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REVIEW PAPER

## Selected nutritional and biochemical strategies to mitigate heat stress in poultry: antioxidant and osmoprotective feed additives\*

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### Abstract

Heat stress poses a significant challenge in poultry production, as high temperatures disrupt physiological homeostasis, impair antioxidant defenses, and reduce productive performance. Birds under thermal stress show alterations in metabolic and endocrine regulation, with decreased feed intake and oxidative damage, which compromise cellular integrity and immune responsiveness. This review synthesizes evidence on biochemical defense mechanisms activated by heat stress and examines nutritional strategies for restoring redox equilibrium and enhancing adaptation. The focus is on minerals and bioactive compounds involved in antioxidant protection and osmotic regulation. Betaine maintains cellular hydration and stabilizes protein structures, supporting growth performance under thermal challenge. Selenium, through selenoproteins, reinforces antioxidant enzyme systems and improves immune competence. Insect-derived proteins provide digestible amino acids, natural antioxidants, and chitin-derived compounds that enhance intestinal functionality and stress tolerance. Sulfur-containing amino acids are essential for glutathione biosynthesis and maintaining hepatic and intestinal integrity. Additional bioactive nutrients, including vitamins A, C, and E, reinforce antioxidant defenses, while short-chain organic acids like butyric acid maintain intestinal morphology, barrier function, and microbial homeostasis. Evidence from experimental studies and meta-analyses shows that element-enriched diets can effectively alleviate heat stress effects, offering a cost-efficient alternative to mechanical cooling systems. These nutritional interventions support animal welfare, improve feed efficiency, and promote sustainable poultry production under adverse climatic conditions.

**Keywords:** heat stress, poultry, osmoprotectants, welfare, antioxidants

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## INTRODUCTION

Despite the continuous growth of the poultry industry and the increasing scale of production worldwide, poultry producers still face numerous challenges (Tańczuk et al. 2019*a,b*). Environmental changes, particularly climate change, pose significant threats to bird welfare. This problem is most pronounced in tropical and subtropical regions. However, birds are also exposed to heat stress in temperate climates, particularly during hot summers. Prolonged exposure to high ambient temperatures can negatively affect bird health and production performance leading to economic losses (Afsal et al. 2018). Several years ago, heat stress in the U.S. poultry industry was estimated to cause losses ranging from \$128 to \$165 million (St-Pierre et al. 2003) – compiled data on the scale of losses caused by various factors, including heat stress in poultry production (Fig. 1).

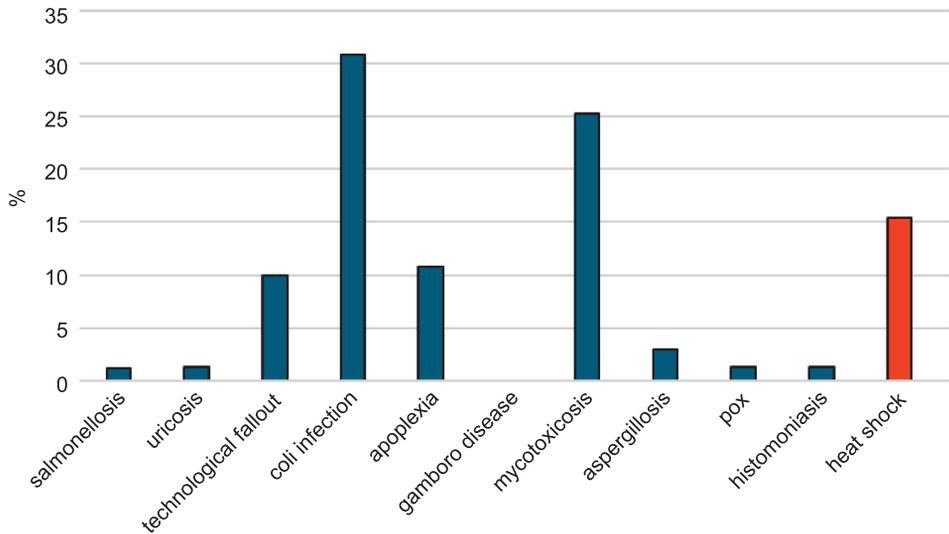


Fig. 1. Scale of economic losses in poultry production (Kapetanov et al. 2016)

Air temperature is not the only factor that is responsible for heat stress. Other factors include air humidity, air movement speed, and intensity of solar radiation. The density of animals, breed, and individual characteristics also play a significant role. The risk of heat stress can be assessed using the temperature-humidity index (THI) (Mirowski, Didkowska 2017). In living organisms, if the temperature exceeds the normal range (thermoneutral zone), it disrupts normal physiological functions and causes cell damage. For poultry, the optimal temperature for the thermoneutral zone is between 18 and 22°C for growing broilers (Shakeri et al. 2020). Above this zone, birds are at risk of heat stress (Mujahid Ahmad et al. 2007, Sohail et al. 2012, Zmrhal et al. 2018).

It is important to note that heat stress extends beyond farm conditions and has far-reaching consequences, as today's consumers prefer products from animals that have been well cared for (Da Silva et al. 2017).

The aim of this review of the literature is to present the mechanisms of action of bioactive feed additives in the context of mitigating or eliminating heat stress in broiler chickens. Although a wide range of nutritional strategies has been proposed to alleviate heat stress in poultry, the present review deliberately focuses on selected feed additives with documented antioxidant, redox-regulating or osmoprotective properties, as well as novel protein sources with functional bioactive potential. These include betaine, selenium, sulfur-containing amino acids, vitamins with antioxidant activity, short-chain organic acids and insect-derived ingredients. Other commonly used approaches, such as dietary electrolytes and probiotics, primarily target acid–base balance or gut microbiota and are therefore not discussed in detail, as they fall outside the biochemical and cellular stress-mitigation framework adopted in this review.

## CONSEQUENCES OF HEAT STRESS: RESPONSE AND MECHANISM

The response of birds to heat stress depends on several factors, such as the duration of exposure, temperature, humidity, bird density, air circulation, and repetition of these conditions (Lara, Rostagno 2013, Johnson 2018).

In the heat discomfort zone, key observations include reduced feed intake (Habashy et al. 2017), decreased physical activity, and disruption of basic behavioral functions (Mohammed et al. 2021).

As birds lack sweat glands, heat exchange is controlled by neuronal thermoreceptors located throughout the bird's body (Curtis 1983). Yahav (2015) categorizes these thermoreceptors into sensory afferent receptors (including thermos-, osmo-, and baroreceptors), integrating (thermoregulatory center), and commanding efferent receptors (encompassing neurological and endocrinological signals). The use of these thermoreceptors initiates biological mechanisms that allow an appropriate thermoregulatory response (Johnson, 2018). When thermal signals are received during heat stress, the hypothalamus integrates these signals and subsequently activates the hypothalamic-pituitary-adrenal axis (HPA axis – Figure 2).

Depending on the nature of the thermal stress factor, either cold or heat, stable thermal homeostasis can be achieved through a balance between heat production and heat loss. Conduction, convection, and radiation are the primary methods of heat loss in birds within their thermal comfort zone (Bahuti et al. 2022).

