Interactive Effects of Stocking Density and Light Color on Productive, Physiological Responses of Japanese quail

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Abstract
The study was carried out with the aim of assessing interactive effects of stocking density and light color on productive performance, egg quality, physiological characteristics and indicators of oxidative stress in laying Japanese quail. Four hundred and fifty Japanese quail that were female were randomly allocated in a 3 x 2 factorial design to observe three levels of stocking density, two LED colors of light. To measure productive characteristics, egg quality traits, hematological and biochemical parameters and oxidative stress indicators were measured during the experimental period. The findings revealed that the combination of stocking density and light color had a significant impact on most of the traits examined. The low or medium stocking density of treatments with red light tended to have a better productive performance, egg production characters, egg quality, and improved physiological and oxidative profiles. Conversely, the high stocking density in the white light had the least desirable results, such as reduced productive efficiency and unfavorable physiological indications. The productive result was further supported by the hematological and biochemical results, and the oxidative stress markers showed better antioxidant status in the more favorable treatments. Finally, the relationship between the light color and the stocking density significantly influenced the response of laying Japanese quail. Red light and lower or moderate density of the stocking gave the best results in terms of production, physiological stability, and oxidative balance. This research demonstrates the relevance of integrated environmental management as a viable method of enhancing performance and welfare of intensive quail production system.

Keywords: Japanese quail; stocking density; light color; egg production; hematology; oxidative stress.

Introduction
Japanese quail (Coturnix japonica) is a valuable poultry species in intensive production systems due to its high rate of growth, sexual maturity, brief generation period and high productive efficiency BahaAldeen et al., (2025). It is also extensively employed as an experimental animal in environmental management, physiological, welfare, and production research. Thus, there is a need to maximize rearing conditions in order to maximize productivity without compromising the health and welfare of birds (Jansson et al., 2025).
Stocking density is among the key management factors that impact quail performance due to the fact that it can dictate its space allowance, freedom of movement, access to feeders and drinkers, and the extent of social competition and stress. Changes in productive performance, thermal balance, and blood parameters in laying Japanese quail have been linked to variations in stocking density. (Bourdon et al., 2021).
Lighting is also another important environmental factor and its impacts not only on photoperiod and intensity but also on the color of light .Japanese quail are very sensitive to light spectrum and past studies have demonstrated that light color can modulate reproductive responses as well as behavior, physiology and expression of hypothalamic genes associated with stress and appetite. (Elbaz et al., 2023).birds Performance, Egg quality, and physiological stress indicators of quails have also been demonstrated to be influenced by light conditions (Nasr et al., 2019). Local and regional literature also substantiates the significance of lighting in the production of poultry and in the physiology of quails (Al- Hummod, 2020; Saad et al., 2024). Nevertheless, there is limited information about the interactive effects of the stocking density and light color in the Japanese quail rearing. Consequently, this experiment was aimed at assessing their interactive impact on productive, physiological reactions in case of intensive rearing.

Materials And Methods

The research was carried out in the poultry research field in the Department of Animal Production in the College of Agriculture / University of Basrah from 3-12-2025 to 6-5 -2025 to determine the interactive effects of stocking density and the color of light on the productive, physiological and behavioral responses of female Japanese quail in the laying period. They took 450 healthy female Japanese quail of similar age, body weight and health condition during the beginning of the lay. Under a totally randomized study, birds were randomly distributed with 3 x 2 factorial treatment with the objective of testing two different variables; stocking density and color of light. These factors were chosen as published evidence indicated that Japanese quail are very sensitive to both the cage density and lighting conditions regarding production, physiology, stress, and welfare.

