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Evaluation and Verification of Synergistic Effects between Far-Infrared Ray and Relevant Additives on Growth Performance in Broiler Chickens

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ABSTRACT This study investigated individual and interactive effects of far-infrared ray (FIR), minerals, and electrolyte-supplemented water on broiler performance, carcass yield, intestinal morphology, and blood metabolites using 2 × 2 × 2 factorial design. 384 one-day-old Ross 308 broilers were assigned to eight treatments with six replicates each. FIR increased average daily gain (P<0.001) and feed intake (P<0.001) during days 1−10, 11−21, and 1−35. FIR elevated dressing percentage (P=0.030), breast (P=0.046), and leg yield (P=0.042) on days 21 and 35. FIR reduced crypt depth (P=0.037) and increased villus height: crypt depth ratio (P=0.041) on day 21 but decreased on day 35 (P=0.035). Electrolyte-supplemented water improved villus height (P=0.033) and crypt depth (P=0.029) on day 35. FIR elevated IL-1β (P=0.044) and lactate (P=0.046) on day 21, and TNF-α (P=0.041) on day 35, but decreased IL-10 (P=0.025), IFN-ɣ (P=0.048), and corticosterone (P=0.027) on both days. Mineral supplementation reduced IL-1β (P=0.031) and lactate (P=0.049) on day 21, while electrolyte-supplemented water decreased lactate (P=0.043). Interaction effects occurred for lactate (FIR × mineral, P=0.038; FIR × water, P=0.041; mineral × water, P=0.046), corticosterone (FIR × mineral, P=0.035) on day 21, and IL-1β (FIR × mineral × water, P=0.044) on day 35. Hence, FIR enhanced growth and alleviated stress.

(Key words: broiler, far-infrared ray, growth performance, intestinal morphology)

INTRODUCTION

Light is a critical environmental factor that influences poultry physiology, performance, and well-being. Recent studies have investigated various lighting characteristics, including intensity, photoperiod, and wavelength, which affect circadian rhythms, endocrine activity, and immune responses in chickens (Olanrewaju et al., 2006). Chicken perceives light not only through their eyes but also through photoreceptors in the skull, transmitting light signals to the hypothalamus and pineal gland (Son, 2015). Their photoreceptors sensitivity surpasses that of humans, enabling them to detect a broader spectrum of light wavelengths (Prescott et al., 2003).

Among the electromagnetic spectrum, infrared radiation (IR) occupies wavelengths between 750 nm and 100 μm, positioned between the visible red spectrum and the terahertz range. According to the International Commission on Illumination (CIE), IR is categorized into near (IR-A: 700−1,400 nm), mid (IR-B: 1,400−3,000 nm), and far-infrared (IR-C: 3,000 nm−0.1 mm) zones (Vatansever and Hamblin, 2012). In poultry sector, far-infrared radiation (FIR; 5−20 μm) has garnered attention due to its potential biological effects distinct from mere thermal radiation. Organic compounds exposed to FIR can generate heat (Liu et al., 2022) while FIR itself has demonstrated non-thermal effects such as enhanced mitochondrial function, improved blood circulation, immune modulation, and wound healing (Imamura et al., 2001; Akasaki et al., 2006; Chang et al., 2016; Lim et al., 2023).

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The application of FIR has expanded across various agricultural and livestock sectors. In horticulture, it has been used to monitor plant growth and development (Cho, 2009), while in the livestock industry, FIR has been utilized for meat preservation and storage (Nam et al., 2004; Rababah et al., 2006). Within the poultry industry, FIR wavelengths ranging from 5 to 20 μm are more commonly applied than near- or mid-infrared rays. Studies have shown that organic compounds exposed to FIR emit heat energy (Liu et al., 2022), but more importantly, FIR exerts biological effects beyond thermal action. Recent evidence indicates that FIR can influence animal tissues through mechanisms distinct from simple heat transfer. These biological effects include enhanced growth, improved blood circulation, modulation of immune responses, and accelerated wound healing (Imamura et al., 2001; Akasaki et al., 2006; Lim et al., 2023). Additionally, FIR has been shown to improve mitochondrial function in neuroblastoma cells (Chang et al., 2016), contributing to key cellular processes such as energy production, growth, calcium signaling, and apoptosis (Osellame et al., 2012). Despite its potential, FIR has been underexplored in poultry science. Previous studies by Lim et al. (2023) demonstrated positive effects of FIR exposure on laying performance and microflora balance in hens, while Son (2015) reported reduced noxious gas emissions and improved blood parameters in FIR-treated broilers. However, comprehensive studies evaluating FIR's influence on broiler performance and physiology remain limited. In addition to FIR, other factors such as mineral supplementation and treated water may synergistically contribute to poultry health. Trace minerals like zinc, selenium, and copper enhance immune function and oxidative balance (Akhavan-Salamat and Ghasemi, 2019; Ghasemi et al., 2020). Modified water types, including electrolyzed reduced water and magnetized water, have been shown to improve gut morphology, antioxidant capacity, hydration, and nutrient utilization in broilers (Azad et al., 2013; Kirkpinar et al., 2023). Therefore, this study aimed to investigate the individual and interactive effects of FIR exposure, mineral compounds, and electrolyte-supplemented water on growth performance, carcass traits, intestinal morphology, and blood metabolites in broilers from hatch to day 35. We hypothesized that these treatments would improve performance parameters while reducing physiological stress.

MATERIALS AND METHODS

The experimental procedures were reviewed and approved by the Animal Ethics Committee of the Chungnam National University (202006A-CNU-092).

