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ANTIOXIDANT STATUS AND QUALITY OF POULTRY AND ANIMAL MEAT UNDER STRESS AND ITS CORRECTION WITH THE USE OF VARIOUS ADAPTOGENS

(review)

N.V. BOGOLYUBOVA ✉, R.V. NEKRASOV, A.A. ZELENCHENKOVA

Ernst Federal Research Center for Animal Husbandry, 60, pos. Dubrovitsy, Podolsk District, Moscow Province, 142132 Russia, e-mail 652202@mail.ru (✉ corresponding author), nek_roman@mail.ru, aly4383@mail.ru
ORCID:
Bogolyubova N.V. orcid.org/0000-0002-0520-7022
Nekrasov R.V. orcid.org/0000-0003-4242-2239
Zelenchenkova A.A. orcid.org/0000-0001-8862-3648

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Abstract

Modern animal breeds and poultry crosses do not fully realize their genetic potential for productivity due to the impact of various stresses (V.I. Fisinin et al., 2015). Recently, there has been a marked public concern about the negative impact of intensive rearing on animal health, food safety and quality. Animal health and welfare are prerequisites for both productive performance and obtaining products that are safe for human (K. Proudfoot et al., 2015). Oxidative stress caused by an imbalance between production and accumulation of oxygen reactive species (ROS) and the ability of a biological system to detoxify these reactive products under feed, climatic, technological, and biological stresses negatively affects health, growth rates and product quality. Due to the high level of polyunsaturated fatty acids and non-heme iron Fe^{3+} and Fe^{2+}, chicken meat is most susceptible to lipid peroxidation compared to beef and pork (I.F. Gorlov et al., 2016). The present review paper summarizes the current state of knowledge on the influence of stress factors, including housing conditions (climatic, stocking density), transportation, feeding, veterinary measures on the antioxidant status, meat oxidative properties and quality on the example of chickens and broilers. Climatic and other conditions determine behavioral, physiological and immune responses of birds, affect their antioxidant, biochemical status and productivity. Meat quality deteriorates, as can be seen from changes in pH, muscle protein structure, increased lipid oxidation and the appearance of meat defects (K. Rosenvold et al., 2003; M. Petracci et al., 2015; P.F. Surai et al., 2019). The negative impact on meat quality depends on the type of stresses (chronic or acute), the animal genotype, and the type of muscle fibers (N.A. Mir et al., 2017; P.A. Gonzalez-Rivas et al., 2020; M. Zhang et al., 2020). Transport stress is the result of the simultaneous action of several stress factors (L. Zhang et al., 2014). The intensity of the impact on the body and the change in biochemical markers of stress depends on the conditions of transportation, feeding and keeping, individual characteristics and health status of the bird. Data on the impact of stress on metabolism in animals and birds are rather contradictory. The use of synthetic or natural antioxidants in animal husbandry is currently being discussed due to their ability to influence oxidative stress and meat quality (A. Gouda et al., 2020). This review also provides an analysis of ways to improve the antioxidant protection and meat quality using natural adaptogens (vitamins E and C, taxifolin and quercetin) as feed additives (M. Mazur-Kuśnirek et al., 2019; V.R. Pirgozliev et al., 2020). The study of biomarkers of antioxidant protection is essential for obtaining high quality meat. The use of antioxidants enhances antioxidant protection, increases animal resistance, and improves product quality. This method of preventing the negative effects of stress in animal husbandry and poultry farming is considered the most acceptable and cheapest, especially when natural adaptogens are combined in the diet, which can be more effective than the action of each adaptogen separately.

Keywords: stress, meat quality, antioxidant status, vitamin E. vitamin C, taxifolin, quercetin

In the world animal husbandry, poultry and pig breeding are among the most actively developing sectors that provide the population with high-quality meat, which is associated with high growth energy and the ability of pigs and

poultry to reproduce quickly. Focus on maximum efficiency and profitability leads to major changes in the methods of maintenance, to automation and even greater intensification of production processes. Modern breeds and crosses have a high genetic potential for productivity, but it cannot be fully realized in practice due to the impact of environmental, technological, nutritional and physiological stress factors [1]. In recent years, there has been a marked increase in public concern about the negative impact of intensive production on animal health and food safety [2]. Animal health is an integral part of well-being, which becomes a prerequisite for both high productivity and the production of products that are safe for humans [3].

The response to stress is complex, multidimensional and can be determined by interactions between stressors, leading to unpredictable outcomes. Depending on the source of stress, animals experience fear, dehydration, and hunger. Increased fatigue and physical injuries additionally potentiate disturbances in the energy and ionic intracellular balance, in the protease system, as well as changes in skeletal muscle proteins. All of these factors affect the conversion of muscle to meat [4, 5]. Understanding and controlling the stress response is critical to animal welfare and meat quality.

Research over the past two decades has convincingly shown that most stress, regardless of source, is associated with an imbalance in free radical production and detoxification [6]. Oxidative stress is a major problem for modern livestock production around the world [7]. Accumulating scientific evidence suggests that oxidative stress can impair health, growth performance, and meat quality [8]. It is considered as a key link in the negative consequences of feed, climatic, technological and biological (internal) stresses at the molecular level [9, 10]. Previously, we paid attention to identifying stresses in pig production and leveling their consequences when using flavonoids as feed additives [11].

The purpose of this review is to summarize modern scientific data on the consequences of stresses of various nature and the use of alimentary factors, in particular vitamins E, C and bioflavonoids, to improve the antioxidant status and quality of animal and poultry meat.

Stress affecting the physiological state of animals and poultry and product quality. *Climate factors.* Temperature stress includes both heat and cold stress. Genetic selection for rapid chest growth and mass over the past few decades has reduced the thermoregulatory capacity of birds in modern commercial breeds, making them more vulnerable to heat stress [12]. Heat stress causes altered behavioral and physiological responses and negatively impacts health, productivity and product quality in poultry [13]. High ambient temperature in summer leads to a deterioration in health, reduces the growth rate and quality of the carcass of broiler chickens [14-16].

Numerous studies have been devoted to the impact of climatic stress on the physiological and productive characteristics of birds. For example, chronic heat exposure impairs growth, gut morphology, and appetite, which may be due to increased secretion or expression of appetite-related hormones and genes and higher expression of nutrient-sensing receptors (T1R1 and T1R3) [17]. Heat stress leads to an increase in rectal temperature ($p = 0.001$), respiratory rate ($p = 0.001$) and blood pH ($p = 0.02$), which characterizes the state of respiratory alkalosis in broilers [18]. Broilers kept at an ambient temperature of 32 °C consume 14% less feed than their counterparts kept at normal temperature. K. Sahin et al. [19] believe that reduced feed intake serves as a protective physiological response to reduce heat production. Other authors [20] also note that a decrease in feed intake by broilers is the main reason for a decrease in live weight gain, an increase in mortality, a decrease in fertility and hatchability, changes in the balance of electrolytes and blood pH [21], disorders of secretion and activity of endogenous

enzymes [22], decrease in serum concentrations of thyroid hormones T_3 and T_4, suppression of immune function [23] and decreased intestinal absorption [24]. High ambient temperature negatively affects broiler productivity [25] due to changes in energy, protein, lipid and mineral metabolism, acid-base and electrolyte blood balances, as well as the concentration of hemoglobin. At 32 °C there is a significant decrease in the activity of the digestive enzymes trypsin, chymotrypsin and amylase. Heat stress leads to a decrease in the content of vitamins (C, E and A) and minerals (Fe, Zn, Se and Cr) in the blood serum and liver, and affects the immune response of poultry [26].

V.R. Pirgozliev et al. [27] found that chronic heat stress in poultry production reduced not only feed intake and body weight gain, but also small intestine weight, total weight of the gastrointestinal tract, liver, spleen, heart, villus height, intestinal villus surface area, and negatively affects the activity of blood glutathione peroxidase (GP). The productivity, physiological and immune responses of the body of broiler chickens to the effects of heat stress depend on the composition and nutritional value of the diet and on the genetic characteristics of the bird [28]. High environmental temperatures cause oxidative stress [29], in which there is an increased production of free radicals in the body due to an increase in body temperature [30], as well as due to an increase in oxygen consumption [31]. Increasing oxygen consumption increases the production of reactive oxygen species (ROS) [32, 33].

