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Effect of fluorescent vs. poultry-specific light-emitting diode lights on production performance and egg quality of W-36 laying hens

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Abstract

More energy-efficient, durable, affordable, and dimmable light-emitting diode (LED) lights are finding applications in poultry production. However, data are lacking on controlled comparative studies concerning the impact of such lights during the pullet rearing and subsequent laying phase. This study evaluated two types of poultry-specific LED light (PS-LED) vs. fluorescent light (FL) with regards to their effects on hen laying performance. A total of 432 Hy-Line W-36 laying hens were tested in two batches using four environmental chambers (nine cages per chamber and 6 birds per cage) from 17 to 41 weeks of age (WOA). Dim-to-red PS-LED and warm-white FL were used in the laying phase. The hens had been reared under a dim-to-blue PS-LED or a warm-white FL from 1 to 16 WOA. The measured performance variables included 1) timing of sexual maturity, 2) egg production performance, 3) egg quality, and 4) egg yolk cholesterol. Results showed that the two types of light used during the laying phase had comparable performance responses for all response parameters ($P > 0.05$) with a few exceptions. Specifically, eggs laid from hens in the PS-LED treatment had lower shell thickness ($P = 0.01$) and strength ($P = 0.03$) than those in the FL treatment at 41 WOA. The two types of light used during the rearing phase did not influence the 17 to 41 WOA laying performance, except that hens reared under the PS-LED laid eggs with lower shell thickness ($P = 0.02$) at 32 WOA as compared to hens reared under the FL. This study demonstrates that the emerging poultry-specific LED lights yield comparable production performance and egg quality of W-36 laying hens to the traditional fluorescent lights.

Keywords

poultry lighting, light characteristic, egg production, egg quality, yolk cholesterol

Disciplines

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(short title) EFFECT OF LIGHT ON HEN LAYING PERFORMANCE

Effect of Fluorescent *vs.* Poultry-Specific Light-Emitting Diode Lights on Production Performance and Egg Quality of W-36 Laying Hens

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ABSTRACT

More energy-efficient, durable, affordable, and dimmable light-emitting diode (LED) lights are finding applications in poultry production. However, data are lacking on controlled comparative studies concerning the impact of such lights during the pullet rearing and subsequent laying phase. This study evaluated two types of poultry-specific LED light (PS-LED) *vs.* fluorescent light (FL) with regards to their effects on hen laying performance. A total of 432 Hy-Line W-36 laying hens were tested in two batches using four environmental chambers (nine cages per chamber and 6 birds per cage) from 17 to 41 weeks of age (WOA). Dim-to-Red PS-LED and warm-white FL were used in the laying phase. The hens had been reared under a Dim-to-Blue PS-LED or a warm-white FL from 1 to 16 WOA. The measured performance variables included 1) timing of sexual maturity, 2) egg production performance, 3) egg quality, and 4) egg yolk cholesterol. Results showed that the two types of light used during the laying phase had comparable performance responses for all response parameters ($P > 0.05$) with a few exceptions. Specifically, eggs laid from hens in the PS-LED treatment had lower shell thickness ($P = 0.01$) and strength ($P = 0.03$) than those in the FL treatment at 41 WOA. The two types of light used during the rearing phase did not influence the 17 to 41 WOA laying performance, except that hens reared under the PS-LED laid eggs with lower shell thickness ($P = 0.02$) at 32 WOA as compared to hens reared under the FL. This study demonstrates that the emerging poultry-specific LED lights yield comparable production performance and egg quality of W-36 laying hens to the traditional fluorescent lights.

Key words: Poultry lighting, Light characteristic, Egg production, Egg quality, Yolk cholesterol

INTRODUCTON

Research on poultry lighting dates back to the early 1930s. Since then, extensive research has led to a broad understanding of lighting effects on poultry. The early studies focused on photoperiod and light intensity, leading to the establishment of general lighting guidelines (e.g., ASABE EP344.4 – Lighting systems for agricultural facilities) for improved animal performance and energy efficiency (ASABE Standard, 2014). Currently, more energy-efficient, durable, affordable, and dimmable light-emitting diode (**LED**) lights are increasingly finding applications in poultry production. As light is a crucial environmental factor that affects bird behavior, development, production performance, health and well-being (Lewis and Morris, 1998; Parvin et al., 2014), the emerging LED lighting in poultry housing has drawn increasing attention from both scientific and industry communities.

Poultry has five types of retinal cone photoreceptors in the eyes. These photoreceptors produce the perception of light colors by receiving lights at the peak sensitivities of approximately 415, 450, 550, and 700 nm, and are directly related to poultry activities and growth (Osorio and Vorobyev, 2008). Besides the retinal cone photoreceptors in the eyes, poultry can also perceive light via extra-retinal photoreceptors in the brain (e.g., pineal gland and hypothalamic gland) (Mobarkey et al., 2010). Light stimuli perceived by the extra-retinal photoreceptors can impact sexual development and reproductive traits of poultry (Harrison, 1972; Lewis and Morris, 2000). However, the extra-retinal photoreceptors can only be activated by long-wavelength radiation that can penetrate the skull and deep tissue of head (Harrison, 1972; Lewis and Morris, 2000). It has been demonstrated that red lights can pass through hypothalamic extra-retinal photoreceptors and stimulate reproductive axis by controlling the secretion of gonadotrophin receptor hormone, and stimulating the release of luteinizing hormone and follicle-stimulating hormone (Lewis and Morris, 2000; Mobarkey et al., 2010). With the knowledge of the spectral sensitivity of poultry and their responses to light stimulus, it seems feasible to impact poultry (e.g., growth, reproduction, and behavior) by manipulating light stimulations to their retinal and extra-retinal photoreceptors.

