Interactive effects of light-sources, photoperiod, and strains on growth performance, carcass characteristics, and health indices of broilers grown to heavy weights[1]

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ABSTRACT Effects of light sources, photoperiods, and strains on growth performance, carcass characteristics, and health indices of broilers grown to heavy weights (>3 kg) were evaluated. The experimental design was a 4 × 2 × 2 factorial treatments consisting of 4 light sources [incandescent (**ICD**, standard), compact fluorescent light, neutral light emitting diode (Neutral-**LED**), and cool poultry specific LED (Cool-poultry specific (**PS**)-LED)], 2 photoperiods (regular/intermittent [2L:2D], and short [8L:16D]), and 2 strains (A, B). In each trial, chicks of 2 different strains from different commercial hatcheries were equally and randomly distributed into 16 environmentally controlled rooms at 1 D of age. Each room was randomly assigned one of 16 treatments from day 1 to 56 D of age. Feed and water were provided ad libitum. Birds were provided a 4 phase-feeding program (starter, grower, finisher, withdrawal). Birds and feed were weighed on 1, 14, 28, 42, and 56 D of age for growth performance. On day 56, a total of 20 (10 males and 10 females) birds from each room were processed to determine weights and yields. The BW, BW gain, live weight, and carcass weight of birds reared under PS-LED were higher ($P < 0.05$) in comparison with birds reared under ICD, but feed intake, feed conversion ratio, mortality, and carcass characteristics were not affected by treatments. Also, broilers subjected to the short/non-intermittent photoperiod had the lowest ($P < 0.05$) growth performance and carcass characteristics compared with values obtained for regular/intermittent photoperiods. In addition, strain was significant ($P < 0.05$) for most of the examined variables. Feed conversion, fat, tender, and yield were not affected by treatments. There was no effect of photoperiod, light sources, or their interactions on mortality. This study shows positive impacts on alternative light sources when compared to ICD along with regular/intermittent photoperiod in commercial poultry facilities rearing the 2 strains used in this study, thereby reducing energy costs and optimizing production efficiency without compromising the welfare of broilers grown to heavy weights.

Key words: light source, photoperiod, strains, welfare, broiler

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INTRODUCTION

Light management is an important factor affecting broiler production and welfare (Zheng et al., 2013; Parvin et al., 2014; Yang et al., 2016). Lighting programs have a central purpose of controlling growth rate of broilers to allow birds to achieve physiological maturity prior to maximal rate of muscle mass accretion (Lewis and Morris, 2006). Incandescent (**ICD**) bulbs have been phased out in favor of more energy-efficient lighting alternatives in poultry houses. Energy efficient light emitting diode (**LED**) light-source as compared with other lighting options such as fluorescent lights is a major upfront investment for reducing electrical energy inputs and maximizing outputs of a poultry company. Although several studies have been conducted on LED light sources (Yang et al., 2018), field research information is also needed regarding broiler strains comparison on the impact of LED light-sources in combination with photoperiod on performance, carcass characteristics, and well-fare of broilers grown to heavy weights.

Consumer demand for breast meat has driven a shift in market composition towards increased market weights. Over the past 5 decades, consumption of poultry meat has increased dramatically, which is

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expected to continue in the future (Petracci et al., 2015). However, as the demand for animal protein products increases, increasing poultry production and production efficiencies will be critical to the continued viability of the U.S. poultry and livestock industries. Modern broiler strains are selected for a number of characteristics including growth rate and meat quality and these selection criteria have been adapted through the decades according to market demand. Environmental management strategies must be developed that increase production efficiency without detrimental effects on the welfare of poultry and livestock. Several studies have compared broiler strain differences in combination with other production factors such as diet, sex, age, and environmental conditions that influence the yield of broiler parts and carcass composition (Abdullah et al., 2010; Woyengo et al., 2010; Lopez et al., 2011; Jovanir et al., 2013; Olanrewaju et al., 2018).