Climate stress has a negative impact on the quality of poultry products. Exposure to this type of stress increases the incidence of meat defects such as pale, soft, and exudative (pale, soft, exudative, or PSE) and dark, firm, and dry (dark, firm, dry, or DFD) [34]. It was found that both acute and chronic exposure to temperature change meat quality indicators. At elevated ambient temperatures, meat exhibits PSE characteristics, while at lower ambient temperatures, DFD [35]. Acute heat stress affects meat pH limits to a greater extent than chronic stress, while chronic heat stress affects color traits (L* and a*) [34]. According to Y. Hashizawa et al. [35], chronic temperature stress (30 °C for 10 days) can also cause deterioration in broiler meat quality and lead to PSE. The effect of chronic heat stress on meat quality was most significant, causing broiler breast stiffness. Consequently, both chronic and acute heat stress degrade poultry meat quality, with exposure to extreme temperatures shortly before slaughter having an even greater impact [36].

Several reviews have detailed the effect of heat stress on meat quality in poultry, ruminants and pigs [29, 36) and characterize meat quality and defects in poultry [37]. Heat stress reduces the myofibril fragmentation index and increases the reactivity of thiobarbituric acid in broiler muscles [18]. In the skeletal muscles of broilers, thermal stress reduces the rate of protein synthesis and the activity of proteolysis [38]. This is partly due to adaptive endocrine changes: for example, thyroid hormones promote growth and their levels are negatively correlated with elevated temperature. In broiler skeletal muscle, exposure to high temperatures suppresses downstream metabolic pathways for insulin signaling, which is an important regulator of muscle metabolism and protein synthesis [39]. Other effects of heat stress on broiler meat quality include decreased muscle glycogen and muscle pH, paler color [40], increased lipid oxidation [41] and altered muscle fiber structure [42].

As J.H. Feng et al. [43] reported, heat exposure (41 °C) increased the oxidation of muscle proteins, which led to a decrease in the gelling properties of broilers' meat. Other investigators have observed that in meat-cross chickens, heat exposure (34 °C for 18 h) increases oxygen production in skeletal muscle mitochondria, and this correlated with an increase in rectal temperature and weight loss [44].

Chronic heat stress (CTS) has been reported to significantly increase fat deposition in broilers [45]. However, this most likely depends on the genotype of the bird. For example, Q. Lu et al. [46] showed that CTS reduced subcutaneous and intermuscular fat in Arbor Acres broilers while increasing abdominal fat in Beijing You chickens. In addition, the same authors found that L* and meat moisture loss increased in CTS-treated Arbor Acres broilers. At the same time, no significant consequences of such exposure to Peking chickens were observed.

L. Zhang et al. [47] found that the proportion of breast muscle in broilers was reduced by chronic chronic heat stress at 4 to 6 weeks of age, while the effect on thigh muscle was the opposite. Other authors have explained that the decrease in pectoral muscle mass in CTS occurs due to suppression of the signaling pathway of insulin-like growth factors, the mammalian target of rapamycin (mTOR) [48]. CTS does not affect the content of moisture, raw protein and raw fat in breast muscle, but generally impairs breast quality in broilers [49], and ante-mortem transport of broilers under short-term heat stress increases the incidence of PSE meat [50, 51].

Cyclic heat stress, when the birds were at 33±1 °C for 10 h (8.00-18.00) and at 22±1 °C the rest of the time, increased the blood concentration of corticosterone and triacylglycerol, droplet moisture loss and the content of malondialdehyde in muscle, and reduced blood glucose, pH_{24}, total muscle antioxidant capacity (T-AOC), catalase (CAT) and glutathione peroxidase (GSH-PX) activity [52].

Thus, the body response to heat stress (acute and chronic) depends on many factors, i.e., breed, muscle type, specific conditions of detention, but one way or another, this type of stress has multiple negative consequences and brings significant losses to the industry.

Stocking density. High stocking densities have been reported to impair broiler meat quality by causing oxidative stress to develop [29, 53]. At the same time, in a number of other studies [54, 55], stocking density did not affect the quality of broiler meat. D.G. Yu et al. [56] found that high stocking densities impair growth performance, gut barrier function, and enhance stress responses [56].

Growing conditions affect behavioral and physiological responses, muscle composition and meat quality. Thus, with an organic housing system that allows broilers to freely occupy a grass pen, the yield of carcasses increases and the organoleptic qualities of meat improve, but lipid peroxidation (LPO) and the accumulation of their oxidation products (thiobarbituric acid reactive substances, TBARS) in the muscles increase [57].

Transportation stress. Pre-slaughter transportation causes stress and injuries which lead to a noticeable decrease in the quality of poultry meat and significant financial losses. Birds may also be exposed to co-occurring stressors during transport, including thermal changes in the transport microenvironment, acceleration, vibration, movement, shock, starvation, lack of water, social stress, noise [58]. All these factors impair metabolism, especially the secretion of stress hormones, as well as increased muscle anaerobic glycolysis [59].

M.H. Tamzil et al. [60] reported that broilers transported for 3 h before slaughter increased erythrocyte and leukocyte counts, heterophile percentage, higher poultry mortality and meat pH, while decreasing lymphocyte percentage, water-holding capacity (WHC) and cooking loss. A dormancy period after transportation for 12 hours reduced the adverse effect of transport stress on meat quality.

Glucose serves as the body's main source of energy and is stored as glycogen [61]. Transport stress accelerates muscle glycolytic metabolism by affecting muscle, glycolytic enzyme activity and glycolytic potential [62-65]. C. Zhang et al. [66] found that broilers transported within 3 hours before slaughter

had decreased muscle glycogen, increased muscle lactate dehydrogenase (LDH) activity, and increased lactate levels. As the transport time increases, the muscles contract strongly, anaerobic processes increase, which causes the accumulation of lactic acid and reduces the pH of the muscles [36, 68]. The structure of muscle proteins is disturbed, the loss of moisture increases [69]. The latter is due to the fact that lower pH causes actin and myosin to condense and shrink into granules, destroying the spatial structure of the tissue, increasing the amount of free water, reducing WHC, which ultimately affects muscle color [70]. Thus, pre-slaughter transport may increase bird stress by reducing muscle glycogen stores and therefore affect the rate and extent of pH decline, as well as meat quality [59]. Rapid anaerobic glycolysis causes lactate to build up in the muscle and pH to decrease, ultimately resulting in PSE meat [70].

Glucose concentrations, increased levels of lactate and uric acid, and serum LDH activity indicate that the birds are under stress [71]. The deterioration of meat quality caused by transport stress is closely associated with negative changes in muscle energy metabolism and antioxidant status [66, 72]. Transportation of poultry can cause excessive production and accumulation of ROS and ultimately lead to oxidative stress [74], which interferes with collagen metabolism [75] and/or leads to lipid peroxidation and protein oxidation [8, 76].

Poultry transportation within 3 h before slaughter increased the loss of live weight, drip losses; the content of malonic dialdehyde (MDA) in muscles and lactate increased, the activity of the thymus, spleen and Fabritius index, pH_{24}, total antioxidant activity of muscles, catalase and GP activity, glycogen content decreased [72]. In earlier studies of these authors, the same conditions of transportation before slaughter increased the blood concentration of corticosterone, the content of MDA and lactate in the muscles, LDH activity in the muscles, while the content of muscle glycogen, total superoxide dismutase (SOD) activity and GP activity decreased, which worsened breast meat quality (lower pH_{24} and higher drip loss) [66].