The emphasis of poultry lighting has been placed on various light colors (e.g., blue, green, red, and white) and lighting sources (e.g., incandescent, fluorescent, and LED lights) in more recent decades (Lewis and Morris, 2000; Parvin et al., 2014). Research has demonstrated that red lights have an accelerating effect on sexual development and maturity of poultry (Woodard et al., 1969; Harrison et al., 1969; Gongruttananun, 2011; Min et al., 2012; Huber-Eicher et al., 2013; Baxter et al., 2014; Yang et al., 2016). In contrast, blue lights were found to be more associated with improving growth, calming the birds, and enhancing the immune response, although the underlying mechanisms have not been clearly delineated (Prayitno et al.1997; Rozenboim et al., 2004; Cao et al., 2008; Xie et al., 2008; Sultana et al., 2013). Based on these earlier research findings, many lighting manufacturers have designed LED lights specifically for poultry production by integrating some light traits that have been shown to be beneficial to certain poultry production aspect (e.g., growth, reproduction, or well-being). Recently there have been anecdotal claims about advantages of some commercial poultry-specific LED lights over traditional incandescent or fluorescent lights with regards to their effects on poultry performance and behavior. However, a thorough literature review revealed that most of the existing studies involving LED lights only investigated monochromatic LED lights. Data from controlled comparative studies are lacking concerning the impact of the emerging poultry-specific LED lights.

A few studies recently compared the emerging LED lights with traditional incandescent or fluorescent lights in pullet and laying hen houses. Hy-Line W-36 pullet reared under a Dim-to-Blue poultry-specific LED light (correlated color temperature (**CCT)** of 4500 Kelvin (**K**)) had comparable performance of body weight, body weight uniformity, and mortality as compared to the counterparts reared under a warm-white fluorescent light (CCT of 2700K), but pullets under the LED light maintained higher circadian activity levels (Liu et al., 2017a). ATAK-S commercial laying hens under incandescent, fluorescent, and cool-daylight LED (CCT of 6200K) lights had no difference in body weight at sexual maturity, feed intake, feed conversion, livability, egg production, or egg quality parameters at 16 to 52 weeks of age (**WOA**) (Kamanli et al., 2015). When comparing a Nodark poultry-specific LED light (CCT of 4100K) with a warm-white fluorescent light in commercial aviary hen houses, no differences were detected in egg weight, hen-day egg production, feed use, or mortality of DeKalb white hens for 20 to 70 WOA (Long et al., 2016a). However, hens under the fluorescent light produced more eggs per hen housed and had better feed conversion than those under the LED light (Long et al., 2016a). This study also revealed that hens under the LED light laid eggs with higher egg weight, albumen height, and albumen weight at 27, thicker egg shells at 40, but lower egg weight at 60 WOA, respectively (Long et al., 2016b). Considering these limited and inconsistent results, along with the increasing adoption of the poultry-specific LED lights, it seems justifiable to further investigate the responses of poultry to the emerging LED lighting.

The objectives of this study were: a) to assess the effects of a Dim-to-Red poultry-specific LED light (**PS-LED**) *vs.* a warm-white fluorescent light (**FL**) on timing of sexual maturity, egg production performance, egg quality, and egg yolk cholesterol content of W-36 laying hens during laying phase at 17 to 41 WOA, and b) to evaluate the earlier exposure to a Dim-to-Blue PS-LED *vs.* a warm-white FL during pullet-rearing phase (1 to 16 WOA) on the above-mentioned parameters. The results are expected to contribute to supplementing the existing lighting guidelines or decision-making about light source for egg production.

MATERIALS AND METHODS

This study was conducted in the Livestock Environment and Animal Production Laboratory at Iowa State University, Ames, Iowa, USA. The experimental protocol was approved by the Iowa State University Institutional Animal Care and Use Committee (IACUC Log # 3-15-7982-G).

Experimental Light, Birds, and Facility

Experimental Light. A Dim-to-Red PS-LED (AgriShift, JLL, LED, 8 W, Once, Inc., Plymouth, MN, USA[1]) and a warm-white FL (MicroBrite MB-801D, cold cathode fluorescent light (**CCFL**), 8W, Litetronics, Alsip, IL, USA) were used for the laying phase; whereas a Dim-to-Blue PS-LED (AgriShift, MLB, LED, 12 W, Once, Inc.) and a warm-white FL (EcoSmart, compact fluorescent light (**CFL**), 9 W, Eco Smart Lighting Australia Pty Ltd, Sydney, Australia) were used for pullet-rearing. The characteristics and the spectral distributions of these light sources are described in Table 1 and Figure 1, respectively.

Experimental Birds. Hy-Line W-36 layers were used in the study. A total of 432 birds in two successive batches (216 birds per batch) were procured from Hy-Line Research Farm Facility at Dallas Center, Iowa, USA. The birds were hatched at Hy-Line hatchery on Mar 19, 2015 and Oct 9, 2015, respectively. All the birds were reared in litter floor rooms until onset of the experiment at 17 WOA. The birds were not beak-trimmed and identified individually with wing bands. Detailed information regarding the rearing conditions (housing, lighting, feeding management, etc.) of the birds and their growing performance (body weight, body weight uniformity, and mortality) during the rearing phase have been presented in a separated paper (Liu et al., 2017a). Of the 216 birds of each batch, half (108) had been reared under the Dim-to-Blue PS-LED and the other half

[1] *Mention of product or company name is for presentation clarity and does not imply endorsement by the authors or Iowa State University, nor exclusion of other suitable products.*

under the warm-white FL. Consequently, the birds were separated into two categories according to their light exposure during the rearing phase, namely, hens with pullet phase under PS-LED (**P_{LED}**) and hens with pullet phase under FL (**P_{FL}**). All the birds had similar physiological and welfare conditions at the experiment onset, including comparable body weight, skeleton and feet health, and feather coverage. Birds from each category were then randomly assigned to 18 groups, with six birds per group.

Experimental Facility. Four identical environmental chambers, each measuring 1.8 × 1.5 × 2.4 m (L×W×H), were used in the laying phase. Two chambers used the Dim-to-Red PS-LED and the other two used the warm-white FL. Each chamber contained nine cages (three cages per tier × three tiers), with each measuring 50 × 56 × 40 cm and holding up to six hens with a space allowance of 467 cm^2/bird. Each cage had a 48 × 15 × 10 cm rectangular feeder outside the front wall, two nipple drinkers on the back wall (36 cm above floor), and a 48 × 60 × 5 cm manure collection pen underneath the wire-mesh floor. The thermal environment conditions in the chambers were controlled using an air handling unit with an air flow rate of 0.24 m^3/s (Parameter Generation & Control, Black Mountain, NC, USA). The indoor temperature and RH were essentially identical in all four chambers, maintained at 20-26°C and 45-65% RH.