1. Birds and Management

A total of 384 one-day-old broiler chickens (Ross 308) were received from the local hatchery (132, Chengo-ro, Oseong-myeon, Pyeongtaek-si, Gyeonggi-do, Republic of Korea) and housed in each raised battery cage (76 × 61 × 46 cm^3), with similar body weights (42.81±0.036 g). Each pen was equipped with two nipple drinkers and a metal trough. The ambient temperature was maintained at 30±1℃ from days 1 to 7 and then gradually decreased to 25±1℃ until d 14 of age. Thereafter 25±1℃ temperature was maintained throughout the experiment. Birds were offered experimental diets on an *ad libitum* basis and had free access to fresh clean drinking water via nipple drinkers throughout the experimental period.

The wavelength of the far-infrared ray applied to the test groups exposed to far-infrared ray was produced using the Energy Pang (Far infrared ray) provided by Cereswaves Korea Co. LTD.

2. Experimental Design, Treatments and Diets

Birds were allocated into one of eight dietary treatments in a completely randomized design. Each treatment contained six replicate cages with eight birds per cage. Dietary treatments were as follows: i) The diet formulated meets the standard or exceeds Ross 308 nutrition specification (Aviagen, 2022) without FIR, ii) Standard diet with mineral compounds, iii) Standard diet with electrolyte-supplement water, iv) Standard diet with mineral compounds and electrolyte-supplement water, v) The diet formulated meets the standard or exceeds Ross 308 nutrition specification (Aviagen, 2022) with FIR, vi) Standard diet with FIR and Mineral compounds, vii) Standard diet with electrolyte-supplement water, viii) Standard diet with mineral compounds and electrolyte-supplement water. Diets were formulated based on corn and soybean meal to meet the Ross 308 nutrition specification (Aviagen, 2022) (Table 1). In

Table 1. Composition (g/kg, as-fed basis) of the experimental diets[1]

Items	Experimental diets[2]		
	Starter (Day 1−10)	Grower (Day 11−21)	Finisher (Day 22−35)
Corn	48.98	55.37	59.55
Soybean meal, 44%	38.78	34.74	28.95
Corn DDGS	5.00	5.00	5.00
Limestone	1.17	0.84	0.74
Mono-calcium phosphate	1.70	1.34	1.09
Salt	0.30	0.30	0.30
Vegetable oil	1.11	1.56	1.48
Beef tallow	2.00	2.00	2.00
DL-methionine, 98%	0.38	0.33	0.32
L-lysine-sulfate, 65%	0.28	0.22	0.27
Vitamin-mineral premix[1]	0.30	0.30	0.30
Calculated values			
Metabolizable energy (kcal/kg)	2,975	3,050	3,100
Crude protein (%)	23.0	21.5	19.5
Calcium (%)	0.95	0.75	0.65
Available P (%)	0.50	0.42	0.36
SID Lys	1.32	1.18	1.08
SID Met + Cys	1.00	0.92	0.86

[1] Provided per kilogram of diet: vitamin A (trans-retinyl acetate), 14,000 IU; vitamin D3 (cholecalciferol), 3,000 IU; vitamin E (DL-α tocopherol acetate), 40 mg; vitamin K3, 2.4 mg; thiamin, 1.2 mg; riboflavin, 50 mg; pyridoxine, 3 mg; vitamin B12, 20 μg; niacin, 40 mg; pantothenic acid, 10 mg; folic acid 0.5 mg; Fe (from iron sulfate), 17 mg; Cu (from copper sulfate), 13 mg; Zn (from zinc oxide), 92 mg; Mn (from manganese oxide), 100 mg; I (from potassium iodide), 1 mg; Co, 0.15 mg; Se (from sodium selenite), 0.25 mg.
DDGS, distillers dried grains with soluble; SID, standardized ileal digestible.

this study, the supplementations of mineral compounds and electrolyte-supplemented water provided by Cereswave company were used. The mineral compounds were top-dressed to the basal diet. The electrolyte-supplemented water was supplied only from day 1 to day 10. Tab water has been supplied to the birds on day 11 to 35, thereafter.

3. Growth Performance Evaluation

Body weights of the birds were recorded individually on day 1 of the experiment. Subsequently, the average body weight (BW) and feed intake (FI) of the birds on a pen basis were measured on day 10, 21, and 35. Based on the measured BW and FI data, average daily feed intake (ADFI), including mortality correction, and feed conversion ratio (FCR) were calculated on a pen basis.

4. Post-Mortem Procedure and Sample Collection

Six birds per treatment (on bird per cage) that were closer to the mean body weight were selected and euthanized by cervical dislocation for sample collection on day 21 and 35. The dressing percentage of meat with giblets (i.e., heart, gizzard, and liver) was calculated by dividing it by the live weight of the birds. Drumsticks (skinless) and breast meat were removed from carcasses and weighed.

Blood sample collections were carried out on day 21 and 35 of the experiment. Blood samples were collected from the brachial vein into a vacutainer coated with lithium heparin

(BD Vacutainer, BD, Franklin Lakes, NJ, USA) before euthanizing the birds. Collected blood samples were quickly transferred to a laboratory for plasma separation.

Abdominal incisions were made on each sacrificed bird and the ileum was separated from the gastrointestinal tract. The ileum was defined as the segment of the small intestine that extended from Meckel's diverticulum to the ileocecal junction (Yu et al., 2025). The removed ileal samples (3 cm piece) were flushed with ice-cold phosphate-buffered saline (PBS, pH 7.4) and placed into plastic containers that contained 10% formaldehyde for fixation and stored until microscopic slide preparation (Wickramasuriya et al., 2019; Wickramasuriya et al., 2020).