When studying the effect of the duration of transportation on the biochemical status and quality of meat, it was shown that 2- and 4-h transportation of broilers before slaughter did not affect the activity of LDH, γ-glutamyl transferase, alanine aminotransferase, creatine kinase and glucose in blood serum, GP in the thigh muscles and mRNA expression heat stress protein in the liver. The concentration of triiodothyronine, thyroxine and insulin in the blood serum decreased after 2 h of transportation and returned to normal after 4 hof transportation. Both variants increased SOD activity in the muscles. In the muscles of the thigh and chest, with an increase in the time of transportation, the amount of MDA and lactic acid increased, fluid losses increased, while the glycogen content decreased. Transportation for 2 h did not affect pH_{24} in the muscles of the chest and thigh, but these parameters decreased with 4 h of transportation [67].

Z. Gou et al. [73] studied the effect of age and duration of transport on stress biomarkers and meat quality in broiler chickens. With an increase in the duration of transportation of medium-sized broiler chickens at the age of 75 days from 0.5 to 3 h, the live weight of the bird linearly decreased, the concentration of adrenocorticotropic hormone, cortisol and corticosterone in plasma, and the activity of glutathione peroxidase increased. At the same time, the content of glucose in the blood did not change. The effect of transporting broiler chickens at this age on meat quality was negligible. Only a decrease in the total antioxidant capacity and drip losses of the pectoral muscle were noted [73].

Thus, transportation stress is the result of the simultaneous action of several stress factors. The intensity of the impact of transport stress on the body of a bird depends on the age, breed, state of health, composition and nutritional value

of the diet, feeding conditions during transport, methods of capture before transport, temperature during transport, and rest time after transport [72, 73]. Data on the impact of transport stress on the metabolism of substances in chickens and broilers are rather contradictory.

Feed stress. Feed stress in poultry occurs when changing feeds, using low-quality ingredients, contamination of feed with xenobiotics, and under the influence of other causes. Thus, fat in the diet significantly affects the growth performance and health of the herd. Poor quality oil reduces the productivity of broiler chickens [77]. Diets rich in polyunsaturated fatty acids (PUFAs) increase lipid peroxidation and reduce antioxidant capacity. Rancid fats undergoing autoxidation processes contain substances that form free radicals. As a result of oxidation reactions, harmful peroxides are formed, which are converted into hydrocarbons, ketones, alcohols, organic acids and aldehydes, including MDA. Oxidation reactions also reduce the content of vitamins A, E and carotenoids [78]. Increased ROS production disturbs the redox balance and leads to oxidative stress with detrimental health consequences [78].

Oxidative stress can be caused by mycotoxins in feed. Ochratoxin A (OTA, a secondary metabolite produced by certain species of *Aspergillus* and *Penicillium*) has an immunosuppressive effect in humans and animals. Ochratoxin A causes oxidative stress, lipid peroxidation and pathological lesions in the tissues of the bursa of Fabricius, spleen and thymus of chickens, as evidenced by a decrease in the amount of catalase and GP and an increase in the content of products that react with thiobarbituric acid (TBA-AP). In addition, the introduction of OTA into the diet leads to apoptosis, which was manifested in an increase in the expression of the *PTEN*, *Bax*, and caspase-3 genes and a decrease in the expression of the *PI3K*, *AKT*, and *Bcl-2* genes [79]. In the review by V. Sorrenti et al. [80] an increase in ROS production and, as a result, oxidative stress and lipid peroxidation are discussed as the causes of OTA toxicity [80]. Repeated exposure of chickens to OTA over a period of time reduces SOD activity, glutathione (GSH), and total antioxidant activity while increasing MDA [81, 82].

Cadmium (Cd) is a heavy metal and one of the most toxic environmental pollutants. Its presence in feed is a serious problem in animal husbandry and agriculture in general. In some cases, the amounts of Cd exceed the maximum allowable. Cd can be ingested by animal feed mineral premixes and can be introduced into plants when cadmium-rich manure is used as organic fertilizer [83]. Cadmium has complex toxicity to mammals ganisms, causes various forms of oxidative damage and damage to animal tissues [84]. Cd induces the formation of free radicals, reduces the activity of antioxidant enzymes [85], and leads to oxidative degradation of lipids [85], proteins and DNA in humans and animals [86]. Hepatotoxicity of cadmium has been described; in chicken liver, it induced oxidative stress and apoptosis [87].

Veterinary manipiulations. Veterinary manipulations also change the redox balance and metabolism, which leads to a deterioration in meat quality. With long-term use of exogenous glucocorticoid dexamethasone, lipid peroxidation products (TBARS) accumulate in plasma and skeletal muscles, which increases the content of saturated fatty acids in broiler skeletal muscles [88]. Exogenous corticosterone causes an imbalance in the skeletal muscle redox system, which affects the oxidative stability of meat during storage [89]. X. Chen et al. [90] found that intraperitoneal administration of 10% H_2O_2 to broilers increased the formation of ROS and decreased the activity of antioxidant enzymes, as a result, increased oxidative stress, decreased the proportion of muscle mass in the carcass, and deteriorated meat quality.

In addition to the considered stresses, other factors can also lead to a

change in the quality of poultry meat. It is well known that the genetic background causes variations in animal responses to stress. The two main genes that induce porcine PSE are known as the *Halothane* gene and the *RN* gene. Their role is reviewed by K. Rosenvold et al. [91]. Genetic selection of broilers for growth rate and increased breast yield is accompanied by myopathy, including deep mammary myopathy and PSE meat, as well as the recently discovered white banding and wood breast [12].

Thus, stresses of various nature negatively affect the state of the immune and antioxidant systems of poultry, which reduces the quality of the products obtained, in particular meat. According to some scientists, chicken meat is more susceptible to LPO processes than beef and pork due to its high content of polyunsaturated fatty acids and non-heme iron (Fe^{3+} and Fe^{2+}). According to the results obtained by I.F. Gorlov et al. [92], the degree of oxidative changes in chilled poultry meat depends on the reactivity of the antioxidant system of the body and the formation of lipid peroxidation products. The weakening of antioxidant activity and the activation of free radical lipid oxidation in the blood plasma of broiler chickens enhance the processes of meat oxidation.

An analysis of stress-induced metabolic changes indicates the importance of reducing the effects of oxidative stress in broiler production and the need for additional protection of the antioxidant system in poultry [6]. It is clear that conditioning avoids critical temperature effects [93], and comfortable transport conditions and balanced diets based on quality ingredients mitigate transport and feed stress. However, often stress cannot be avoided or the technical solution is costly. In this case, it seems appropriate to use natural antioxidants, the main regulators of many physiological processes, as additives to feed or water. The redox balance between anti- and pro-oxidants in feed, gastrointestinal tract, blood and tissues is an important factor in protecting animals from stress and its consequences [94].

We have previously studied the effect of taxifolin on stress in young pigs [95-98]. Particular attention has been paid to the effect of the adaptogen on meat quality [99, 100]. An analysis of publications shows the promise of this approach in poultry farming.

The use of nutritional factors to improve the antioxidant status and quality of animal and poultry meat. Recently, antioxidants have attracted increasing attention in all branches of animal husbandry due to their effect on oxidative stress and meat quality [101-103]. By origin, antioxidants (AO) can be divided into synthetic and natural. Natural AO, as a rule, are molecules present in parts of plants (leaves, bark, seeds, and fruits). The most important are tocopherols (fat-soluble vitamin E) and ascorbic acid (water-soluble vitamin C). The first comes only as part of the diet, and the second is synthesized in the body of poultry [104].

Vitamin E (VE). Natural vitamin E includes four tocopherols and four tocotrienols. RRR-α-tocopherol is the most abundant form in nature and has the highest biological activity [105]. Vitamin E was recognized as an essential nutrient almost a century ago when H.M. Evans and K.S. Bishop (1922) discovered a fat-soluble herbal preparation that restored fertility in rats under dietary restrictions. The compound was named tocopherol (Greek for "bearing offspring"), and to date, its activity has been measured in terms of reproduction in rodents. The main function of α-tocopherol is that it is a lipid-soluble antioxidant that prevents various oxidative damage. α-Tocopherol is necessary for normal permeability of lipid bilayers, cell adhesion, and is involved in the regulation of gene expression. Although the transport of this vitamin and other lipids shares some common steps, some tissues have specific transport mechanisms, including the α-tocopherol transporter protein (αTTP) [106]. VE deficiency is associated with increased

oxidative stress, central and peripheral neuropathies, and impaired immune function. VE is an effective antioxidant that maintains cell integrity during normal cellular metabolism and inflammation [107]. In the poultry industry, the addition of VE is necessary to maintain the fertility and hatchability of the parent flock. It also plays a major role in the prevention of foodborne encephalopathy and myopathy in chickens and turkeys [108].