Birds Assignment, Light Program, and Birds Husbandry

Birds Assignment. For each test batch, eighteen 6-bird groups of each bird category (P_{LED} or P_{FL}) were randomly assigned to the four environmental chambers (Fig. 2). Specifically, nine groups of P_{LED} or P_{FL} were randomly assigned to nine cages in two chambers equipped with PS-LED and the other nine groups were randomly assigned to nine cages in the other two chambers equipped with FL, with four or five groups per chamber. Birds were then separated into two categories according to the light conditions for the laying phase, namely, hens with layer phase under PS-LED (**L_{LED}**) and hens with layer phase under FL (**L_{FL}**). Consequently, birds were designated by their light exposure during laying and rearing phases, i.e., L_{LED}-P_{LED}, L_{LED}-P_{FL}, L_{FL}-P_{LED}, and L_{FL}-P_{FL}.

Light Program. Daily photoperiod used in the study, varying with bird age, followed the Hy-Line W-36 Commercial Layers Management Guideline (Hy-Line International, 2016), i.e., 11-h light at 17 WOA; increased by 0.5 h per week till 23 WOA; then increased by 0.25 h per week until reaching a 16-h light at 31 WOA; 16-h light afterwards. Light intensity was determined using a spectrometer (GL SPECTIS 1.0 Touch, JUST Normlicht Inc., Langhorne, PA, USA) coupled with a software (SpectraShift 2.0, Once, Inc.) specifically designed for measuring poultry-perceived light intensity in p-lux (Prescott et al., 2003). Inside each environmental chamber, two light bulbs were installed on the side wall (same side as the feeders). The light bulbs were partially covered by lightproof film strips to provide a relatively uniform light distribution among the cages. Light intensities were 25 p-lux at the feeder level for all the cages at the beginning of the experiment and then lowered to 15 p-lux at 21 WOA due to observed aggression among some birds. The CV of the light intensity distributions at the feeders in each chamber was < 10%.

Birds Husbandry. All the layers were housed in the environmental chambers for a 25-week test period (17 to 41 WOA). Commercial corn and soy diets were formulated to meet the nutritional recommendations for layers based on their production rate and egg size (Hy-Line International, 2016), i.e., pre-lay diet [16.50% CP, 2911-2955 kcal/kg ME], peaking diet [16.00% CP, 2844-2955 kcal/kg ME], and layer diet [15.50% CP, 2844-2944 kcal/kg ME]. Feed and water were available *ad-libitum* throughout the test period. A daily quantity of feed was manually added to each feed trough in the morning (07:00 h-08:00 h) to prevent spillage. The remaining feed was weighed at the end of each week to determine weekly feed use. Eggs were collected daily from each cage in the afternoon (15:00 h -16:00 h). The number of eggs and total weight for each cage were recorded. Birds were visually inspected daily. Birds with apparent injury (bleeding, open wounds, etc.) were removed from the cage according to the IACUC protocol. Manure pens were cleaned twice a week. Hens were weighed at 17 (placement), 21 (sexual maturity), 25, 29, 33, and 41 WOA on a cage basis.

Data Collection and Measurements

Timing of Sexual Maturity. Age at sexual maturity was determined for each bird group by determining the age of each group when their egg production rate reached 50%. Hens were then weighed to determine the body weight at sexual maturity on a cage basis.

Egg Production Performance**.** The test period was divided into six sub-periods (**SP**), i.e., SP 1, 2, 3, 4, 5, and 6 were 17 to 21, 22 to 25, 26 to 29, 30 to 33, 34 to 37, and 38 to 41 WOA. Hen-day egg production, egg weight, daily feed intake, and feed conversion ratio during each SP and over the entire test period (17 to 41 WOA) were calculated for each cage based on the experiment records (daily egg number, daily egg mass, and weekly feed use). Eggs per hen-housed by the end of the test period (41 WOA) was also calculated.

Egg Quality**.** Egg quality parameters were analyzed at 23, 32, and 41 WOA, with 12 fresh eggs per cage measured at each age. All the eggs were collected in two or three consecutive days and were tested within 24 h after collection. Egg weight, albumen height, Haugh unit, yolk color factor, shell strength, and shell thickness were measured using a Digital Egg Tester (NABEL DET 6000, NABEL Co., Ltd., Kyoto, Japan). Yolk was separated from the albumen to determine yolk weight and yolk percentage. Albumen weight was calculated by subtracting yolk and shell weights from egg weight. Mean values of the 12 eggs of each cage were then calculated for the subsequent statistical analyses. The separated yolks were mixed homogenously for each cage for the subsequent cholesterol determination.

Egg Yolk Cholesterol. Yolk cholesterol concentration and total cholesterol content were analyzed at 23, 32, and 41 WOA following the analysis of egg quality. The yolk samples of the four or five cages from the same category of birds (P_{LED} or P_{FL}) in each chamber were randomly combined into two samples for the subsequent cholesterol determination, thus forming four samples per chamber. The concentration and total cholesterol in yolk samples were determined using a colorimetric method by applying a Wako commercial cholesterol kit (Cholesterol E, Wako Pure Chemical Industries, Ltd., Osaka, Japan). Yolk samples were dried using a freeze dryer (Virtis Genesis 25LE, SP Scientific Company, NY, USA) and ground with a mortar and pestle. Each freeze-dried yolk sample was separated into two subsamples for analysis. All the operations followed the standard procedures stated in the cholesterol kit manual. Specifically, a small quantity of freeze-dried yolk sample (2 mg) was well mixed with 2 mL of buffer and color reagent from the kit. For the blank and standard samples, deionized water and standard cholesterol regent provided in the kit was used, respectively. The mixtures were incubated for 75 min at 37ºC for color development and then filtered with 0.45 µm polytetrafluoroethylene filter (Thermo fisher Scientific Inc., MA, USA). All the samples were then tested at 600 nm using a Multi-Mode Microplate Reader (Synergy H4 Hybrid, BioTek Instruments, Inc., Winooski, VT, USA). Cholesterol concentration was calculated using the equation derived from the curve developed using the standard samples.