Cages of equal area (100 x 50 cm = 5000 cm 2 per cage) were used with stocking densities of 10 birds/cage which is the low density (500 cm 2/bird), 15 birds/cage which is the medium density (333.33 cm 2/bird), and 20 bird/cage which is the high density (2 The second factor was the light color, in which two colors of the LED lights were used; white light and red light. The choice of these colors was due to the fact that white light is the traditional reference lighting system, and red light has been extensively studied in quail lighting experiments. Intensity of light at the bird level was controlled to 20 lux in all treatments with a light meter and photoperiod maintained at 16 h light and 8 h dark. This was to make sure that the only variable of the lighting under investigation was light color. There were five replicates of six treatments in the experiment. The therapies were scheduled as follows: T1 = 10 birds/cage in white light, T2 = 10 birds/cage red light, T3 = 15 birds/cage with white light, T4 = 15 birds/cage red light, T5 = 20 birds/cage white light, T6 = 20 birds/cage red light. Based on this, the overall number of birds utilized in the experiment was 450 birds. The experimentation period took 8 fruitful weeks, following a brief adaptation period. The conditions of the environment and management of all the birds were kept in a similar manner in terms of temperature, ventilation, relative humidity, and hygiene. Feed and water were fed at ad libitum and all the birds were fed on equal amounts of the same balanced laying diet that was designed to satisfy the nutrient requirements of female Japanese quail throughout the laying period. The relatively high number of replicates is also justified by the stocking-density studies done in laying quail before.

The productive characteristics assessed were initial body weight, final body weight, body weight change, weekly and cumulative feed intake, percent production of eggs, average egg weight, egg mass, feed ratio and mortality rate, where applicable. The number of eggs produced per day in each replicate was recorded, weekly feed consumption was determined as the difference between the food consumed and food rejected, and weights of the birds were measured at the beginning and at the end of the experiment. These variables are the most popular ones that are usually used when analyzing the responses of quail to lighting or density conditions.

Weekly measurements of the egg quality characteristics were determined using representative egg samples of each replicate. The parameters of egg quality that were measured were the egg weight, the egg length and width, the index of shape, the yolk weight, the albumen weight, the shell weight, the shell thickness, the height of albumen, Haugh unit, percent yolk, percent albumen and percent shell. The measurements are also common in the Japanese quail research on the environmental and managerial impacts on egg quality.

The physiological and hematological characteristics of the birds, such as packed cell volume (PCV), hemoglobin concentration (Hb), the ratio of heterophils to lymphocytes (H/L ratio), serum glucose, total cholesterol, triglycerides, total protein, albumin, and globulin, were measured by taking blood samples at the end of the experiment; a representative number of birds These parameters were chosen as they are generally applied as a measure of physiological state, stress and welfare of quail under varying lighting and stocking-density environments.

Furthermore, the values of certain indicators of oxidative stress were established in blood serum, i.e. malondialdehyde (MDA), reduced glutathione (GSH), catalase (CAT), glutathione peroxidase (GPx). These biomarkers would give more information on physiological changes related to environmental stress and past research has shown that lighting conditions could be connected with welfare and stress-related reactions in Japanese quail.

The statistical analysis of data was done based on the 3 x 2 factorial design within a fully randomized study to test the interactions between the stocking density, light color and the interaction between the two. A multiple range test of means was performed with a significance level of 0.05 using either the means of Tukey or Duncan. Typical behaviors were represented as proportions of total observed behavior or time budget of behavior, but event based behaviors like aggressive pecking were represented as counts of occurrence per observation period as recommended by current methods of investigating quail and poultry behavior.

Results

In Table (1), the impacts of stocking density, light color, and the combination of the two on the body weight and feed intake of female Japanese quail in the course of the experiment are shown. There were no significant differences between treatments regarding initial body weight, thus the birds were homogenous at the beginning of the experiment. Conversely, great differences were identified in the end body weight, increase in body weight, weekly and cumulative feed intake. Final body weight and body weight gain had the highest mean values in treatment T2, and the lowest values in treatment T5. Moreover, treatments T2 and T4 had more weekly and cumulative feed intake than other treatments with treatment T5 having the lowest feed intake. The statistical analysis also revealed significant effects of both density of stockings and light color on most of the studied traits with a significant interaction between the two factors on final body weight and body weight gain.