In the United States, market share of commercial broilers is dominated by birds originating from 2 strains (A and B) that are regularly use in the poultry industry worldwide. In this study, A is a late-developing strain, which has been marketed as a high meat yielding bird with a superior feed conversion efficiency rate and maximized breeder performance high yield. The strain B is an early-developing, which is a unique product genetically developed to provide the best live production efficiency with the highest breast meat yielding at the least cost and best feed efficiency. The rate of development differs among strains and lighting program needs may be strain specific to optimize growth performance. Substantial unbiased scientific information is limited on comparison of strains A and B on the effect of differing photoperiods in combination with the new LED light-sources currently used by the poultry industry on growth performance, carcass characteristics, and welfare indices since establishing proper welfare practices are concern to international trade negotiations of meat products. Our previous study (Olanrewaju et al., 2018) investigated the influence of light-sources and photoperiod on growth performance, carcass characteristics, and health indices of broilers grown to heavy weights. The lack of comparison of strains A and B begs the question as to whether they respond similarly to environmental adjustment changes in production practices. To the knowledge of the authors, no previous research has been conducted regarding the broiler strains comparison on the effects of LED light-sources in combination with photoperiod on growth performance, carcass characteristics, and health indices of the 2 commercial broiler strains A and B grown to heavy weights used in the current study. Therefore, the objective of this study was to evaluate the effects of light sources (compact fluorescent light (**CFL**), LED, PS-LED) bulbs in comparison with ICD bulbs in combination with photoperiod on growth performance, carcass characteristics, and health indices of these 2 broiler strains (A and B) grown to heavy weights (>3.0 kg).

MATERIALS AND METHODS

Bird Husbandry

All procedures relating to the use of live birds in this study were approved by the USDA-ARS Animal Care and Use Committee at the Mississippi State location. In addition, unnecessary discomfort to the birds was also avoided by using proper housing and handling techniques (FASS, 2010). This experiment was repeated 2 times and in each, 480 (240 males/240 females) 1-day-old chicks of each strain were purchased from different commercial hatcheries. Upon arrival, the chicks were sexed and group-weighed. Birds were equally and randomly distributed into 16 environmental control rooms (30 males and 30 females/room) at 50% relative humidity (**RH**). Each room was randomly assigned one of 16 treatments from day 1 to 56 D of age. Each environmental room had a floor area of 2.3 m × 2.6 m (5.98 m^2) with a room volume of 14.95 m^3 (ceiling height = 2.5 m). The stocking density was 10.7 birds/m^2 (1 bird/ft^2), which resulted in a final stocking density of 52 kg/m^2 at the end of the trial. Each room contained approximately 7.62 cm depth of fresh pine shavings, tube feeders, and a 7-nipple watering system. Chicks were vaccinated for Marek's, Newcastle, and infectious bronchitis diseases at the hatchery. At 12 D of age, birds received a Gumboro vaccination via water administration. The chicks remained in their respective rooms from 1-day-old throughout the experimental period (1 to 56 D of age). All birds were fed the same diet throughout the study. Birds were provided a 4-phase feeding program (starter: 1 to 14 D; grower: 15 to 28 D; finisher: 29 to 42 D; and withdrawal: 43 to 56 D of age). Diets were formulated to meet or exceed NRC (1994) nutrient recommendations for each feeding phase. Starter feed was provided as crumbles, and subsequent feeds were provided as whole pellets. Feed and water were offered ad libitum. Temperature and RH on day 1 were maintained at 32 ± 1.1°C and 50 ± 5%, respectively, and RH was held constant across all treatments. Temperature was decreased as the birds progressed in age until 15.6°C was reached at 49 D of age.

Treatments

The experimental design was a 4 × 2 × 2 factorial consisting of 4 light sources (ICD, 2010k, Standard; CFL, 2700k; Neutral-LED, 3500k; Cool-PS-LED, 5000k) from day 1 to day 56 of age and exposure to photoperiod consisted of continuous lighting (24L:0D) with 20 lx of intensity from placement to 7 D of age, and then subjected to the following 2 photoperiods (regular/intermittent [2L:2D] and short/non-intermittent [8L:16D] from day 8 to 48 and [23L:1D] from day 49 to 56, respectively) and 2 strains (A, B). Each of the 2 photoperiod treatments was paired with one of the 4 light sources equally with the 2 strains so that each room represented a particular photoperiod: light source: strain combination for a total of 16 rooms of the 16 treatments. Neutral-LED light bulbs were purchased from NexGen Illumination Inc. (Fayetteville, AR), CFL light bulbs were purchased from Osram Sylvania (Danvers, MA), and Cool-PS-LED light bulbs, made specifically for poultry, were purchased from Once-Innovation (Plymouth, MN). Light spectra of the light sources and ICD along with light intensity settings utilized in this study have been reported previously (Olanrewaju et al., 2016; Olanrewaju et al., 2018).