Statistical Analysis

Statistical analyses were performed using SAS Studio (SAS Studio 3.5, SAS Institute, Inc., Cary, NC, USA). All variables were analyzed with linear mixed models by implementing PROC MIXED procedure. As the experiment followed a split-plot design, the environmental chambers (whole plots) and the individual cages (split-plots) were treated as the experimental units for light treatments during the laying phase and the rearing phase, respectively. All the variables were analyzed separately for each age or period. The Tukey-Kramer tests were used for pairwise comparisons, if applicable. Normality and homogeneity of variance of data were examined by residual diagnostics. Effects were considered significant when $P < 0.05$. Unless otherwise specified, data are presented as least squares means with the standard error of the mean (**SEM**).

RESULTS

Overall, light sources of PS-LED and FL during the laying phase of 17 to 41 WOA or during the rearing phase of 1 to 16 WOA had no effect on timing of sexual maturity (Table 2), egg production performance (Table 3), egg quality parameters (except for ST and SS) (Table 4), or yolk cholesterol of laying hens (Table 5). However, interaction between light exposure during the laying and rearing phases were found on EW, SS, and ST. Detailed results for each performance aspect are presented in the following sections.

Timing of Sexual Maturity

L_{LED} and L_{FL}, or P_{LED} and P_{FL} had comparable ASM and BWSM (Table 2).

Egg Production Performance

L_{LED} and L_{FL}, or P_{LED} and P_{FL} had comparable HDEP, EHH, EW, DFI, and FCR for the test period of 17 to 41 WOA (Table 3). However, L_{FL}-P_{FL} laid eggs with significantly lower EW than L_{FL}-P_{LED} (57.9 ± 0.36 g *vs.* 58.9 ± 0.36 g, $P = 0.01$). When comparing production performance of the laying hens for each SP, L_{LED} had significantly higher DFI at 34 to 37 WOA and tended to have higher DFI and HDEP at 38 to 41 WOA as compared to L_{FL}. P_{LED} had significantly higher

DFI at 30 to 33 WOA and 38 to 41 WOA, and tended to have higher HDEP at 30 to 33 WOA as compared to P_{FL}. In addition, L_{FL}-P_{FL} laid eggs with significantly lower EW than L_{FL}-P_{LED} (59.5 ± 0.32 g *vs.* 60.6 ± 0.32 g, $P = 0.03$) at 30 to 33 WOA.

Egg Quality

L_{LED} and L_{FL}, or P_{LED} and P_{FL} had comparable EW, AW, AH, HU, YW, YP, and YCF at 23, 32, and 41 WOA (Table 4). However, L_{LED} laid eggs with significantly lower ST and SS at 41 WOA as compared to L_{FL}. P_{LED} laid eggs with significantly lower ST at 32 WOA as compared to P_{FL}. In addition, L_{FL}-P_{LED} laid eggs with significantly higher EW than L_{LED}-P_{LED} (63.3 ± 0.41 g *vs.* 61.7 ± 0.41 g, $P = 0.04$) at 41 WOA. L_{FL}-P_{FL} laid eggs with significantly higher SS than L_{LED}-P_{FL} (38.9 ± 0.41 N *vs.* 37.4 N, $P = 0.04$) at 41 WOA. Besides, L_{FL}-P_{LED} laid eggs with the highest ST (0.44 ± 0.00 mm), while L_{LED}-P_{LED} laid eggs with the lowest ST (0.42 ± 0.00 mm) at 41 WOA.

Egg Yolk Cholesterol

L_{LED} and L_{FL}, or P_{LED} and P_{FL} had comparable YCC and TCC at 23 and 32 WOA (Table 5). However, L_{LED} tended to lay eggs with lower YCC and TCC at 41 WOA than L_{FL} ($P = 0.06$ and 0.07, respectively).

DISCUSSION

Our review of literature revealed limited data from comparative studies regarding the effects of poultry-specific LED lights on laying hen performance. The current study assessed timing of sexual maturity, egg production, egg quality, and egg yolk cholesterol of Hy-Line W-36 laying hens subjected to poultry-specific LED lights *vs.* fluorescent lights during rearing and laying phases, and showed that the light treatments during rearing or laying phase led to comparable laying hen performance.

Effect of Light on Timing of Sexual Maturity

Earlier studies demonstrated that exposure to long-wavelength lights (e.g., red light) could accelerate sexual development and maturity of poultry as compared to exposure to short-wavelength lights (e.g., blue and green) (Woodard et al., 1969; Gongruttananun, 2011; Min et al., 2012; Hassan et al., 2013; Huber-Eicher et al., 2013; Baxter et al., 2014; Yang et al., 2016). Based on this result, it seems reasonable to assume that a lighting source emitting relatively higher proportion of light at long-wavelength range would be more efficient in facilitating sexual development and advancing sexual maturity of juvenile hens than a lighting source emitting lower proportion of light at long-wavelength range, especially when all the other factors remain the same (e.g., photoperiod, light intensity, and nutrition). However, our results from the current study did not support this hypothesis. In this study, the Dim-to-Red PS-LED (about 48% of light components are red lights) and the warm-white FL (about 19% of light component are red lights) led to comparable sexual development of the W-36 laying hens. These results might infer that advancement of sexual maturity of poultry is not proportional to the amount of stimulation (e.g., red light radiation) perceived by the birds. There may exist a threshold in poultry's response to long-wavelength radiation. When the amount of the long-wavelength radiation reaches the threshold, the reproductive axis of poultry may not be further stimulated. The typical lighting sources used in commercial poultry production systems, such as incandescent, fluorescent, and poultry-specific LED lights, emit considerable amounts of red light. Consequently, these lighting sources may provide sufficient exposure to the birds to yield comparable sexual maturity. This inference seems consistent with findings from several earlier studies. Pyrzak et al. (1986) found incandescent, cool-white fluorescent, and sunlight-simulating fluorescent lights had no effect on age at the first egg of juvenile hens. Kamanli et al. (2015) found the use of incandescent, fluorescent, or white LED light did not cause a significant difference in body weight at sexual maturation. On the contrary, Bobadilla-Mendez et al. (2016) found that white LED light was more efficient at activating the reproductive cycle, hastening the onset of sexual maturity, and increasing the development of reproductive organs after puberty of female Japanese quail as compared to incandescent and fluorescent lights. As quail and laying hen are very different in their physiology (e.g., quail reaches sexual maturity much earlier than laying hens), the different responses to lighting sources may be attributed to their physiological differences.

