DOI: https://doi.org/10.21323/2414-438X-2025-10-3-284-292
Received 12.06.2025
Accepted in revised 10.09.2025
Accepted for publication 15.09.2025

Available online at https://www.meatjournal.ru/jour
Original scientific article
Open Access

INFLUENCE OF MODULATED STRESS ON THE COMPOSITION AND QUALITY OF THE BROILERS MEAT

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Keywords: *Broilers, chemical composition of meat, quality, modulated stress*

Abstract
The purpose of this work is to conduct comprehensive studies aimed at studying the effect of modulated stress of cage density in the poultry houses on the body of domestic cross-breed of the broilers "Smena-9", in particular -on the chemical composition, some qualitative characteristics and antioxidant status of their muscle tissue. An experiment was conducted in the conditions of the physiological yard of the Federal Research Center for Animal Husbandry named after Academy Member L. K. Ernst in 2023 on 2 groups of the broilers (n = 40, N = 80) (control group and experimental group) of the domestic cross-breed of the broilers "Smena-9". The control group was kept under the conditions of the cage density recommended for this cross-breed (Stress-). The poultry cage density in the experimental group (Stress +) was increased by 10 % from the 21st day of the poultry's life in order to create stress conditions. To study the effect of modulated stress on the composition and quality of meat, we conducted poultry slaughterings at the age of 24 (n = 10, N = 20), 34 (n = 10, N = 20) and 52 (n = 10, N = 20) days. Stress led to significant changes in the pH of the breast flesh: 45 minutes after slaughter, the index was 5.55 versus 5.59 units (p = 0.004), and 24 hours later — 5.44 versus 5.60 units. (p = 0.08). The values of the WHC of the experimental group were also lower than those in the control group on the 34^{th} and 52^{nd} days. The stress factor under study was not critical for the development of acute oxidative stress; the greatest changes were observed in age dynamics. There is a decrease in the pH of the breast flesh depending on the age aspect (p < 0.05) in both groups. On day 52, there was a significant (p < 0.01) decrease in TAC content in the breast of poultry of both groups, in the heart muscle in the control group (p = 0.06) and the experimental group (p < 0.001), there was an increase in the activity of SOD and catalase. The data obtained will allow the development of ways to regulate the quality of poultry products.

For citation: Bogoluybova, N.V., Nekrasov, R.V., Zelenchenkova, A.A., Kolesnik, N.S., Lahonin, P.D., Bogolyubova, Ju. A. et al. (2025). Influence of modulated stress on the composition and quality of the broilers meat. *Theory and Practice of Meat Processing*, 10(2), 284–292. https://doi.org/10.21323/2414-438X-2024-10-3-284-292

Funding:
This research was carried out with the financial support of the Russian Science Foundation, project No 22-16-00024-P.

Introduction

Poultry meat products are a popular product among the population due to their relatively low cost and rich chemical composition [1]. Poultry meat is a rich source of omega-3 fatty acids, and its use in human nutrition provides a positive effect on vascular health [2].

Since 2016, poultry meat has occupied a leading position in the structure of meat products consumption in the Russian Federation, and the volumes of this production are growing annually [3].

In terms of broilers meat production, Russia is one of the leading countries, occupying the fifth place in the world ranking. In January-September 2024, poultry meat production in Russia (in live weight) exceeded the figure for the same period last year by 2.4 % and amounted to 5.2 million tons [4].

To meet the growing demand for poultry meat, selection and breeding work is continuously carried out to improve the efficiency of broiler poultry farming, aimed at obtaining fast-growing breeds. But poultry health and the quality of poultry products may negatively correlate with the level of metabolic processes [5,6]. In addition, the impact of thermal, physiological, process stresses, including transport stress affecting the body leads to a decrease in the quality of poultry products [7,8]. There are occurrences of various myopathies, changes in the texture and taste of meat, which leads to a decrease in consumer demand [9]. It is known, for example, that heat stress causes a decrease in protein content and an increase in fat in chicken meat [10]. An explanation for this mechanism is given in the work of Zaboli et.al. [11]. It has been shown that an increase in corticosterone secretion causes an increase in protein breakdown and an increase in fat deposition [11]. In another study, cage density stress in poultry negatively affected breast muscle pH [12]. Under the influence of stress, the color of muscle tissue can change towards the development of a darker shade of color [13]. Thus, a higher cage density contributes to the change in color of the chicken breast and the production of a paler coloring [14]. These researchers also assessed liver color because of its important role in fatty acid synthesis. Broilers kept at cage density of 29 kg/m^2 had the lowest relative liver weight and featured red liver color, while broilers who were bred at cage density of 37 kg/m^2 had a more yellow liver color [15]. Both chronic and short-term heat stress can contribute not only to negative color changes, but also to a decrease in muscle pH, water-holding capacity (WHC), and juiciness of meat [16]. In the study of Liu et.al [16] it was noted that chronic heat stress reduces the density of muscle fibers, increases the content of connective tissue and leads to intracellular vacuolization. Transcriptome analysis in this study showed that the effect of stress on meat quality was associated not only with metabolism and oxidative stress, but also with impaired transduction, violated immune system, cell growth and cell death.