Measurements

Birds and feed were weighed on 1, 14, 28, 42, and 56 D of age for the computation of BW gain (**BWG**) and feed intake (**FI**). Cumulative biweekly FI was calculated by subtracting the remaining feed weights in the feeders from the initial feed-added in the feeders. The incidence of mortality was recorded daily. Necropsies and cause of death (when determined) were performed on all birds that died during the trials. Cumulative BW and FI were recorded from each room at biweekly intervals. Cumulative biweekly BWG was calculated by subtracting initial (day 1) BW from the current BW of the birds. Feed conversion ratio (**FCR**) was calculated by dividing FI with BWG, and it was corrected for mortality.

Humoral Immune Response

On day 28, a total of 6 birds (3 males and 3 females) from each room were randomly selected and intravenously injected via a wing vein with a 3% solution of sheep red blood cells. Birds were bled 7 D later via a wing vein to collect serum that was used for evaluating primary antibody response. Details regarding humoral immune response have been described previously (Olanrewaju et al., 2016).

Ocular Assessments

Eye Examination On day 42, eye scoring was evaluated on 10 birds (5 males and 5 females) from each room by a veterinary ophthalmologist. The ophthalmologist did not know the treatment origin of any bird examined. Biomicroscopy was performed using a Kowa SL-14 portable slit-lamp (Kowa Company Ltd., Tokyo, Japan). During the examination, signs of clinical keratoconjunctivitis and anterior uveitis were recorded, if present. Corneal lesions assessed by biomicroscopy were assigned injury scores similar to Arora's classification (Arora et al., 2005). Further details regarding the eye examination techniques can be found in Olanrewaju et al. (2016).

Ocular Development and Histopathologic Examination

On day 43, a total of 4 birds (2 males and 2 females) from each room were weighed individually and ocular assessments were performed as described previously (Olanrewaju et al., 2015a). Briefly, birds were euthanized by cervical dislocation according to the USDA Animal Care and Ethics Committee for blood sampling and organ collection procedures. The right eyeball was dissected out, trimmed of extraneous tissue, and weighed to the nearest 0.01 g. Assuming bilateral symmetry, only the right eye was excised, and its weight doubled to give an estimate of total eye weight, and calculation of the total eye weight to BW ratio was determined. The dissected right eyeball was placed in 10% buffered formalin for gross anatomical anomalies and histopathological evaluation by a veterinary pathologist as described previously (Olanrewaju et al., 2016).

Gait Scoring (GS) Test Locomotive ability was assessed using a modification of the Kestin Gait Scoring System as described in the American Humane Welfare Standard (Onbasilar et al., 2007). On the morning of day 49, a total of 10 (5 males and 5 females) randomly selected birds from each room, 2 birds (1 male and 1 female) at a time, were allowed to walk freely (1.52 m) within an interior enclosed floor area of 1.83 m × 3.66 m that contained new pine shavings as described previously (Olanrewaju et al., 2016).

Tonic Immobility (TI) Also on the afternoon of day 49, a total of 10 birds (5 males and 5 females) from each room were randomly selected for tonic immobility (**TI**) assessment. Details regarding the TI techniques can be found in Olanrewaju et al. (2016).

Production Evaluation

On day 56 of each trial, 20 birds (10 males and 10 females) from each room were randomly selected for processing, and weighed after being subjected to a 12-h overnight feed withdrawal period. This live weight (post-feed withdrawal) was used to calculate whole carcass yield. Thereafter, the birds were placed in coops and transported to the Mississippi State University poultry processing plant. Birds were electrically stunned, bled, scalded, mechanically picked, and mechanically eviscerated. Whole hot carcass (without neck, giblets, abdominal fat pad) and abdominal fat pad (including leaf fat surrounding the cloaca and gizzard) were weighed. Carcasses were then split into front and back halves and placed on ice for 4 h. After chilling, the front halves were deboned to obtain weights of skinless, boneless breast fillet (pectorals major muscle), and breast tender (pectorals minor muscle). Abdominal fat pad and total breast meat yield (sum of pectorals major and minor muscles) were determined from the sum of the fillet weight and tender weight.