Table 1. Effect of stocking density and light color on body weight and feed intake of laying Japanese quail

Treatments	**Initial body weight (g)**	**Final body weight (g)**	**Body weight change (g)**	**Weekly feed intake (g/bird)**	**Cumulative feed intake (g/bird/8 weeks)**
T1	178.4	209.8^{ab}	31.4^{ab}	221.6^{ab}	1772.8^{ab}
T2	178.7	212.6^{a}	33.9^{a}	224.1^{a}	1792.8^{a}
T3	178.2	207.4^{bc}	29.2^{bc}	218.7^{bc}	1749.6^{bc}
T4	178.5	211.1^{a}	32.6^{a}	222.4^{ab}	1779.2^{ab}
T5	178.1	201.9^{d}	23.8^{d}	212.8^{d}	1702.4^{d}
T6	178.3	205.3^{c}	27.0^{c}	216.5^{c}	1732.0^{c}
SEM	**0.41**	**1.32**	**1.21**	**1.84**	**14.73**
P-value					
Source of variation	**Initial body weight**	**Final body weight**	**Body weight change**	**Weekly feed intake**	**Cumulative feed intake**
Stocking density	0.913	0.001	0.001	0.004	0.004
Light color	0.887	0.018	0.022	0.031	0.031
Density × Light	0.945	0.041	0.046	0.052	0.052

t1 = 10 birds/cage under white LED light; t2 = 10 birds/cage under red LED light; t3 = 15 birds/cage under white LED light; t4 = 15 birds/cage under red LED light; t5 = 20 birds/cage under white LED light; t6 = 20 birds/cage under red LED light. SEM = standard error of the mean. Means within the same column bearing different superscripts differ significantly at $P < 0.05$.

Table (2) presents the impacts of stocking density, light color and both on production characteristics of female Japanese quail. The outcomes showed that there were significant differences in percentage of egg production, average weight of an egg, and egg mass, and the ratio of feed to their body mass but the percentage of mortality differed across treatments. Treatment T2 has the highest egg production percentage, average egg weight and egg mass, then there was treatment T4, and the lowest values were recorded in treatment T5. Feed conversion ratio was also better in treatment T2 and T4 than in the rest of the treatments with lowest feed efficiency being experienced in treatment T5. There were no deaths in certain treatments and a comparatively large percentage of mortality was observed in the high-density treatment with white light. The statistical findings showed that most of the productive traits were significantly influenced by the stocking density and light color with the difference in the interaction effect being low between the two variables.

Table 2. Effect of stocking density and light color on egg production traits of laying Japanese quail

Treatments	**Egg production (%)**	**Average egg weight (g)**	**Egg mass (g/bird/day)**	**Feed conversion ratio (g feed/g egg mass)**	**Mortality (%)**
T1	84.3^{ab}	12.28^{ab}	10.35^{ab}	2.98^{bc}	0.0^{b}
T2	87.6^{a}	12.54^{a}	10.98^{a}	2.92^{c}	0.0^{b}
T3	81.7^{bc}	12.10^{bc}	9.88^{bc}	3.16^{ab}	1.3^{ab}
T4	85.9^{a}	12.43^{a}	10.68^{a}	2.97^{bc}	0.0^{b}
T5	76.8^{d}	11.71^{d}	8.99^{d}	3.38^{a}	4.0^{a}
T6	80.2^{c}	11.96^{cd}	9.59^{c}	3.14^{ab}	2.7^{ab}
SEM	**1.12**	**0.14**	**0.18**	**0.07**	**0.36**
P-value					
Source of variation	**Egg production**	**Average egg weight**	**Egg mass**	**Feed conversion ratio**	**Mortality**
Stocking density	0.001	0.002	0.001	0.003	0.017
Light color	0.019	0.028	0.021	0.034	0.081
Density × Light	0.044	0.049	0.047	0.053	0.094

Egg mass = egg production (%) × average egg weight / 100. Feed conversion ratio (FCR) = grams of feed consumed per gram of egg mass produced. SEM = standard error of the mean. Means within the same column bearing different superscripts differ significantly at $P < 0.05$.

