boosting melatonin secretion, IgG levels, and the expression of immune genes like AvBD-1 and IL-6. Conversely, white or blue light prioritizes physical growth, leading to higher feed consumption and increased body weight (Li *et al.*, 2021a, b; Kankova *et al.*, 2022). Green light reduces serotonin

concentration, increases age-related pecking behavior, and upregulates hypothalamic 5-HTT expression, whereas white light increases CRH, 5-HTR1A, and 5-HTR1B expression (Özkan *et al.*, 2022). Green light exposure for 12 hours shortens incubation time, increases serum insulin-like growth factor 1 (IGF-1), increases relative liver weight, and modifies pineal gland follicle size and structure. It also alters arylalkylamine N-acetyltransferase (AANAT), brain/muscle ARNT-like-1 (BMAL1), circadian locomotor output cycles kaput (CLOCK), and cryptochrome-1 (CRY1) expression (Wang *et al.*, 2021). Providing green LED light at 0.1 W/m² from day 18 to hatch increases somatotrophic axis expression (Dishon *et al.*, 2021).

Beyond wavelength, light intensity, and specific light combinations exert distinct effects. In quail, 250 lux of green light reduces embryonic mortality and improves chick spread, growth performance, pre-slaughter weight, and carcass weight, compared with 150 or 350 lux (Ali *et al.*, 2023). A combination of green and red light at 250 lux enhances hatchability, late-stage embryonic survival, chick spread, growth performance, serum chemistry, and carcass traits relative to a green-blue or blue-red combination (Safwan *et al.*, 2023). Although many studies report positive effects of incubation lighting on hatchability and post-hatch performance, findings are not fully consistent. For example, Riaz *et al.* (2024) reported no significant effects of white, green, or red LEDs on pre-hatch development, post-hatch growth, production traits, or welfare. However, the inconsistency in literature regarding the effects of illuminated incubation comes down to a complex web of biological, environmental, and methodological variables that differ from one study to another.

This review aims to synthesize current evidence on LED lighting, spectral wavelengths, and intensities during incubation to clarify optimal lighting conditions for maximizing hatchability and post-hatch performance. To ensure a comprehensive and unbiased synthesis of the existing evidence, a structured literature search was conducted prior to drafting this review. Scientific articles were identified through major academic databases, including PubMed, Web of Science, Scopus, and Google Scholar. The systematic search targeted original research articles published between 2000 and 2025. However, classic foundational studies, international technical guides (e.g., FAO, 2004), and essential textbook or review sources were manually retrieved and included to provide necessary physiological, historical, and methodological context, using combinations of the following keywords and Boolean operators: lighted incubation, avian embryo, poultry incubation lighting, LED incubation, embryonic development, hatchability, photostimulation, light

wavelength, and post-hatch performance. Only peer-reviewed original research articles written in English were considered eligible. Reference lists of relevant publications were also screened manually to identify additional studies not captured in the database searches. Studies were included: (i) the effects of light exposure during incubation on embryonic development, hatchability, physiology, behavior, or post-hatch performance; or (ii) the influence of specific lighting parameters such as wavelength, intensity, photoperiod, or LED technology. Exclusion criteria included: studies not involving avian species, papers lacking experimental data (e.g., opinion pieces), conference abstracts without full text, and articles not providing clear incubation lighting protocols. No restrictions were applied regarding bird species, study design, or type of lighting system to ensure broad coverage of current knowledge.

EMBRYOGENESIS IN BIRDS

Avian embryogenesis is a complex process starting from fertilization to hatching (Yahav and Brake, 2014). Birds are oviparous, and fertilization within the female reproductive tract initiates embryonic development. A freshly laid egg exhibits low internal oxygen tension and depends on external heat to support development, but it contains most of the structural and nutritional components required for embryogenesis (Mueller *et al.*, 2022). Atmospheric oxygen diffuses through microscopic pores in the eggshell, while water vapor and CO₂ produced by the embryo diffuse outward (Lock *et al.*, 2024). Incubation typically ranges from 21 to 42 days, depending on the species (FAO, 2004); it may occur naturally or artificially, with artificial incubation providing controlled conditions from oviposition to hatching (Abd El-Hack *et al.*, 2022). Optimal artificial incubation conditions generally include 36 - 39 °C (species-dependent), 50-65 % relative humidity, an airflow of 0.4 m/s, and hourly egg turning to prevent adhesion of the embryo to the eggshell (Kosemani *et al.*, 2025; Leaphart *et al.*, 2025).

Key developmental milestones include blastoderm formation, organogenesis, and establishment of the circulatory system, which supports nutrient distribution and waste removal (Ribatti, 2022). Following fertilization, rapid cleavage produces a blastoderm that differentiates into three germ layers: ectoderm, mesoderm, and endoderm, the germ layers that give rise to all tissues and organs (Benchikh, 2024). Subsequently, organogenesis proceeds, the heart begins to beat, and the major systems, such as the musculoskeletal, nervous, and digestive systems, begin to take shape (Mühr *et al.*, 2023). The yolk provides the primary nutrients and energy for embryonic development (Blackburn and Stewart, 2021), while albumen serves as an additional nutritional reservoir, and the shell and membranes regulate water loss and gas exchange. During

early life, oviparous vertebrates are particularly vulnerable to environmental stressors due to limited parental protection (especially in poultry) and wide variability in incubation environments (Lock *et al.*, 2024).