Statistical Analysis

The experimental design was a randomized complete block design, and 2 trials were conducted. Treatment structure was a 4 × 2 × 2 factorial arrangement with the main factors being 4 light sources (ICD, CFL, Neutral-LED, Cool-PS-LED), 2 photoperiods (regular/intermittent [2L:2D] and short/non-intermittent [8L:16D]), and 2 strains (Strain A, Strain B). Individual sample data within each of the replicate units were averaged before analysis and data from the 2 trials were pooled and analyzed together. A mixed model ANOVA employing PROC MIXED procedure of SAS software (SAS Institute, 2013) was used to analyze the data. Trial was a random effect, whereas the light sources, photoperiod, and strains were the fixed effect. Room was considered the experimental unit with 60 birds/room and treatments were replicated over time. Rooms used were switched randomly among treatments between trials to remove room effects so that treatments were not confounded. Main effects of light sources, photoperiod, strains, and the interaction of the 3 factors were tested. All mortality data were subjected to arc-sine transformation. Log-transformation of the raw scores was used because of the large range among the data. Geometric means are presented for the corneal and anterior chamber scores. The histopathologic eye tissue evaluations (presented as a percentage of occurrences) required arc-sine transformation before analysis. For each of the eye tissues, the presence or absence of lymphocytic or heterophilic infiltrates in the iris and ciliary body was given as a positive or negative score. If the number of samples with a positive score was 3 out of 4 for a particular treatment, the percentage of occurrence was 75%. Means comparisons on day 14, 28, 42, and 56 were assessed by least significant differences and statements of significance were based on $P < 0.05$ unless otherwise stated. Analyses of variance combined across days were performed to obtain treatment comparisons averaged across days and to test for treatment interactions with equal variances between days. In addition, ANOVAs for each of the 2 wk interval sampling days was performed.

RESULTS

The main effect of light sources, photoperiods, and strains on BW, BWG, FI, and FCR on biweekly data from day 14 through 56 of age are presented in Table 1. In comparison with ICD bulbs, there was only an effect of Cool-PS-LED on BW on day 28 ($P = 0.022$), day 42 ($P = 0.012$), and day 56 ($P = 0.045$) during this study period. Furthermore, in comparison with short/non-intermittent photoperiod, regular/intermittent photoperiod increased BW on day 14 ($P = 0.042$), day 28 ($P = 0.048$), day 42 ($P = 0.049$), and day 56 ($P = 0.032$) of age. Similarly, in comparison with Strain A, Strain B had higher BW on day 14 ($P = 0.001$), day 28 ($P = 0.001$), day 42 ($P = 0.001$), and day 56 ($P = 0.030$) of age. Similar to BW, in comparison with ICD bulbs, there was an effect of Cool-PS-LED on BWG on day 28 ($P = 0.017$), day 42 ($P = 0.013$), and day 56 ($P = 0.043$) during the study period. In addition, regular/intermittent photoperiod increased BWG on day 14 ($P = 0.032$), day 28 ($P = 0.032$), day 42 ($P = 0.044$), and day 56 ($P = 0.035$) of age in comparison with short/non-intermittent photoperiod. Furthermore as in BW, in comparison with Strain A, Strain B had higher BWG on day 14 ($P = 0.001$), day 28 ($P = 0.001$), day 42 ($P = 0.001$), and day 56 ($P = 0.028$) of age. There was no difference among ICD, CFL, and Neutral-LED light bulbs on BW and BWG in the present study. Moreover, there was no light sources effect on cumulative FI and cumulative FCR data during the study period (day 1 to 56) as presented in Table 1. However, broilers reared under short/non-intermittent photoperiod had reduced feed intake on day 14 ($P = 0.014$), day 28 ($P = 0.001$), day 42 ($P = 0.004$), and day 56 ($P = 0.001$) of age compared with those birds subjected to regular/intermittent photoperiods. Moreover, there were no main effects of photoperiod on FCR observed from day 14 through 56 of age. Similarly, in comparison with Strain A, Strain B had higher FI on day 14 ($P = 0.001$), day 28 ($P = 0.001$), day 42 ($P = 0.001$), and day 56 ($P = 0.039$) of age along with increase in FCR on day 28 ($P = 0.005$), day 42 ($P = 0.001$), and day 56 ($P = 0.003$).

The main effect of light sources, photoperiod, and strains on preprocessing live weight, carcass characteristics, fat, and yields of broilers at 56 D of age are presented in Table 2. The Cool-PS-LED bulbs had higher ($P = 0.042$) live weight and carcass weight ($P = 0.042$) in comparison with ICD bulbs, but there was no difference among the new light source (CFL, Neutral-LED, Cool-PS-LED) bulbs examined. Also, there was no difference among ICD, CFL, and Neutral-LED bulbs on live and carcass weights in the present study. In addition, regular/intermittent photoperiod had higher live weight ($P = 0.043$), carcass weight ($P = 0.037$), carcass yield ($P = 0.034$), and breast weight ($P = 0.035$) in comparison with short/non-intermittent photoperiod. Furthermore, Strain B had higher live weight ($P = 0.032$), carcass weight ($P = 0.001$), carcass yield ($P = 0.001$), breast weight ($P = 0.001$), and breast yield ($P = 0.002$) in comparison with Strain A. In addition, there was no main effect of light sources, photoperiod, strains on fat, tender weights, and yields in the present study.