5. Sample Preparation and Laboratory Analysis

Collected blood samples were centrifuged (LABOGENE 1248R, Gyrozen Co., Ltd., Daejeon, Korea) at 3,000 × g for 10 min at 4℃ and the plasma was separated and stored at −80℃ (UniFreez U 400, DAIHAN Scientific Co., Ltd, Wonju, Korea) until analysis. The concentrations of interleukin 1β (IL-1β), interleukin 10 (IL-10), interferon-gamma (IFN-ɣ), tumor necrosis factor α (TNF-α) in plasma were quantified using commercially available ELISA kits (MyBioSource, San Diego, CA) according to the manufacturers' instructions described by (Pineiro et al., 2009; Yu et al., 2021). Cortisol concentrations were determined from the plasma with a cortisol ELISA kit (CUSABIO, Wuhan Huamei lotech Co., Ltd., Wuhan, China) used in accordance with the manufacturer's instructions. Lactate concentration was determined by lactate assay kit (Sigma Aldrich, Co., Burlington, USA) using the manufacturer's instructions. Briefly, glucose was determined from the collected plasma using a glucose assay kit (Asan Pharmaceutical Co. Ltd., Seoul, Republic of Korea), following the manufacturer's instructions (Yu et al., 2024).

To analyze the ileal morphometry, we followed the method described by (Oketch et al., 2022). Briefly, ileal samples fixed in 10% formaldehyde were used for sample preparation. Ring-shaped ileal tissue samples, six diagonal histological sections (4−6 μm), were excised and dehydrated, followed by impregnation in paraffin wax. The height of 10 well-align villi and their associated crypts were observed with an inverted microscope (Eclipse TE2000, Nikon Instruments Inc., Melville, NY 11747-3064, USA) and the height and width of the villi and the depth of the crypts were measured through the analysis of images of histological sections made from the computerized image-capture software (NIS-Elements Viewer software, Version: 4.20; NIS Elements, Nikon, USA). The height of the villi is defined as the distance from their tip to the base and the width of the villi was measured at the half-height point. The depth of the crypt was defined as the distance from the top of the crypt to the muscularis mucosa (Seyyedin and Nazem, 2017).

6. Statistical Analysis

All data were analyzed using the general linear model (GLM) procedure for one-way ANOVA in SPSS software (version 26, Armonk, NY). Furthermore, all data were checked for normal distribution and analyzed using a 3-way ANOVA considering the main effect of far infrared ray, mineral compounds, electrolyte-supplemented water, and their interactions. The pen was used as an experimental unit for all growth performance measurements. Selected individual birds were considered as the experimental unit for the proportion of carcass trait weights, intestinal morphology, and blood metabolites. Means were separated using Tukey's HSD test ($P<0.05$).

RESULTS

1. Growth Performance

The effect of FIR, mineral compounds, and electrolyte-supplemented water in diets on growth performance in broilers from hatching to 35 days as presented in Table 2, showed that birds exposed to FIR had a higher ($P<0.001$) body weight than those without FIR on day 10, 21 and 35. Notably, the exposed FIR and mineral compounds supplementation observed a higher ($P<0.001$) body weight than birds without FIR on days 21 and 35. However, birds fed with electrolyte-supplemented water had lower ($P<0.05$) body weight than those without electrolyte-supplemented water on day 35. Birds exposed to FIR had a higher ($P<0.001$) average daily gain than those without FIR on day 1−10, 11−21, and 1−35. Especially, the exposed FIR and mineral compounds supplementation had a higher ($P<0.001$) average daily gain than those without FIR in overall periods (day 1−35). Birds

Table 2. Effects of far infrared ray radiation, mineral compounds and electrolyte-supplemented water supplementation on growth performance in broilers[1]