Effect of Light on Egg Production Performance

Some earlier studies also demonstrated that exposure to long-wavelength lights (e.g., red light) could facilitate egg production of poultry as compared to exposure to short-wavelength lights (Pyrzak et al., 1987; Min et al., 2012; Huber-Eicher et al., 2013; Borille et al., 2013; Hassan et al., 2014; Baxter et al., 2014; Wang et al., 2015; Yang et al., 2016). Thus, the initial hypothesis for the study was that the Dim-to-Red PS-LED would lead to improved egg production performance as compared to the warm-white FL. However, the results from the current study did not support this hypothesis. Instead, the Dim-to-Red PS-LED and the warm-white FL in this study led to comparable egg production performance of the hens at 17 to 41 WOA. Again, these results seem to provide evidence supporting the existence of a threshold in poultry response to long-wavelength radiation beyond which the reproductive axis (e.g., egg production) would not be further stimulated. The results of the current study agreed well with several earlier studies. Siopes (1984) found that there were no significant differences in feed intake and egg production of turkey breeder hens between incandescent and fluorescent lights during two 20-week reproductive cycles. Gongruttananun (2011) found that Thai-native hens exposed to red light or natural daylight supplemented with fluorescent light had comparable egg production performance. Kamanli et al.

(2015) found the use of incandescent, fluorescent, or LED light did not cause significant differences in daily feed intake, feed conversion efficiency, or egg production. Liu et al. (2017b) also found that Hy-Line W-36 pullets (14 to 16 WOA) and laying hens (41 to 45 WOA) had comparable daily feed intake under the Dim-to-Red poultry-specific LED and the warm-white fluorescent lights during a light preference test. Similar to the current study, Long et al. (2016a) reported comparable egg weight, hen-day egg production, and feed use of Dekalb white hens under a Nodark poultry-specific LED *vs.* a warm-white fluorescent light in commercial aviary houses. However, hens under the fluorescent light had higher eggs per hen housed (321 *vs.* 308) and better feed conversion (1.99 *vs.* 2.03 kg feed/kg egg) than those under the LED light (Long et al., 2016a). In terms of the light exposure during rearing period, Schumaier et al. (1968) found the rearing light color of red, green, or white had no effect on egg production or egg weight of White leghorn hens at 20 to 61 WOA. Wells (1971) found that red and white lights used during rearing had no effect on peak egg production, eggs per hen-housed, feed consumption, or feed conversion of Hybrid-3 laying hens at 20 to 52 WOA. The current study agreed with these earlier findings as the two light treatments during rearing did not cause any difference in production performance of hens during the subsequent laying phase.

Effect of Light on Egg Quality Parameters

Some earlier studies found that exposure to short-wavelength lights (e.g., green and blue lights) led to improved egg quality (e.g., increased egg weight, shell thickness, or shell strength) as compared to exposure to long-wavelength lights (e.g., red light) (Pyrzak et al., 1987; Er et al., 2007; Min et al., 2012; Hassan et al., 2014; Li et al., 2014). Interestingly, the improved egg quality in these cited studies, to a certain extent, was associated with the relatively lower egg production rate of birds as reported in the studies. Among the many cited studies that reported no differences between or among lights in sexual maturity or egg production performance of birds (Wells, 1971; Gongruttananun, 2011; Borille et al., 2013; Borille et al., 2015; Kamanli et al., 2015; Nunes et al., 2016), the different lighting sources or spectra were also found to have no effect on egg quality. For example, Borille et al., (2013) found that the internal egg quality (albumen height, specific gravity, and Haugh units) of ISA Brown hens at 56 to 72 WOA were not influenced by lighting source of incandescent light, blue, yellow, green, red, or white LED light. Kamanli et al. (2015) found that the use of incandescent, fluorescent, or LED light did not cause significant differences in egg quality parameters. On the other hand, a few studies reported opposite results. Li et al. (2014) found that hens exposed to red light laid heavier eggs with a greater egg shape index than hens exposed to white, blue or green light. Min et al. (2012) found the birds reared under red light exhibited significantly increased egg shell thickness compared to birds reared under incandescent light and blue light. In general, the results from this study are consistent with the most findings from the earlier studies. Namely, the Dim-to-Red PS-LED and the warm-white FL in the current study led to comparable egg quality parameters of laying hens in terms of the egg weight, albumen weight, Haugh unit, yolk weight, yolk percent, or yolk color factor at 23, 32 and 41 WOA. However, hens under the PS-LED light laid eggs with significantly lower shell thickness and shell strength than hens under the fluorescent light at 41 WOA in the current study. These results are opposite to an earlier study conducted by Long et al. (2016b) who reported that Dekalb white hens in commercial aviary houses under a poultry-specific LED laid eggs with significantly higher shell thickness at 40 WOA as compared to hens under a warm-white fluorescent light. One speculation is that Hy-Line W-36 hens used in the current study may have different responses to the lights as compared to Dekalb white hens due to their genetic differences. These two breeds of hens have been found to have different responses to dietary energy (Harms et al., 2000). However, the speculation of genetic differences regarding responses to the lights remains to be further examined.