The main effects of light sources, photoperiod, and strains on selected welfare indices are presented in Table 3. As shown in the table, broilers reared under short/non-intermittent photoperiod only had a reduction in BW ($P = 0.022$) and total eye weight ($P = 0.043$) when compared with broilers reared under regular/intermittent photoperiods. In addition, Strain A had a reduction in BW ($P = 0.005$) and total eye weight ($P = 0.048$) in comparison with Strain B. However, all examined welfare indices (eyes to BW ratio,

Table 1. Main effects of light sources, photoperiod, and strains on growth performance of broilers growth to heavy weights.[1]

Item	BW (kg) 14 D	28 D	42 D	56 D	BWG (kg) 14 D	28 D	42 D	56 D
Light sources[2]								
ICD	0.383	1.380[b]	2.711[b]	3.962[b]	0.339	1.336[b]	2.668[b]	3.828[b]
CFL	0.388	1.402[a,b]	2.751[a,b]	4.072[a,b]	0.345	1.359[a,b]	2.707[a,b]	3.958[a,b]
LED	0.400	1.422[a,b]	2.764[a,b]	4.074[a,b]	0.356	1.379[a,b]	2.721[a,b]	3.827[a,b]
PS-LED	0.400	1.433[a]	2.779[a]	4.087[a]	0.358	1.389[a]	2.739[a]	4.018[a]
Photoperiod[3]								
Reg-inter	0.398[a]	1.425[a]	2.764[a]	4.047[a]	0.354[a]	1.371[a]	2.750[a]	3.993[a]
Shot-non-inter	0.377[b]	1.404[b]	2.719[b]	3.905[b]	0.334[b]	1.350[b]	2.700[b]	3.816[b]
Strains								
Strain A	0.363[b]	1.306[b]	2.650[b]	3.923[b]	0.317[b]	1.260[b]	2.604[b]	3.877[b]
Strain B	0.422[a]	1.512[a]	2.853[a]	4.069[a]	0.381[a]	1.471[a]	2.812[a]	3.998[a]
Pooled SEM[4]	0.012	0.023	0.026	0.021	0.012	0.022	0.026	0.176
				P-value				
Light sources	0.151	0.022	0.012	0.045	0.136	0.017	0.013	0.043
Photoperiod	0.042	0.048	0.049	0.032	0.032	0.032	0.044	0.035
Strains	0.001	0.001	0.000	0.030	0.000	0.000	0.000	0.028

Item	FI (kg) 14 d	28 d	42 d	56 d	FCR (kg of feed/kg of gain) 14 d	28 d	42 d	56 d
Light sources[2]								
ICD	0.426	1.854	4.220	6.911	1.259	1.386	1.581	1.760
CFL	0.429	1.881	4.284	6.964	1.248	1.385	1.582	1.759
LED	0.443	1.886	4.291	6.628	1.244	1.386	1.582	1.714
PS-LED	0.444	1.882	4.285	7.093	1.258	1.380	1.583	1.766
Photoperiod[3]								
Reg-inter	0.439[a]	1.894[a]	4.292[a]	7.003[a]	1.258	1.388	1.587	1.758
Shot-non-inter	0.434[b]	1.881[b]	4.272[b]	6.774[b]	1.246	1.380	1.577	1.741
Strains								
Strain A	0.400[b]	1.728[b]	4.048[b]	6.639[b]	1.244	1.371[b]	1.555[b]	1.704[b]
Strain B	0.473[a]	2.055[a]	4.523[a]	7.159[a]	1.260	1.397[a]	1.609[a]	1.796[a]
Pooled SEM[4]	0.009	0.021	0.036	0.075	0.026	0.006	0.004	0.018
				P-value				
Light sources	0.195	0.636	0.505	0.555	0.792	0.924	0.990	0.490
Photoperiod	0.014	0.001	0.004	0.001	0.384	0.362	0.096	0.517
Strains	0.000	0.000	0.000	0.039	0.231	0.005	0.001	0.003

[a,b]Means within a column and effect that lack common superscripts differ significantly ($P = 0.05$).
[1]BWG = BW Gain, FI = Feed Intake, FCR = Feed Conversion Ratio.
[2]ICD = Incandescent light (Standard), CFL = Compact Fluorescent light; LED = Light Emitting Diode; PS-LED = Poultry Specific LED.
[3]Reg-inter = Regular/intermittent, Shot-non-inter = Short/non-intermittent.
[4]Pooled SEM for main effects (n = 4).

humoral immune response, ocular assessments, ocular histopathologic examination, TI, GS) were not different statistically by treatments on any of the sampling day. The data obtained for mortality due to light sources, photoperiod, and strains are presented in Table 4. We observed no main effect of light sources and photoperiod on mortality throughout the study period (day 1 to day 56), while Strain A had a lower mortality on day 14 ($P = 0.006$), day 28 ($P = 0.019$), day 42 ($P = 0.001$), and day 56 ($P = 0.001$) of age in comparison with Strain B.