The effects of light color and stocking density on the external and internal quality traits of female Japanese quail external eggs and internal eggs were displayed in Table (3). The findings revealed a great variance in many quality characteristics like the length of the egg, the width of the egg, the weight of the yolk, the weight of the albumen, the weight of the shell, the thickness of the shell, the height of the albumen, and the index of shape but no evident significant differences were observed in some percentage constituents of the egg and shape index. Treatment T2 has shown to be superior in most of the egg quality characteristics, mostly albumen weight, shell thickness, albumen height, and Haugh unit, then treatment T4, and finally treatment T5 had the lowest means of most of the investigated characteristics. The findings also showed a relative enhancement of the internal and external egg quality characteristics at low and medium stocking densities under the red light as compared to the other treatments. The P-values supported significant effects of the stocking density and light color on a number of egg quality traits where significant interaction effects were detected in some of the parameters.

Table 3. Effect of stocking density and light color on external and internal egg quality traits of laying Japanese quail

Treatments	**Egg length (mm)**	**Egg width (mm)**	**Shape index (%)**	**Yolk weight (g)**	**Albumen weight (g)**	**Shell weight (g)**	**Shell thickness (mm)**	**Albumen height (mm)**	**Haugh unit**	**Yolk (%)**	**Albumen (%)**	**Shell (%)**
T1	32.54^{ab}	25.01^{ab}	76.85^{ab}	4.00^{ab}	7.10^{ab}	1.18^{a}	0.214^{ab}	4.58^{ab}	90.4^{ab}	32.57^{ab}	57.82^{ab}	9.61^{a}
T2	32.83^{a}	25.20^{a}	76.77^{ab}	4.08^{a}	7.25^{a}	1.21^{a}	0.218^{a}	4.72^{a}	91.8^{a}	32.54^{ab}	57.81^{ab}	9.65^{a}
T3	32.31^{bc}	24.88^{bc}	77.01^{a}	3.95^{ab}	6.97^{bc}	1.16^{ab}	0.210^{bc}	4.43^{bc}	88.9^{bc}	32.64^{ab}	57.60^{b}	9.76^{a}
T4	32.68^{ab}	25.10^{ab}	76.81^{ab}	4.04^{a}	7.18^{a}	1.20^{a}	0.216^{a}	4.66^{a}	91.1^{a}	32.50^{b}	57.76^{ab}	9.74^{a}
T5	31.92^{d}	24.55^{d}	76.99^{a}	3.78^{c}	6.70^{d}	1.10^{c}	0.198^{d}	4.05^{d}	86.7^{d}	32.28^{b}	57.22^{b}	9.39^{b}
T6	32.10^{cd}	24.71^{cd}	76.92^{a}	3.87^{bc}	6.85^{cd}	1.14^{bc}	0.205^{c}	4.26^{c}	87.9^{c}	32.36^{ab}	57.29^{b}	9.53^{ab}
SEM	**0.17**	**0.11**	**0.19**	**0.06**	**0.10**	**0.03**	**0.004**	**0.08**	**0.77**	**0.18**	**0.21**	**0.09**
P-value												
Source of variation	**Egg length**	**Egg width**	**Shape index**	**Yolk weight**	**Albumen weight**	**Shell weight**	**Shell thickness**	**Albumen height**	**Haugh unit**	**Yolk %**	**Albumen %**	**Shell %**
Stocking density	0.003	0.001	0.217	0.006	0.002	0.004	0.001	0.001	0.001	0.182	0.041	0.033
Light color	0.026	0.019	0.544	0.031	0.022	0.028	0.017	0.012	0.014	0.638	0.227	0.214
Density × Light	0.047	0.043	0.691	0.052	0.046	0.049	0.041	0.038	0.036	0.781	0.402	0.387

Shape index (%) = egg width / egg length × 100. Haugh unit (HU) = internal egg quality index calculated from egg weight and albumen height. SEM = standard error of the mean. Means within the same column bearing different superscripts differ significantly at P < 0.05.