FACTORS AFFECTING EMBRYOGENESIS

Over the last decade, many studies have examined the effect of slight deviations from optimal incubation temperature ($\pm 1.5^\circ\text{C}$) on embryonic development (Yalcin *et al.*, 2022). Both elevated and reduced temperatures impair yolk sac absorption and yolk nutrient utilization by altering the expression of genes involved in digestion and absorption, ultimately compromising chick quality (Dayan *et al.*, 2020). Moderate temperature fluctuations during embryonic development resulted in reduced hatchability, increased day-old chick (DOC) weight, and delayed hatching. Temperatures of $36\text{--}36.5^\circ\text{C}$ on day 15 prolong external pipping and delay emergence, whereas early-stage exposure to 38.1°C reduces DOC weight and yolk sac mass, and increases chick length (Lin *et al.*, 2017). Exposure to 38.6°C further decreases hatchability (Avşar *et al.*, 2022). Conversely, Wijnen *et al.* (2020) showed that exposure to 38.9°C during week 2 accelerates embryo development, shortens the hatch window, and reduces incubation duration with no effect on DOC weight. Muir and Groves (2018) observed higher hatchability, more late-hatch chicks, and increased bone ash when eggs were incubated at 37.2°C to 37.8°C for 13 days.

Along with temperature, humidity is also a key factor. Water loss during incubation must fall within an optimal range; losses below 9.1% or above 18.5% increase mortality (Lin *et al.*, 2024). A relative humidity between 40 and 70% is generally recommended. Low humidity reduces chick body weight and can harden the chorion, making hatching difficult and lowering hatchability (Bruzual *et al.*, 2000). Excessive humidity leads to early hatching and poor chick quality (Peebles, 2023). Ventilation is equally essential for regulating O_2 uptake and CO_2 removal; inadequate ventilation creates hypoxic and hypercapnic conditions detrimental to the embryo (Juá *et al.*, 2024). Adequate O_2 levels are vital for embryonic metabolic pathways; deficiencies induce hypoxia, which suppresses metabolic rates and impairs energy production due to low breathing rates and hinders cell proliferation, differentiation, and growth. In the case of artificial incubation, proper ventilation with an O_2 level of 21% to 23% in the setter is recommended, with a lower CO_2 level, as a high level of CO_2 causes respiratory acidosis and disruption of acid-base balance in the developing embryo and may lead to embryo death (Juá *et al.*, 2024).

In the last decade, interest has increased regarding the role of light during avian embryonic development. Light exposure

can influence physiology, post-hatch behavior, growth, cognitive ability, stress resilience, and fear responses (de Haas, 2020). These effects may be mediated by hemisphere lateralization and the entrainment of circadian rhythms before hatching (Yalcin *et al.*, 2022). Although timing, duration, intensity, and spectral composition of light exposure exert significant effects during embryogenesis, there is still a need to deeply understand the effect of light on embryo development.

PHOTORECEPTION IN THE EMBRYO

Light exposure during embryonic development significantly influences hatching performance, embryonic growth, stress responsiveness, welfare, behavior, and overall post-hatch performance in poultry species (Yalcin *et al.*, 2022). Avian embryos can perceive light as early as 2 days of incubation, with fully functional photoreception established by embryonic day (ED) 18 (Yalcin *et al.*, 2022; Oso *et al.*, 2023). Light perception during this period is mediated not only by retinal photoreceptors but also by extraretinal photoreceptors located in the pineal gland and hypothalamus, specifically within the paraventricular and the lateral septal areas (Surbhi and Kumar, 2015). These hypothalamic photoreceptors, commonly referred to as deep brain photoreceptors (DBPs), allow embryos to respond to light stimuli even before the visual system is fully developed (Yalcin *et al.*, 2022).

Retinal and pineal photoreceptors, activated according to the photoperiod, contribute to circadian regulation of physiology and behavior through melatonin secretion, whereas DBPs are implicated in longer-term seasonal and developmental regulation, including gonadal maturation and growth responses to photoperiodic cues (Surbhi and Kumar, 2015). These photoreceptors express a variety of opsins capable of detecting specific wavelengths and converting light signals into electrochemical impulses propagated through neural circuits to regulate downstream physiological pathways (Lee *et al.*, 2021). Opsins expressed in the hypothalamus have been associated with regulation of the major endocrine axes: the hypothalamic-pituitary-adrenal (HPA), hypothalamic-pituitary-gonadal (HPG), and hypothalamic-pituitary-thyroid (HPT) axes (Özkan *et al.*, 2022). Moreover, light exposure can influence embryonic neurological development from as early as embryonic day 3 (Sampaio *et al.*, 2024). The embryonic response to light is therefore dependent on the timing, intensity, and spectral composition of the light provided.