Z.Y. Niu et al. [109] showed that the use of VE in the diet of broilers increased the total activity of superoxide dismutase (T-SOD) and glutathione peroxidase (GSH-Px) and reduced blood levels of MDA ($p < 0.05$). At the same time, the expression of SOD and GSH-Px mRNA in the liver of broilers increased when additional VE was added to the diet. These results indicate a positive effect of VE in broiler nutrition on meat quality by improving antioxidant status through the regulation of antioxidant enzyme gene expression [109].

Emphasizing the important properties of vitamin E in diets, J.V. Van Vleet et al. [110] described the changes occurring in the cells and organs, skeletal muscles of a bird suffering from exudative diathesis, a disease associated with a lack of VE and selenium and oxidative damage to membranes. According to these authors, blood plasma GP represents the first barrier of antioxidant protection for capillary cells, since it prevents the lipoperoxyl radical from attacking PUFAs in the membrane. Vitamin E present in the membrane acts as a second AO barrier, stopping the spread of the LPO chain. In selenium and VE deficiency, none of these antioxidant mechanisms is activated, leading to lipid peroxidation and its pathological consequences [111].

Ascorbic acid, ascorbate (anion of ascorbic acid), vitamin C (VC). It is a water-soluble antioxidant compound that protects cells from oxidative damage and improves immune system function [112, 113]. Vitamin C is not part of any metabolic pathway, but serves as a necessary cofactor in many enzymatic reactions—collagen, carnitine, and catecholamine synthesis, microsome metabolism, or tyrosine synthesis and catabolism. Vitamin C is a cofactor for dopamine beta-hydroxylase, which is involved in the conversion of dopamine to norepinephrine in nerve tissues [114]. In addition to the biosynthesis of norepinephrine, VC is required for the bioconversion of tyrosine to other catecholamines such as dopamine, norepinephrine, and epinephrine. Feeding tyrosine and VC during stress periiods can reduce stress hormones and reduce body weight loss [115]. Vitamin C also improves hormone stability and activity, regulates body temperature, synthesis of 1,25-dihydroxyvitamin D, and immune system function. It is present in high concentrations in immune cells and is quickly depleted during times of stress. It is not known exactly how VS enhances immune system function, but some evidence points to its effect on phagocytes, cytokine production, lymphocytes, and the number of cell adhesion molecules in monocytes [116].

Vitamin C is a powerful biological antioxidant. Its feeding is effective in reducing oxidative stress in animals reared under various stress conditions [117, 118]. However, VC supplementation has not been widely used in the poultry industry because it is believed that poultry synthesizes sufficient amounts of VC in the body [119]. Although birds produce endogenous vitamin C, vitamin C requirements or the body's synthetic capacity may vary due to individual characteristics, breed, health, environmental conditions [120], which can lead to BC deficiency. Heat stress is one of the most common causes of increased need for additional BC in the diet. F. Rafiee et al. [121] report that VC reduces the adverse effects of heat stress on broiler performance and health [121]. VC can also act as a co-antioxidant in conjunction with other antioxidants, providing a synergistic effect. For example, there is a strong relationship between VC and VE, while both of them have a positive effect on the immune system, increasing antibody production,

macrophage activity and humoral immunity in broilers and laying hens.

The currently known plant-derived antioxidants are mostly flavonoids belonging to the vitamin P group, which has become known as bioflavonoids. Bioflavonoids include antioxidants such as quercetin, rutin, hesperidin, cyanidin, and taxifolin (dihydroquercetin, DHQ).

DHQ is found in small amounts in many plants. In the late 1960s, it was isolated in the USSR by a group of scientists headed by Professor N.A. Tyukavkina from larch wood. Even a small concentration of DHQ with regular use can normalize vascular permeability, reduce the risk of cardiovascular and oncological diseases, prevent blood clots, increase immunity, and improve the general condition of the body [122].

Flavonoids find use as anti-inflammatory, antioxidant compounds, which also have antibacterial effects [123-125]. In vitro studies have shown that quercetin is the most potent antioxidant among its six metabolites and butylated hydroxytoluene [126]. Quercetin introduced into the diet of mice increases the content of glutathione in the blood serum [127]. The use of quercetin in broiler diets increases their immune status [128], the expression of superoxide dismutase (*SOD1*), glutathione peroxidase (*GPx1*), as well as *GLUT2*, peptide transporter 1 (*PEPT1*) and fatty acid synthase (*FAS*) genes [129]. M. Koudoufio et al. [130] consider the use of flavonoids as modulators of genes involved in redox signaling.

Since DHQ is an adaptogen that has a positive effect on the antioxidant status of animals, a number of studies have been conducted on the effect of its feeding alone and in combination with vitamins on the antioxidant and biochemical status of the body, including under stressful conditions. R.V. Nekrasov et al. [95] showed a positive effect of DHQ in pigs under stress (improvement of the oxidative function of the blood, normalization of the number of leukocytes, increase in the number of erythrocytes, hematocrit, metabolic rate and endurance). Methods for improving meat quality using feed antioxidants and adaptogens have been studied [96-98]. It was found that the meat of pigs subjected to simulated stress (regrouping) and fed with a diet of 32 mg DHQ/kg of feed had an increased VSS, contained less fat and more protein than in analogue animals, not treated with adaptogens [99]. The hypothesis was tested that the resistance of pork to the development of hydrolytic and oxidative processes can be increased by introducing DHQ into the feed (confirmed dose of 32 mg/kg). In the experimental group, interrelated trends were noted for an increase in the amount of antioxidants in the blood, an increase in the degree of unsaturation of fat in bacon, and the resistance of muscle and adipose tissue to oxidative processes [100]. Similar effects have been noted in other studies [131-134].

Let us consider in more detail the role of antioxidant adaptogens in the formation of antioxidant protection and meat quality in poultry when such preparations are fed in pure and in combination. The table presents data from different authors over the past 5 years (2017-2022) on the use of vitamins C and E, as well as quercetin and taxifolin, in feeding chickens and broilers, including under various stresses. We searched the available literature in Science Direct, Scopus, PubMED and Google Scholar databases for the following keywords: dihydroquarcetin, taxifolin, quercetin, broilers, stress, meat quality, vitamin C, vitamin E.

Although an adult bird is able to synthesize vitamin C under normal conditions, the need for it increases during times of stress. Feeding ascorbic acid to poultry has been reported to be beneficial [89]. It has been shown that additional feeding of VC significantly reduces the metabolic signs of stress, improves the productivity and immune status of the bird. The optimal feeding dose in terms of the effectiveness of introducing VC into feed and water for broilers and laying hens under conditions of stress of various etiologies, apparently, is 200-250 mg/kg

of feed (the doses up to 1000 mg/kg were studied). Under chronic stressful conditions, such as extreme environmental temperatures, the amount of corticosterone in the body rises, which can ultimately reduce the effectiveness of VC feeding. Under normal conditions, VC controls the release of adrenal corticosterone by decreasing its production and secretion, but during times of stress, endogenous VC is depleted in the adrenal glands, causing systemic secretion of this potent adrenal glucocorticoid. The addition of BC from an exogenous source such as feed can help mitigate the detrimental effects of stress to minimize its negative impact on hen performance [191]. Feeding in combination with other biologically active substances (BAS) enhances the work of vitamin C [112, 113, 153]. A number of studies have shown a positive effect of vitamin C on the amount of ROS [121, 135, 140], productivity [145, 150] and quality of broiler meat [138, 139, 141] under OS caused by TS, high bird density [56], transportation [112, 154], toxicosis [149, 151, 153].