Item			BW (g)				ADG (g/d)				ADFI (g/d)				FCR (g/g)			
FIR	Mineral com-pounds	Electrolyte-supplemented water	d 1	d 10	d 21	d 35	d 1–10	d 11–21	d 22–35	d 1–35	d 1–10	d 11–21	d 22–35	d 1–35	d 1–10	d 11–21	d 22–35	d 1–35
Yes	No	No	42.81	272.1	1,020.82	2,585.84	22.93	68.06	111.79	72.66	26.79	85.99	156.93	106.08	1.17	1.26	1.40	1.46
		Yes	42.81	283.13	1,023.85	2,509.85	24.03	67.34	106.14	70.49	28.02	84.82	149.79	100.65	1.17	1.26	1.41	1.43
	Yes	No	42.83	277.40	1,056.46	2,603.35	23.46	70.82	110.49	73.16	27.34	86.52	154.23	101.7	1.16	1.22	1.40	1.39
		Yes	42.79	289.67	1,050.46	2,531.47	24.69	69.16	105.79	71.11	28.75	87.14	146.81	99.77	1.17	1.26	1.39	1.40
No	No	No	42.88	227.46	856.05	2,356.42	18.46	57.14	107.17	66.10	21.72	73.04	148.57	92.76	1.18	1.28	1.39	1.40
		Yes	42.92	219.27	828.17	2,305.37	17.64	55.35	105.51	64.64	20.63	70.44	155.06	94.34	1.17	1.27	1.47	1.46
	Yes	No	42.73	219.35	854.38	2,389.28	17.66	57.73	109.64	67.04	20.86	72.95	155.98	98.8	1.18	1.27	1.42	1.47
		Yes	42.69	215.22	829.73	2,291.38	17.25	55.86	104.40	64.25	20.25	70.45	149.45	91.81	1.17	1.26	1.43	1.43
SEM			0.036	2.002	6.024	16.185	0.200	0.523	1.090	0.462	0.239	0.539	1.629	0.854	0.002	0.005	0.013	0.011
Main effects																		
FIR																		
Yes			42.81	280.58^{b}	1,037.90^{b}	2,557.63^{b}	23.78^{b}	68.85^{b}	108.55	71.85^{b}	27.73^{b}	86.12^{b}	151.94	102.05^{b}	1.17^{a}	1.25	1.40	1.42
No			42.80	220.33^{a}	842.08^{a}	2,335.61^{a}	17.75^{a}	56.52^{a}	106.68	65.51^{a}	20.87^{a}	71.72^{a}	152.27	94.43^{a}	1.18^{b}	1.27	1.43	1.44
SEM			0.035	2.040	6.011	16.140	0.204	0.517	1.072	0.461	0.343	0.747	2.276	1.246	0.002	0.005	0.013	0.011
Mineral compounds																		
Yes			42.76	250.41	947.76	2,453.87	20.77	63.40	107.58	68.89	24.30	79.27	151.62	98.02	1.17	1.25	1.41	1.42
No			42.85	250.50	932.22	2,439.37	20.76	61.98	107.65	68.47	24.29	78.57	152.59	98.46	1.17	1.27	1.42	1.44
SEM			0.034	4.888	15.600	22.960	0.489	1.040	1.081	0.656	0.561	1.184	1.608	1.045	0.002	0.008	0.018	0.015
Electrolyte-supplemented water																		
Yes			42.80	251.82	933.05	2,409.52^{a}	20.90	61.93	105.46	67.62^{a}	24.42	78.21	150.28	96.64	1.17	1.26	1.43	1.43
No			42.81	249.08	946.93	2,483.72^{b}	20.63	63.44	109.77	69.74^{b}	24.18	79.63	153.93	99.84	1.17	1.26	1.40	1.43
SEM			0.049	6.907	22.067	31.574	0.488	1.039	1.034	0.638	0.338	0.560	1.181	1.587	0.002	0.006	0.013	0.011
P-value																		
FIR			0.885	<.001	<.001	<.001	<.001	<.001	0.396	<.001	<.001	<.001	0.92	<.001	0.040	0.105	0.312	0.346
Mineral compounds			0.198	0.983	0.205	0.657	0.998	0.182	0.973	0.655	0.98	0.523	0.767	0.799	0.847	0.148	0.746	0.503
Electrolyte-supplemented water			0.885	0.498	0.256	0.027	0.496	0.157	0.055	0.027	0.623	0.198	0.269	0.069	0.390	0.582	0.393	0.947
FIR × Mineral compounds			0.198	0.142	0.203	0.876	0.148	0.409	0.732	0.879	0.194	0.499	0.57	0.207	0.481	0.738	0.806	0.123
FIR × Electrolyte-supplemented water			0.885	0.032	0.310	0.993	0.032	0.763	0.693	0.993	0.029	0.298	0.272	0.776	0.524	0.325	0.385	0.714
Mineral compounds × Electrolyte-supplemented water			0.665	0.741	0.905	0.743	0.735	0.810	0.764	0.744	0.732	0.663	0.314	0.462	0.922	0.323	0.360	0.535
FIR × Mineral compounds × Electrolyte-supplemented water			0.885	0.863	0.800	0.696	0.861	0.838	0.607	0.696	0.876	0.698	0.334	0.085	0.864	0.404	0.594	0.098

FIR, far infrared ray; BW, bodyweight; ADG, average daily gain; ADFI, average daily feed intake; FCR, feed conversion ratio; SEM, Pooled standard error of the mean.

[a,b] Values in a column with different superscripts differ significantly (P<0.05).

[1] Mean values are based on 6 replicates per treatment.

fed electrolyte-supplemented water showed lower (P<0.05) average daily gain than birds not fed electrolyte-supplemented water. Birds exposed to FIR s4howed a higher (P<0.01) average daily feed intake than birds without FIR in the starter (day 1−10), grower (day 11−21), and overall periods (day 1−35). Birds exposed to FIR had a lower (P<0.05) feed conversion ratio than those not exposed to FIR in the starter period (day 1−10).

2. Carcass Traits

Table 3 summerizes the effects of far infrared ray radiation, mineral compound, and electrolyte-supplemented water supplemnetation on carcass traits in broiler. Birds exposed to FIR had higher (P<0.01) dressing percentages than those not exposed to FIR on day 21. Breast meat percentage was higher (P<0.05) in birds exposed to FIR than those not exposed to FIR on day 35. However, birds exposed to FIR showed lower (P<0.001) breast meat percentage and leg meat percentage than birds not exposed to FIR on day 21. On day 35, leg meat percentage was lower (P<0.001) in birds exposed to FIR than in birds not exposed to FIR. The dressing percentage was higher (P<0.01) in birds exposed to FIR and fed mineral compounds than other birds on day 21 arising from an interaction between FIR and mineral compounds. However, the leg meat percentage was lower (P<0.05) in birds exposed to FIR and fed mineral compounds than other birds on day 21. The dressing percentage was higher (P<0.01) in birds exposed to FIR and fed electrolyte-supplemented water than in other birds on day 21 due to the interaction between FIR and electrolyte-supplemented water. However, the percentage of leg meat was lower (P<0.05) in birds exposed to FIR and electrolyte-supplemented water than other birds on day 21. Birds exposed to FIR and fed electrolyte-supplemented water had a higher (P<0.01) dressing percentage. The percentage of breast meat was higher (P<0.05) in birds exposed to FIR and fed electrolyte-supplemented water than other birds on day 35. The percentage of leg meat was higher (P<0.05) in birds fed mineral compounds and electrolyte-supplemented water than in other birds on day 21 based on interactions between mineral compounds and electrolyte-supplemented water. However, the dressing percentage was lower (P<0.05) in birds fed mineral compounds and electrolyte-supplemented water than other birds on day 21. Breast meat percentage was higher (P<0.05) in birds fed mineral compounds and electrolyte-supplemented water than other birds on day 35.