Light plays a central role in regulating the embryonic circadian rhythm, particularly through its effects on the pineal gland. Early exposure to light synchronizes the circadian clock by modulating pineal gene expression and establishing rhythmic melatonin secretion (Li *et*

al., 2024a). The presence of light suppresses melatonin synthesis by inhibiting the enzyme arylalkylamine N-acetyltransferase (AANAT), which converts serotonin into melatonin. Conversely, during darkness, norepinephrine is released at pineal synapses, activating AANAT through phosphorylation of the cyclic adenosine monophosphate(cAMP)-responsive element-binding protein (CREB), ultimately increasing melatonin synthesis (Horodincu and Solcan, 2023). Photoreception is further mediated by the cAMP and cyclic guanosine monophosphate (cGMP), signaling pathways, which regulate circadian gene expression (e.g., CRY2) and microRNAs (e.g., gga-miR-34b-5p) essential for maintaining circadian rhythmicity (Li *et al.*, 2024b).

In the retina, melanopsin (Opn4) within intrinsically photosensitive retinal ganglion cells detects light and transmits circadian information to the brain (Pan *et al.*, 2025). Although only 0.5 to 5% of these cells are intrinsically photosensitive, they generate electrical signals that are relayed to the suprachiasmatic nucleus (SCN) via the retinohypothalamic tract (RHT) (Ashton *et al.*, 2022; Guarnieri, 2024). The SCN, acting as “master clock”, regulates circadian rhythms and influences downstream physiological systems, including the HPA axis, thereby modulating metabolic regulation, feeding behavior, and endocrine activity (Gu *et al.*, 2021; Li *et al.*, 2024a). Although the RHT is not fully developed in early embryonic stages, melanopsin-expressing retinal cells are still believed to mediate light detection and circadian entrainment.

During the early embryonic stage, DBPs play a more predominant role than the retina in photoreception. Opsins, such as encephalopsin (Opn3), neuropsin (Opn5), and vertebrate ancient opsin (VA opsin), are expressed in

the paraventricular organ (PVO) and other brain regions and enable the embryo to detect light independently of the eyes (Schöneberg, 2025). These opsins activate G-protein-coupled receptors (GPCRs), triggering intracellular signaling cascades (Yee *et al.*, 2023). GPCRs activation leads to dissociation of G-protein subunits and initiation of the key pathways, including the phosphoinositide (PLC) and cAMP pathways (Chung and Wong, 2021; Li *et al.*, 2024b). In the PLC pathway, hydrolysis of phosphatidylinositol 4,5-bisphosphate (PIP2) produces inositol trisphosphate (IP3) and diacylglycerol (DAG), promoting intracellular calcium release and protein kinase C (PKC) activation (Özkan *et al.*, 2022; Liccardo *et al.*, 2022). On the other hand, cAMP pathways activate protein kinase A (PKA) through adenylate cyclase-mediated conversion of ATP to cAMP (Chung and Wong, 2021). Both pathways lead to phosphorylation of transcription factors like cAMP and CREB, regulating circadian gene transcription, including CLOCK, BMAL1, PER, and CRY (Ashton *et al.*, 2022). Through these mechanisms, avian embryos synchronize their physiological processes with environmental light cues, influencing developmental trajectories that extend into post-hatch life.

EFFECT OF LIGHT ON HATCHING PERFORMANCE

A growing body of evidence demonstrates that light exposure during incubation profoundly affects embryonic physiology, developmental trajectories, and hatching outcomes. The magnitude and direction of these effects depend on light wavelength, intensity, duration, and photoperiod, with green and blue wavelengths generally producing the most consistent improvements in embryonic growth, hatch timing, and physiological maturation, as summarized in Table 1.

Table 1: Light’s effects on the physiology, growth, and behavior of avian embryos during the incubation period.

Species/ Strains	Condition	Effects	References
Broiler	Continuous green light	Resulted in increased mitotic activity in satellite cells of pectoral muscles, Upregulation of the mRNA expression of specific myogenic regulatory factors (MyoD, myogenin, and myostatin) in the later embryo.	Yalcin <i>et al.</i> (2022)
Broiler	Intermittent green light exposure on ED (15,16 and 18)	Stimulated somatotrophic axis and higher levels of GHRH, liver GHR, and IGF-1 genes and GH plasma levels.	Dishon <i>et al.</i> (2021)
Broiler	Continuous light 24 h L, 12L:12D, 24D	Higher growth hormone level at day 0 of chick for 24 D than other treatments	van der Pol <i>et al.</i> (2019)
Broiler	12L:12D, white, red, green and blue light	Observed higher pineal melatonin during scotophase in green and white light and blue, with the lowest.	Drozdová <i>et al.</i> (2021)
Broiler	Continuous light exposure	Resulted in stimulation of pineal melatonin secretion and growth hormone synthesis.	Sampaio <i>et al.</i> (2024)