In the Liao et al. [17] experiment, the pre-slaughter transportation of broilers led to the generation of reactive oxygen forms, increased antioxidant capacity in the mitochondria of the pectoral muscle, thus contributing to the development of meat PSE.

The purpose of this work is to conduct comprehensive studies aimed at studying the effect of modulated stress of cage density in the body of domestic cross-breed broilers "Smena-9" on the chemical composition, some qualitative characteristics and the antioxidant status of muscle tissue (thighs and breasts). The data will be useful for developing effective strategies aimed at improving poultry products derived from fast-growing poultry crosses.

Objects and methods

2 groups of broilers ($n=40$, $N=80$) (control group and experimental group) of the domestic cross-breed of broiler "Smena-9" were formed in the physiological yard of the Federal Research Center for Animal Husbandry named after Academy Member L. K. Ernst and an experiment was conducted on those two groups. As the main ration for chickens of all groups, total mixed ration made of compound feeds were used, in due relevance to the poultry growing periods: from 0 till 11th day — starting compound feed (till 11th day), during the period of growth (12–26th day) — growth mix was given, and the finishing period (27–52th day) — the poultry received the finishing ration. (Table 1).

The broilers were kept in the specialized cages for BB-1 broilers (Stimuli Group LLC, Russia). When determining the normal and increased cage density, we were guided by the relevant standards for working with meat cross-breed of poultry "Smena 9"[1]. The control group was kept under the conditions of the recommended cage density for this cross (Stress-). The poultry cage density in the experimen-

[1] Efimov, D.N., Egorova, A.V., Emanuilova, Zh.V., Ivanov, A.V., Konopleva, A.P., Zotov, A.A. et al. (2020). Manual for working with poultry of meat cross-breed “Smena 9” with autosexing maternal parent form. Sergiev Posad: All-Russian Research and Technological Poultry Institute, 2020.

Table 1. Composition and nutritional value of concentrates for broilers

Item	Unit	Starting compound	Growth compound	Finishing compound
Wheat	%	35.00	40	55
Corn	%	24.00	20	10
Wheat bran	%	—	—	5
Full-fat soybeans	%	—	9	5
Soybean meal	%	26.00	9	10
Sunflower cake	%	5.00	14.4	10
Sunflower oil	%	0.60	—	—
Fish meal	%	1.70	—	—
Feed yeast	%	3.00	3	3
Lysine monochlorhydrate 98 %	%	0.20	0.2	0.2
Feed methionine 98 %	%	0.30	0.3	0.3
Monocalcium phosphate	%	1.20	1.2	1.2
Feed chalk	%	1.80	1.8	1.8
Salt	%	0.20	0.2	0.2
Premix P5–1	%	1.00	1	1
Nutritional values				
Metabolizable energy	Kcal/100g	308.00	313.00	315.30
Metabolizable energy	MJ/kg	12.90	13.10	13.20
Dry matter	%	89.42	89.28	91.47
Crude protein	%	22.91	21.03	19.98
Crude fat	%	3.21	4.92	3.73
Linoleic acid	%	1.64	2.61	2.01
Crude fiber	%	4.32	5.41	5.12
Crude ash	%	3.41	3.10	3.07
NES	%	52.15	50.82	55.69
Starch	%	34.32	34.74	38.72
Sugar	%	3.30	2.83	2.79
Lysine	%	1.28	1.03	0.97
Methionine	%	0.63	0.61	0.58
Methionine + cystine	%	0.96	0.93	0.87
Threonine	%	0.79	0.70	0.64
Tryptophan	%	0.28	0.25	0.24
Arginine	%	1.35	1.25	1.13
Valin	%	1.03	0.96	0.91
Histidine	%	0.55	0.50	0.46
Glycine	%	0.97	0.92	0.84
Isoleucine	%	0.96	0.87	0.81
Leucine	%	1.48	1.36	1.25
Phenylalanine	%	1.02	0.91	0.86
Tyrosine	%	0.71	0.62	0.58
Ca	%	1.04	0.95	0.95
P	%	0.74	0.71	0.74
Na	%	0.13	0.11	0.11
Cl	%	0.22	0.21	0.21
Vitamin A	mln. IU/t	12.00	12.00	12.00
Vitamin D3	mln. IU/t	4.00	4.00	4.00
Vitamin E	%	30.00	30.00	30.00
Vitamin K	%	4.00	4.00	4.00
Vitamin B1	%	4.00	4.00	4.00
Fe	%	40.00	40.00	40.00
Cu	%	20.00	20.00	20.00
Zn	%	100.00	100.00	100.00
Mn	%	120.00	120.00	120.00
Se	%	0.30	0.30	0.30