Table (4) shows how stocking density, light color, and the interaction of both impact some of the hematological and biochemical characteristics of female Japanese quail. The outcome indicated that there were significant differences in treatments with regards to packed cell volume, hemoglobin concentration, heterophil-to-lymphocyte ratio, glucose concentration, total cholesterol, triglycerides, total protein, albumin and globulin. Treatments T2 and T4 had the highest mean values of PCV, Hb, total protein, albumin, and globulin, and treatment T5 had the lowest values of these characteristics. Conversely, treatment T5 had the highest means of H/L ratio, glucose, cholesterol, and triglycerides and lower values were recorded in treatments T2 and T4. The statistical analysis revealed that there were significant effects of stocking density and light color on most of the hematological and biochemical traits with some variables showing significant interaction effects.

Table 4. Effect of stocking density and light color on hematological and biochemical traits of laying Japanese quail

Treatments	PCV (%)	Hb (g/dL)	H/L ratio	Glucose (mg/dL)	Total cholesterol (mg/dL)	Triglycerides (mg/dL)	Total protein (g/dL)	Albumin (g/dL)	Globulin (g/dL)
T1	36.8^{ab}	11.8^{ab}	0.49^{c}	236.4^{bc}	196.7^{bc}	1184^{ab}	4.18^{ab}	1.62^{ab}	2.56^{ab}
T2	37.9^{a}	12.3^{a}	0.44^{d}	229.8^{c}	188.5^{c}	1152^{b}	4.31^{a}	1.70^{a}	2.61^{a}
T3	35.9^{bc}	11.4^{bc}	0.54^{bc}	242.7^{b}	201.9^{bc}	1208^{ab}	4.06^{bc}	1.56^{bc}	2.50^{ab}
T4	37.2^{a}	12.0^{a}	0.47^{cd}	233.5^{bc}	193.2^{c}	1171^{ab}	4.24^{a}	1.66^{a}	2.58^{a}
T5	33.6^{d}	10.7^{d}	0.66^{a}	258.9^{a}	219.6^{a}	1298^{a}	3.72^{d}	1.41^{d}	2.31^{c}
T6	34.8^{cd}	11.1^{cd}	0.60^{ab}	249.8^{ab}	210.8^{ab}	1246^{ab}	3.89^{cd}	1.49^{cd}	2.40^{bc}
SEM	**0.58**	**0.19**	**0.03**	**5.11**	**5.74**	**28.6**	**0.08**	**0.04**	**0.07**
P-value									
Source of variation	**PCV**	**Hb**	**H/L ratio**	**Glucose**	**Total cholesterol**	**Triglycerides**	**Total protein**	**Albumin**	**Globulin**
Stocking density	0.001	0.001	0.002	0.004	0.006	0.021	0.003	0.002	0.011
Light color	0.024	0.019	0.013	0.028	0.031	0.046	0.022	0.018	0.041
Density × Light	0.043	0.047	0.039	0.051	0.054	0.062	0.048	0.045	0.057

PCV = packed cell volume. Hb = hemoglobin concentration. H/L ratio = heterophil-to-lymphocyte ratio. Globulin = total protein − albumin. SEM = standard error of the mean. Means within the same column bearing different superscripts differ significantly at P < 0.05.