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Species/ Strains	Condition	Effects	References
Broiler	(12L:12D) photoperiod of green light (ED1-ED18)	Light-exposed chicks hatched 3.4 h earlier than the control group.	Tong <i>et al.</i> (2018)
Broiler	Green light (50 lux)	Increased thyroxine (T ₄) level.	Yu <i>et al.</i> (2018)
Broiler	Exposure to red light during the incubation period	Higher gene expression of AvBD-1, increased local immune response in the gut.	Kankova <i>et al.</i> (2022)
Broiler	12L:12D white, fluorescent light	Strong humoral immune response.	Yalcin <i>et al.</i> (2022)
Beijing Young	12L:12D, Dark group with no light	Higher globulin and lysozyme content, higher activities of glutathione peroxidase and superoxide dismutase, and lower malondialdehyde content.	Geng <i>et al.</i> (2021)
Broiler	Intermittent light from ED5-ED14, leading to continuous green light exposure	Up-regulation of Pax7 and myostatin expression, an increase in the pectoral myogenic cell number and myogenic cells proliferation activity.	Wang <i>et al.</i> (2021)
Broiler	Light exposure for 0,12 and 24 h	Significant improvement in hatch window, hatchability percentage, and hatch of fertile percentage.	Riaz <i>et al.</i> (2021)
Brown layer	Green light exposure	Reduced serotonin level.	Özkan <i>et al.</i> (2022)
Brown layer	16L:8D, green and white light	CRH, 5-HTR1A, and 5-HTR1B hypothalamic expression levels were higher in the white-lighted group.	Özkan <i>et al.</i> (2022)
Developmental			
Broiler	Green light stimulation	Significantly longer beak length and crown-rump of the embryo, longer third toe length.	Tong <i>et al.</i> (2018)
Broiler	Green light (50 lux)	Resulted in increased weight of embryo, body length, and hatchability ($p < 0.001$).	Yu <i>et al.</i> (2018)
Beijing You	12L:12D, Dark group with no light	Hatching rate increased in the light group (93.64%) compared to the dark group (87.22%).	Geng <i>et al.</i> (2021)
Broiler	Continuous light exposure	Increased embryo-muscle weight.	Sampaio <i>et al.</i> (2024)
Broiler	Continuous light 24 h L, 12L: 12D, 24D	Lower embryonic ossification was observed in the 24 L treatment on days 13 and 14, lower femur length, decreased tibia tarsus weight, length, cortical area, and mean cortical thickness.	van der Pol <i>et al.</i> (2019)
Broiler	LED light of red and green color	Increased hatchability and improved chick quality.	Archer (2017)
Broiler	Red light, blue light, and dark period	Male chicks in the dark period had a higher weight of the bursa of fabricia than males in blue light.	Li <i>et al.</i> (2021b)
Broiler	(24D, 24L, 12L:12D) Green, white and red light	With high-intensity exposure, chick weight on hatching decreased. The green light resulted in increased body weight, 12L:12D, and showed better leg health.	Tainika and Bayraktar (2022)
Behavioral			
Broiler	Combining light and thermal manipulation during incubation	Improved resistance of chicks against heat stress, lower fear, improved spatial abilities, and cognitive functions.	Yalcin <i>et al.</i> (2022)
Broiler	Red and green light	This resulted in lower fear and stress susceptibility in chicks.	Archer (2017)
Broiler	Light of red and blue color, and dark period	Light color exposure in embryos showed an influence on embryo response.	Li <i>et al.</i> (2021a)

The influence of incubation lighting on hatching performance is fundamentally driven by the activation of non-visual photoreceptors specifically inside the avian embryonic pineal gland and the retina which are responsive to light stimulation as early as the first week of incubation (Wang *et al.*, 2021). Photoperiodic light exposure, particularly in the green and white spectra, upregulates the activity of the embryonic somatotrophic axis, stimulating the expression of growth hormone and

insulin-like growth factors (Dishon *et al.*, 2017). This hormonal surge accelerates embryonic metabolism, cellular proliferation, and nutrient utilization from the yolk sac (Dayan *et al.*, 2020). Furthermore, light stimulation enhances the rhythmic secretion of melatonin and activates the circadian clock network, which plays a pivotal role in synchronizing the developmental rate of the embryos within the incubator (Oso *et al.*, 2023; Li *et al.*, 2024b). On a physical level, this advanced physiological maturity

promotes stronger embryonic muscle development and increases late-stage pipping activity, ultimately narrowing the hatch window and improving overall hatchability rates without compromising post-hatch chick quality (Tainika and Bayraktar, 2022; Yin *et al.*, 2024).

Light exposure consistently improves several morphological traits. Abdulateef *et al.* (2021) reported significantly higher embryo weight on day 19 in eggs incubated under red (33.55 g), blue (33.93 g), and green light (34.70 g) compared with complete darkness (30.00 g; $p < 0.01$). Their study also revealed a substantial enhancement in hatchability under green light (77.0%), which was significantly higher than blue (72.0%), red (69.0%), and dark incubation (66.7%). The same authors documented marked improvements in neurophysiological traits under photostimulation: Embryos incubated under green and blue light exhibited significantly larger neuron diameters (45.63 μm and 43.03 μm , respectively) and heavier brain weights compared with red light and dark incubation, suggesting wavelength-dependent modulation of neural development. These findings align with the notion that green and blue wavelengths penetrate the eggshell more effectively and exert a stronger influence on the central nervous system during critical periods of neuronal growth.