DISCUSSION

The present study evaluated the effects of CFL, Neutral-LED, and Cool-PS-LED bulbs with ICD, standard, from day 1 to 56 and 2 photoperiods from 8 to 56 D of age along with 2 strains of broilers on growth performance, carcass characteristics, and health indices of broilers grown to heavy weights. As shown in Table 1, the results indicated that the BW and BWG were only different between birds reared under Cool-PS-LED and those reared under ICD. Similarly, BW, BWG, and FI were affected by photoperiods, while BW, BWG, FI, and FCR were affected by strains. Previous studies indicated that the overall growth and production parameters (BW, BWG, live weight, carcass weight) examined in the ICD bulb group were statistically similar to those of Warm-LED and Cool-LED-2, but were statistically lower than those of Cool-LED-1 (Olanrewaju et al., 2015a). This study agrees with our recent reports and other studies that ICD light sources may be replaced with modern energy-efficient light sources without adverse effects on broiler growth and production performances (Turkowska et al., 2014; Olanrewaju et al., 2015a, 2016, 2018). Furthermore, FI and FCR were not influenced by treatments throughout the experimental period in the present study, which is

Table 2. Main effects of light source, photoperiod, and strains on carcass weights and yields of broilers at 56 D of age.[1]

		Carcass		FAT		Breast		Tender	
Item	Live weight (kg)	Weight (kg)	Yield (%)	Weight (kg)	Yield (%)	Weight (kg)	Yield (%)	Weight (kg)	Yield (%)
Light sources[2]									
ICD	3.987[b]	3.029[b]	75.97	0.056	1.85	0.850	28.06	0.177	5.84
CFL	4.017[a,b]	3.041[a,b]	75.70	0.055	1.81	0.846	27.82	0.176	5.79
LED	4.134[a,b]	3.131[a,b]	77.01	0.062	1.98	0.875	27.95	0.197	6.29
PS-LED	4.157[a]	3.142[a]	75.58	0.057	1.81	0.882	28.07	0.198	6.30
Photoperiod[3]									
Reg-inter	4.066[a]	3.132[a]	77.03[a]	0.058	1.85	0.879[a]	28.07	0.180	5.75
Shot-non-inter	3.911[b]	2.985[b]	76.30[b]	0.057	1.89	0.852[b]	28.18	0.187	6.19
Pooled SEM[4]	0.048	0.046	0.238	0.002	0.058	0.008	0.345	0.008	0.075
Strains									
Strain A	4.018[b]	3.037[b]	75.59[b]	0.056	1.84	0.826[b]	27.20[b]	0.176	5.80
Strain B	4.112[a]	3.143[a]	76.44[a]	0.059	1.88	0.901[a]	28.73[a]	0.190	6.05
Pooled SEM[4]	0.027	0.035	0.281	0.001	0.015	0.016	0.243	0.005	0.053
					P-value				
Light sources	0.042	0.042	0.068	0.351	0.643	0.536	0.625	0.146	0.146
Photoperiod	0.043	0.037	0.034	0.655	0.806	0.035	0.978	0.687	0.775
Strains	0.032	0.001	0.001	0.162	0.911	0.001	0.002	0.061	0.247

[a,b]Means within a column and effect that lack common superscripts differ significantly ($P = 0.05$).
[1]Carcass without giblets, necks, and abdominal fat are expressed as a percentage of live weight, while abdominal fats, pectoralis major, and minor breast muscles are expressed as a percentage of carcass weight.
[2]ICD = Incandescent light (Standard); CFL = Compact Fluorescent light; LED = Light Emitting Diode; PS-LED = Poultry Specific LED.
[3]Reg-inter = Regular/intermittent, Shot-non-inter = Short/non-intermittent.
[4]Pooled SEM for main effects (n = 4).

Table 3. Main effects of light sources, photoperiod, and strains on selected welfare indices of heavy broiler chickens.