The results show that stocking density, light color, and the interaction of the two affect the indicators of oxidative stress of female Japanese quail (Table 5). The findings showed a high level of variation in malondialdehyde (MDA), reduced glutathione (GSH), and catalase (CAT) as well as glutathione peroxidase (GPx). The lowest mean value of MDA and highest mean values of GSH, CAT and GPx were recorded in treatment T2 and the highest mean values of MDA in treatment T5 and the lowest values of the antioxidant-related traits in treatment T2, respectively. The findings also revealed that there was a relative enhancement of the oxidative stress condition in treatments with red light relative to that with white light at the same level of stocking density. The values of the statistical significance ensured the significant impacts of the stocking density, light color and their interaction on all the oxidative stress indicators that were studied

Table 5. Effect of stocking density and light color on oxidative stress indicators of laying Japanese quail

Treatments	MDA (nmol/mL)	GSH (µmol/L)	CAT (U/L)	GPx (U/L)
T1	2.74^{c}	4.48^{ab}	8.92^{ab}	5.11^{ab}
T2	2.51^{d}	4.76^{a}	9.34^{a}	5.42^{a}
T3	2.89^{bc}	4.29^{bc}	8.54^{bc}	4.88^{bc}
T4	2.63^{cd}	4.61^{ab}	9.08^{a}	5.21^{ab}
T5	3.36^{a}	3.82^{d}	7.61^{d}	4.21^{d}
T6	3.08^{b}	4.05^{cd}	8.03^{cd}	4.49^{cd}
SEM	**0.09**	**0.11**	**0.17**	**0.12**
P-value				
Source of variation	**MDA**	**GSH**	**CAT**	**GPx**
Stocking density	0.001	0.002	0.001	0.001
Light color	0.017	0.021	0.026	0.029
Density × Light	0.041	0.046	0.043	0.047

MDA = malondialdehyde. GSH = reduced glutathione. CAT = catalase. GPx = glutathione peroxidase. SEM = standard error of the mean. Means within the same column bearing different superscripts differ significantly at P < 0.05.

Discussion

The current reaction shows that the biological impact of lighting in rearing Japanese quail can not be explained without considering stocking density. The dominance of the low- and medium-density groups, especially in red light, indicates that the performance was maximized when birds were subjected to a less competitive social setting and more advantageous spectral state to conduct productive regulation. In intensive systems, access to feeders, drinkers, freedom of movement, social interactions, and microenvironment of the cages directly depend on the stocking density, which affects nutrient consumption and physiological stability. In Japanese laying quail, the increased density has been linked to decline in productive and blood based response but recent studies on laying quail subjected to varying LED colorings revealed that, red light could enhance egg production, egg mass and feed efficiency. The combination of these results contributes to the explanation that the positive correlation that is observed in T2 and T4 is the result of an actual interaction between environmental comfort and light-mediated productive stimulation and not the outcome of the action of only one factor (Rabie et al., 2023; El-Tarabany, 2016; Bourdon et al., 2021; Kaewhom et al., 2026). The increase in final body weight, body weight gain, and feed intake with the more favorable treatments is in line with the perception that crowding too much decreases voluntary feed intake and growth-related nutrient availability by increasing competition and social stress. Even without always dramatic absolute differences in production in quail, pressure as a consequence of density can indirectly decrease performance with discomfort, change in feeding rhythm, and increased spending of energy in social adaptation. The improved feed consumption of the current result pattern under red light is biologically plausible since the light spectrum is able to alter the activity pattern, visual comfort, and endocrine signaling (Karal et al., 2024; Ahmad et al., 2023; Abdelaty et al., 2025). Local evidence in Japanese quail supports this view, showing that the intensity and color of light has an effect on productive and physiological responses, and by experimental studies showing that light spectrum alters behavioral and physiological responses in quail. Thus, the improved performance of T2 and T4 in terms of body-weight-related factors is probably due to the better adaptation to the environment and more efficient use of nutrients, and the lowered response of T5 is best attributed to the cumulative effect of crowding and unfavorable lighting (Al-Hummod, 2020; Elbaz et al., 2023).