tal group (Stress +) was increased by 10 % from the 21st day of the poultry's life to create stress conditions. The length of the poultry cage was 0.99 m, the width was 0.61 m, and the cage area was 0.60 m^2. On a weekly basis, the area of the cage for poultry of the experimental group was adjusted using sliding plywood partitions as the live weight of the poultry increased (the standard for poultry weight was the value of the cage area "minus" 10 %).

Table 2. Poultry cage density in groups 2, 3 and 4 (Stress +)

Live weight, kg	The norm of head/ m^2, according to the manual	Number of heads in a group (roosters and hens)	Stress + (density increased by 10 %)	Cage area, m^2	Frontal feeding area width, cm
0.3–0.4	72	17	79.2	0.21	2.09
0.4–0.5	66	17	72.6	0.23	2.28
0.5–0.7	61	17	67.1	0.25	2.47
0.6–0.8	55	12	60.5	0.20	2.74
0.7–0.9	50	12	55	0.22	3.01
0.8–1.0	46	12	50.6	0.24	3.27
0.9–1.1	42	12	46.2	0.26	3.58
1.1–1.2	38	12	41.8	0.29	3.96
1.3–1.4	32	12	35.2	0.34	4.70
1.5–1.6	28	7	30.8	0.23	5.38
1.7–1.8	26	7	28.6	0.24	5.79
1.9–2.0	23	7	25.3	0.28	6.55
2.1–2.2	21	7	23.1	0.30	7.17
2.3–2.6	17	7	18.7	0.37	8.86

To study the effect of modulated stress on the composition and quality of meat, we performed poultry slaughterings at the ages of 24 ($n = 10$, $N = 20$), 34 ($n = 10$, $N = 20$) and 52 ($n = 10$, $N = 20$) days and the following parameters were evaluated: chemical composition of meat (dry matter (GOST 33319-2015[2]), fat (GOST 23042-2015[3]) and ash (GOST 31727-2012 (ISO 936:1998)[4]). Crude protein content was calculated. Fatty acid composition of abdominal fat (GOST R55483-2013[5]) (gas chromatograph GC2010, Shimasu, Japan), meat pH — using a Testo 205 pH meter (China); water holding capacity — these values were assessed by pressing method according to Grau and Hamm in the modification of Volovinskaya; the amount of water-soluble antioxidants (AWSA)- was assessed on the device Tsvet-Yauza-01-AA (Khimavtomatika, Russia) by the amperometric method. The activity of glutathione peroxidase, catalase, the concentration of glutathione reduced, total antioxidant status (TAS), superoxide dismutase (SOD) were assessed, using commercial Elabscience kits ("Elabscience Biotechnology, Inc.", China) on the Immunochem-2100 device (High Technology, Inc., USA).

The content of mineral components was determined using the following methods. The calcium content of meat was determined according to Methodological recommendations for chemical and biochemical studies of livestock products and feeds[6] The phosphorus content of meat was determined according to Methodological recommendations for chemical and biochemical studies of livestock products and feeds[6] The magnesium content of meat was determined according to Methodological recommendations for chemical and biochemical studies of livestock products and feeds[6].

The methods are described in more detail in our previous publication [18].

Studies were carried out with approval by the bioethical commission (No. 3, May 27, 2022). The experiments were carried out in accordance with the requirements of the Federal Law of the Russian Federation[7], the Declaration of Helsinki[8], the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes[9]

Mathematical and statistical processing of the results was implemented with the help of Microsoft Office Excel 2003, STATISTICA 10 (Statistica 13RU, StatSoft, USA) using methods of variance and factor analysis, involving the Dunnett's test and Tukey's test, t-test. The differences were considered as statistically significant at $p < 0.05$, highly significant at $p < 0.01$; $p < 0.001$.

Results and discussion

Poultry meat is an important source of high-quality proteins, fats and minerals [19]. In recent years, due to the active development of industrial poultry farming and the emergence of fast-growing poultry crosses, attention has been paid to the poultry meat product quality. Food quality is a complex concept that includes a set of properties closely related to physical and chemical characteristics, texture, and taste that satisfy the consumer [20]. Consumers are increasingly paying attention to the quality, safety

[2] GOST 33319-2015 “Meat and meat products. Method for determination of moisture content”. Moscow: Standartinform, 2019. Retrieved from https://docs.cntd.ru/document/1200123927 Accessed May 17, 2025 (In Russian).