The stimulatory effects of green light on somatic development have been repeatedly confirmed. Rozenboim *et al.* (2004) demonstrated that green photostimulation increased yolk temperature in a time-dependent manner, with each minute of exposure raising yolk temperature by approximately 0.01% of baseline. Although continuous exposure caused persistent temperature elevations, an intermittent cycle (15 min light/ 15 min dark) prevented excessive thermal accumulation while preserving developmental benefits. Embryos incubated under intermittent green light showed higher body weight on embryonic days 14, 15, 17, and 20, together with a sustained increase in pectoralis major muscle percentage from day 9 to day 21 relative to dark incubation. These results reinforce the hypothesis that green light enhances muscle accretion via mechanisms linked to the somatotrophic axis.

Other studies corroborate the positive influence of green light on hatchability. Yameen *et al.* (2020) observed that eggs exposed to 12 h of light exhibited higher hatchability compared with those incubated in continuous darkness, along with reduced late embryonic mortality. Although 24 h of light increased moisture loss and altered mortality patterns, it nevertheless improved certain hatch window dynamics, with light-stimulated chicks emerging earlier during specific pre-hatch intervals. Differences among strains were also reported, highlighting the importance of genotype in modulating embryonic responses to

photoperiod. Notably, eggs incubated with 12 h of light produced heavier chicks at hatch, while continuous light reduced chick weight at pull-time, suggesting a non-linear relationship between photoperiod and energy utilization during development. Riaz *et al.* (2024) similarly reported higher hatchability and hatch-of-fertile percentages under both 12 h and 24 h photoperiods compared with dark incubation, together with narrower hatch windows. Importantly, illuminated embryos exhibited lower heterophil-to-lymphocyte ratios and reduced physical asymmetry, indicating an improved pre-hatch stress response. These findings reinforce the concept that embryonic photostimulation not only accelerates developmental processes but also supports improved physiological resilience at hatch.

The influence of lighting on endocrine regulation during late embryogenesis has been explored in detail by Tong *et al.* (2018), who compared illuminated and dark-incubated embryos under identical incubation conditions. Although overall hatchability of the focal chicks was higher in the control group when considering cumulative mortality, photostimulation advanced the mean hatch time by approximately 3.4 h, with a larger proportion of focal chicks hatching earlier than their dark-incubated counterparts. Hormonal analyses revealed that light exposure modified the temporal trajectories of melatonin (MT), corticosterone (CORT), and thyroid hormones (T_3 and T_4) during the 12:12 h light–dark cycle. While absolute concentrations were not consistently different between treatments at individual time points, light altered the rhythmic fluctuations of these hormones. For example, MT in the dark group sharply increased during the first 3 h of scotophase, whereas the light group showed a more gradual rise with a peak at 9 h. Similarly, T_3 levels in light-exposed embryos were significantly higher during the illuminated period ($p = 0.02$), suggesting that photostimulation may facilitate earlier maturation of metabolic pathways. These endocrine modulations, although subtle, may contribute to the accelerated hatching observed in illuminated embryos.

Importantly, not all studies have reported improvements in hatchability. Drozdová *et al.* (2021), for instance, found no significant differences in hatchability among red, white, green, and blue light treatments, despite reporting wavelength-specific effects on pineal melatonin synthesis. This inconsistency highlights the complexity of the system and suggests that experimental factors such as eggshell properties, breeder flock age, light intensity, and thermal environment may interact with photostimulation in determining hatchability outcomes.

Taken together, the available evidence indicates that embryonic photostimulation consistently enhances growth

trajectories and developmental maturity, particularly under green and blue wavelengths. However, improvements in hatchability are not universally observed and may depend on species, strain, photoperiod, and incubation conditions. The variability across studies underscores the necessity for standardized protocols that consider both the physiological sensitivity of the embryo to specific wavelengths and the potential interactions between lighting, temperature, and humidity.

EFFECT OF LIGHT ON POST-HATCH GROWTH PERFORMANCE

The enhancement of post-hatch growth performance via lighted incubation is primarily driven by the photostimulation of the embryonic somatotrophic axis and the acceleration of muscle development. *In ovo* photoperiodic exposure particularly using green or white monochromatic light stimulates embryonic photoreceptors, triggering intracellular cascades that upregulate the expression of growth hormone (GH) and insulin-like growth factor-1 (IGF-1) genes (Dishon *et al.*, 2017; Wang *et al.*, 2021). This prenatal activation of the somatotrophic axis enhances yolk sac nutrient absorption and energy utilization during the late incubation stage, providing a robust metabolic foundation for post-hatch vitality (Dayan *et al.*, 2020; Lin *et al.*, 2024). Furthermore, specific green light wavelengths penetrate the eggshell to stimulate myofiber hyperplasia by accelerating the proliferation and differentiation of muscle satellite cells during embryogenesis (Rozenboim *et al.*,

2004; Wang *et al.*, 2022). Consequently, chicks incubated under appropriate light regimes exhibit superior post-hatch feed consumption, efficient muscle accretion, and significantly higher early body weight gain compared to those incubated in continuous darkness (Riaz *et al.*, 2021; Li *et al.*, 2021b).