Heat loss through these mechanisms is generally referred to as sensible heat loss. Using these means, birds dissipate heat through unfeathered parts (head, comb, wattle, shank, crest, footpad, outstretched wings, and breast contact with the ground) and peripheral tissues (tongue, larynx, and trachea)

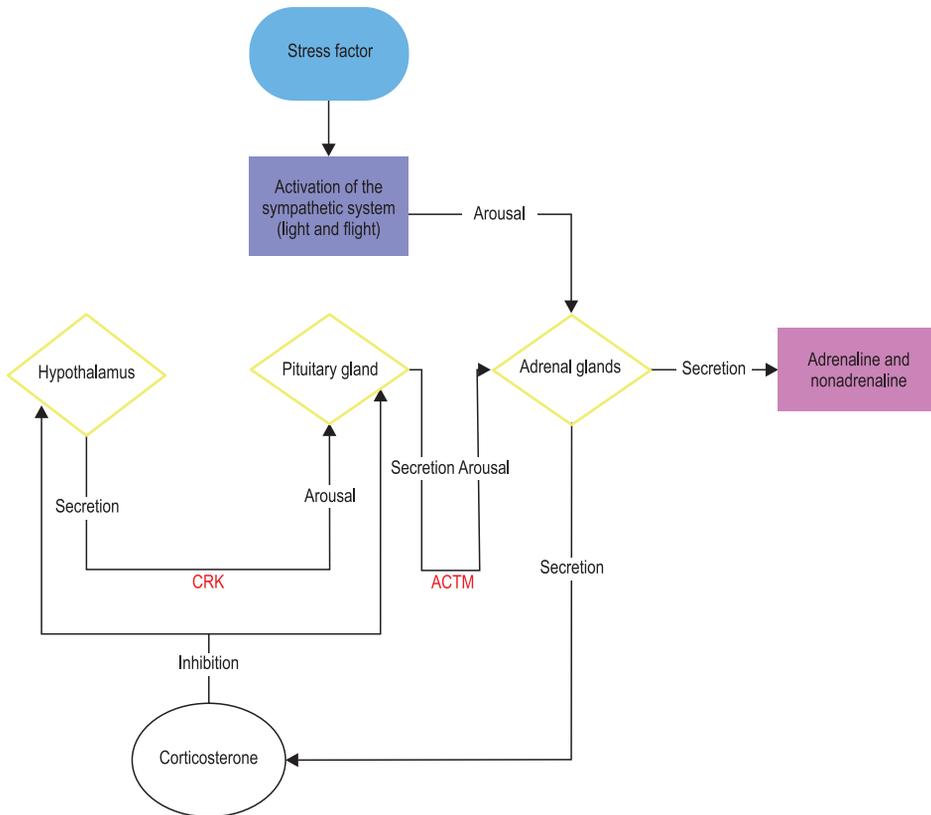


Fig. 21. HPA axis (source: the authors)

(Rostagno 2020), as well as increased panting, which can lead to elevated blood pH and consequently respiratory alkalosis, causing bone deterioration and lameness (Konca, Büyükkiliç Beyzi 2021, Ahmad et al. 2022). Prolonged exposure to elevated ambient temperatures results in chronic heat stress, which disrupts oxidative, immune, and endocrine homeostasis in poultry. Sustained activation of the HPA leads to increased circulating corticosterone levels, negatively affecting growth performance, nutrient utilization, and immune competence (Lara, Rostagno 2013, Johnson 2018). At the cellular level, chronic heat stress enhances the production of reactive oxygen species (ROS) while simultaneously reducing the activity of key antioxidant enzymes, including superoxide dismutase (SOD) and glutathione peroxidase (GPx), thereby promoting oxidative damage to lipids, proteins, and cellular membranes (Mujahid et al. 2007, Habibian et al. 2015). These oxidative disturbances are closely associated with impaired immune responses, manifested by reduced lymphocyte activity and antibody production, which increase susceptibility to infections in heat-stressed birds (Nawab et al. 2018, Ahmad et al. 2022).

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## STRATEGY TO RESTRICT HEAT STRESS AND ITS EFFECTS

### Betaine

Glycine betaine (N,N,N-trimethylglycine) is a zwitterionic compound synthesized by bacteria, plants, invertebrates, and mammals (De Zwart et al. 2003). In plants, it functions as an organic osmolyte, accumulating in chloroplasts where it plays a vital role in safeguarding thylakoid membranes. This protection is crucial for maintaining photosynthetic efficiency under environmental stressors such as drought, salinity, extreme temperatures, UV radiation, and heavy metals, which can adversely affect subcellular structures. In higher plants, betaine is synthesized in chloroplasts from serine via ethanolamine, choline, and betaine aldehyde. This biosynthetic pathway involves the conversion of choline to betaine aldehyde by choline monoxygenase (CMO), followed by the conversion to betaine by betaine aldehyde dehydrogenase (BADH) (Ashraf, Foolad 2007). Research indicates that in a neutral environment, betaine exists as a zwitterionic ion and serves as a methyl group donor (Zhao et al. 2018). Studies conducted in subtropical climates have demonstrated that the addition of betaine to feed or water reduces dehydration by enhancing water retention in cells, tissues, and organs, thereby maintaining energy balance and feed intake in animals (Kidd 2004, Ayo et al. 2014). Betaine is significant in poultry nutrition, contributing to protein metabolism and acting as a methyl group donor. It can substitute other methylation sources such as choline and methionine, providing benefits to birds under heat stress and improving carcass traits (Rama Rao et al. 2011, Shakeri et al. 2018). Betaine can replace up to 25% of methionine without negatively impacting broiler production performance (Zhan et al. 2006, Yang et al. 2008). As a methyl group donor and osmolyte, betaine influences lipid metabolism by stimulating fatty acid oxidative catabolism through carnitine synthesis (Craig 2004). Betaine can be supplemented as isolated betaine from natural sources, synthetic anhydrous betaine, and synthetic betaine-HCl (Awad et al. 2022). Research has shown that dietary betaine supplementation enhances the performance of heat-stressed broilers, particularly at higher concentrations. The addition of betaine to broiler diets has been associated with increased blood albumin concentration, attributed to its role as a methyl group source for protein metabolism. Studies have demonstrated that betaine can mitigate the effects of heat stress on poultry production performance (Al-Sagan et al. 2021). Table 1 illustrates the impact of different betaine doses in feed on production outcomes and bird welfare.

### Selenium

Selenium is a trace element of significant biological importance. Although not essential for plants and fungi, they have adaptive strategies to convert the mineral forms of Se present in soil into organic forms, mainly selenomethionine and methylcysteine (White 2016). In animal nutrition,