3. Intestinal Morphology

The effects of far infrared ray radiaion, mineral compound, and electrolyte-supplemented water supplemetation on intestinal morphology of broilers are presented in Table 4. Birds exposed to FIR had lower (P<0.05) crypt depth and villus height : crypt depth ratio than birds not exposed to FIR on day 21. However, birds exposed to FIR showed lower (P<0.05) villus height than birds not exposed to FIR on day 35. Birds fed electrolyte-supplemented water showed higher (P<0.05) villus height and crypt depth than birds not provided electrolyte-supplemented water on day 35.

4. Blood Metabolites

The results regarding intestinal morphology of broilers under far infrared ray radiation, mineral compound, and electrolyte-suppelmented water supplementation are shown in Table 5. Birds exposed to FIR had higher (P<0.05) IL-1β, lactate contents than birds not exposed to FIR on day 21. However, birds exposed to FIR had lower (P<0.05) IL-10, IFN-ɣ, and corticosterone contents than birds not exposed to FIR on day 21 and 35. Furthermore, birds exposed to FIR had a lower (P<0.05) TNF-α content than birds not exposed to FIR on day 35. Birds fed mineral compounds had lower (P<0.05) IL-1β and lactate contents than birds not provided mineral compounds on day 21. Birds fed electrolyte-supplemented water had a lower (P<0.05) lactate content than birds not provided electrolyte-supplemented water on day 21. There was an interaction for lactate content not only between mineral compounds and electrolyte-supplemented water but also between FIR, mineral compounds, and electrolyte-supplemented water on day 21. Furthermore, there was an interaction for lactate and corticosterone between FIR and mineral compounds.

DISCUSSION

Recently, the use of FIR in animal production has gained attention due to its reported biological effects beyond simple heat generation, such as improvements in growth, immune function, and tissue health (Akasaki et al., 2006; Lim et al., 2023). While FIR has been used in various areas of agri-

Table 3. Effects of far infrared ray radiation, mineral compound, and electrolyte-supplemented water supplementation on carcass traits in broilers[1]

Item			d 21			d 35		
FIR	Mineral compounds	Electrolyte-supplemented water	Dressing[2] (%)	Breast[3] (%)	Leg[4] (%)	Dressing (%)	Breast (%)	Leg (%)
Yes	No	No	87.22	25.05	10.45	90.21	26.67	10
		Yes	89.01	25.53	9.44	90.23	26.48	10.03
	Yes	No	88.74	24.29	9.74	89.77	25.55	9.64
		Yes	88.91	25.58	9.18	90.91	27.14	9.71
No	No	No	88.10	26.53	11.39	90.80	26.54	10.46
		Yes	87.73	26.54	11.19	89.71	24.34	11.18
	Yes	No	87.76	27.05	11.21	90.03	25.67	10.72
		Yes	86.07	26.90	11.85	89.27	25.69	10.65
SEM			0.147	0.186	0.070	0.137	0.192	0.074
Main effects								
FIR								
Yes			88.47[b]	25.11[a]	9.70[a]	90.28	26.46[b]	9.85[a]
No			87.42[a]	26.76[b]	11.41[b]	89.95	25.56[a]	10.76[b]
SEM			0.177	0.183	0.087	0.147	0.206	0.076
Mineral compounds								
Yes			87.87	25.96	10.50	90.00	26.01	10.18
No			88.02	25.91	10.62	90.24	26.01	10.42
SEM			0.193	0.219	0.153	0.148	0.216	0.100
Electrolyte-supplemented water								
Yes			87.93	26.14	10.42	90.03	25.91	10.39
No			87.96	25.73	10.70	90.21	26.11	10.21
SEM			0.193	0.217	0.151	0.210	0.305	0.142
P-value								
FIR			<.001	<.001	<.001	0.241	0.024	<.001
Mineral compounds			0.629	0.907	0.384	0.377	0.986	0.115
Electrolyte-supplemented water			0.938	0.276	0.050	0.525	0.615	0.213
FIR × Mineral compounds			0.006	0.292	0.013	0.194	0.546	0.483
FIR × Electrolyte-supplemented water			0.001	0.206	<.001	0.009	0.025	0.348
Mineral compounds × Electrolyte-supplemented water			0.017	0.673	0.028	0.194	0.013	0.207
FIR × Mineral compounds × Electrolyte-supplemented water			0.804	0.520	0.481	0.476	0.773	0.171

FIR, far infrared ray; SEM, Pooled standard error of the mean.
[a,b] Values in a column with different superscripts differ significantly (P<0.05).
[1] Mean values are based on 6 replicates per treatment.
[2] (Carcass weight / live body weight) × 100.
[3] (Breast meat weight / carcass weight) × 100.
[4] (Leg meat weight / carcass weight) × 100.