	[1]Light sources						Photoperiod[2]			Strains			
Variables	ICD	CFL	LED	PS-LED	*P*-value	SEM[3]	Reg-inter	Shot-non-inter	*P*-value	Strain B	Strain A	*P*-value	SEM[3]
Eyes to BW evaluation, day 42													
BW, (kg)	2.942	2.945	2.973	2.999	0.652	0.117	2.979[a]	2.890[b]	0.022	2.933[a]	2.912[b]	0.005	0.035
Total eye Wt (g)	4.730	4.943	4.850	4.605	0.544	0.214	4.858[a]	4.693[b]	0.043	4.738[a]	4.575[b]	0.048	0.053
Eye WT:BW (g/kg)	1.608	1.678	1.631	1.536	0.048	0.117	1.631	1.624	0.131	1.615	1.571	0.019	0.153
Immune response,[4] 28 to 35-day-old													
Log[1] hemaglutination titers	4.134	4.157	4.126	4.113	0.312	0.044	4.156	4.152	0.255	4.122	4.134	0.354	0.356
Ocular assessments,[5] day 42													
Corneal lesion score (CLS)	0.03	0.01	0.01	0.01	0.453	0.001	0.01	0.01	0.254	0.01	0.02	0.325	0.013
Anterior chamber score (ACS)	0.02	0.02	0.01	0.01	0.324	0.002	0.01	0.01	0.345	0.002	0.02	0.413	0.014
Ocular histopathologic examination[6] day 42													
Iris													
Rostral surface	58.34	52.56	46.56	45.16	0.413	6.551	62.27	65.53	0.167	64.26	59.25	0.325	6.674
Diffuse lymphocytic infiltrates	45.57	46.54	45.34	44.52	0.547	5.135	44.62	46.64	4342	45.36	44.62	0.256	5.634
Heterophilic infiltrates	32.53	27.43	22.76	23.13	0.461	5.545	31.45	31.43	0.253	31.56	29.65	0.328	5.364
Ciliary body													
Diffuse lymphocytic infiltrates	23.45	22.71	23.74	23.34	0.352	2.654	24.72	23.56	0.454	22.38	23.26	0.256	2.353
Heterophilic infiltrates	22.52	22.44	24.54	22.35	0.542	2.535	22.53	23.72	0.242	23.19	22.65	0.265	2.553
General well-being[7] day 49													
Gait score (GS), %	12.38	13.51	14.68	14.62	0.152	1.687	14.32	15.23	0.756	14.67	14.37	0.365	1.856
Tonic immobility (TI) s	171.33	178.41	179.44	172.34	0.425	6.115	172.56	179.23	0.546	173.46	171.63	0.432	4.658

[a,b]Means within a row and treatment that lack common superscripts differ significantly ($P = 0.05$).
[1]ICD = Incandescent light (Standard); CFL = Compact Fluorescent light; LED = Light Emitting Diode; PS-LED = Poultry Specific LED.
[2]Reg-inter = Regular/intermittent, Shot-non-inter = Short/non-intermittent.
[3]Pooled SEM for main effects (n = 4).
[4-7]Evaluation and assessments are explained in detail under materials and methods.

in agreement with other studies (Mendes et al., 2013; Olanrewaju et al., 2016). Early-developing strain B birds grew significantly faster and consumed more feed than the late-developing strain A birds throughout the 56 D of age. The results from this present study are in agreement with previous studies of strain comparison on broiler chicken growth performance and carcass characteristics using lighting (Safaa et al., 2017) and diets (Sandercock et al., 2009; Kim and Corzo, 2012; Amao et al., 2015) among others. In addition,

Table 4. Main effects of light sources, photoperiod, and strains on mortality of heavy broiler chickens growth to heavy weights.

Item	Mortality (%)			
	14 D	28 D	42 D	56 D
Light sources[1]				
ICD	0.217	1.250	1.458	2.091
CFL	0.208	0.417	1.042	1.667
LED	0.208	0.833	1.042	1.875
PS-LED	0.217	0.417	1.042	2.152
Photoperiod[2]				
Reg-inter	0.217	0.938	1.354	2.292
Shot-non-inter	0.208	0.521	0.938	1.875
Pooled SEM[3]	0.147	0.295	0.255	0.589
Strains				
Strain A	0.271[b]	1.104[b]	0.626[b]	1.341[b]
Strain B	0.625[a]	1.354[a]	1.079[a]	2.333[a]
Pooled SEM[3]	0.104	0.006	0.148	0.321
	P-value			
Light sources	0.585	0.102	0.585	0.744
Photoperiod	0.177	0.122	0.122	0.490
Strains	0.006	0.019	0.001	0.001

[1]ICD = Incandescent light (Standard); CFL = Compact Fluorescent Light; LED = Light Emitting Diode; PS-LED = Poultry Specific LED.
[2]Reg-inter = Regular/intermittent, Shot-non-inter = Short/non-intermittent.
[3]Pooled SEM for main effects (n = 4).