Effect of betaine dosage on broiler chicken feed in heat stress

Dosage (mg kg <sup>-1</sup> feed)	Effect	Author
500.00	improvement in body weight gain (BWG) compared to heat-stressed controls; increase in feed intake and improvement in feed conversion ratio (FCR); improvement in nitrogen and energy retention; increase in antioxidant enzyme activities (SOD, CAT, GPx); reduction in malondialdehyde (MDA) levels; partial improvement in immune response	Liu et al. (2019)
640.00	reduction in serum uric acid levels, which in turn can decrease its excretion, thus limiting ammonia emission in poultry houses and nitrogen emission into the environment	Mahmoudi et al. (2018)
1000.0	improvement in BWG and feed intake under heat stress; enhancement of nitrogen and energy retention; improvement of FCR; improvement in hepatic antioxidant status under heat stress; enhancement of mitochondrial antioxidant enzyme activities (SOD, GPx); reduction in hepatic and mitochondrial MDA levels; attenuation of heat stress induced oxidative damage in liver and mitochondria; partial restoration of redox balance and protection of hepatic function; improved immune indicators: immunoglobulin A, immunoglobulin G (IgA, IgG)	Liu et al. (2019), Al-Sagan et al. (2021), Wen et al. (2021)
2000.0	marked improvement in nutrient digestibility and nitrogen retention; improvement of FCR; stimulation of antioxidant defense systems; pronounced reduction in oxidative damage markers (MDA); modulation of the immune response (higher immunoglobulin concentrations)	Liu et al. (2019)

it is an essential nutrient that supports physiological processes, including regulation of the immune system, redox mechanisms, and other key cellular processes involved in adaptive and innate immune responses. As an essential trace element, Se is an integral part of selenoproteins involved in various physiological processes in production animals. In feed formulations, selenium can be provided to animals in both inorganic (e.g. selenite) and organic forms (selenomethionine derived from yeast) (Dalgaard et al. 2018). According to research findings, Se supplementation with inorganic forms can have certain drawbacks, including high selenium toxicity (above recommended doses), low penetration efficiency in animal products, and limited capacity to maintain reserves in animals (Surai, Fisinin 2016). Increased Se supplementation is not always beneficial because selenoprotein synthesis is controlled by genes and reflects the ability of these active molecules to cope with various stresses. However, to effectively respond to environmental challenges by modulating selenoprotein synthesis, sufficient Se reserves should be available, and the ability to build up Se reserves in the body is considered a major advantage of organic selenium in animal nutrition (Surai, Fisinin 2016). Selenium plays a particularly significant role in intensive poultry farming. Chickens used in mass production exhibit high growth intensity

and good production results but are very sensitive to various environmental stresses. Se, as a component of various selenoproteins, can support the maintenance of antioxidant defense, prevent tissue damage, and contribute to optimizing performance (Surai, Fisinin 2014). Broiler chickens exposed to high environmental temperatures have been shown to experience heat and oxidative stress, which ultimately reduces their production performance and weakens their immune system. The synthesis of antioxidant enzymes such as SOD and GPx is responsible for protecting birds during periods of stress (Sahin et al. 2009, Habibian et al. 2015). This also underscores the significant role of selenium in poultry nutrition, as the main form of GPx is selenium dependent (Habibian et al. 2015). Selenium is incorporated into selenocysteine, which is the active center of GPx and thioredoxin reductase (TRx) enzymes. When exposed to high temperatures, the production of superoxide radical ( $O_2^{\cdot-}$ ) increases in hen tissues. SOD converts  $O_2^{\cdot-}$  to hydrogen peroxide ( $H_2O_2$ ), thus limiting Fenton reactions. Selenium-dependent GPx reduces  $H_2O_2$  to water while oxidizing glutathione (GSH) to oxidized glutathione (GSSG). GPx also reduces lipid peroxides and protects cell membranes from peroxidation. TRx, which is also selenium dependent, regenerates the thioredoxin system, promoting protein renewal and maintaining the redox state. Through these reactions, excess ROS are effectively neutralized, preventing tissue damage during heat stress. Due to its numerous vital functions and antioxidant properties, selenium is one of the most crucial dietary components for poultry exposed to heat stress. Optimal selenium supplementation (from 0.2 to 0.5 mg kg<sup>-1</sup>) can improve the antioxidant status and immunocompetence of broiler chickens under heat stress conditions (Habibian et al. 2015).

## Insecta

Over 1900 insect species are potentially utilized as food, offering a sustainable production method for both human consumption and animal feed (Kowalska 2019). According to Commission Regulation (EU) 2017/893, insects reared within the EU must be non-pathogenic and safe for plants, animals, and humans. Approved species for animal feed include flies (*Hermetia illucens*, *Musca domestica*), beetles (*Tenebrio molitor*, *Alphitobius diaperinus*), and crickets (*Acheta domesticus*, *Grylloides sigillatus*, *Gryllus assimilis*) (EU 2017/893). Insect farming for animal feed encounters challenges related to sanitation, cultural acceptance, and legislation (FAO, 2014). It has a lower environmental impact compared to conventional farming, thereby reducing pressure on resources and greenhouse gas emissions. Insects convert organic waste into nutrients, thereby promoting a circular economy (Halloran et al. 2017). Regulations (EU 2022/1104) restrict insect feed to materials of plant origin. Insect-derived products enhance poultry growth, nutrient digestibility, gut health, and immunity (Elahi et al. 2022). Stelios et al. (2024) evaluated the addition of *Tenebrio molitor*, *Hermetia illucens*,

and *Zophobas morio* larvae to feed under heat stress conditions. The inclusion of 5% larvae improved feed intake during early growth stages. The group fed with *Tenebrio molitor* larvae exhibited lower liver MDA levels, indicating reduced oxidative stress, suggesting that insect-based diets support broiler growth and decrease oxidative stress. Bortoluzzi *et al.* (2018) and Wu *et al.* (2018) indicate that birds respond positively to protein with balanced amino acids in hot environments, improving growth, gut development, and immunity in broilers. Thus, insects represent an excellent protein source with a high concentration of amino acids for poultry under heat stress (Verkerk *et al.* 2007, Pearce *et al.* 2013, Habashy *et al.* 2017, Elahi *et al.* 2022). Invertebrates in poultry diets provide beneficial fatty acids and chitin. While not supplying essential nutrients, chitin aids in the development of the gastrointestinal microbiome and affects tract development by stimulating peristalsis (Hossain, Blair 2007, Longvah *et al.* 2011). Historically used as medicine, insects can reduce antibiotic use in poultry due to their antimicrobial properties. Their larvae produce antimicrobial peptides effective against pathogens (Elahi *et al.* 2022). Insect exoskeletons contain melanin, which possesses antibacterial and antifungal properties, prevents tumors and liver diseases, and mitigates stress effects (Van Huis *et al.* 2013, Nekrasov *et al.* 2018, Ushakova *et al.* 2018). Zulkifli *et al.* (2022) and Torres-Castillo and Olazarán-Santibáñez (2023) noted that insects contain natural antioxidants such as vitamins E, C, carotenoids, and phenolic compounds. These bioactive compounds influence broiler tissue oxidation and can alleviate oxidative stress (Stelios *et al.* 2024). El-Sayed *et al.* (2022) observed decreased HSP70 gene expression in birds receiving insect protein, attributed to its protective properties. Thus, insect-based diets may enhance broiler health under elevated temperatures. The incorporation of insects into poultry nutrition is predominantly constrained by the stringent legal regulations of the European Union concerning permissible species and feed substrates, as well as by elevated production costs and the limited availability of raw materials. Additional challenges encompass microbiological safety concerns, variability in the nutritional composition of insects, and the presence of chitin, which, in excess, can diminish nutrient digestibility. Moreover, limited market acceptance and a paucity of long-term studies impede the widespread adoption of insect protein in poultry feed.

### **Amino acids**

Amino acids are an essential component of poultry feed and, in most cases, feed formulations were balanced to meet the physiological requirements of birds. However, due to various stress factors, such as heat stress, additional support for the antioxidant system in poultry is required (Musharaf, Latshaw 1999, Awad *et al.* 2014, Liu *et al.* 2016, Attia *et al.* 2017, Smulikowska, Rutkowski 2018, Aviagen 2019, Ma *et al.* 2021, Livingston *et al.* 2022).