[3] GOST 23042-2015 «Meat and meat products. Methods of fat determination». Moscow: Standartinform, 2019. Retrieved from https://docs.cntd.ru/document/1200133107. Accessed May 17, 2025 (In Russian).

[4] GOST 31727-2012 (ISO 936:1998) «Meat and meat products. Determination of total ash». Moscow: Standartinform, 2013. Retrieved from https://docs.cntd.ru/document/1200098742. Accessed May 17, 2025 (In Russian).

[5] GOST R55483-2013 «Meat and meat products. Determination of fatty acids composition by gas chromatography». Moscow: Standartinform, 2019. Retrieved from https://docs.cntd.ru/document/1200103852/ Accessed May 17, 2025 (In Russian).

[6] Drozenko, N.P., Kalinin, V.V., Raetskaya, Yu. I. (1981). Methodological recommendations for chemical and biochemical studies of livestock products and feed. Dubrovitsy, 1981.

[7] Federal Law of the Russian Federation dated December 27, 2018 No. 498-FZ “On the responsible treatment of animals and on amendments tocertain legislative acts of the Russian Federation.”Retrieved from https://docs.cntd.ru/document/552045936. Accessed May 17, 2025 (In Russian).

[8] WMA Declaration of Helsinki — ethical principles for medical research involving human subjects Retrieved from https://www.wma.net/policiespost/wma-declaration-of-helsinki-ethical-principles-for-medical-research-involving-human-subjects/ Accessed May 17, 2025.

[9] ETS No. 123, Strasbourg, 1986) (European Convention for the Protection of Vertebrate Animals used for Experimental and Other Scientific Purposes. Retrieved from https://rm.coe.int/168007a67b. Accessed May 17, 2025.

and nutritional value of meat, directly linking them with an animal's welfare.

The stress of poultry cage density leads to the development of heat stress, which provides a negative impact on feed consumption and digestion efficiency, meat quality and livestock safety [21].

The analysis of the chemical composition of the meat of the "Smena 9" cross-breed broilers in age dynamics (Table 3) showed that there were no significant changes in the chemical composition of the thigh flesh both in the control group and the group under the influence of the factor being studied. Changes in the moisture content, basic organic substances and mineral substances were not significant on the 24th, 34th and 52nd days taken into account. With age, there was a certain trend ($p = 0.07$) to accumulate Ca in the poultry meat of the control group, in contrast to the experimental group, where these changes were not noted. At the end of the experiment, there were no differences in the ratio of moisture and protein in poultry thigh meat (3.63 versus 3.62, respectively in the control group and experimental group).

According to [22] various cage densities practiced during the first 10 days of poultry growing do not significantly affect slaughter yield parameters, abdominal fat content, carcass yield, color and pH values in breast and thigh meat. It is concluded that growing broiler chickens with dividing the area of the poultry house in half during the first 10 days of their lives (36 chickens/m^2) can help increase overall farming productivity due to ease of maintenance, efficient heating and better control of livestock.

On the other hand, in [23] it was noted that live weight, breast weight, leg weight, and fat weight increase linearly along with age. Conversely, the ratio of water to protein, breast fat, and breast collagen values decrease linearly along with age.

It is noted that the age of poultry slaughter is reflected in the amino acid composition. For example, amino acids, peptides, and phospholipids predominated in young chickens, especially in the pectoral muscles of Lueyang black-bone chickens. The study of the amino acid composition of muscles is of great practical importance in assessing the quality of meat, as it determines the taste properties. We plan to study this issue in our further research [24].

In our studies, some age-related changes also occurred in the muscle tissue of the poultry breast of the control group. Thus, breast fat and magnesium levels decreased in the broilers of the control group at the age of 34 days ($p < 0.05$). In the experimental group of the broilers, these changes were leveled, apparently, under the influence of the stress factor. Stress negatively affects the quality of broiler breast meat, including the fat content. Some studies [25] show that chronic heat stress (CTS) increases fat deposition in broilers. CTS affected meat quality parameters such as acidity (it decreased), tenderness, and water holding capacity (it increased). Stress contributed to a decrease in subcutaneous and intramuscular fat in Arbor Acres broilers, while increasing the abdominal fat content in Beijing You chickens [8].

The poultry is very sensitive to oxidative reactions. Transport, feed, veterinary and temperature stresses increase the level of oxidative reactions in cells of various tissues, which leads to the occurrence of oxidative stress. At the end of the experiment, a lower ratio of moisture and protein was found in poultry breast meat exposed to the influence of stress (3.01 in the experimental group versus 3.10 in the control group), which is probably related to the stressful effects of housing conditions.