Light exposure during incubation exerts marked effects on growth performance, physiological maturation, and carcass traits of poultry, although the magnitude and direction of these responses depend strongly on photoperiod, wavelength, and light intensity. Several studies indicate that appropriate photostimulation enhances feed efficiency and carcass traits without compromising general livability (Table 2). Riaz *et al.* (2021) reported that chicks incubated under 12 hours of light displayed significantly improved FCR compared with both 24 h light and dark incubation, despite the absence of differences in feed intake, body weight gain, or livability. Carcass yield also improved under illuminated incubation (Riaz *et al.*, 2021), whereas leg quarter yield was higher in chicks originating from dark and 24 h light incubation compared with the 12 h group, suggesting that sustained or absent light may differentially direct nutrient partitioning during embryogenesis (Riaz *et al.*, 2021). Studies involving different breeds corroborate this selective sensitivity. Yameen *et al.* (2020) found that 12 h light incubation produced chicks with significantly higher initial body weight than those incubated in the dark, while 24 h illumination produced the lowest chick weight.

Table 2: Light and its effect during incubation on different species of poultry.

Species/ strains	Light color	Duration (light: dark)	Intensity	Results	References
Broiler	Green (LED)	12L:12D	100-130 lux 1200-1400 lux	Longer beak, third toe length, and crown-rump length	Tong <i>et al.</i> (2018)
Broiler	Red, blue, and green (LEDs)	12L:12D	0.1 W/m ²	Increased embryo weight, hatchability, and chick weight at 1 day of age.	Abdulateef <i>et al.</i> (2021)
Broiler	Green (LED)	15 mins on and 15 mins off	0.1 W/m ²	Increased body weight and higher pectoral muscle.	Rozenboim <i>et al.</i> (2004)
Broiler	Red and white light (LEDs)	12L:12D	0.04 W/m ²	Increased pineal melatonin biosynthesis during scotophase	Drozdová <i>et al.</i> (2021)
Broiler	White light (LED)	12L:12D	250 lux	Higher hatchability, hatch of fertile, improved FCR and carcass yield.	Riaz <i>et al.</i> (2021)
Broiler	White light (LED)	12L:12D	250 lux	Improved hatching traits.	Yameen <i>et al.</i> (2020)
Broiler	Green and red (LEDs)	24 hours till 18 th day of incubation	0.1-0.2 lux	Improved hatchability.	Tainika and Bayraktar (2022)
Beijing You	White (LED)	12L:12D	200 lux	Higher hatchability, longer bones, improved certain serum immune and antioxidant indexes, and reduced leg issues.	Geng <i>et al.</i> (2021)
Broiler	Green (LED)	15 mins on and 15 mins off	0.1 watt/m ²	Increased hypothalamic expression of GHRH and liver growth hormone receptor (GHR) levels.	Dishon <i>et al.</i> (2017)

Table continues on next page.....

Species/ strains	Light color	Duration (light: dark)	Intensity	Results	References
Broiler	Green	16L:8D	50 lux	Increased chick length, weight, hatchability, testosterone, and T_4 hormone levels.	Yu <i>et al.</i> (2018)
Broiler	White (LED)	12L:12D	500 lux	Improved leg health.	van der Pol <i>et al.</i> (2019)
Turkey	Green	24 hours till 28 th day of incubation	0.1 W/m ²	Improved body weight.	Rozenboim <i>et al.</i> (2003)
Layer	White (incandescent)	24 hours till 18 th day of incubation	60 W	Better orientation to feeders.	Chiandetti <i>et al.</i> (2013)
Broiler	Color rendering index 90	12L:12D	550 lux	More feed intake, shorter latencies to leave the box during the emergence test and to right during the tonic immobility test, flapped their wings less intensely during the inversion test.	Archer and Mench (2014)
Broiler	Green, red, and white (LEDs)	24 hours till 21 st day of incubation	250 lux	Lower plasma corticosterone and higher plasma serotonin concentrations.	Archer (2017)

Although chicks incubated in darkness showed the highest post-hatch feed intake, body weight gain, and livability, those exposed to 12 h light retained the most favorable FCR, supporting the hypothesis that moderate photoperiods facilitate more efficient metabolic programming. Strain differences further influenced these outcomes: Hubbard chicks exhibited higher initial chick weight, whereas Ross and Hubbard displayed superior body weight and FCR compared with Cobb strains (Yameen *et al.*, 2020). These genotype-dependent interactions emphasize the need for tailored lighting strategies for specific commercial breeds.