A review of literature sources also showed that the optimal dose of vitamin E feeding to chickens and broilers is 100-400 mg/kg of feed. In a number of studies, the use of BE in diets did not have a positive effect on growth rates [157, 160, 167], but contributed to a decrease in poultry mortality [170]. In other studies, the use of VE alone or in combination with other antioxidants in the diet of broilers contributed to an increase in growth rate and feed conversion [159, 162, 163], AOS parameetetrs [166, 169], and feed consumption [168]. The biological properties of VE in the body are manifested in an increase in the concentration of tocopherol in muscles [165, 166], blood plasma [166], and liver [169]. When feeding the vitamin alone and in combination with other antioxidants, an increase in the antioxidant activity of the blood and muscle tissue was noted [162, 165-167]. Feeding VE to broilers and chickens leads to an increase in the brightness of muscle tissue, in particular breast [155, 157, 169, 170], an increase in muscle pH [157, 170], an increase in the relative mass of the liver [157], stomach [159]. Enrichment of broiler diets with BAS complex (selenium with vitamins E and C) improves the function of vital organs, immune system response and growth performance of broilers under conditions of heat stress [192]. The combination of these supplements alleviates the symptoms of TS more effectively than their individual forms, due to the combination of several mechanisms in a synergistic effect. It has been shown that selenium and vitamins E and C closely interact: protect proteins and lipids from oxidative damage and activate the function of the immune system. The combination of VE and selenium can reduce the negative consequences of OS in the body of birds caused by xenobiotics of a chemical nature [165].

It has also been found that quercetin supplementation leads to a significant increase in the expression of genes associated with oxidative fibers, promoting the switch of skeletal fibers from glycolytic type II to oxidative type I [192]. In vitro studies have shown that quercetin acts as an antioxidant due to its ability to scavenge free radicals through the successive transfer of two electrons and the formation of an oxidized electrophilic product (quinone). In vivo, quercetin tends to generate reactive oxygen species by transferring electrons to oxygen catalyzed by transition metals. The resulting superoxide rapidly dismutes to hydrogen peroxide, which is fairly stable. Hydrogen peroxide or quinone are most likely responsible for the cytoprotective effects by inducing cellular endogenous antioxidant responses [193]. They are controlled by the transcription factor Nrf2 which is activated in response to the presence of hydrogen peroxide and electrophiles and then binds to related antioxidant elements located in the promoter regions of cytoprotective, antioxidant, and detoxification enzyme genes, including those involved in the synthesis and recycling of the widespread endogenous the antioxidant glutathione [194-196].

The effect of vitamins C and E, quercetin and taxifolin on the antioxidant status and parameters of meat in chickens and broilers

Experiment design (genotype, number of animals, age, antioxidant dosage)	Stress type	Antioxydant status	Carcass yield, meat quality, condition of internal organs	Blood biochemil parameters, immunity status	Productivity and other biological effects	References
			Vitamin C			
Broiler chickens Ross 308 (n = 160 heads), from days 25 to 42; 250 mg VC/kg feed	Chronic heat stress (35±2 °C for 8 h dayly, 9 am-5 pm)	A 27.90 % increase in GP	Not studied	Decrease in the amount of LDLP, the ratio of heterophils to lymphocytes in the blood	Increasing BW	[121]
Broiler chickens Ross 308 (n = 162), from days 3 to 35; 200 mg VC/kg feed	Heat stress (32-34/27-29 °C day/nignt)	An increase in AOS in the blood, a decrease in the expression of mRNA of interleukin (IL)-1β, IL-6, interferon (IFN)-γ, Toll-like receptors (TLR)-4 and HSP70 in the liver, a decrease in LPO processes in the blood and liver, mRNA expression of pro-inflammatory cytokines and HSP70	Liver and spleen weight unchanged, statistically significant ($p < 0.05$) increase in relative thymus weight	Not studied	No significant difference in live weight, feed conversion	[135]
Broiler chickens Ross 308 (n = 384), from 0 to 22 weeks; 200 mg BC/kg feed	Absent	Not studied	Not revealed	No effect on the content of alkaline phosphatase in blood serum	No effect on BW, intestinal morphology (villous height, depth of Lieberkün crypts and their ratio), strength and ash content of the tibia. Better feather integrity, reduced number of tail and wing feathers	[136]

Continued Table

Broiler chickens Ross 308 (n = 1368 heads, ♀:♂ = 1:1), from days 21 to 35; 200 mg VC/kg feed	Stocking density (low, 9 birds/m^2 and high, 18 birds/m^2)	Did not affect AOS in the liver (OAS and MDA)	Not revealed	No change in the concentration of H:L (hetero-phil:lymphocyte) in the blood and CORT (cortisol) in feathers, a decrease in the value of TER (transepithelial electrical resistance) in the mucosa of the jejunum as a parameter of intestinal permeability	No impact on growth performance	[56]
Broiler chickens (n = 96, ♀), from day 1 to week 4; 0, 250, 500 or 1000 mg AA/kg feed	Heat stress (дup to 36 °C for 6-10 h)	Not studied	An increase in adrenal weight	Maintaining the concentration of total protein, a slight increase in glucose, cholesterol, a decrease in the concentration of sodium in plasma, an increase in the amount of calcium and phosphorus, potassium	AA, especially at a dose of 250 mg/kg, reduces the negative effects of HS on metabolism and productivity; reduces the ADG of non-heat stressed birds	[137]
Broiler chickens Ross (n = 330), from day 4 to week 6; 0, 10, 50, 100 and 200 mg AA/kg feed	Absent	Not studied	An increase in the yield of steamed and chilled carcasses, the breast muscle weight; the meat is more red, an improved bone strength, increased Ca and P accumulation in the bones	The lymphocyte subpopulation showed more CD4 and T-cell receptor-II (TCR-II) cells	Increased growth, the digestibility of nutrients; AA (200 mg/kg) increases productivity and immunity	[138]
Broiler chickens Ross 308 (n = 270, ♀135, ♂135), day 35; 50 mg VC/l, 100 mg VC/l, 1 g AA/l, 1.5 g AA/l, 50 mg VC/l + 1 g AA/l, 50 mg VC/l + 1.5 g AA/l, 100 mg VC/l + 1 g AA/l and 100 mg VC/l + 1.5g AA/l drinking water	Transporatation stress	Not studied	Not studied	Decreased values of all stress indicators (glucose, albumin, globulin, uric acid, calcium, AlAT, AsAT, creatine kinase and T3). Increasing the concentration of T4	100 mg VC/l + 1.5 g AA/l with drinking water reduces the negative impact of transport stress on the body	[112]

Continued Table

Hens and roosters, line Mandarah (♀288, ♂ 36), from weeks 32 to 48; 1000 mg betaine/kg, 200 mg AA/kg, 150 mg tocopherol acetate/kg feed and their combination	Chronic heat stress (38±1 °C; 55-65 % humidity) for 3 days weekly, 11^{00} am–3^{00} pm)	Not studied	Increased weight of the liver, spleen, thyroid, ovaries, oviduct and length of the oviducts	Decreased values of stress markers (glucose, estrogen, progesterone, T_3, T_4)	Increased productivity	[139]
Broiler chickens Ross 308 (n = 120), from days 25 to 54; 15 g VC/100 l drinking water (equial to 11.25 mg/kg bodyweight)	Oxidative stress (caused by SA on day 35)	Reducing the degree of influence of the OS: a decrease in the concentration of MDA in the blood serum, an increase in OAS	Recovery of histopathological changes	No effect on the concentration of interleukin-6 in the synovial fluid	Not studied	[140]
Broiler chickens Cobb 500 (n = 1680), from days 21 to 38 (final growing); 500 mg VC/kg feed	Heat stress (34±1 °C for 8 h dayly)	Decrease in the concentration of MDA in the pectoral muscle, a decrease in LPO	Not studied	A decrease in the concentration of UA, lactate, no effect on CPK, LDH, T_3, T_4	Not studied	[141]
Laying hens (n = 96), from week 28 for 10 weeks; 0, 50, 100 and 200 mg VC/kg feed	Absent	Not studied	Not studied	Increasing the concentration of vitamins in the blood	Not studied	[142]
Laying hens Isa Brown (n = 13200), from month 13 for 40 days; 1 g VC/kg	Heat stress (+23.84 °C for 20 days followed by +25.54 °C for 20 days with 1 g VC/kg).	Not studied	Not studied	Not studied	Not found	[143]
Broiler chickens (n = 100), from day 22 of feeding to the end of growing (day 42); 2 g VC/l water (200 mg active substance/l)	Heat stress (after 28 days of feeding, the temperature was above the optimal values)	Not studied	Not studied	Increasing the number of erythrocytes, a reduced effect of hemolysis of erythrocytes	Not studied	[144]
Laying hens White Leghorn (n = 96); 100, 200 and 300 mh AA	Heat stress, randomly grouped hens were kept at 26±1,0 °C and under heat stress (40±5.0 °C)	Not studied	Not studied	No change in the concentration of HSP70 (heat shock protein). Decreased corticosterone concentration	Increased feed efficiency ratio, productivity index, egg production (%) in the group fed 300 mg of AA	[145]
Hens Hy-Line W-36, from weeks 65 to 69; 200 mg VC/kg feed	Heat stress, neutral (22 °C) and high (32 °C) temperature	Not studied	Not studied	An increase in the concentration of Na and P in the blood, a decrease in the concentration of Ca and P compared to TN	No significant effect noted	[146]