The spectral characteristics of indoor lighting can also affect the quality of poultry meat. For example, it was found that higher rates of juice loss were found in breast meat samples obtained from the broilers grown under neutral and cold LED lighting. At the same time, the levels of fatty acids changed [26].

The results of the study indicate that prolonged exposure to stress on the broiler's body significantly affects the metabolism of the pectoral muscle of fast-growing broiler chickens. Apparently, the pectoral muscle, compared with the femoral, is more deeply involved in the energy and protein metabolism of the stressed broilers, which may have important consequences for energy homeostasis in the body and growth indicators [27]. This is also shown in our work. The greatest changes in the chemical composition of muscle tissue are found in the breast meat. It can be concluded that breast is an indicator of changes in metabolic status of the body.

Magnesium is one of the essential macronutrients for the body of animals and poultry. The lack of magnesium in the diet of chickens causes a slowdown and then cessation of growth, excessive excitability and death of the poultry. Despite its involvement in numerous biological functions, magnesium (Mg) supplementation is usually overlooked in the broiler diet. Magnesium supplementation implements a clear interaction with the absorption/accumulation of Calcium in the blood and its accumulation in the pectoral muscles. The addition of magnesium can provide a positive effect on certain meat quality indicators, such as WHC and color. The magnesium supplement protects against protein oxidation in the liver and plasma of the broilers. This effect may be associated with increased catalase activity in such tissues. Magnesium supplementation [28] reduces the incidence of myopathies by almost 2 times. In our studies, the broilers of the experimental group at the age of 34 days had a higher magnesium content in the breast flesh ($p < 0.05$) in comparison with the control group.

Numerous studies have shown that intensive genetic breeding and improved feeding programs have increased the growth rate, feed digestion efficiency, and meat productivity of broiler chickens. Unfavorable conditions of housing can negatively affect the quality and composition of poultry meat [13].

An important feature of meat is an improper change in the pH value during autolysis, which leads to a significant change in quality parameters. For example, one study compared the initial pH of the pectoral muscle of broiler chickens exposed to stress and that of the poultry that were not exposed to it. The stressed poultry showed a higher initial pH (6.24 vs. 6.10, $p < 0.0001$) [29].

In general changes in meat acknowledged as PSE are related to temperature, pH and postmortem glycolysis, and in addition, muscle tissue type, poultry genotype and stress factor play a major role. pH measured at 24 hours after slaughter is considered a predictor of technological qualities [30]. Lu et al. [31] emphasized that increased mitochondrial energy production during early heat stress inevitably increased the level of reactive oxygen species and caused permanent oxidative stress, therefore lowering the pH at 24 hours.

It should also be noted that changes in the chemical composition of the breast of broilers exposed to stress of cage density at the age of 34 days (13 days after the onset of stress) are observed in an increase in fat and magnesium levels (Table 3). By day 52nd, significant differences between the groups were observed only with respect to magnesium content. At the same time, the fat level also tends to increase in the group of poultry with stress ($p = 0.13$). The qualitative characteristics of broiler meat of the experimental groups in age dynamics are presented in the Table 4. We found that the stress to which the poultry was subjected led to significant changes in the pH of the breast flesh. So, 45 minutes after slaughter, the concentration of hydrogen ions in breast meat was 5.55 versus 5.59 units ($p = 0.004$), and after 24 hours — 5.44 versus 5.60 units. ($p = 0.08$). In general, it is considered that the optimal pH level of broiler breast meat (measured 24 hours after poultry slaughter) is 5.5–6.2, a value of 5.44 indicates signs of poor-quality meat of PSE category. At the same time, there is a decrease in the pH of the breast flesh in the age aspect ($p < 0.05$) in both the control and experimental poultry groups. The age-related decrease in pH is probably associated with the intensive growth of poultry in the final fattening period.

Since red muscle fibers contain more myoglobin and hemoglobin and less glycogen compared to white, they are less susceptible to developing PSE. We found a more pronounced decrease in the pH of thigh flesh in the age-related aspect in the group of poultry exposed to stress. A significant decrease in pH ($p < 0.05$) was noted in this group both 45 minutes after slaughter and within 24 hours, which confirms the negative effect of the stress factor being under study. In contrast to the experimental group, in the control group the pH of the thigh flesh decreased with age only 24 hours after slaughter.

Oxidative stress occurs when there is an excess of oxidants and a deficiency of enzymatic and non-enzymatic antioxidants. Oxidative stress can cause damage to the cell membranes, causing disruption of the integrity of the structure, and then the nucleus, which leads to cell death [32].