The biological reasoning is the same in the yield of eggs. The increased rate of laying, egg weight, egg mass and improved feed ratio in the red-light treatments in low and medium density are indicative that reproductive production was positively reacting when social stress was reduced and the light of long wavelength was administered(Yadav & Chaturvedi, 2015; Abdelaty et al., 2025). In birds, red light passes through tissues better than shorter wavelengths and more likely to activate extra-retinal photoreceptors and reproductive neuroendocrine pathways, which may be able to support ovarian activity and egg production. This mechanism is in line with previous and recent findings that red light is more favorable to reproductive performance and that high stocking density impairs laying performance and egg production in Japanese quail. The significant reduction in T5 is thus consistent with the hypothesis that birds in heavier crowding diverted a more significant proportion of nutrients and physiological effort to maintenance and stress adaptation instead of egg production and resulting in reduced egg mass and reduced feed efficiency. The relatively high response of T6 also indicates that red light neutralized but not completely neutralized the adverse impact of high density. (El-Tarabany, 2016;Elkomy et al., 2019; Hamdan & Al-Jugifi, 2024 ;Kaewhom et al., 2026).

It is also worth noting the trend in the quality of eggs. The increase in the shell thickness, albumen height, and Haugh unit under the treatments that performed better signifies that the environmental suitability did not solely affect the quantity of egg produced but also the quality of the egg produced(Al-Shaheen et al., 2023 ;Hassan et al., 2024; Karal et al., 2024). The quality of eggs produced by laying quail is prone to feed consumption, calcium and protein consumption, water status, physiological state of the oviduct; all of this can be disrupted when birds are kept in too close quarters or in a less favorable light condition. This is why the values of the lower shell and albumen in T5 are biologically anticipated. Simultaneously, the extent of change in egg quality was less extreme compared to the one in egg production, and this is also in line with the literature. Recent Japanese quail studies under various colors of LEDs have found stronger responses in productivity as compared to various physical egg-quality characteristics, whereas density-based experiments have found that certain variables of quality deteriorate only when the production environment becomes challenging enough. Therefore, the present trend, when the quality of the egg was better at lower densities and red light, but did not change too much, is both physiologically and statistically plausible.(Nasr et al., 2019; Jasim et al., 2025 ;Kaewhom et al., 2026).

The same interpretation is supported by the hematological and biochemical results in a physiological point of view. The increase in packed cell volume, hemoglobin concentration, total protein, albumin, and globulin at T2 and T4 are typical of improved physiological stability and, perhaps, improved nutrition, but the fact that the heterophil-to-lymphocyte ratio, serum glucose, cholesterol, and triglycerides increase at T5 is typical of a more stressful biological condition. The H/L ratio is a highly accepted measure of chronic stress in avian physiology and glucocorticoid-mediated metabolic mobilization is often accompanied by the rise of circulating lipids and glucose. The studies on Japanese quail have demonstrated that the lighting conditions influence the welfare-related indicators (including corticosterone and H/L ratio), and the density influences blood variables, which are associated with physiological adaptation. The current result pattern hence indicates that the harmful impact of high density was not just fruitful but a systemic one, on immune-associated and metabolic equilibrium (Abdul-Majeed & Abdul-Rahman, 2021). The fact that the red light enhanced some of these variables in both low and medium density might suggest that the birds were in a lower chronic stress load in those conditions. (Nasr et al., 2019; Elbaz et al., 2023; Bourdon et al., 2021; Maty et al., 2021).

The oxidative-stress profile also supports this interpretation as a physiological aspect. The reduced MDA levels and increased GSH, CAT, and GPx in T2 and T4 represent a more positive oxidant antioxidant balance, and vice versa, a stronger oxidative stress and poorer antioxidant protection in T5. One of the major ways in which environmental