Continued Table

Hens Bovan (n = 80), from month 4 for 6 weeks); 1000 mg AA/kg feed, 500 mg AA/kg feed, 500 mg AA in water, 1000 mg AA in water	Absent	Not studied	Not studied	No significant change in the ratio of heterophils and lymphocytes	Increase in weight, body temperature, total number of leukocytes	[147]
Broiler chickens Cobb 500 (n = 45), days from 1to 35; 30, 60, 90, 120 mg AA/kg feed	Absent	Not studied	Not studied	Not studied	Increase in body weight, weight gain and feed intake	[148]
Broiler chickens (n = 240), from days 0 to 42; 100, 200 mg VC under various levels of OTA	Toxicosis (OTA)	Not studied	Positive effect on the weight of the liver, kidneys, bursa of Fabricius	Reducing the amount of TP and cholesterol in the blood, increasing the concentration of UA and alkaline phosphatase	Partial reduction in the adverse effects of OTA on performance, relative organ mass and biochemical parameters	[149]
Broiler chickens Shiver (n = 180), from day 1 to week 8; 0, 500 и 1000 mg VC/kg feed	Heat stress, neutral (24 °C) and high (35 °C) temperature	Not studied	Not studied	Not studied	Significant improvement in ADG and FCR	(150]
Broiler chickens Ross (n = 368, ♂, 8 groups of n = 46 each) from day 3 to week 5; 300 mg VC/kg feed and in combination with yeast (SC 3 g + 300 mg/kg feed), and when fed feeds contaminated with OTA (200 mg/kg)	Toxicosis (OTA)	Not studied	Not studied	Not studied	Reducing the toxic effect of OTA when using a combination of VC with yeast	[151]
Broiler chickens Ross 308 (n = 1824, ♂), from days 0 to 35; 200 g VC/1000 l drining water	Heat stress (35 °C during 8^{00} am–2^{00} pm dayly)	Not studied	Not studied	Decrease in the concentration of corticosterone in the blood	Slight increase in productive indicators	[152]
Broiler chickens Ross 308 (n = 160, ♂), from days 25 to 42; lemon verbena (0.5% or 1,0%) and VC (250 mg/kg feed)	Chronic heat stress (35±2 °C for 8 h dayly, 9^{00} амд–5^{00} pm)	An increase in GP by 51.81% with 1.0% lemon verbena and by 27.90% with VC	Higher relative weight of bursa of Fabricius and breast due to 1.0% lemon verbena	Decrease in the ratio of heterophils to lymphocytes, the amount of LDLP decreased by 15.85 and 17.57% when feeding 0.5 and 1.0% lemon verbena	Not studied	[121]

Continued Table

Broiler chickens Cobb 500 (n = 251), from days 1 to 42; 300 mg $CuSO_4$/kg feed separately abd in combination with vitsmin C (250 mg/kg feed), vitsmin E (250 mg/kg feed) and their combination	Toxicosis ($CuSO_4$)	Reduced toxicity due to improved AOS	The addition of vitamins C and E, alone or in combination, had a beneficial effect on microscopic changes in the architecture of the kidneys, impaired OS	Reducing the negative consequences of OS, which manifested itself in a decrease in the number of red blood cells, hemoglobin concentration, hematocrit value, a state of hypoglycemia with an increase in the content of uric acid and creatinine in the blood serum	Preventive effects of dietary antioxidants on hematobiochemical changes, OS and kidney damage caused by $CuSO_4$ toxicity	[153]
Broilers (n = 128); 250 mg VC/l, 500 mg VC/l or 750 mg VC/l	Trransportation stress (24 or 48 km)	Not studied	Not studied	Decreased blood glucose	The addition of VC during transport had a positive effect on weight retention, heart rate and reduced mortality	[154]
			Vitmin E			
Broilers Cobb 500 (n = 750, ♂), from days 42 to 54; 30, 90, 150, 210 and 270 mg VE/kg feed	Absent	Not studied	Increasing the brightness of the breast muscles, increasing the pH of the meat	Not studied	Not studied	[155]
Broiler chickens (n = 96, ♂), from days 1 to 22; 22.00, 220.00 IU VE/kg diet	Veterinary maniplations (birds aged 22 days were injected subcutaneously with *Escherichia coli* 0111:B4 LPS)	Low *IL6* mRNA in the jejunum	Not studied	Not studied	Not studied	[156]
Broiler chickens Ross 308 (n = 420), from day 6 for 26 days; 33, 65 and 100 IU VE/kg feed (vitamin E of various origin)	Absent	Decreased lipid oxidation in the breast, thigh muscles, decreased mRNA expression of pro-inflammatory (IFN-γ, IL-1 and IL-6) and anti-inflammatory cytokines (IL-4, IL-10 and TGF-4) in the jejunum	Reddening of breast meat, slight increase in the relative weight of the liver, spleen, thymus, and bursa of Fabricius	Not studied	No effect on growth rates	[157]

Continued Table

Layinf hens Lohmann (n = 216), from week 50 for 12 weeks; 0, 20, 100 IU VE/kg feed	Absent	It did not affect the content of CF and cholesterol, the expression of acetyl-CoA carboxylase, lipoprotein lipase, fatty acid synthase, or the expression of CMKLR1 mRNA in the liver. An increase in the content of MDA, a decrease in the activity of GP in the blood serum and in the ovaries, a significant increase in the activity of GP in the liver and in the serum, the activity of SOD in serum, the expression of mRNA, SOD in the liver and ovaries	Not studied	Not studied	Not studied	[158]
Broiler chickens Ross 308 (n = 120, ♂), days from c 1 to 42; 100, 200 mg VE/kg feed	Absent	No differences in the activity of OAS or SOD. Increasing the concentration of total tocopherols and vitamin E in the blood serum, liver, and pectoral muscles	An increase in the weight of the stomach, the pH of the stomach contents; pectoral muscles are light with low pH, muscle tissue had a higher yellowness, high concentration of omega-6 PUFAs, low atherogenic index	Not studied	Increased BW	[159]
Parent flock Ross 308 (n = 512 of hens aged 71 weeks and n = 576 of hens aged 75 weeks); 100, 200 or 400 mg VE/kg feed for 12 weeks	Absent	Decreased MDA in ovaries, egg yolks and serum, brain and yolk sac of chickens, AOS in serum and ovaries, increased AOS in egg yolks and yolk sac of chickens, α-tocopherol content in egg yolks	Not studied	Not studied	No effect on egg production and egg hatchability	[160]
Broiler chickens Hubbard-Cobb (n = 960), days from 0 to 42; 200 mg VC and VE added with electrolytes/kg feed	Heat stress (30 °C, 60 % humidity for days from 21 to 42 with various intervals)	Not studied	Not studied	Absent	Adding electrolytes in the diet with the addition of sodium bicarbonate and vitamins C and E reduced the negative effects of heat stress on productivity	[161]