Beyond gross performance, light exposure modulates organ development and endocrine profiles. White light at 200 lux in Beijing-You chicken eggs improved long bone development, antioxidant status, and early leg health (Geng *et al.*, 2021), although body weight and several organ weights at hatch remained unaffected. Nevertheless, relative brain weight approached significance ($p = 0.052$), suggesting potential neural sensitivity to photoperiod. Similarly, Abdulateef *et al.* (2021) observed that embryos incubated under green or blue light exhibited higher 1-day-old body weight than those from dark or red-light conditions, highlighting wavelength-specific neuroendocrine effects.

Current research in ornithological science indicates that light sources and wavelengths profoundly affect bird performance, welfare, and physiology (Soliman *et al.*, 2023; Abdel-Moneim *et al.*, 2024). Dishon *et al.* (2017) demonstrated that intermittent green light (15 min cycles at 0.1 W/m²) significantly increased hypothalamic growth hormone-releasing hormone (GHRH) expression and hepatic growth hormone receptor abundance. Yu *et al.* (2018) reported that exposure to 50 lux green light for 16 h not only enhanced hatchling body weight and length but

also elevated circulating T_4 and testosterone concentrations, hormones strongly associated with growth acceleration. Red-light incubation has also been shown to improve body weight during days 18–21 post-hatch compared with blue light (Drozdová *et al.*, 2021), underscoring the nuanced interactions between wavelength and physiological programming.

Welfare-related traits and behavioral development are likewise strongly influenced by embryonic photostimulation. Early hemispheric lateralization induced by light exposure has been linked to improved attentional control, visual discrimination, and reduced fear responses. Chiandetti *et al.* (2013) observed that pullets incubated under incandescent light accessed feeders more efficiently than those incubated in darkness. Green-light incubation enhanced approach behavior towards humans at 400 lux (Kliphuis *et al.*, 2024), whereas full-spectrum light at 550 lux increased feeding motivation shortly after dawn in broilers (Archer and Mench, 2014). Light also modulated neuroendocrine stress markers: green, red, and white light at 250 lux significantly increased plasma serotonin while reducing corticosterone in hatchlings compared with dark incubation (Archer, 2017). Behavioral resilience tests further confirmed these effects, with light-incubated chicks showing faster emergence, shorter tonic immobility, and reduced wing flapping during inversion compared with dark-incubated controls (Archer and Mench, 2014).

Post-hatch musculoskeletal traits and leg health appear responsive to certain light regimens. Incubation under white light at 500 lux improved broiler leg health compared with dark incubation or lower-intensity schedules (van der Pol *et al.*, 2019). However, studies differ on the extent to which photostimulation impacts bone morphology or gait

score. While Riaz *et al.* (2021) found no differences in gait or feather score at day 35, Yameen *et al.* (2020) reported that chicks from 12 h and 24 h light incubation exhibited higher feather scores on day 15, though these differences disappeared by day 35. Physical asymmetry, an indicator of developmental instability, was highest in dark-incubated birds and lowest in 24 h light-exposed chicks, suggesting that continuous light may stabilize certain developmental processes even when other traits are negatively affected.

It was observed that green, red, and white light at 250 lux during incubation of broiler eggs led to chicks with significantly higher plasma serotonin and lower plasma corticosterone concentrations than the chicks incubated in the dark, ultimately lowering fear and stress susceptibility (Archer, 2017). Similarly, broiler birds incubated under fluorescent light at 550 lux throughout the incubation quickly left the box during the emergence test, recovered quickly during the tonic immobility test, and flapped less intensely during the inversion test than the birds incubated under 12 hours of light given on the 14th day and the dark group. In the same study by Archer and Mench (2014), the broiler birds incubated under light vocalized the least during the isolation test compared to birds incubated in the dark.

Carcass composition and meat quality traits are also modulated by light exposure. Yameen *et al.* (2020) documented that breast and thigh yields were significantly higher in chicks from 12 h light incubation, whereas abdominal fat was elevated in 24 h light-incubated birds. Carcass yield was greater in 0 h and 12 h light treatments than in 24 h, reinforcing the detrimental effect of continuous illumination on nutrient distribution. Meat quality traits responded selectively: shear force was higher in progeny from dark and 12 h light incubation, while color parameters (L^* , a^* , b^*), a standardized color measurement system, varied with light duration and strain. Notably, meat redness at 24 h post-slaughter was significantly higher in the 12 h light group (Yameen *et al.*, 2020), an indicator often associated with better consumer acceptability.

Collectively, these findings indicate that intermediate photoperiods (particularly 12L:12D), moderate intensities (200-500 lux), and specific wavelengths (especially green light) consistently produce favorable growth performance, endocrine profiles, welfare indicators, and carcass characteristics. Conversely, continuous light (24 h) often impairs chick quality, reduces hatchling weight, increases late embryonic mortality, and contributes to excessive abdominal fat deposition. Dark incubation, while promoting feed intake and livability in some contexts, generally results in inferior FCR, impaired behavioral development, and heightened stress sensitivity.