Effect of Light on Egg Yolk Cholesterol

Our literature review revealed very limited information regarding the effect of lights on egg yolk cholesterol. In laying hens, cholesterol is primarily biosynthesized in the liver and ovary of birds, and the egg represents a major excretory route of cholesterol (Elkin 2006). Elkin (2006) reviewed common strategies for reducing egg cholesterol content and pointed out that cholesterol content in egg yolks are mainly affected by genetics of birds, dietary nutrients, and feed intakes. Obviously, light has not been considered as an influential factor for egg cholesterol content. A recent study conducted by Long et al. (2016b) showed that the light exposure affected the cholesterol content, although the influence seems to be limited as compared to the other factors. When applying a Nodark poultry-specific LED light and a warm-white fluorescent light in commercial aviary hen houses, Long et al. (2016b) found that the total cholesterol of eggs laid by Dekalb white hens under the LED light was significantly lower than that under fluorescent light at 60 WOA, albeit no difference between the lights in total egg cholesterol at 27 or 40 WOA, or in yolk cholesterol concentration at 27, 40, or 60 WOA. Results of the current study also inferred that the light exposure may affect the cholesterol metabolism in laying hens, although the underlining mechanism was not understood. In this study, the Dim-to-Red PS-LED and the warm-white FL led to comparable egg yolk cholesterol content at 23 and 32 WOA, but the hens under the PS-LED tended to lay eggs with lower cholesterol than hens under the fluorescent light at 41 WOA. As most earlier lighting studies had not investigated egg cholesterol and potential effects of lights on egg cholesterol metabolism, it would be prudent to include egg cholesterol as a measurement in future lighting studies and to further study the underlining principle.

CONCLUSIONS

The Dim-to-Red PS-LED and the warm-white FL during the laying period of 17 to 41 WOA led to comparable laying performance in all the aspects except for eggshell thickness and strength. Hens under the PS-LED laid eggs with significantly lower shell thickness and strength as compared to hens under the FL at 41 WOA. In addition, eggs in the PS-LED tended to have lower yolk cholesterol content at 41 WOA. Light exposure to the Dim-to-Blue PS-LED or the warm-white FL during pullet rearing (1 to 16 WOA) showed no effect on the subsequent laying performance at 17 to 41 WOA, with the exception that hens reared under the PS-LED laid eggs with significantly lower shell thickness at 32 WOA than hens reared under the FL. Thus, this study demonstrated that the poultry-specific LED lights may provide a viable alternative to the traditional fluorescent lights for maintaining the Hy-Line W-36 laying hen production performance.

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Figure Captions:

Figure 1. Spectral characteristics of the warm-white fluorescent light, Dim-to-Blue PS-LED, and Dim-to-Red PS-LED involved in this study.

Figure 2. Treatment arrangements in the study.

Table 1. Characteristics of the warm-white fluorescent light, Dim-to-Blue PS-LED [1], and Dim-to-Red PS-LED involved in this study

Light Type	CCT [2] (K)	Flicker Frequency (Hz)	Spectral Distribution
Warm-white fluorescent light [3]	2700	120	Discrete spectrum, main spectral spikes at 545 and 610 nm
Dim-to-Blue PS-LED	4550	120	Continuous spectrum, spectral spikes at 450 and 630 nm, with a predominant spectral output at 430-460 nm
Dim-to-Red PS-LED	2000	120	Continuous spectrum, spectral spikes at 450 and 630 nm, with a predominant spectral output at 610-640 nm

[1] PS-LED = poultry-specific LED light
[2] CCT = correlated color temperature
[3] Fluorescent light refers to both compact fluorescent light (CFL) and cold-cathode fluorescent light (CCFL). CFL and CCFL have essentially identical spectral characteristics.

Table 2. Age and body weight at sexual maturity (50% rate of lay) as affected by light during rearing and laying phases [1]

Parameter	Light during Laying (L)			Light during Rearing (R)			p-value		
	L_{LED} [2]	L_{FL} [3]	SEM	P_{LED} [4]	P_{FL} [5]	SEM	L	R	L×R
ASM [6] (d)	143.4	141.7	0.67	142.9	142.2	0.55	0.14	0.23	0.21
BWSM [7] (kg)	1.45	1.46	0.01	1.46	1.45	0.01	0.77	0.57	0.72

[1] Data are least square means ± SEM.
[2] L_{LED} = hens with layer phase under PS-LED
[3] L_{FL} = hens with layer phase under FL
[4] P_{LED} = hens with pullet phase under PS-LED
[5] P_{FL} = hens with pullet phase under FL
[6] ASM = age at sexual maturity (d)
[7] BWSM = body weight at sexual maturity (kg)

Table 3. Egg production at 17 to 41 weeks of age (WOA) as affected by light during rearing and laying phases [1]

Parameter	Period (WOA)	Light during Laying (L)			Light during Rearing (R)			p-value		
		L_{LED} [2]	L_{FL} [3]	SEM	P_{LED} [4]	P_{FL} [5]	SEM	L	R	L×R
EHH [6]	17 to 41	125.0	124.7	1.50	125.6	124.1	2.56	0.87	0.75	0.86
HDEP [7] (%)	17 to 21	11.7	13.7	1.06	12.0	13.4	0.91	0.25	0.17	0.28
	22 to 25	89.5	90.5	0.31	90.0	90.0	0.62	0.10	0.99	0.62
	26 to 29	95.0	94.8	0.92	95.1	94.7	0.85	0.92	0.71	0.48
	30 to 33	94.7	93.9	0.50	95.1	93.4	0.58	0.33	0.08	0.35
	34 to 37	92.2	90.7	0.97	91.3	91.6	0.99	0.35	0.83	0.22
	38 to 41	90.2	87.6	0.79	88.7	89.1	0.86	0.08	0.77	0.33
	17 to 41	74.9	75.1	0.49	75.2	74.9	0.61	0.78	0.76	0.90
EW [8] (g)	17 to 21	47.7	47.8	0.35	47.8	47.7	0.33	0.85	0.77	0.17
	22 to 25	53.7	53.9	0.33	53.8	53.8	0.26	0.80	0.81	0.29
	26 to 29	57.8	57.8	0.28	57.9	57.6	0.32	0.97	0.35	0.18
	30 to 33	59.9	60.0	0.25	60.0	59.9	0.23	0.73	0.63	0.05
	34 to 37	60.6	61.0	0.34	60.8	60.8	0.27	0.35	0.95	0.14
	38 to 41	61.8	62.0	0.32	61.9	61.9	0.28	0.57	0.96	0.22
	17 to 41	58.3	58.4	0.31	58.4	58.3	0.25	0.80	0.54	0.01
DFI [9] (g/day-bird)	17 to 21	71.2	72.0	0.95	71.6	71.7	0.75	0.56	0.88	0.41
	22 to 25	94.9	94.7	0.87	95.5	94.2	0.79	0.88	0.20	0.26
	26 to 29	103.9	104.4	0.83	104.8	103.4	0.78	0.69	0.18	0.95
	30 to 33	106.2	105.3	0.98	106.7[a]	104.8[b]	0.80	0.55	0.02	0.10
	34 to 37	106.1[a]	103.8[b]	0.49	105.3	104.6	0.74	0.04	0.57	0.26
	38 to 41	109.0	107.2	0.51	109.2[a]	107.0[b]	0.65	0.07	0.05	0.33
	17 to 41	96.9	96.4	0.49	97.3	96.0	0.53	0.55	0.10	0.21
FCR [10] (kg feed/kg egg)	17 to 21	19.68	13.52	3.22	17.82	15.38	2.58	0.25	0.32	0.41
	22 to 25	1.98	1.95	0.02	1.98	1.95	0.02	0.29	0.24	0.58
	26 to 29	1.90	1.91	0.02	1.91	1.90	0.02	0.72	0.66	0.87
	30 to 33	1.88	1.87	0.01	1.87	1.87	0.01	0.75	1.00	0.43
	34 to 37	1.90	1.88	0.02	1.90	1.88	0.02	0.39	0.47	0.16
	38 to 41	1.97	1.97	0.02	2.00	1.94	0.02	0.82	0.09	0.17
	17 to 41	2.22	2.20	0.02	2.22	2.21	0.02	0.43	0.62	0.77