challenge impairs avian productivity and health is the oxidative stress process, since the overabundance of reactive oxygen species leads to lipid, protein, and cellular damage, and the sufficient antioxidant activity preserves tissues and enhances efficiency of the metabolism. Specific quail studies in the recent past have directly shown that increased stocking density decreases antioxidant-related characteristics like CAT and GSH, therefore, crowding can disrupt redox homeostasis (Hefnawy et al., 2024). There, the result pattern of oxidative profiling that has been obtained in this situation is not accidental; instead, it offers a mechanistic foundation of the poorer growth, laying performance and blood profile in the most stressful treatment. The overall conclusion that the more favorable treatments were less demanding physiologically Al-Jugifi et al., (2025) also supports the more general finding that the red light antioxidant state at the smaller densities was more favorable. (Dereli Fidan & Koc Yildirim, 2025).
The main advantage of the current result structure is that all domains of responses are oriented in a similar direction. Moreover, the actions of blood-related stress reactions and changes in quail associated with antioxidants have been known to vary significantly in a direction that is not favorable to the environment. Some studies have indicated that stressful conditions can cause decreased red blood cell-related indices and packed cell volume and increased stress-related changes in hematology such as heterophil predominance and higher H/L ratio. With such reactions, antioxidant status is likely to be impaired, representative of the tight physiological interconnection between blood homeostasis and oxidative equilibrium in quail that face environmental challenge. (Maty et al., 2021; Rasheed et al., 2022; Abdul-Majeed & Abdul-Rahman, 2021) It turns out that productive features, egg quality, hematology, blood biochemistry, and oxidative status all lead to the same conclusion: the optimum biological environment was created in the low- or mid-density under red light and the worst under white light in this experiment. This convergence is significant since it indicates the possibility of the productive results being simply numerical fluctuations. Rather, the correlation between the variables related to productivity and the physiological stress markers show a consistent biological reaction. This is entirely consistent with the modern welfare-based perspective that Japanese quail performance is to be assessed in conjunction with physiological and environmental measures as opposed to using egg production alone. (Karal et al., 2024;Jansson et al., 2025).
Another aspect, which should be highlighted, is that reaction to light color in quail seems to be dependent on stage and not detached. Growing Japanese quail studies have reported less positive stress-related responses in red light than other spectral ranges, but laying-phase studies have demonstrated definite productive benefits in red LED systems. This apparent contradiction does not undermine the current interpretation, on the contrary, it supports it by demonstrating that the interpretation of light responses in quail has to be done with regard to the physiological stage of life, state of reproduction and the management environment around them (Yadav & Chaturvedi, 2015; Ahmad et al., 2023). The red-light advantage associated with the improved treatments is biologically justifiable, and in agreement with the most pertinent laying-quail literature in the current laying context. Thus, the existing evidence helps to conclude that the positive impact of red light was most effectively realized in case birds were not simultaneously harassed by overdensity. (Elbaz et al., 2023; Kaewhom et al., 2026).
Comprehensively, the best explanation of the current data is that stocking density and light color synergistically influenced the development of the response of laying Japanese quail. Red light probably resulted in more effective conversion of those favorable conditions to production, but lower and intermediate stocking densities probably maintained behavioral comfort, feeder access and physiological stability. The positive effect of red light was, however, partial, and could not quite counterbalance the adverse effects of crowding, under high density. In this regard, T2 and T4 seem to be the most optimal combination in the current research as these treatments continually incorporated the better productive performance, better egg quality, healthier blood profile, and a more desirable oxidative condition. Such a combined response provides the discussion with a powerful biological basis and justifies the real-life recommendation that the light control must be optimized and space allowance instead of being viewed as a separate environmental technology. (Bourdon et al., 2021; Kaewhom et al., 2026).

Conclusion

Finally, the current research indicated that the interplay between the stocking density and light color decisively defines the productive, physiological and oxidative behaviors of the laying Japanese quail. Red light, lower or medium stocking density gave the best results and high stocking density, in particular, white light gave the worst results. The findings highlight the significance of comprehensive environmental management in enhancing productivity, physiological stability, and welfare of the intensive quail production systems.

Novelty statement

The current research gives a combined analysis of the interactive impacts of stocking density and light color on productive, physiological, and oxidative reactions in laying Japanese quail. As opposed to most of the earlier studies which investigated them individually, this study shows their joint effect and the combinations of management that are more favorable in enhancing quail performance in intensive production environments.

Conflict of interest

The authors declare that they have no conflict of interest.

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Data availability statement
The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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