We have studied the content of water-soluble antioxidants combination in breast, thigh, liver and heart flesh, as well as the content of glutathione in breast flesh. We found that there were no significant differences between the control group samples and the experimental group samples on the 24th, 34th and 52nd days. This indicates that the studied factor (a decrease in content value as a chronic factor of influence) was not critical for the development of acute oxidative stress. There was no more significant consumption of antioxidants in the experimental group. At the same time, a detailed analysis of the age-related dynamics of the content of the studied antioxidants in organs and tissues indicates that there were no changes in the content of TAS in both breast and thigh flesh along with age, as well as in the concentration of glutathione in breast flesh ($p > 0.05$). At the same time, on the 52nd day there was a significant ($p < 0.01$) decrease in TAS in the liver of both control groups samples and experimental group samples, as well as an accumulation of TAS in the heart muscle: there was a trend of its accumulation in the control group ($p = 0.06$), while in the experimental group it was significantly higher ($p < 0.001$). We assume that the genetic factor played a significant role in this case, and the content factor we are studying is secondary. The same can be noted in the content of enzymes in the flesh of the breast (SOD, catalase). No intergroup differences were found on the 24th, 34th, and 52nd days being considered.

The study reports that stress can increase the activity of antioxidant enzymes in the liver and serum [33], as well as the expression of superoxide dismutase and catalase genes in the spleen [34]. Other authors have observed a significant increase in the level of reduced glutathione in the liver of broilers exposed to heat stress [35].

It has been shown that regardless of the duration of stress, it can cause a deterioration in the quality of meat, a decrease in water holding capacity, changes in color, texture, smell, and shelf life shortening.

WHC is one of the most important indicators of meat quality, as lean meat contains 75% water, which can be lost during slicing, cooking, or storage. These losses directly affect the sensory properties (for example, reduce the juiciness) during processing and delivery of meat to the consumer [36]. WHC which directly affects the color and tenderness of meat, is one of the most important functional properties of raw meat. Increasing the water content in muscles, which increases their tenderness, juiciness, elasticity and appearance, improves the quality and economic value of meat [37]. The disruption of protein structures and their denaturation (under the influence of high temperatures and low pH) leads to a decrease in their ability to hold water, which determines the color, soft structure and increased wateriness in PSE meat. This leads to an increase in drip loss or a decrease in moisture retention. In our study, there were no significant changes in the WHC value in both the experimental poultry group and the control group, although there was a slight downward trend in the values of this parameter with age, both in the flesh of the breast and in the flesh of the thigh. At the same time, the values of the WHC of the experimental group were lower than in the control group on the 34th and 52nd days, which is probably due to the effect of the

Table 3. Chemical composition of broiler meat of experimental groups in age dynamics,% (M ± SEM, n = 10)

Indicator	Age 24 days			Age 34 days			Age 52 days			p-value (the values of the control group in age dynamics)	p-value (the values of the experimental group in age dynamics)
	Group		p-value	Group		p-value	Group		p-value		
	control	experimental		control	experimental		control	experimental			
Breast meat											
Moisture	74.87 ± 0.24	75.10 ± 0.32	0.58	75.10 ± 0.17	74.72 ± 0.19	0.22	73.96 ± 0.26	73.26 ± 0.22	0.12	0.44	0.35
Protein	23.07 ± 0.13	22.65 ± 0.27	0.18	23.14 ± 0.17	23.34 ± 0.25	0.52	23.87 ± 0.27	24.34 ± 0.16	0.22	0.84	0.72
Fat	0.82 ± 0.22	1.056 ± 0.24	0.49	0.64 ± 0.09	0.74 ± 0.12*	0.22	0.99 ± 0.06	1.20 ± 0.15	0.13	0.04	0.61
Ash	1.23 ± 0.02	1.20 ± 0.02	0.14	1.12 ± 0.01	1.20 ± 0.04	0.11	1.18 ± 0.01	1.19 ± 0.01	1.0	0.56	0.69
Calcium	0.057 ± 0.002	0.054 ± 0.003	0.39	0.05 ± 0.002	0.06 ± 0.001	0.55	0.059 ± 0.001	0.056 ± 0.002	0.79	0.76	0.74
Phosphorus	0.197 ± 0.002	0.191 ± 0.002*	0.04	0.17 ± 0.004	0.18 ± 0.003	1.0	0.172 ± 0.03^{C}	0.168 ± 0.03	0.50	0.15	0.10
Magnesium	0.031 ± 0.002	0.031 ± 0.001	1.00	0.025 ± 0.001	0.026 ± 0.0011***	< 0.001	0.029 ± 0.001	0.031 ± 0.001*	0.05	0.008	0.72
Thigh meat											
Moisture	75.01 ± 0.51	74.22 ± 0.74	0.39	74.56 ± 0.32	74.34 ± 0.29	0.40	74.38 ± 0.50	73.11 ± 0.80	0.71	0.85	0.86
Protein	17.26 ± 1.57	18.61 ± 0.24	0.41	19.37 ± 0.17	19.16 ± 0.23	0.29	20.48 ± 0.20	20.21 ± 0.21	0.06	0.14	0.90
Fat	4.81 ± 0.63	6.17 ± 0.73	0.18	5.08 ± 0.43	5.40 ± 0.33	0.65	4.08 ± 0.42	5.65 ± 0.64	0.37	0.52	0.83
Ash	2.79 ± 1.78	1.00 ± 0.017	0.33	1.0 ± 0.01	1.1 ± 0.04	0.14	1.05 ± 0.01	1.03 ± 0.02	0.60	1.0	0.62
Calcium	0.04 ± 0.001	0.05 ± 0.006	0.21	0.04 ± 0.001	0.05 ± 0.001	0.23	0.05 ± 0.002	0.052 ± 0.004	0.23	0.07	0.41
Phosphorus	0.160 ± 0.004	0.165 ± 0.003	0.31	0.15 ± 0.003	0.15 ± 0.003	0.70	0.152 ± 0.002	0.141 ± 0.004	0.42	0.41	0.48
Magnesium	0.024 ± 0.001	0.026 ± 0.001	0.43	0.02 ± 0.001	0.04 ± 0.02	0.42	0.024 ± 0.001	0.024 ± 0.0003	0.44	0.61	0.51