Continued Table

Broiler chickens Arbor Acres (n = 108), days from 7 to 35; 0.1 mg Se nanoparticles/kg feed, 100 mg VE/kg feed and all additives combined	Absent	Increase in AOS when feeding a complex of selenium nanoparticles and VE	Not studied	Increasing the amount of calcium and phosphorus in plasma. Increasing the content of albumin in the feeding Se + VE. Decreased cholesterol, increased triglycerides	Increasing BW and ADG, increasing feed conversion	[162]
Broiler chickens Ross (n = 720) days from 22 to 42; organic Zn (0.0 mg/kg and 120 mg/kg feed) and VE as DL-α-tocopherol acetate (0.0 mg/kg, 300 mg/kg and 600 mg/kg feed)	Heat stress (average temperature and relative humidity of 30.0 °C and 57.7 % for days from 22 to 33, and of 30.7 °C and 58.9 % for days from 34 to 42)	Not studied	No effect on the slaughter yield and the yield of abdominal fat	Not studied	VE supplement improved productivity from day 22 to day 33	[163]
Broiler chickens (n = 100), a subletal dose of 100 mg thiamethoxam/kg bodyweight + 150 mg VE/kg bodyweight or 0.25 мг Se/ml, or vitamin E + Se in drinking water	Toxic stress (thiamethoxam)	Not studied	Not studied	Positive effects of the combination of vitamin E and selenium on hematobiochemical parameters	Reducing the degree of toxic stress	[164]
Broiler chickens Ross 308 (n = 400), days from 21 to 42; VE (200 IU/kg feed), VC (250 mg/kg feed), Se (0,2 mg/kg feed), or VE + VC + Se of the indicated dosage)	Oxidative stress (5 % flaxseed oil in the diet)	An increase in the concentration of α-tocopherol, a decrease in the content of MDA in the pectoral muscle, inhibition of LPO processes in fresh, frozen, freshly cooked meat	No changes in the slaughter yield of breast, drumstick, wings, back and abdominal fat, WHC, pH_{24}, pH_{48}, breaset muscle color	Not studied	Not studied	[165]
Broiler chickens Cobb (n = 150), days from 1 to 21; 200 mg VE/kg feed	Absent	An increase in the concentration of γ-tocopherol in the blood plasma and in the meat of the thigh, the concentration of γ-tocopherol in the meat of the thigh on the 1st day, followed by a decrease. Reducing the concentration of MDA	Not studied	Not studied	Increase in ADG, decrease in feed conversion	[166]

Continued Table

Broiler chickens Ross 708 (n = 210), days from 0 to 58; 10, 200 IU VE/kg feed or omega-3, or VE + omega-3	Absent	Not studied	No difference in meat yield, in muscle mass, in pH, in losses during thawing, cooking; an increase in yellowness in the pectoral muscles, a decrease in the fat content in the pectoral muscles	Not studied	No significant effect of vitamin E, n-3 fatty acids, or a combination of these on growth performance	[167]
Broiler chickens Ross 708 (n = 28), from day 1 to week 5; natural (α-tocopherol acetate — AsAT, 35 mg/kg feed) or synthetic vitamin E (10 and 58 mg/kg feed)	Absent	Not studied	Increasing the concentration of α-tocopherol in the liver and muscles	Increasing the concentration of α-tocopherol in plasma	Increase in feed consumption by 1.72-1.81 times, ADG by 1.58-1.65 times	[168]
Broiler chickens Ross 308 (n = 945), days from 3 to 42; 200 mg VE/kg feed (Kavimix-E-50 α-tocopherol acetate) in the study of bioactive preparations	Absent	Increase in VE concentration in the liver (total VE and α-tocopherol) with the addition of VE	Reduced yellowness of meat and skin	Increased plasma carotenoid concentration in the VE treated group	Decreased feed intake with no negative effect on growth rate throughout the experiment in groups fed 200 mg VE	[169]
Chiks of experimental Polish meat line (n = 420, ♂), days from 1 to 63; 44, 200 mg VE (DL-α-tocopherol acetate)/kg feed	Absent	Decreased content of MDA, oxidative changes in the muscles of chickens 48 h after slaughter	Increasing carcass yield. No effect on the percentage of chest and leg muscles. An increase in the mass of the heart and stomach from the bodyweight, a decrease in the liver. Decreased abdominal fat. Increased pH_{24} and WHC of muscles and reduced losses during cooking. Darker meat, more saturated red and less saturated yellow. Improveв consumer properties of meat. Reducing the diameter and surface area of the fibers, the ratio of fibers to the total area	Not studied	No effect on growth rates, a decrease in mortality	[170]

Continued Table

Quercetins						
Broiler chickens Cobb 500 (n = 150), days from 1 to 42; 0.5, 1 g quercetin/kg feed	Absent	Not studied	Increase the brightness of the breast muscles, increase oxidative stability, decrease in MDA	Not studied	Not found	[171]
Broiler chickens Ross 308 (n = 120), days from 1 to 35; 0.2, 0.4 and 0.8 g quercetin/kg feed	Absent	Increase in the gut expression of mRNA for SOD (*SOD1*), GP (*GSH-Px*)	Not studied	Not studied	Increasing growth intensity and improving feed conversion	[129]
Broiler chickens Ross 308 (n = 80, ♂), days from 7 to 28 and from 28 to 35; extract of *Larix sibirica* (85 % dihydroquercetin) at 0.5 g/kg feed	Absent	Not studied	Change in redness of the breast muscles	Not studied	Not studied	[172]
Broiler chickens meat cross Smena 7 (n = 300), days from 1 to 42; 0.5 mg dihydroquercetin/kg bodyweight	Absent	Not studied	More dry matter and fat, less tryptophan and ash	Not studied	Not studied	[173, 174]
Broiler chickens (n = 300), days from 1 to 42; 0.5 mg dihydroquercetin/kg bodyweight	Absent	Not studied	Not studied	Not studied	Improved feed conversion by 9.2%	[175]
Broiler chickens (n = 300), days from 1 to 42; 0.5 kg dihydroquercetin/t premix	Absent	Not studied	Increased protein concentration in liver tissues and breast muscles	Not studied	Not studied	[176]
Broiler chickens (n = 160), days from 1 to 42; 0.5 mg dihydroquercetin/kg bodyweight	Absent	Not studied	Not studied	Not studied	Increase in productivity by 33.4%, derease in livestock smortality by 5.3%	[176]
Broiler chickens line Vencobb 400 (n = 192), days from 7 to 42; 1g quercetin/kg feed added with oil	Oxidative stress (caused by fat in the diet)	Not studied	Reducing the negative impact on meat quality of additional inclusion of fat in the diet	Not studied	Increased slaughter yield	[177]
Broiler chickens lina Cobb 500 (n = 40), days from 1 to 60; 0.5, 0.75 and 1 g dihydroquercetin/100 kg combned feed	Absent	Not studied	Not studied	Not studied	Increase in bodyweight by 11.91-32.78%	[178]