Additional supplementation may include higher levels of sulfur amino acids (SAA), such as methionine and cysteine. In addition to their structural role, which is essential for muscle development and growth, these amino acids are crucial for glutathione synthesis in the liver of birds. Glutathione, an important antioxidant, plays a vital role in maintaining adequate levels of reactive oxygen species (ROS – Kidd 2004). The ratio of reduced glutathione (rGSH) to GSSG is a measure of redox balance in cells (Sarsour, Persia 2022).

Supplementation with sulfur amino acids (SAAs) can improve the antioxidant status of birds and serve a protective function in the intestines, due to the presence of polyamines, which are synthesized primarily from methionine (Kidd 2004, Bekebrede et al. 2020).

In a study by Sarsour and Persia (2022), the feed was enriched with 1.24%, 1.13% and 1.04% SAA compared to the control group. Under heat stress conditions, the ratio of rGSH to GSSG in the liver decreased, indicating an improved redox state with increased supplementation of sulfur amino acids.

In contrast, a study conducted by Han et al. (2017) in avian embryos found that heat stress contributed to a decrease in the levels of free amino acids (Leu, Phe, Lys, Arg) in their tissues. A significant reduction in Leu levels was observed in the brain and liver, suggesting that Leu may be a critical amino acid for embryogenesis under heat stress. The dry content 774  $\mu\text{g}$  Leu  $\text{g}^{-1}$  of egg mass indicates that this amino acid plays a significant role in embryonic development (Nimalaratne et al. 2011).

Chicks that were given *ovo* amino acids, specifically L-Leu (35  $\mu\text{mol}$ /egg on the seventh day of embryonic development), exhibited lower body temperatures during hatching, even when the eggs were incubated at elevated temperatures. The results indicate that injected L-Leu has the potential to reduce body temperature during hatching and stimulate the growth rate and amino acid metabolism in the tissues of chicks. The authors speculate that L-Leu supplementation also influenced the development of the hypothalamic-pituitary-thyroid (HPT) axis and the hypothalamic-pituitary-adrenal (HPA) axis, which are responsible for the thermotolerance of birds after hatching (Tzschentke 2008).

### Other nutritional strategies

In addition to the strategies mentioned above, some commonly known and effective methods in poultry production are listed (Table 2).

Given the above, many strategies for preventing heat stress and its effects are known. Producers and farm managers can choose appropriate methods to optimize poultry health and performance. However, certain approaches – such as in *ovo* amino acid administration and the use of insect-derived feed additives – remain largely experimental methods that require further research and validation (EFSA 2015, Yehia et al. 2024).

Feeding strategies dedicated to broiler chickens under heat stress

Product	Dosage	Effect	Author
Sodium butyrate	500.00 - 1200.0 mg kg <sup>-1</sup>	alleviation of lung injury; restoration of the lung and intestinal microbiota; lowered mortality, improved intestinal morphology, antioxidant status, and tight junctions; better ADG, FCR, antioxidant capacity, reduced inflammation and improved barrier function; dose-dependent improvements in growth, liver antioxidant enzymes, decreased MDA	Lan et al. (2020), Ruixia et al. (2024), Niu et al. (2025), Sarker et al. (2025)
Vitamins	vitamin E - 250.00 mg kg <sup>-1</sup> vitamin A - 15.000 IU kg <sup>-1</sup> vitamin C - 200.00 mg kg <sup>-1</sup> folic acid - 1.5000 mg kg <sup>-1</sup> others: D, K, B1, B2, B6, B12, pantothenic acid, biotin, niacin	increased feed intake; improved BWG; increased serum triiodothyronine concentration; increased serum alkaline phosphatase activity; increased serum Ca and P concentrations; elevated thyroid hormone levels; enhanced antibody titres against Newcastle disease virus; reduced ROS levels; improved CAT and SOD activity, as well as TAC (total antioxidant capacity); elevated tissue levels of HSP70 (HSP70 tends to participate in pathways that protect the organism from the harmful effects of ROS). Most vitamins cannot be synthesized by birds and must be provided through feed. However, the feed alone is not sufficient to meet the vitamin requirements. Vitamin-supplemented diets play an important role in the treatment and prevention of diseases, as vitamins allow the animal to utilize proteins and energy to improve health, FCR, growth, and reproduction, as well as reduce stress, including heat stress.	Sahin et al. (2001), Abudabos et al. (2018), Alagawany et al. (2020), Gouda et al. (2020), Pečjak et al. (2022)
Phytase	500.00 -1000.0 mg kg <sup>-1</sup>	better absorption of nutrients; hormonal modulation through phytase activity; support for homeostasis	Dos Anjos Lima et al. (2025)
Electrolytes (Na, K, Cl)	dietary electrolyte balance (DEB): 250-300 mEq kg <sup>-1</sup>	maintenance of acid base balance; stabilization of blood pH; improved feed intake and thermoregulation	Livingston et al. (2022)
Zinc (Zn)	40-100 mg kg <sup>-1</sup>	enhanced antioxidant enzyme activity; improved immune competence; protection against oxidative damage	Sahin et al. (2009)
Probiotics ( <i>S. cerevisiae</i> , <i>L. acidophilus</i> )	2 g kg <sup>-1</sup>	improved growth performance; enhanced blood parameters: higher packed cell volume (PCV), increased red and white blood cell counts (RBC, WBC), increased lymphocyte proportion, reduced heterophil to lymphocyte ratio, higher serum total protein and albumin concentrations, reduced serum AST activity	Attia et al. (2017)
Phytogenic feed additives ( <i>Scutellaria baicalensis</i> L.)	1000 mg kg <sup>-1</sup>	reduced respiratory rate and wing lift behavior under heat stress; improved protection against inflammation and infection with <i>Salmonella Enteritidis</i>	Zmrhal et al. (2018)

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## SUMMARY

Rising global temperatures represent an escalating challenge for poultry production systems by disrupting physiological homeostasis, redox balance, and metabolic efficiency (Lin et al. 2006, Lara, Rostagno 2013, Nawab et al. 2018). Heat stressed birds reduce voluntary feed intake as an adaptive response to limit endogenous heat production; however, this strategy inevitably compromises growth performance, nutrient utilization, and immune competence (Lin et al. 2006, Nawab et al. 2018). At the cellular level, prolonged thermal exposure promotes excessive reactive oxygen species (ROS) generation while attenuating endogenous antioxidant capacity, thereby accelerating oxidative damage to lipids, proteins, and biological membranes (Lara, Rostagno 2013, Shakeri et al. 2018). This review highlights the central role of targeted nutritional interventions in mitigating the multifactorial consequences of heat stress. Compounds such as betaine, selenium, sulfur containing amino acids, antioxidant vitamins, short-chain organic acids, and insect-derived ingredients exert their protective effects through complementary mechanisms involving osmotic regulation, glutathione-dependent redox control, preservation of intestinal integrity, and modulation of immune responses (Shakeri et al. 2018, Abdel-Moneim et al. 2021). Importantly, no single dietary additive provides complete protection against heat stress, underscoring the necessity of integrated nutritional strategies tailored to environmental conditions, feed composition, and bird physiology (Lara, Rostagno 2013). Particular attention should be given to synergistic combinations of micronutrients, such as selenium with vitamins E and C or betaine with sulfur amino acids, which collectively enhance antioxidant defenses, cellular hydration, and tissue resilience (Shakeri et al. 2018, Abdel-Moneim et al. 2021). Emerging feed resources, including insect-based proteins, further align nutritional mitigation strategies with circular bioeconomy principles by improving resource efficiency while delivering bioactive compounds that support gut health and stress tolerance (Halloran et al. 2017, Elahi et al. 2022).