[1] Data are least square means ± SEM. For each category data in the same row with different superscripts are significantly different ($P < 0.05$)
[2] L_{LED} = hens with layer phase under PS-LED
[3] L_{FL} = hens with layer phase under FL
[4] P_{LED} = hens with pullet phase under PS-LED
[5] P_{FL} = hens with pullet phase under FL
[6] EHH = eggs per hen housed
[7] HDEP = hen-day egg production (%)
[8] EW = egg weight (g)
[9] DFI = daily feed intake (g/bird-day)
[10] FCR = feed conversion ratio (kg feed/kg egg)

Table 4. Egg quality at 23, 32, and 41 weeks of age (WOA) as affected by light during rearing and laying phases [1]

Parameters	Age (WOA)	Light during Laying (L)			Light during Rearing (R)			p-value		
		L_{LED} [2]	L_{FL} [3]	SEM	P_{LED} [4]	P_{FL} [5]	SEM	L	R	L×R
EW [6] (g)	23	53.7	53.6	0.24	53.7	53.6	0.25	0.84	0.71	0.41
	32	60.1	60.2	0.16	60.3	60.0	0.22	0.50	0.26	0.27
	41	62.0	62.7	0.33	62.5	62.2	0.29	0.25	0.31	0.05
AW [7] (g)	23	36.5	36.2	0.21	36.4	36.3	0.19	0.43	0.74	0.24
	32	39.1	39.2	0.14	39.3	39.0	0.17	0.80	0.29	0.16
	41	39.7	40.0	0.34	39.9	39.8	0.28	0.52	0.66	0.12
AH [8] (mm)	23	9.6	9.7	0.07	9.6	9.7	0.07	0.22	0.27	0.39
	32	9.1	9.1	0.06	9.1	9.1	0.07	0.90	0.64	0.97
	41	9.0	9.0	0.06	9.0	9.1	0.07	0.77	0.42	0.86
HU [9]	23	98.4	98.8	0.31	98.3	98.9	0.32	0.46	0.25	0.58
	32	95.1	95.0	0.31	94.9	95.2	0.32	0.91	0.56	0.92
	41	93.5	92.6	0.38	92.9	93.2	0.36	0.14	0.47	0.26
ST [10] (mm)	23	0.44	0.44	0.00	0.44	0.44	0.00	0.43	0.96	0.76
	32	0.43	0.43	0.00	0.43^{b}	0.44^{a}	0.00	0.89	0.02	0.15
	41	0.42^{b}	0.44^{a}	0.00	0.43	0.43	0.00	0.01	0.53	0.01
SS [11] (N)	23	42.4	42.1	0.30	42.0	42.5	0.34	0.55	0.43	0.77
	32	39.1	39.2	0.36	39.0	39.3	0.39	0.88	0.43	0.87
	41	37.5^{b}	38.8^{a}	0.22	38.2	38.1	0.38	0.03	0.99	0.01
YW [12] (g)	23	11.4	11.5	0.08	11.5	11.5	0.08	0.40	0.83	0.79
	32	14.8	14.9	0.05	14.9	14.8	0.07	0.26	0.34	0.41
	41	16.0	16.2	0.10	16.2	16.0	0.09	0.22	0.17	0.22
YP [13] (%)	23	21.3	21.6	0.11	21.4	21.4	0.10	0.15	0.96	0.16
	32	24.6	24.8	0.07	24.7	24.7	0.08	0.23	0.55	0.15
	41	25.8	25.9	0.08	25.9	25.8	0.09	0.53	0.54	0.16
YCF [14]	23	6.9	6.9	0.04	6.9	6.9	0.04	0.51	0.31	0.54
	32	6.7	6.7	0.04	6.7	6.7	0.04	0.64	0.77	0.91
	41	7.1	7.1	0.04	7.1	7.1	0.04	0.33	0.70	0.42

[1] Data are least square means ± SEM. For each category data in the same row with different superscript letters are significantly different ($P < 0.05$).
[2] L_{LED} = hens with layer phase under PS-LED
[3] L_{FL} = hens with layer phase under FL
[4] P_{LED} = hens with pullet phase under PS-LED
[5] P_{FL} = hens with pullet phase under FL
[6] EW = egg weight (g)
[7] AW = albumen weight (g)
[8] AH = albumen height (mm)
[9] HU = Haugh Unit
[10] ST = shell thickness (mm)
[11] SS = shell strength (N)
[12] YW = yolk weight (g)
[13] YP = yolk percentage (%)
[14] YCF = yolk color factor

Table 5. Egg cholesterol content at 23, 32, and 41 weeks of age (WOA) as affected by light during rearing and laying phases [1]