* the differences between the control and experimental groups are statistically significant at $p < 0.05$, *** at $p < 0.001$.

Table 4. Qualitative characteristics of broiler meat of the experimental groups in age dynamics, % (M ± SEM, $n = 10$)

Indicator	Age 24 days			Age 34 days			Age 52 days			p-value (the values of the control group in age dynamics)	p-value (the values of the experimental group in age dynamics)
	Group		p-value	Group		p-value	Group		p-value		
	control	experimental		control	experimental		control	experimental			
Breast pH-45	6.19 ± 0.08	6.20 ± 0.11	0.83	6.20 ± 0.03	6.10 ± 0.02	0.55	5.59 ± 0.04	5.55 ± 0.06*	0.004	0.007	0.0005
Breast pH-24	5.81 ± 0.15	5.76 ± 0.12	0.80	5.47 ± 0.19	5.49 ± 0.04*	0.02	5.60 ± 0.03	5.44 ± 0.11	0.08	0.13	0.28
Thigh pH-45	6.20 ± 0.09	6.08 ± 0.11	0.27	5.96 ± 0.07	5.91 ± 0.08	0.14	6.00 ± 0.04	5.95 ± 0.03	0.25	0.62	0.04
Thigh pH- 24	5.98 ± 0.14	5.93 ± 0.15	0.56	5.83 ± 0.05	5.65 ± 0.04	0.20	5.56 ± 0.04	5.52 ± 0.06	0.14	0.05	0.05
TAS in the breast, mg/g	0.256 ± 0.03	0.238 ± 0.05	0.18	0.084 ± 0.004	0.090 ± 0.04	0.73	0.140 ± 0.008	0.149 ± 0.01	0.44	0.08	0.07
TAS in the thigh, mg/g	0.238 ± 0.03	0.209 ± 0.03	0.35	0.209 ± 0.012	0.213 ± 0.01	0.50	0.204 ± 0.02	0.196 ± 0.02	0.13	0.52	0.11
TAS in the liver, mg/g	0.839 ± 0.07	0.829 ± 0.05	0.67	0.776 ± 0.08	0.941 ± 0.06	0.38	0.116 ± 0.01	0.121 ± 0.02	0.50	0.01	2×10^{12}
TAS in the heart, mg/g	0.187 ± 0.01	0.193 ± 0.01	0.18	0.258 ± 0.03	0.272 ± 0.03	0.64	0.505 ± 0.03	0.455 ± 0.02	0.43	0.06	4.6×10^{9}
Reduced glutathione in breast, μM/g	32.07 ± 12.87	39.96 ± 1.64	0.83	83.63 ± 7.36	67.24 ± 2.49	0.32	82.57 ± 19.12	58.49 ± 14.53	0.48	0.79	0.51
SOD in the breast, Units/g	8.13 ± 2.30	7.14 ± 0.25	0.89	12.96 ± 0.68	10.65 ± 2.11	0.64	11.50 ± 0.15	11.80 ± 0.94	0.98	0.02	0.65
Catalase in the breast, Units/g	17.22 ± 1.51	24.02 ± 3.69	0.07	28.02 ± 1.75	20.07 ± 2.75	0.09	26.49 ± 0.95	22.16 ± 3.22	0.57	0.63	0.74
Breast WHC, %	61.06 ± 1.30	62.12 ± 0.90	0.79	60.80 ± 0.75	58.33 ± 0.45	0.12	57.88 ± 0.92	56.29 ± 0.75	0.72	0.08	0.76
Thigh WHC, %	59.55 ± 0.72	62.04 ± 1.04	0.10	58.93 ± 1.65	56.96 ± 1.31	0.91	60.75 ± 0.88	55.32 ± 1.48	0.28	0.56	0.35

* differences between the control and experimental groups are statistically significant at $p < 0.05$.

stress factor, which also correlated with the values (decrease) of pH during this period.