Future research should prioritize long-term and multi-seasonal studies to elucidate the interactive effects of combined dietary interventions on metabolic adaptation, oxidative status, and product quality. Framing nutritional strategies within the broader context of elemental homeostasis and adaptive metabolism positions them as essential tools for sustaining productivity, animal welfare, and food security in poultry production under increasingly adverse climatic conditions.

## Author contributions

I.T. – conceptualization, literature investigation, data curation, writing – original draft preparation, visualization; A.K.Ž. – methodology, literature review, writing – review and editing, A.R. – review and editing. All authors have read and agreed to the published version of the manuscript.

## Conflicts of interest

The authors ensure that they have neither professional nor financial connections related to the manuscript sent to the Editorial Board.

## REFERENCES

- Abdel-Moneim, A.E., Shehata, A.M., Khidr, R.E., Paswan, V.K., Ibrahim, N.S., El-Ghoul, A., Aldhumri, S.A., Gabr, S.A., Mesalam, N.M., Elbaz, A.M., Elsayed, M.A., Wakwak, M.M. and Ebeid, T.A. (2021) 'Nutritional manipulation to combat heat stress in poultry – A comprehensive review', *Journal of Thermal Biology*, 98, 102915, available: <https://doi.org/10.1016/j.jtherbio.2021.102915>
- Abudabos, A.M., Al-Owaimer, A.N., Hussein, E.O.S. and Ali, M.H. (2018) 'Effect of natural Vitamin C on performance and certain haemato-biochemical values in broiler chickens exposed to heat stress', *Pakistan Journal of Zoology*, 50(3), 951-955, available: <https://doi.org/10.17582/journal.pjz/2018.50.3.951.955>
- Afsal, A., Sejian, V., Bagath, M., Krishnan, G., Devaraj, C. and Bhatta, R. (2018) 'Heat stress and livestock adaptation: Neuro-endocrine regulation', *International Journal of Veterinary and Animal Medicine*, 1(2), 108, available: <https://doi.org/10.31021/ijvam.20181108>
- Ahmad, R., Yu, Y.H., Hsiao, F.S.H., Su, C.H., Liu, H.C., Tobin, I., Zhang, G. and Cheng, Y.-H. (2022) 'Influence of heat stress on poultry growth performance, intestinal inflammation, and immune function and potential mitigation by probiotics', *Animals*, 12(17), 2297, available: <https://doi.org/10.3390/ani12172297>
- Alagawany, M., Elnesr, S.S., Farag, M.R., Tiwari, R., Yatoo, M.I., Karthik, K., Michalak, I. and Dhama, K. (2020) 'Nutritional significance of amino acids, vitamins and minerals as nutraceuticals in poultry production and health – a comprehensive review', *Veterinary Quarterly*, 41(1), 1-29, available: <https://doi.org/10.1080/01652176.2020.1857887>
- Al-Sagan, A.A., Al-Yemni, A.H., Abudabos, A.M., Al-Abdullatif, A.A. and Hussein, E.O. (2021) 'Effect of different dietary betaine fortifications on performance, carcass traits, meat quality, blood biochemistry, and hematology of broilers exposed to various temperature patterns', *Animals*, 11(6), 1555, available: <https://doi.org/10.3390/ani11061555>
- Ashraf, M. and Foolad, M.R. (2007) 'Roles of glycine betaine and proline in improving plant abiotic stress resistance', *Environmental and Experimental Botany*, 59(2), 206-216, available: <https://doi.org/10.1016/j.envexpbot.2005.12.006>
- Attia, Y.A., Al-Harhi, M.A., El-Shafey, A.S., Rehab, Y.A. and Kim, W.K. (2017) 'Enhancing tolerance of broiler chickens to heat stress by supplementation with vitamin E, vitamin C and/or probiotics', *Annals of Animal Science*, 17(4), 1155-1169, available: <https://doi.org/10.1515/aoas-2017-0012>
- Aviagen™ EPI (2019). Broiler—Ross 308, available: <https://modernhatch.eu/wp-content/uploads/2021/01/Ross-308-broiler-PO-AND-NS-2019-PL.pdf> (accessed 1 July 2022)
- Awad, E.A., Fadlullah, M., Zulkifli, I., Farjam, A.S. and Chwen, L.T. (2014) 'Amino acids fortification of low-protein diet for broilers under tropical climate: Ideal essential amino acids profile', *Italian Journal of Animal Science*, 13(2), 270-274, available: <https://doi.org/10.4081/ijas.2014.3166>
- Awad, W.A., Ruhnau, D., Gavráu, A., Duplecz, K. and Hess, M. (2022) 'Comparing effects of natural betaine and betaine hydrochloride on gut physiology in broiler chickens', *Poultry Science*, 101(12), 102173, available: <https://doi.org/10.1016/j.psj.2022.102173>
- Ayo, J.O., Danbirini, S., Egbuniwe, I.C. and Sinkalu, V.O. (2014) 'Cloacal temperature responses and some performance indices in Black Harco pullets administered with betamint during the hot-dry season', *Journal of Veterinary Science and Technology*, 5(2), 1-8, available: <https://doi.org/10.4172/2157-7579.1000166>
- Bahuti, M., Yanagi Junior, T., Ribeiro, B.P.V.B., Campos, A.T., Freire, M.S. and de Lima, R.R.