Table 4. Effects of far infrared ray radiation, mineral compounds, and electrolyte-supplemented water supplementation on intestinal morphology in broilers[1]

Item			d 21				d 35			
FIR	Mineral compounds	Electrolyte-supplemented water	Villus height (μm)	Crypt depth (μm)	Villus height: crypt depth ratio	Villus width (μm)	Villus height (μm)	Crypt depth (μm)	Villus height: crypt depth ratio	Villus width (μm)
Yes	No	No	958.22	142.59	7.14	102.17	1,083.72	139.67	8.09	102.77
		Yes	915.15	137.09	7.06	103.40	1,145.23	159.33	7.52	98.96
	Yes	No	887.58	155.57	5.87	98.45	1,138.81	140.53	8.52	103.96
		Yes	846.44	140.82	6.35	102.67	1,127.62	173.33	6.55	111.47
No	No	No	964.29	216.77	4.50	120.52	1,158.08	150.15	7.97	107.96
		Yes	960.03	186.11	5.51	107.00	1,343.48	179.25	7.83	112.54
	Yes	No	817.90	189.46	4.65	98.56	1,150.02	145.11	8.25	105.95
		Yes	1,033.41	168.40	6.58	109.12	1,279.37	153.46	8.65	113.09
SEM			18.175	6.041	0.245	3.373	20.951	4.908	0.284	2.654
Main effects										
FIR										
Yes			901.85	144.02[a]	6.61[b]	101.67	1,123.85[a]	153.22	7.67	104.29
No			943.90	190.18[b]	5.31[a]	108.80	1,232.74[b]	156.99	8.17	109.89
SEM			27.277	8.428	0.353	4.604	30.363	7.068	0.393	3.592
Mineral compounds										
Yes			896.33	163.56	5.86	102.20	1,173.96	153.11	7.99	108.62
No			949.42	170.64	6.05	108.27	1,182.63	157.10	7.85	105.56
SEM			27.067	9.677	0.378	4.621	32.403	7.066	0.396	3.625
Electrolyte-supplemented water										
Yes			938.76	158.10	6.38	105.55	1,223.93[b]	166.34[b]	7.64	109.02
No			907.00	176.10	5.54	104.92	1,132.66[a]	143.87[a]	8.21	105.16
SEM			27.428	9.522	0.368	4.664	30.988	6.680	0.392	3.616
P-value										
FIR			0.254	<.001	0.012	0.297	0.013	0.702	0.380	0.298
Mineral compounds			0.152	0.561	0.698	0.374	0.837	0.686	0.810	0.567
Electrolyte-supplemented water			0.387	0.144	0.096	0.927	0.035	0.027	0.320	0.472
FIR × Mineral compounds			0.651	0.209	0.111	0.572	0.517	0.251	0.472	0.480
FIR × Electrolyte-supplemented water			0.049	0.519	0.202	0.757	0.122	0.704	0.224	0.708
Mineral compounds × Electrolyte-supplemented water			0.135	0.994	0.455	0.322	0.447	0.847	0.705	0.517
FIR × Mineral compounds × Electrolyte-supplemented water			0.142	0.699	0.861	0.439	0.921	0.393	0.401	0.682

FIR, far infrared ray; SEM, Pooled standard error of the mean.

[a,b] Values in a column with different superscripts differ significantly ($P<0.05$).

[1] Mean values are based on 6 replicates per treatment.

Table 5. Effects of far infrared ray radiation, mineral compounds, and electrolyte-supplemented water supplementation on blood metabolites in broilers[1]