PRACTICAL APPLICATIONS AND CHALLENGES IN THE POULTRY INDUSTRY

The integration of lighted incubation protocols into commercial hatchery systems presents both promising opportunities and substantial practical challenges. Although a large body of experimental research indicates that appropriate light stimulation can enhance embryonic development, improve hatchability, modulate endocrine and circadian programming, and promote favorable behavioral and welfare outcomes, the poultry industry still largely relies on dark incubation. This conservative approach stems from long-standing concerns regarding potential reductions in hatchability, increased energy expenditure associated with unwanted secondary heating, and the possibility that non-optimized lighting parameters may compromise chick performance rather than enhance it (Rozenboim *et al.*, 2003). One of the major constraints limiting widespread adoption is the absence of standardized and universally applicable guidelines for light wavelength, photoperiod, and intensity across breeds and production types. Empirical studies have demonstrated that responses to light are influenced not only by the spectral properties of the source but also by species- and strain-specific differences, incubation equipment, shell pigmentation, and even parental flock age (Li *et al.*, 2021a, b). As a consequence, protocols that are beneficial in one genetic line or management system do not necessarily yield the same results elsewhere, creating uncertainty for industry stakeholders. Another practical limitation involves the interaction between lighting and thermal regulation.

Several studies have shown that continuous or prolonged photostimulation, particularly with short wavelengths such as green light, can incrementally increase yolk temperature, potentially shifting the metabolic heat production profile of the embryo. In large-scale commercial setters, which operate with narrow thermal margins, even minor temperature deviations may translate into significant variation in hatch windows and chick quality if not carefully controlled. This necessitates the integration of lighting technologies that minimize heat emission, alongside ventilation and thermal compensation systems capable of counterbalancing subtle metabolic changes (Yin *et al.*, 2024; Iwuchukwu *et al.*, 2025). Light distribution within commercial incubators also poses technical challenges. Achieving uniform exposure across a high-density tray layout is difficult because eggs located at different positions within the setter receive unequal light intensities. Variability in shell thickness and pigmentation further affects light penetration, leading to inconsistent stimulation among embryos. Advanced LED systems, including embedded or fibre-optic illumination, have been proposed to address these limitations, but their implementation requires substantial infrastructural

modification and cost investment.

From an economic standpoint, hatcheries must balance the potential improvements in chick quality, welfare, and later performance against the initial cost of retrofitting incubation equipment with programmable LED modules and the risk that suboptimal parameterization may reduce productivity. The benefits reported in research settings, such as enhanced muscle development, improved stress resilience, or superior feed efficiency, must therefore be validated through large-scale, multi-flock trials to confirm their financial feasibility under commercial conditions.

Despite these constraints, the increasing availability of energy-efficient LED technology and the growing emphasis on precision incubation have stimulated renewed interest in lighted incubation. As the industry progresses toward more welfare-oriented and data-driven production models, photostimulation may become an attractive tool for achieving predictable and favorable developmental outcomes. Collaborative research between academia, hatchery manufacturers, and integrators will be essential to establish species- and strain-tailored lighting guidelines, optimize integration with thermal and ventilation systems, and ensure consistent, reproducible benefits. Ultimately, addressing these challenges will be critical for the translation of experimental findings into scalable, commercially practical incubation strategies.

CONCLUSIONS

Light exposure during incubation acts as a potent biological cue that drives embryonic programming and shapes post-hatch success, modulating avian embryogenesis via distinct spectral pathways. While monochromatic green and blue wavelengths accelerate myogenic development, somatotrophic signaling, and hatchability, red and white light profoundly influence melatonin dynamics, immune function, and stress responsiveness collectively enhancing structural development, behavioral phenotypes, and post-hatch adaptability. Despite these extensive biological benefits, widespread commercial adoption is restricted by unresolved optimal parameters for spectrum, photoperiod, and intensity across varying strains, species, and hatchery microclimates, alongside practical hurdles regarding energy costs, equipment engineering, and narrow thermal margins. The considerable variation in reported outcomes underscores the critical need to standardize experimental protocols to ensure reproducibility. Moving forward, the poultry industry must prioritize developing precision lighting systems aligned with temporal embryonic physiology, integrating photostimulation with broader incubation factors, and establishing an industry-aligned framework to generate evidence-based guidelines,

ultimately leveraging lighted incubation to advance sustainable, welfare-oriented production.

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NOVELTY STATEMENT

This review provides a comprehensive synthesis of recent advances in lighted incubation, bridging the gap between molecular mechanisms of avian photoreception (retinal and deep-brain pathways) and practical hatchery management. Unlike previous reviews, it critically evaluates how specific spectral wavelengths and photoperiods interact with physiological axes, embryonic metabolic programming, and post-hatch welfare, offering a roadmap for standardizing precision lighting protocols in commercial poultry production.

AUTHOR'S CONTRIBUTION

SA: Designed and supervised the article. SA, KE-S, GB, and BM: Data collection and writing the original draft. SA, KE-S, GB, BM, UE, AM and MA: Writing and editing the final version. All authors have given approval to the final version of the manuscript.

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During the preparation of this work, the author(s), in some sentences, used Google Gemini, Grammarly, and ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

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