- (2022) 'Heat transfer model for predicting hen's core temperature', *Computers and Electronics in Agriculture*, 193, 106676, available: <https://doi.org/10.1016/j.compag.2021.106676>
- Bekebrede, A.F., Keijer, J., Gerrits, W.J.J. and de Boer, V.C.J. (2020) 'The molecular and physiological effects of protein-derived polyamines in the intestine', *Nutrients*, 12(1), 197, available: <https://doi.org/10.3390/nu12010197>
- Bortoluzzi, C., Rochell, S.J. and Applegate, T.J. (2018) 'Threonine, arginine, and glutamine: Influences on intestinal physiology, immunology, and microbiology in broilers', *Poultry Science*, 97(3), 937-945, available: <https://doi.org/10.3382/ps/pex394>
- Craig, S.A. (2004) 'Betaine in human nutrition', *The American Journal of Clinical Nutrition*, 80(3), 539-549, available: <https://doi.org/10.1093/ajcn/80.3.539>
- Curtis, S.E. (1983) 'Environmental Management in Animal Agriculture', Iowa State University Press, Ames, IA.
- Dalgaard, T.S., Briens, M., Engberg, R.M. and Lauridsen, C. (2018) 'The influence of selenium and selenoproteins on immune responses of poultry and pigs', *Animal Feed Science and Technology*, 238, 73-83, available: <https://doi.org/10.1016/j.anifeeds.2018.01.020>
- Da Silva, D.C.F., de Arruda, A.M.V. and Gonçalves, A.A. (2017) 'Quality characteristics of broiler chicken meat from free-range and industrial poultry system for the consumers', *Journal of Food Science and Technology*, 54(7), 1818-1826, available: <https://doi.org/10.1007/s13197-017-2612-x>
- De Zwart, F.J., Slow, S., Payne, R.J., Lever, M., George, P.M., Gerrard, J.A. and Chambers, S.T. (2003) 'Glycine betaine and glycine betaine analogues in common foods' *Food Chemistry*, 83(2), 197-204, available: [https://doi.org/10.1016/S0308-8146\(03\)00063-3](https://doi.org/10.1016/S0308-8146(03)00063-3)
- Dos Anjos Lima, L.A., Maia, M.I.L., Afo, D.I.B., Maia, A.F., Givisiez, P.E.N., Guerra, R.R., Braz, C.U. and Saraiva, E.P. (2025) 'Effects of exogenous phytase supplementation on the modulation of hormonal responses in Japanese quails (*Coturnix japonica*) at high environmental temperatures during the production phase', *Poultry Science*. 104(10), 105590, available: <https://doi.org/10.1016/j.psj.2025.105590>
- EFSA Scientific Committee (2015) 'Scientific opinion on a risk profile related to production and consumption of insects as food and feed', *EFSA Journal*, 13(10), 4257, 1-60, available: <https://doi.org/10.2903/j.efsa.2015.4257>
- Elahi, U., Xu, C.C., Wang, J., Lin, J., Wu, S.G., Zhang, H.J. and Qi, G.H. (2022) 'Insect meal as a feed ingredient for poultry', *Animal Bioscience*, 35(2), 332-346, available: <https://doi.org/10.5713/ab.21.0435>
- El-Sayed, M.A., Hatab, M.H., Ibrahim, N.S., Assi, H.A., Saleh, H.M., Sayed, W.A. and Rumpold, B.A. (2022) 'Comparative study of growth and HSP70 gene expression in Japanese quails fed different levels of black soldier fly, *Hermetia Illucens*', *Research Square*, available: <https://doi.org/10.21203/rs.3.rs-1347627/v1>
- European Commission (2017) 'Commission Regulation (EU) 2017/893 of 24 May 2017 amending Annexes I and IV to Regulation (EC) No 999/2001 of the European Parliament and of the Council and Annexes X, XIV and XV to Commission Regulation (EU) No 142/2011 as regards the provisions on processed animal protein (Text with EEA relevance)', *Official Journal of the European Union*, L138, 92-116, available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32017R0893>. (accessed: 10 September 2025)
- European Commission (2022) 'Commission Regulation (EU) 2022/1104 of 1 July 2022 amending Regulation (EU) No 68/2013 on the Catalogue of feed materials (Text with EEA relevance)', *Official Journal of the European Union*, L177, 4-74, available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022R1104>. (accessed: 10 September 2025)
- FAO (2014) 'Insects to Feed the World', 1st International Conference, 14-17 May, Wageningen (Ede), The Netherlands.
- Gouda, A., Amer, S.A., Gabr, S. and Tolba, S.A. (2020) 'Effect of dietary supplemental ascorbic acid and folic acid on the growth performance, redox status, and immune status of broiler

- chickens under heat stress', *Tropical Animal Health and Production*, 52, 2987-2996, available: <https://doi.org/10.1007/s11250-020-02316-4>
- Habashy, W.S., Milfort, M.C., Fuller, A.L., Attia, Y.A., Rekaya, R. and Aggrey, S.E. (2017) 'Effect of heat stress on protein utilization and nutrient transporters in meat-type chickens', *International Journal of Biometeorology*, 61(12), 2111-2118, available: <https://doi.org/10.1007/s00484-017-1414-1>
- Habibian, M., Sadeghi, G., Ghazi, S. and Moeini, M.M. (2015) 'Selenium as a feed supplement for heat-stressed poultry: a review', *Biological Trace Element Research*, 165(2), 183-193, available: <https://doi.org/10.1007/s12011-015-0275-x>
- Halloran, A., Hanboonsong, Y., Roos, N. and Bruun, S. (2017) 'Life cycle assessment of cricket farming in north-eastern Thailand', *Journal of Cleaner Production*, 156, 83-94, available: <https://doi.org/10.1016/j.jclepro.2017.04.017>
- Han, G., Yang, H., Bahry, M.A., Tran, P.V., Do, P.H., Ikeda, H., Furuse, M. and Chowdhury, V.S. (2017) 'L-Leucine acts as a potential agent in reducing body temperature at hatching and affords thermotolerance in broiler chicks', *Comparative Biochemistry and Physiology Part A: Molecular and Integrative Physiology*, 204, 48-56, available: <https://doi.org/10.1016/j.cbpa.2016.10.013>
- Hossain, S.M. and Blair, R. (2007) 'Chitin utilisation by broilers and its effect on body composition and blood metabolites', *British Poultry Science*, 48(1), 33-38, available: <https://doi.org/10.1080/00071660601156529>
- Johnson, J.S. (2018) 'Heat stress: Impact on livestock well-being and productivity and mitigation strategies to alleviate the negative effects', *Animal Production Science*, 58(8), 1404-1413, available: <https://doi.org/10.1071/AN17725>
- Kapetanov, M., Pajić, M., Ljubojević, D. and Pelić, M. (2016) 'Heat stress in poultry industry', *Archives of Veterinary Medicine*, 8(2), 87-101, available: <https://doi.org/10.46784/e-avm.v8i2.117>
- Kidd, M.T. (2004) 'Nutritional modulation of immune function in broilers', *Poultry Science*, 83(4), 650-657, available: <https://doi.org/10.1093/ps/83.4.650>
- Konca, Y. and Büyükkılıç Beyzi, S. (2021) 'Effects of betaine supplementation to broiler diets under heat stress', *Tavukçuluk Araştırma Dergisi (Journal of Poultry Research)*, 18(2), 16-22, available: <https://doi.org/10.34233/jpr.1059735>
- Kowalska, D. (2019) 'Insects as a source of nutrients in animal feed', *Roczniki Naukowe Polskiego Towarzystwa Zootechnicznego*, 15(3), 25-37, available: <https://doi.org/10.5604/01.3001.0013.5131>
- Lan, R., Zhao, Z., Li, S. and An, L. (2020) 'Sodium butyrate as an effective feed additive to improve performance, liver function, and meat quality in broilers under hot climatic conditions', *Poultry Science*, 99(11), 5491-5500, available: <https://doi.org/10.1016/j.psj.2020.06.042>
- Lara, L. and Rostagno, M. (2013) 'Impact of heat stress on poultry production', *Animals*, 3(2), 356-369, available: <https://doi.org/10.3390/ani3020356>
- Lin, H., Jiao, H.C., Buyse, J. and Decuyper, E. (2006) 'Strategies for preventing heat stress in poultry', *World's Poultry Science Journal*, 62(1), 71-85, available: <https://doi.org/10.1079/WPS200585>
- Liu, Q.W., Feng, J.H., Chao, Z., Chen, Y., Wei, L.M., Wang, F., Sun, R.P. and Zhang, M.H. (2016) 'The influences of ambient temperature and crude protein levels on performance and serum biochemical parameters in broilers', *Journal of Animal Physiology and Animal Nutrition*, 100(2), 301-308, available: <https://doi.org/10.1111/jpn.12368>
- Liu, W., Yuan, Y., Sun, C., Balasubramanian, B., Zhao, Z. and An, L. (2019) 'Effects of dietary betaine on growth performance, digestive function, carcass traits, and meat quality in indigenous yellow-feathered broilers under long-term heat stress', *Animals*, 9(8), 506, available: <https://doi.org/10.3390/ani9080506>