Item			d 21							d 35						
FIR	Mineral compounds	Electrolyte-supplemented water	IL-1β (pg/mL)	IL-10 (ng/mL)	TNF-α (pg/mL)	IFN-γ (ng/mL)	Glucose (mg/dL)	Lactate (nmol/μL)	Corti-costerone (ng/mL)	IL-1β (pg/mL)	IL-10 (ng/mL)	TNF-α (pg/mL)	IFN-γ (ng/mL)	Glucose (mg/dL)	Lactate (nmol/μL)	Corti-costerone (ng/mL)
Yes	No	No	1,295.51	2.19	590.77	1.10	197.17	674.38[c]	10.36	1,351.31[a]	2.50	838.60	2.10	288.16	190.19	9.97
		Yes	1,064.79	2.86	666.46	1.08	187.72	277.09[ab]	10.02	3,488.76[b]	2.36	1,083.20	1.55	265.17	113.56	9.97
	Yes	No	484.68	1.67	609.93	0.93	193.08	353.75[abc]	7.31	2,037.53[ab]	2.29	815.33	1.34	286.67	181.75	8.51
		Yes	949.75	2.36	551.21	1.28	177.19	544.39[bc]	8.08	1,274.11[a]	1.94	679.33	1.70	275.10	108.41	9.65
No	No	No	848.33	2.82	486.51	1.98	179.92	502.57[bc]	11.23	1,717.15[ab]	3.51	561.94	3.16	369.12	214.33	12.03
		Yes	630.85	4.39	472.24	1.93	188.69	309.52[ab]	11.97	1,519.31[a]	4.36	733.71	4.17	292.93	194.38	12.63
	Yes	No	597.66	3.53	517.72	3.01	176.12	189.12[ab]	12.31	1,281.57[a]	5.93	696.07	3.79	279.86	193.34	11.40
		Yes	504.60	3.68	543.93	3.92	178.85	108.14[a]	13.01	1,281.57[ab]	4.99	609.97	4.95	289.52	183.51	12.80
SEM			58.947	0.240	28.209	0.223	3.332	28.238	0.309	148.646	0.240	33.323	0.350	11.856	12.279	0.371
Main effects																
FIR																
Yes			948.68[b]	2.27[a]	604.59	1.10[a]	188.79	462.41[b]	8.94[a]	2,037.93	2.28[a]	854.12[b]	1.68[a]	278.78	148.48	9.52[a]
No			645.36[a]	3.61[b]	505.10	2.71[b]	180.90	277.34[a]	12.13[b]	1,609.90	4.70[b]	650.42[a]	4.02[b]	307.86	196.39	12.22[b]
SEM			128.726	0.471	53.632	0.450	6.482	69.245	0.649	238.372	0.343	49.923	0.473	16.554	17.198	0.504
Mineral compounds																
Yes			634.17[a]	2.81	555.69	2.29	181.31	298.85[a]	10.18	1,628.70	3.79	700.17	2.95	282.79	166.75	10.59
No			959.87[b]	3.07	554.00	1.52	188.38	440.89[b]	10.89	2,019.13	3.18	804.36	2.75	303.84	178.12	11.15
SEM			90.179	0.360	39.316	0.351	4.598	50.502	0.561	239.072	0.422	53.154	0.532	16.685	17.870	0.574
Electrolyte-supplemented water																
Yes			787.50	3.32	558.46	2.05	183.11	309.79[a]	10.77	2,050.94	3.41	776.55	3.09	280.68	149.96	11.26
No			806.55	2.55	551.23	1.76	186.57	429.96[b]	10.30	1,596.89	3.56	727.99	2.60	305.95	194.90	10.48
SEM			96.340	0.352	39.309	0.359	4.643	51.115	0.564	237.848	0.426	54.016	0.530	16.622	17.285	0.571
P-value																
FIR			0.014	0.008	0.085	<.001	0.243	0.002	<.001	0.158	<.001	0.004	0.002	0.227	0.058	<.001
Mineral compounds			0.009	0.600	0.976	0.095	0.295	0.016	0.254	0.197	0.214	0.126	0.776	0.380	0.646	0.451
Electrolyte-supplemented water			0.872	0.116	0.899	0.508	0.606	0.040	0.453	0.135	0.763	0.470	0.482	0.293	0.075	0.298
FIR × Mineral compounds			0.251	0.600	0.383	0.102	0.971	0.048	0.006	0.216	0.062	0.109	0.475	0.293	0.853	0.659
FIR × Electrolyte-supplemented water			0.255	0.855	0.982	0.770	0.175	0.767	0.683	0.438	0.843	0.932	0.404	0.738	0.228	0.772
Mineral compounds × Electrolyte-supplemented water			0.090	0.472	0.679	0.458	0.642	0.004	0.669	0.090	0.301	0.021	0.703	0.311	0.892	0.518
FIR × Mineral compounds × Electrolyte-supplemented water			0.233	0.457	0.443	0.743	0.988	0.041	0.649	0.003	0.415	0.648	0.790	0.437	0.945	0.907

FIR, far infrared ray; IL-1β, interleukin-1 beta; IL-10, interleukin-10; TNF-α, tumor necrosis factor-alpha; IFN-γ, interferon-gamma; SEM, Pooled standard error of the mean.

[a,b] Values in a column with different superscripts differ significantly ($P<0.05$).

[1] Mean values are based on 6 replicates per treatment.

culture, studies focusing on its effects in broiler chickens are still limited (Son, 2015; Lim et al., 2023). Therefore, the present study investigated the synergistic effect of FIR, mineral compounds, and electrolyte-supplemented water on growth performance, carcass traits, intestinal morphology, and blood metabolites of broiler from hatch to day 35. Our findings indicate that FIR radiation improved growth performance in broilers over the experiment. Broilers exposed to FIR showed significantly higher average daily gain and feed intake, on days 1 to 10, days 11 to 21 and across the entire trial. The increased feed intake might be a consequence of enhanced growth performance, as birds with faster growth naturally require more nutrients to support their development. According to (Son, 2015), broilers exposed to FIR radiation exhibited greater body weight and improve feed efficiency compared to those not receiving FIR treatment. Previous research shown that FIR radiation enhanced L-arginine bioavailability through capillaries dilation (Yu et al., 2006), and stimulates mitochondrial energy metabolism at the cellular level (Desmet et al., 2006). Thus, the improved growth performance observed in this study may be associated with more efficient amino acid utilization and enhanced energy production within the body. In addition to these mechanisms, recent literature suggests that FIR interacts with the electrolyte-supplemented water. FIR exposure can alter hydrogen bonding in water molecules, reducing the size of water clusters and improving their permeability (Lin and Lin, 2021). This structural change may improve the solubility and transport of water-soluble compounds, including minerals, through the digestive tract. As mineral absorption plays a key role in supporting metabolic processes and bone development in broilers, improved water structure and mineral bioavailability might have contributed to the observed growth enhancement. In contrast, mineral supplementation did not significantly affect ADG or FI during any period. This lack of response may be attributed to adequate baseline mineral levels in the basal diet or limited bioavailability of the supplemented form (Zhang et al., 2023). Interestingly, broilers that did not receive electrolyte-supplemented water showed a significantly higher ADG over 1－35 and greater body weight at day 35, suggesting that electrolyte addition may not always benefit growth under certain conditions.