In another study, on the contrary, the WHC of broiler chicken meat was higher under the influence of heat stress, as evidenced by their lower losses during draining compared with the control group (not exposed to stress) [25]. An increase in the WHC of meat has also been observed by other researchers when the poultry was exposed to high cage density in poultry rearing [38].

Cluster analysis (Figure 1) indicates the mutual dependence of the studied parameters and can have a predictive aspect to identify factors leading to deterioration in product quality. The dendrogram shows the presence of a close correlation between the pH values and the AWSA in organs and tissues, which correlation must be taken into account in further programs for rearing and feeding intensively growing young poultry. In addition, WHC of the tissues is closely related to the activity of antioxidant enzymes (SOD, catalase).

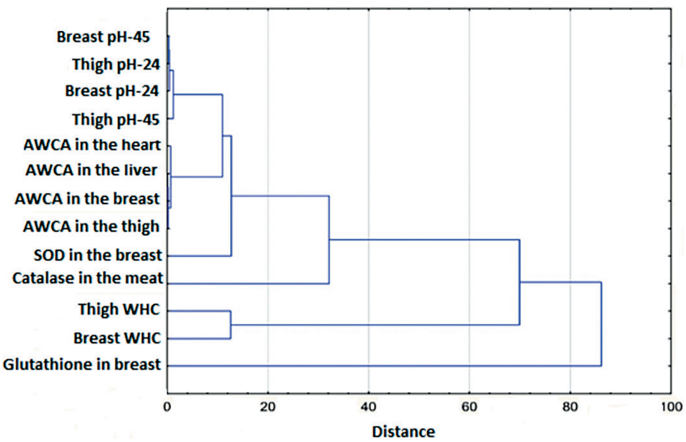

Figure 1. Results of cluster analysis on the correlation between antioxidant content in meat in various tissues and the distance

The correlation between qualitative parameters of broiler chicken muscle tissue and antioxidant capacity has also been shown in the works of other authors. For example, a decrease in WHC in muscles was accompanied by a decrease in lipid peroxidation products [39]. According to the authors, a decrease in the WHC index is an undesirable phenomenon, since breast muscles with higher lightness and lower ability to hold water are prone to the formation of meat of PSE category [40]. Other researchers have found negative correlations between the pH of broiler breast meat and WHC [41].

Given the close correlation between the antioxidant status of the body and the quality of meat, research aimed at developing and using various sources of antioxidants in nutrition is promising, especially during periods of the poultry exposure to climatic, technological and feed stresses. The use of dietary sources of antioxidants may be a good strategy for the prevention and control of oxidative stress. Positive effects of antioxidant applying include increased live weight gain, slaughter yield, and improved quality of meat. The use of antioxidants in feed may reduce muscle lipid breakdown and improve meat stability.

Conclusion

As a result of comprehensive studies, it has been established that the modulated stress conditions of poultry cage density provide an impact on the composition and quality parameters of the muscle tissue (thighs and breasts) of broiler chickens. Changes were noted only in the pectoral muscle of the poultry and depended on the age of the poultry, that is, on the duration of exposure to stress. The effect of modulated stress affected the fat content (causing its increase) and minerals (it changed the content of magnesium and phosphorus). At the age of 34 days, stress affected the final pH (pH 24), causing it to increase in the pectoral muscle. The level of WHC tended to decrease in the muscles of broiler chickens at both 34 and 52 days of age. In conclusion, improving the quality of broiler chicken meat depends on various factors. Any violation of these factors can negatively affect the quality of the meat. The strong influence of genotype on meat quality, as well as the importance of feeding and poultry housing conditions, cannot be overlooked. Cage density is a crucial factor in the poultry production, and maintenance stress can lead to decreased product quality, which consumers perceive as tough meat. Understanding these factors is essential for studying these mechanisms and developing approaches for producing broiler chicken meat that not only meets economic demands but also promotes human nutrition. To improve meat quality exposed to stress in the future, it will be necessary to explore various feed additives based on natural antioxidants that can prevent oxidative stress and enhance product quality. Using the above factors, it is possible to achieve the desired meat composition and product type properties, as well as to ensure high quality of meat.

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The authors declare no conflict of interest.