- Livingston, M.L., Pokoo-Aikins, A., Frost, T., Laprade, L., Hoang, V., Nogal, B., Phillips, C. and Cowieson, A.J. (2022) 'Effect of heat stress, dietary electrolytes, and vitamins E and C on growth performance and blood biochemistry of the broiler chicken', *Frontiers in Animal Science*, 3, 807267, available: <https://doi.org/10.3389/fanim.2022.807267>
- Longvah, T., Mangthya, K. and Ramulu, P. (2011) 'Nutrient composition and protein quality evaluation of eri silkworm (*Samia ricinii*) prepupae and pupae', *Food Chemistry*, 128(2), 400-403, available: <https://doi.org/10.1016/j.foodchem.2011.03.041>
- Ma, B., Zhang, L., Li, J., Xing, T., Jiang, Y. and Gao, F. (2021) 'Heat stress alters muscle protein and amino acid metabolism and accelerates liver gluconeogenesis for energy supply in broilers', *Poultry Science*, 100(1), 215-223, available: <https://doi.org/10.1016/j.psj.2020.09.090>
- Mahmoudi, M., Azarfar, A. and Khosravinia, H. (2018) 'Partial replacement of dietary methionine with betaine and choline in heat-stressed broiler chickens', *Journal of Poultry Science*, 55(1), 28-37, available: <https://doi.org/10.2141/jpsa.0170087>
- Mirowski, A. and Didkowska, A. (2017) 'Influence of heat stress on calves', *Życie Weterynaryjne*, 92(6), 441-442.
- Mohammed, A., Mahmoud, M., Murugesan, R. and Cheng, H.W. (2021) 'Effect of a synbiotic supplement on fear response and memory assessment of broiler chickens subjected to heat stress', *Animals*, 11(2), 427, available: <https://doi.org/10.3390/ani11020427>
- Mujahid, A., Pumford, N.R., Bottje, W., Nakagawa, K., Miyazawa, T., Akiba, Y. and Toyomizu, M. (2007) 'Mitochondrial oxidative damage in chicken skeletal muscle induced by acute heat stress', *Journal of Poultry Science*, 44(4), 439-445, available: <https://doi.org/10.2141/jpsa.44.439>
- Musharaf, N.A. and Latshaw, J.D. (1999) 'Heat increment as affected by protein and amino acid nutrition', *World's Poultry Science Journal*, 55(3), 233-240, available: <https://doi.org/10.1079/WPS19990017>
- Nawab, A., Ibtisham, F., Li, G., Kieser, B., Wu, J., Liu, W., Zhao, Y., Nawab, Y., Li, K., Xiao, M. and An, L. (2018) 'Heat stress in poultry production: Mitigation strategies to overcome the future challenges facing the global poultry industry', *Journal of Thermal Biology*, 78, 131-139, available: <https://doi.org/10.1016/j.jtherbio.2018.08.010>
- Nekrasov, R.V., Zelenchenkova, A.A., Chabaev, M.G. and Ushakova, N.A. (2018) 'Melanine protein-energy additive from *Hermetia illucens* larvae in nutrition of calves', *Sel'skokhozyaistvennaya Biologiya (Agricultural Biology)*, 53(2), 374-384.
- Nimalaratne, C., Lopes-Lutz, D., Schieber, A. and Wu, J. (2011) 'Free aromatic amino acids in egg yolk show antioxidant properties', *Food Chemistry*, 129(1), 155-161, available: <https://doi.org/10.1016/j.foodchem.2011.04.058>
- Niu, Q., Lu, Y., Ren, M., Zhu, J., Zhao, Y., Zhang, R., Yang, X. and Sun, Q. (2025) 'Alterations of lung and gut microbiota in sodium butyrate alleviating heat stress-induced lung injury of broilers', *Poultry Science*, 104(2), 104796, available: <https://doi.org/10.1016/j.psj.2025.104796>
- Pearce, S.C., Gabler, N.K., Ross, J.W., Escobar, J., Patience, J.F., Rhoads, R.P. and Baumgard, L.H. (2013) 'The effects of heat stress and plane of nutrition on metabolism in growing pigs', *Journal of Animal Science*, 91(5), 2108-2118, available: <https://doi.org/10.2527/jas.2012-5738>
- Pečjak, M., Leskovec, J., Levart, A., Salobir, J. and Rezar, V. (2022) 'Effects of dietary vitamin E, vitamin C, selenium and their combination on carcass characteristics, oxidative stability and breast meat quality of broiler chickens exposed to cyclic heat stress', *Animals*, 12(14), 1789, available: <https://doi.org/10.3390/ani12141789>
- Rama Rao, S.V., Raju, M.V.L.N., Panda, A.K., Saharia, P. and Shyam Sunder, G. (2011) 'Effect of supplementing betaine on performance, carcass traits and immune responses in broiler chicken fed diets containing different concentrations of methionine', *Asian-Australasian Journal of Animal Sciences*, 24(5), 662-669, available: <https://doi.org/10.5713/ajas.2011.10286>