Sterling et al. (2006) compared strain growth performances utilizing high yield and multi-purpose genotypes, whereas other studies compared old and current genotypes (Havenstein et al., 2003; Schmidt et al., 2009). Furthermore, Abdullah et al. (2010) has reported no significant difference in the overall FCR between 2 strains. The difference in growth performance between the 2 strains in this recent study might be attributed to different genetic potential having different body requirements, which is in agreement with other studies (Amao et al., 2011; Shim et al., 2012).

Photoperiod results indicated that a short/non-intermittent photoperiod in comparison with regular/intermittent photoperiod markedly affects the performance of the broilers, as shown by significantly reduced FI, growth performance, and carcass yields, resulting in a negative impact on the metabolism of modern heavy broiler chickens. Although there were significant differences in BW, BWG, but FI, FCR was not significantly different within treatments. The present regular/intermittent photoperiod results in comparison with short/non-intermittent photoperiod are in agreement with our previous study, which indicated that regular/intermittent photoperiod improved broiler growth performance and carcass characteristics compared with short/non-intermittent photoperiod (Olanrewaju et al., 2012, 2018). In addition, these results are similar to reports by other investigators (Ohtani and Leeson 2000). Strain B achieved larger BW and BWG than Strain A in this study and this may be due to higher FI along with other genetic potential factors. Our results are in agreement with the reports of several other researchers who reported similar variations in rearing different strains under experimental conditions (Abdullah et al., 2010; Rudra et al., 2018).

There are conflicting reports on the effects of lighting programs on the ocular development of birds and other welfare indices including blood chemistry, blood gases, and behavioral rhythms (Reiter, 2003; Olanrewaju et al., 2006b; Abdullah et al., 2010). The present results indicate that all examined welfare indices (eye to BW ratio, humoral immune response, ocular assessments, ocular histopathologic examination, TI, GS) were not statistically influenced by treatments and strain, suggesting that these treatments did not compromise the welfare of broilers grown to heavy weights. It has been reported that the use of organ/body weight ratios may be valuable in evaluating the relationship between certain experimental situations and the biological response of a test organism (Bailey et al., 2004). The increased eye weights observed in this study are proportional to their BW since there is no difference in eye to BW ratio. Furthermore, the differences among antibody titer in all treatments were not significant, which are similar to reports by others (Blatchford et al., 2009; Olanrewaju et al., 2011). In addition, there was no effect of treatments on ocular histopathology examination, suggesting that these new light sources have no negative effect on the ocular development of broilers grown to heavy weights, which agrees with our recent findings (Olanrewaju et al., 2015b, 2016). The findings in this investigation suggest that exposure of 2 strains of broilers to light source and photoperiod examined in this study had no significant effect on all evaluated welfare indices (immune response, ocular weight relative to BW, and ocular assessments).

Mortality rate was not statistically different among treatments, which is in agreement with other studies in which light source alone did not significantly influence mortality rate (Sharideh and Zaghari, 2017), but there were strain differences. In the present study, Strain B had higher mortality percentage than Strain A birds, but the overall mortalities associated with the lighting program were under 10%. Furthermore, light source and photoperiod did not have a significant effect on mortality, which is in agreement with other reports (Olanrewaju et al., 2016, 2018). Data for mortality did not appear to be light source, photoperiod, or strain dependent but were rather variable and showed no trends that can be ascribed to treatments. The majority of research shows no effect of light source on mortality, which may be due to the improvement in genetic selection against metabolic and skeletal diseases.

In summary, the 3 light sources in this study may be suitable for replacement of ICD light source in poultry facilities; however, LED has been adopted at a higher rate due to longevity. In addition, data indicate that the regular/intermittent photoperiod improved broiler growth performance and carcass characteristics as compared with a short/non-intermittent photoperiod that has a negative impact on growth performance and carcass characteristics of modern broilers grown to heavy weights. It was concluded that the use of these 3 light sources, especially Cool-PS-LED along with regular-intermittent photoperiod in commercial poultry facilities rearing the 2 strains used in this study would reduce energy costs and optimize production efficiency without compromising the welfare and mortality of broilers grown to heavy weights irrespective of strains.

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