Parameters	Age (WOA)	Light during Laying (L)			Light during Rearing (R)			p-value		
		L_{LED} [2]	L_{FL} [3]	SEM	P_{LED} [4]	P_{FL} [5]	SEM	L	R	L×R
YCC [6] (mg/g yolk)	23	10.1	10.0	0.27	10.1	9.9	0.24	0.77	0.48	0.90
	32	8.5	8.8	0.31	8.7	8.6	0.26	0.48	0.82	0.33
	41	8.3	8.7	0.12	8.5	8.5	0.16	0.06	0.78	0.18
TCC [7] (mg/egg yolk)	23	115.0	115.2	3.34	116.4	113.8	3.18	0.97	0.54	0.95
	32	125.6	131.9	4.69	129.7	127.8	3.94	0.39	0.65	0.31
	41	132.6	141.4	2.76	137.0	137.1	2.88	0.07	0.98	0.23

[1] Data are least square means ± SEM.
[2] L_{LED} = hens with layer phase under PS-LED
[3] L_{FL} = hens with layer phase under FL
[4] P_{LED} = hens with pullet phase under PS-LED
[5] P_{FL} = hens with pullet phase under FL
[5] YCC = yolk cholesterol content (mg/g yolk)
[6] TCC = total cholesterol content (mg/egg yolk)

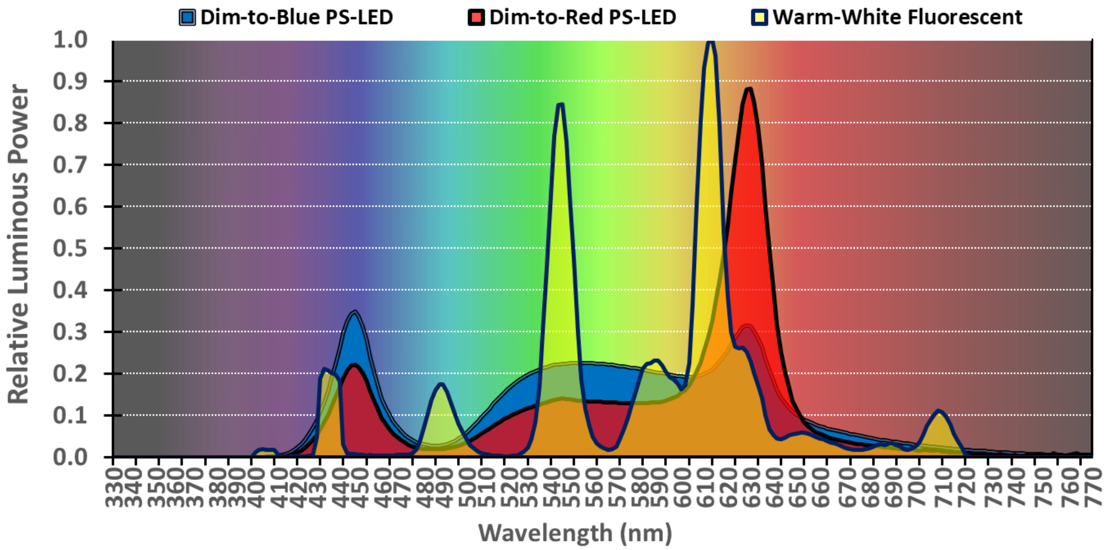

Figure 1. Spectral characteristics of the warm-white fluorescent light, Dim-to-Blue PS-LED, and Dim-to-Red PS-LED involved in this study. PS-LED = poultry-specific LED light. Fluorescent light refers to compact fluorescent light (CFL) and cold-cathode fluorescent light (CCFL) which have essentially identical spectral characteristics.

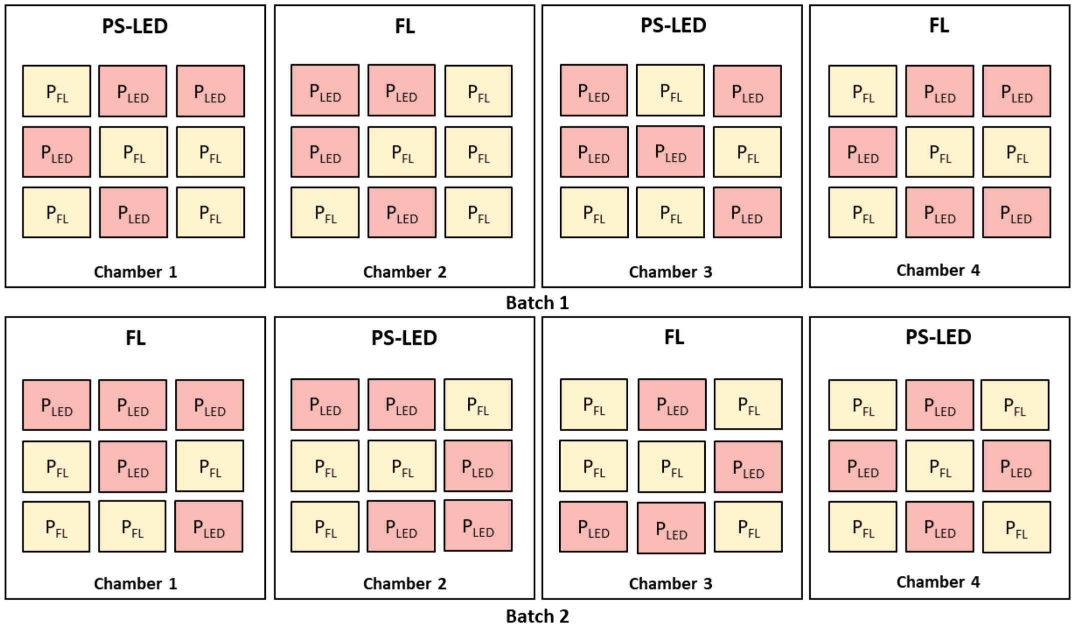

Figure 2. Treatment arrangements in the study. PS-LED = poultry-specific LED light; FL = fluorescent light; P_{FL} = hens with pullet phase under FL; P_{LED} = hens with pullet phase under PS-LED. “PS-LED” and “FL” stand for light type used in the environmental chamber.