- Rostagno, M.H. (2020) 'Effects of heat stress on the gut health of poultry', *Journal of Animal Science*, available: <https://doi.org/10.1093/jas/skaa090>
- Ruixia, L., Wu, F., Wang, Y. and Yin, F. (2024) 'Sodium butyrate alleviates heat stress-induced damage to morphology, antioxidant status, inflammatory response and barrier integrity in jejunum of broilers', *Italian Journal of Animal Science*, 23(1), 215-226, available: <https://doi.org/10.1080/1828051X.2024.2308619>
- Sahin, K., Sahin, N., Kucuk, O., Hayirli, A. and Prasad, A.S. (2009) 'Role of dietary zinc in heat-stressed poultry: A review', *Poultry Science*, 88(10), 2176-2183, available: <https://doi.org/10.3382/ps.2008-00560>
- Sahin, K., Sahin, N., Onderci, M., Yaralioglu, S. and Kucuk, O. (2001) 'Protective role of supplemental vitamin E on lipid peroxidation, vitamins E, A and some mineral concentrations of broilers reared under heat stress', *Veterinárni Medicina*, 46, 140-144
- Sarker, M.T., Wang, S., Wang, S., Xia, W., Zhang, Y., Jin, C., Huang, X., Li, K., Elokil, A., Lv, Y., Zheng, C. and Chen, W. (2025) 'Sodium butyrate alleviates high ambient temperature-induced oxidative stress, intestinal structural disruption, and barrier integrity for growth and production in growing layer chickens', *BMC Veterinary Research*, 21, 131, available: <https://doi.org/10.1186/s12917-025-04583-5>
- Sarsour, A.H. and Persia, M.E. (2022) 'Effects of sulfur amino acid supplementation on broiler chickens exposed to acute and chronic cyclic heat stress', *Poultry Science*, 101(7), 101952, available: <https://doi.org/10.1016/j.psj.2022.101952>
- Shakeri, M., Cottrell, J.J., Wilkinson, S., Ringuet, M., Furness, J.B. and Dunshea, F.R. (2018) 'Betaine and antioxidants improve growth performance, breast muscle development and ameliorate thermoregulatory responses to cyclic heat exposure in broiler chickens', *Animals*, 8(10), 162, available: <https://doi.org/10.3390/ani8100162>
- Shakeri, M., Oskoueian, E., Le, H.H. and Shakeri, M. (2020) 'Strategies to combat heat stress in broiler chickens: Unveiling the roles of selenium, vitamin E and vitamin C', *Veterinary Sciences*, 7(2), 71, available: <https://doi.org/10.3390/vetsci7020071>
- Smulikowska, S. and Rutkowski, A. (eds) (2018) 'Recommended Allowances and Nutritive Value of Feedstuffs for Poultry 5th ed.', The Kielanowski Institute of Animal Physiology and Nutrition, Polish Academy of Sciences, Jablonna, Poland, and Polish Branch of WPSA. (in Polish)
- Sohail, M.U., Hume, M.E., Byrd, J.A., Nisbet, D.J., Ijaz, A., Sohail, A. and Shabbir, M.Z. (2012) 'Effect of supplementation of prebiotic mannan-oligosaccharides and probiotic mixture on growth performance of broilers subjected to chronic heat stress', *Poultry Science*, 91(9), 2235-2240, available: <https://doi.org/10.3382/ps.2012-02182>
- Stelios, V., Ilias, G., Ioannis, P., Christos, A., Elias, P. and Paschalis, F. (2024) 'Effect of three different insect larvae on growth performance and antioxidant activity of thigh, breast, and liver tissues of chickens reared under mild heat stress', *Tropical Animal Health and Production*, 56(2), 120, available: <https://doi.org/10.1007/s11250-024-03923-1>
- St-Pierre, N.R., Cobanov, B. and Schnitkey, G. (2003) 'Economic losses from heat stress by US livestock industries', *Journal of Dairy Science*, 86 (Suppl. 1), E52-E77, available: [https://doi.org/10.3168/JDS.S0022-0302\(03\)74040-5](https://doi.org/10.3168/JDS.S0022-0302(03)74040-5)
- Surai, P.F. and Fisinin, V.I. (2014) 'Selenium in poultry breeder nutrition: An update', *Animal Feed Science and Technology*, 191, 1-15, available: <https://doi.org/10.1016/j.anifeedsci.2014.02.005>
- Surai, P.F. and Fisinin, V.I. (2016) 'Selenium in sow nutrition', *Animal Feed Science and Technology*, 211, 18-30, available: <https://doi.org/10.1016/j.anifeedsci.2015.11.006>
- Tańczuk, M., Junga, R., Kolasa-Więcek, A. and Niemiec, P. (2019a) 'Assessment of the energy potential of chicken manure in Poland', *Energies*, 12(7), 1244, available: <https://doi.org/10.3390/en12071244>
- Tańczuk, M., Junga, R., Werle, S., Chabiński, M. and Ziółkowski, Ł. (2019b) 'Experimental

- analysis of the fixed bed gasification process of the mixtures of the chicken manure with biomass', *Renewable Energy*, 136, 1055-1063, available: <https://doi.org/10.1016/j.renene.2017.05.074>
- Torres-Castillo, J.A. and Olazarán-Santibáñez, F.E. (2023) 'Insects as source of phenolic and antioxidant entomochemicals in the food industry', *Frontiers in Nutrition*, 10, 1133342, available: <https://doi.org/10.3389/fnut.2023.1133342>
- Tzschentke, B. (2008) 'Monitoring the development of thermoregulation in poultry embryos and its influence by incubation temperature', *Computers and Electronics in Agriculture*, 64(1), 61-71, available: <https://doi.org/10.1016/j.compag.2008.05.003>
- Ushakova, N.A., Dontsov, A.E., Sakina, N.L., Ratnikova, I.A., Gavrilova, N.N., Bastrakov, A.A., Kozlova, A.A., Nekrasov, R.V. and Ostrovsky, M.A. (2018) 'Melanin and melanogenesis at different life stages in *Hermetia illucens*', *Biology Bulletin*, 45(1), 47-50, available: <https://doi.org/10.1134/S1062359018010120>
- Van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G. and Vantomme, P. (2013) 'Edible insects: future prospects for food and feed security', FAO Forestry Paper 171, Rome, available: <https://www.fao.org/4/i3253e/i3253e.pdf>
- Verkerk, M.C., Tramper, J., van Trijp, J.C.M. and Martens, D.E. (2007) 'Insect cells for human food', *Biotechnology Advances*, 25(2), 198-202, available: <https://doi.org/10.1016/j.biotechadv.2006.11.004>
- Wen, C., Leng, Z., Chen, Y., Ding, L., Wang, T. and Zhou, Y. (2021) 'Betaine alleviates heat stress-induced hepatic and mitochondrial oxidative damage in broilers', *Journal of Poultry Science*, 58(2), 103-109, available: <https://doi.org/10.2141/jpsa.0200003>
- White, P.J. (2016) 'Selenium accumulation by plants', *Annals of Botany*, 117(2), 217-235, available: <https://doi.org/10.1093/aob/mcv180>
- Wu, Q.J., Liu, N., Wu, X.H., Wang, G.Y. and Lin, L. (2018) 'Glutamine alleviates heat stress-induced impairment of intestinal morphology, intestinal inflammatory response, and barrier integrity in broilers', *Poultry Science*, 97(8), 2675-2683, available: <https://doi.org/10.3382/ps/pey123>
- Yahav, S. (2015) 'Regulation of body temperature: Strategies and mechanisms', *Sturkie's Avian Physiology*, 6th ed., 869-905, available: <https://doi.org/10.1016/B978-0-12-407160-5.00037-3>
- Yang, W.R., Sun, H., Yang, Z.B., Wang, Y., Jiang, S.Z. and Zhang, G.G. (2008) 'Effects of betaine supplementation to methionine-deficient diet on growth performance and carcass characteristics of broilers', *American Journal of Animal and Veterinary Sciences*, 3(3), 78-84.
- Yehia, M., Alfonso-Avila, A. R., Allard, J.-M. A., Ouellet, V. and Alnahhas, N. (2024) 'The potential of in ovo-fed amino acids to alleviate the effects of heat stress on broiler chickens during the finisher phase', *Poultry Science*, 103(7), 103821, available: <https://doi.org/10.1016/j.psj.2024.103821>
- Zhan, X.A., Li, J.X., Xu, Z.R. and Zhao, R.Q. (2006) 'Effects of methionine and betaine supplementation on growth performance, carcasses composition and metabolism of lipids in male broilers', *British Poultry Science*, 47(5), 576-580, available: <https://doi.org/10.1080/00071660600963438>
- Zhao, G., He, F., Wu, C., Li, P., Li, N., Deng, J., Zhu, G., Ren, W. and Peng, Y. (2018) 'Betaine in inflammation: Mechanistic aspects and applications', *Frontiers in Immunology*, 9, 1070, available: <https://doi.org/10.3389/fimmu.2018.01070>
- Zmrhal, V., Lichovníková, M. and Hampel, D. (2018) 'The effect of phytogenic additive on behavior during mild-moderate heat stress in broilers', *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 66(4), 939-944, available: <https://doi.org/10.11118/actaun201866040939>
- Zulkifli, N.F.N.M., Seok-Kian, A.Y., Seng, L.L., Mustafa, S., Kim, Y.S. and Shapawi, R. (2022) 'Nutritional value of black soldier fly (*Hermetia illucens*) larvae processed by different methods', *PLoS One*, 17(2), e0263924, available: <https://doi.org/10.1371/journal.pone.0263924>