The yield of dressing percentage, a key indicator of farm productivity in the poultry industry, reflects the overall efficiency of broiler production. In this study, FIR radiation increased the dressing percentage in broilers. Still, the trend suggests a potential benefit of FIR exposure on carcass composition. One possible explanation for this is that FIR radiation enhances amino acid utilization (Yu et al., 2006), leading to a greater proportion of muscles mass in broilers. Supporting this, previous research has shown that FIR exposure may improve capillary circulation and nutrient delivery to peripheral tissues (Yu et al., 2006), which in turn could facilitate protein synthesis and muscle growth. FIR may also support carcass yield indirectly by enhancing mitochondrial energy metabolism and overall metabolic efficiency (Desmet et al., 2006). While direct evidence linking FIR to carcass trait changes in poultry remains limited, these physiological mechanisms offer a plausible explanation for the improvements observed in this study. In contrast, mineral supplementation and electrolyte-supplemented water did not result in significant changes in carcass traits. This may be because the basal diet already met the birds' nutritional requirements for tissue development, making further improvements in carcass deposition unlikely (Bao et al., 2007).

A well-developed gastrointestinal structure promotes more effective feed utilization and enhances intestinal immunity by strengthening epithelial barriers, limiting endotoxin passage, and reducing susceptibility to pathogens (Teng and Kim, 2018; Swaggerty et al., 2019). In this study, FIR radiation altered intestinal morphology at both day 21 and day 35. On day 21, FIR significantly reduced crypt depth and increased the villus height to crypt depth ratio, indicating improved intestinal maturity and absorptive efficiency. However, on day 35, villus height was lower in the FIR group, which may reflect a shift in mucosal turnover dynamics or an adaptation to early intestinal development. The improved villus height to crypt depth ratio observed on day 21 may be partly attributed to FIR's effect on gut microflora. Previous studies have shown that FIR reduces harmful intestinal bacteria in poultry (Lim et al., 2023). A reduction in pathogenic load could alleviate inflammation and promote mucosal regeneration, contributing to favorable intestinal architecture (Xu et al., 2003). Although deeper crypts are generally associated with higher maintenance energy requirements (Iji et al., 2001), the observed reduction in crypt depth under FIR exposure suggests a more stable and efficient epithelial turnover at earlier stages. While the decline in villus height at day 35 warrants further investigation, the morphological changes overall support the hypothesis that FIR influences intestinal development and may enhance nutrient absorption during the critical early growth phase of broilers. In addition to FIR, electrolyte-supplemented water significantly increased both villus height and crypt depth at day 35, with higher values observed in birds receiving the supplemented water. These morphological improvements could reflect enhanced intestinal absorptive capacity during the later growth stage, potentially driven by improved epithelial hydration, ionic balance, and mucosal integrity. Electrolyte inclusion might have helped maintain osmotic gradients and facilitate water transport across enterocytes, thereby supporting overall nutrient absorption (Kiela and Gishan, 2016). The increased villus height and deeper crypt depths also indicate of greater epithelial turnover and expanded absorptive surface area (Rhoads et al., 1997), which together contribute to more efficient digestion and absorption, ultimately enhancing growth performance. In contrast, mineral supplementation did not produce significant changes in intestinal morphology, which may be attributed to sufficient baseline mineral levels in the diet (Bao et al., 2007).

In this study, FIR exposure led to distinct immunological and stress-related responses in broilers. On day 21, broilers receiving FIR showed increased IL-1β and lactate levels, while IL-10 and IFN-γ were significantly reduced. Additionally, corticosterone levels decreased, suggesting a potential alleviation of physiological stress. On day 35, IL-1β and TNF-α were both elevated, IL-10 remained lower, and IFN-γ continued to be reduced. Notably, corticosterone levels again decreased, reinforcing the stress-reducing potential of FIR treatment. Although the full mechanisms underlying these shifts are not yet fully understood in poultry, studies in other animal models offer plausible insights. FIR has been reported to reduce IFN-γ and promote nitric oxide-mediated anti-inflammatory signaling (Kim et al., 2019), which may partly explain the observed suppression of IFN-γ in this study. Meanwhile, the reduction in corticosterone suggests an effect on the hypothalamic-pituitary-adrenal (HPA) axis, potentially moderating the broilers' physiological stress response (Leung et al., 2011, 2012). The observed increase in pro-inflammatory cytokines such as IL-1β and TNF-α, alongside decreased IFN-γ and IL-10, suggests that FIR may modulate immune responses in a complex and time-dependent manner. While some markers indicate inflammation, others reflect stress attenuation. Therefore, further research is warranted to clarify how FIR influences immune signaling pathways and the balance between pro- and anti-inflammatory responses in poultry. Notably, mineral supplementation significantly reduced IL-1β and lactate levels on day 21, suggesting and anti-flammatory effect and improved metabolic balance in the early phase of the trial. This is consistent with the known roles of trace minerals such as zinc and selenium in regulating immune function and reducing oxidative stress (Bao et al., 2007; Ghasemi et al., 2020). However, no significant changes were observed in other immune or stress markers, indicating that the effects of mineral supplementation were limited or selective under these conditions. Similarly, electrolyte-supplemented water significantly reduced lactate levels on day 21, with higher values observed in birds that did not receive electrolyte supplementation. This may reflect improved hydration status or acid-base balance, though no significant effects were seen for cytokine or corticosterone levels.

SUMMARY

This study demonstrated that far-infrared radiation (FIR) can positively influence growth performance, carcass traits, intestinal morphology, and blood metabolites in broiler chickens. FIR exposure improved nutrient absorption, enhanced gut structure, and reduced markers of inflammation and stress, suggesting its potential as a non-invasive management strategy to improve broiler health and productivity. However, as current research on FIR in poultry remains limited, especially in broiler chickens, further studies are warranted to clarify its underlying mechanisms and optimize its application in commercial production systems.

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