Continued Table

Broiler chickens line Cobb 500 (n = 40), days from 1 to 60; 0.5, 0.75 and 1 g dihydroquercetin/100 kg combned feed	Absent	Not studied	Not studied	Bringing to normal hematological parameters	Not studied	[179]
Broiler chickens line Cobb 500 (n = 40), days from 1 to 60; 0,5, 0,75 and 1 g dihydroquercetin/100 kg combned feed	Absent	Not studied	Increase in the mass of the butchered carcass by 15-38%, muscle tissue by 3%, pectoral muscles by 0.3-2%, edible part of the carcass - by 2-6%	Not studied	Decrease in the mortality by 20-30%, in bodyweight by 12-33%	[180]
Broiler chickens Ross 308 (n = 320), days from 7 to 35, extract of *Larix sibirica* (85 % dihydroquercetin) at 0.5 g/kg feed and dihydroquercetin with VE at 0.3 g/kg feed	Chronic heat stress (35 °C)	Increased activity of GP in the blood and OAS	Increased heart mass and cecum size (dihydroquercetin); weight gain in the spleen and liver (dihydroquercetin + VE)	Not studied	Not found	[27]
Broiler chickens Ross 308 (n = 100), days from 7 to 21; extract of *Larix sibirica* (85 % dihydroquercetin) at 0.5, 1.5 and 4,5 g/kg feed	Absent	Increased GP activity at maximum dosage	Not studied	Not studied	Slight increase in bodyweight at maximum dosage	[181]
Broiler chickens Arbor Acre (n = 240), days from 1 to 42; 97 % quercetin at a dosage of 0.02, 0.04 and 0.06 % of ration	Absent	Not studied	Not studied	An increase in the index of the spleen and thymus. Increased production of immunoglobulin A (IgA), interleukin-4 (IL-4), immunoglobulin M (IgM) and tumor necrosis factor-α (TNF-α). Increased expression of TNF-α, TNF receptor-associated Factor-2 (TRAF-2), NF-κBp65 and interferon-γ (IFN-γ) mRNA and expression of NF-κB-alpha (IκB-α) inhibitor	Slight effect	[182]

Continued Table

Broiler chickens Arbor Acres (n = 240, ♂), days from 1 to 21, 200 or 500 mg quercetin/kg feed	Oxidative stress (caused by lipopolysaccharides)	Reducing the amount of ROS, MDA. Increased activity of peroxidase, SOD, glutathione content. Reduced damage to jejunal mitochondria and increased expression of genes associated with mitochondrial DNA copy number	Not studied	Alleviation of oxidative damage to the gut through the MAPK/Nrf2 signaling pathway	Not studied	[183]
Broiler chickens Arbor Acre (n = 480), days from 1 to 42; > 95 % quercetin at a dosage of 0.2, 0.4 and 0.8 g/kg feed	Oxidative stress (caused by oxidized oil)	Decreased MDA	Not studied	Activation of Nrf2 and related genes (*CAT, GP 2, SOD1, HO-1*, and thioredoxin) in the ileal mucosa. Strengthening the intestinal barrier by increasing the expression and secretion of mucin 2 (MUC2)	Not studied	[184]
Broiler chickens Arbor Acres (n = 300), days from 1 to 42; 0.2, 0.4 and 0.6 g quercetin/kg feed	Oxidative stress (caused by streptozotocin)	Increasing the activity of antioxidant enzymes, reducing the content of MDA and NO. Activation of expression of genes associated with the PI3K/PKB signaling pathway	Not studied	Activation of expression of genes associated with the PI3K/PKB signaling pathway, regulation of glucose metabolism	Not studied	[185]
Broiler chickens Arbor Acres (n = 640), days from 1 to 35; 97 % quercetin at a dosage of 250, 500 and 1000 mg/kg feed	Chronic heat stress (32 °C for 24 h from day 4)	Increased activity of SOD (T-SOD) and AOS	Decrease in MDA concentration, decrease in the amount of abdominal fat	Increasing the concentration of tumor necrosis factor-α (TNF-α)	Increased bodyweight	[186]
Broiler chickens Cobb (n = 40), days from 1 to 42; 0.5 g quercetin/kg feed	Oxidative stress (caused by OTA)	Normalization of enzyme activity	Not studied	Reducing the immunotoxic effects of OS due to the activation of the PI3K/AKT signaling pathway for its immunomodulatory, antioxidant, and antiapoptotic activities	Not studied	[79]
Broiler chickens Ross 308 (n = 210), days from 1 to 42; 500 and 1000 mg quercetin/kg feed, and 1000 mg quercetin/kg feed + 250 mg VE/kg feed	Absent	Not studied	Not studied	Not studied	Increasing bodyweight of chickens and feed intake	[187]

Continued Table

Broiler chickens Ross 308 (n = 1088), days from 1 to 35; 0.2, 0.4 и 0.6 g quercetin/kg feed	Absent	Not studied	Increase in WHC, decrease in moisture loss of the pectoral muscle	Not studied	Increased ADG, feed intake, nutrient digestibility	[188]
Broiler chickens Arbor Acres (n = 480); 0, 0.2, 0,4 and 0.6 g quercetin/kg feed	Absent	Not studied	The percentage of fat in the abdominal cavity was significantly reduced due to the favorable modulation of the intestinal microbiota	Not studied	Quercetin improved lipid metabolism by modulating gut microbial and AMPK/PPAR signaling pathways	[189]
Broiler chickens Ross 308 (n = 300), 100, 200, 300 mg quercetin/kg feed	Absent	Not studied	Not studied	Not studied	Improved feed conversion rates	[190]

N o t e. HS — heat stress, VC — vitamin C, VE— vitamin E, GP — glutathione peroxidase, LDLP — low density lipoproteins, BW — bodyweight, LPO — lipid peroxidation, AOS — antioxidant status, AP — alkaline phosphatase, OAS — overall antioxidant status, MDA — malonic dialdehyde, AA — ascorbic acid, AlAT — alanine aminotransferase, AsAT — aspartate aminotransferase, OS — oxidative stress, SA — septic arthritis, UA — uric acid, OTA — ochratoxin A, ADG — average daily gain, CF — crude fat, SOD — superoxide dismutase, PUFA — polyunsaturated fatty acids, WHC — moisture holding capacity, DHQ— dihydroquercetin, ROS— reactive oxygen species, TH — thermoneutral, TP — total protein, FCR — feed convertion rate, BAS — bioactive substances.

Thus, quercetin exerts protective functions either directly, by activating antioxidant enzymes, or indirectly, by stimulating transcription factors that enhance the antioxidant defense status, especially under stress. In the sources we considered, quercetin was included in the diets of poultry in the amount of 0.2-1 g/kg of feed. Feeding quercetin at the indicated dosages promotes an increase in the expression of antioxidant defense genes [129], a decrease in the concentration of MDA, ROS, an increase in glutathione activity [184], including under conditions of oxidative [185, 186] and heat stress [79]. The dosage of the introduction of taxifolin (dihydroquercetin) into the diets of broilers and chickens is much less than that of quercetin, due to its increased biological activity - 0.005-0.01 g/kg of feed. The authors noted an improvement in the quality of broiler meat under the influence of DHQ [173, 174, 180].

In conclusion, it should be noted that modern studies of stresses and their adjustment in livestock and poultry farming are quite numerous, but in some part contradictory, so the search for the most effective feed products that counteract the effects of stress remains relevant. Biomarkers are needed to allow for an in vivo assessment of the quality of the products obtained, and the study of correlations between indicators of the biochemical, antioxidant, hormonal status of the animal and the quality of meat. This will allow more targeted use of antioxidants in animal and poultry nutrition. It is necessary to take into account the synergistic effect of antioxidants-adaptogens on the body and slaughter products when used in complex diets, especially under stresses of various nature. In our opinion, the use of natural flavonoids in combination with vitamins is promising, which will enhance antioxidant protection, resistance and, as a result, provide improved quality meat products. It is possible that it is the combination of natural adaptogens as feed additives that will be the most effective method in protecting against the effects of stress. This is the reason for the interest in continuing such studies both in poultry and in monogastric animals.

So, in poultry farming, stresses of various nature (climatic, transport, feed, veterinary, placement density) have a significant impact on the body, primarily on the immune and antioxidant systems. Also, unfavorable conditions lead to significant losses in safety and gains in live weight, feed conversion decreases. The most significant negative impact of stress on product quality. With a decrease in the proportion of muscle mass, lipid peroxidation products accumulate, which lowers the pH of the meat and increases the proportion of meat PSE (pale, soft, exudative). The most effective and simple method of protection against stress and its negative consequences should be recognized as feeding animals with antioxidants. Many studies have established a significant positive role of vitamins C and E, as well as bioflavonoids when fed to laying hens and broilers under various stresses observed in modern industrial poultry farming. Vitamins and bioflavonoids enhance the expression of antioxidant defense genes and reduce lipid peroxidation. They protect proteins and lipids from oxidative damage and increase immune function in general, which leads to an improvement in the quantitative and qualitative indicators of meat productivity.

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