



Nutritional Strategies for Mitigating Heat Stress in Broilers: A Review of Acid-base Balance and Osmoregulation

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 0009-0005-4474-0216

ABSTRACT

This review focused on the mechanisms of action and effects of these dietary additives in maintaining acid-base balance and osmoregulation under heat stress conditions. Heat stress, a major challenge affecting poultry production, particularly in tropical and subtropical regions. It disrupted acid-base balance, reduced feed intake, impaired growth performance, and increased mortality in broilers. Nutritional interventions such as ammonium chloride, sodium bicarbonate, betaine, and vitamin C have shown significant potential in alleviating heat stress by improving physiological and metabolic responses. The findings suggested that strategic supplementation of these additives could enhance performance, improve immunity, and support overall broiler health. Furthermore, heat stress was associated with oxidative stress and electrolyte imbalance, which adversely affected cellular integrity and metabolic efficiency in broilers. Ammonium chloride and sodium bicarbonate were reported to play a significant role in regulating systemic pH and maintaining electrolyte balance, thereby supporting physiological stability during thermal stress. Betaine acted as an osmo-protectant and methyl donor, contributing to improved cellular hydration, nutrient utilization, and intestinal health. Vitamin C functioned as a potent antioxidant that helped reduce oxidative damage and enhanced immune response under stress conditions. Overall, the reviewed literature indicated that the inclusion of these dietary additives, either individually or in combination, improved feed efficiency, growth performance, and survivability of broilers. These findings highlighted the importance of adopting appropriate nutritional strategies to mitigate heat stress and sustain productivity in poultry production systems.

KEYWORDS: Heat stress, broilers, acid-base balance, osmoregulation

Citation (VANCOUVER): Thote et al., Nutritional Strategies for Mitigating Heat Stress in Broilers: A Review of Acid-base Balance and Osmoregulation. *International Journal of Bio-resource and Stress Management*, 2026; 17(10), 01-07. [HTTPS://DOI.ORG/10.23910/1.2026.7150](https://doi.org/10.23910/1.2026.7150).

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Data Availability Statement: Legal restrictions are imposed on the public sharing of raw data. However, author have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

Conflict of interests: The author has declared that no conflict of interest exists.

1. INTRODUCTION

India's poultry sector has expanded considerably over the past two decades due to the adoption of scientifically proven rearing and feeding practices. India currently ranks second in egg production and fifth in poultry meat production with approximately 122 billion eggs annually. Per capita egg availability increased from 62 eggs in 2014–15 to 101 eggs annum⁻¹ in 2022–23, while meat availability increased from 5.5 to 7.1 kg annum⁻¹ during the same period. This rapid growth highlights the importance of poultry in ensuring food and nutritional security in developing countries (Anonymous, 2023). However, the expansion of the poultry industry has also increased challenges affecting sustainable production, among which heat stress is considered one of the most serious constraints, particularly in tropical and subtropical regions. Heat stress occurs when birds are unable to maintain thermal balance under high ambient temperature and humidity. Broilers are homeothermic animals and perform optimally within a thermoneutral zone of 18–22 °C. Exposure to temperatures above this range adversely affects physiological, metabolic, and endocrine functions, leading to reduced productivity and welfare (Lara and Rostagno, 2013; Sailo and Das, 2016). Initially, birds dissipate heat through radiation and convection; however, under severe heat stress, evaporative cooling through panting becomes the primary mechanism. Excessive panting causes loss of carbon dioxide (CO₂), resulting in reduced blood pCO₂, altered acid-base balance, and respiratory alkalosis (Borges et al., 2007). Consequently, heat stress reduces feed intake, body weight gain, feed conversion efficiency, immune response, and increased heterophil-to-lymphocytes ratio in broilers (Chand et al., 2017; Sayed and Downing, 2015). In addition, oxidative stress and physiological imbalance further aggravate production losses under high-temperature conditions (Shakeri et al., 2020; Nutautaitė et al., 2020). Several environmental modifications, including improved ventilation and cooling systems, have been adopted to minimize heat stress. However, these strategies are often costly and difficult to implement under small-scale farming conditions. Therefore, nutritional interventions are increasingly gaining importance as economical and practical approaches for alleviating heat stress (Tahreem, 2019). Dietary supplementation of additives such as sodium bicarbonate, ammonium chloride, betaine, and vitamin C has shown beneficial effects in maintaining acid-base balance, electrolyte equilibrium, osmoregulation, and antioxidant status in heat-stressed broilers. Betaine acts as an effective osmo-protectant that stabilizes cellular structure and water balance under stressful conditions. Previous studies reported that betaine supplementation improved growth performance, oxidative stability, breast muscle quality, and hematological parameters in broilers exposed to heat stress

(Nutautaitė et al., 2020; Yeasmin et al., 2023). Similarly, Rokade et al. (2024) observed that betaine hydrochloride supplementation effectively mitigated heat stress during hot summer conditions by improving performance and survivability in broiler chickens. Vitamin C also plays an important role as a potent antioxidant that enhances stress tolerance, immune response, and hematological parameters in heat-stressed birds (Hassan and Asim, 2020). Previous findings further indicated that vitamin C supplementation improves the adaptive capacity of broilers under high environmental temperatures (Al-Tamimi et al., 2019). Therefore, understanding the physiological impacts of heat stress and developing effective nutritional mitigation strategies are essential for sustainable poultry production. This review aimed to evaluate the role of ammonium chloride, sodium bicarbonate, betaine, and vitamin C in alleviating heat stress in broilers, with emphasis on their role in maintaining acid-base balance, osmoregulation, and overall production performance under high-temperature conditions.

2. EFFECT OF AMMONIUM CHLORIDE IN POULTRY

Ammonium chloride (NH₄Cl) is a systemic acidifier that plays a critical role in managing acid-base balance and improving broiler performance, particularly under heat stress conditions.

3. MECHANISM OF ACTION

Ammonium chloride releases hydrogen ions (H⁺) during metabolism, effectively lowering blood pH and countering respiratory alkalosis caused by heat-induced panting (Teeter et al., 1985; Moghaddam et al., 2006). This acidification process helps stabilize blood pH and maintain homeostasis. Additionally, NH₄Cl supplementation regulates blood electrolyte concentrations, notably increasing chloride (Cl⁻) levels, which are essential for restoring acid-base balance during thermal stress (Moghaddam et al., 2006; Teeter et al., 1985).

4. BENEFITS OF AMMONIUM CHLORIDE SUPPLEMENTATION

4.1. Heat stress alleviation

Research shows that NH₄Cl supplementation reduces mortality and alleviates the adverse effects of acute and chronic heat stress in broilers. It achieves this by stabilizing blood pH, improving metabolic efficiency, and maintaining electrolyte balance (Teeter et al., 1985; Moghaddam et al., 2006). Similarly, Majekodunmi et al. (2015) reported that supplementation of drinking water with 0.5% ammonium chloride reduced respiratory rate and mortality in broilers reared under natural heat stress, indicating improved

physiological adaptation to elevated environmental temperatures.

4.2. Enhanced performance

NH₄Cl supplementation has been shown to significantly enhance body weight gain and maintain optimal levels of blood potassium and chloride, which are critical for preventing electrolyte imbalances. These improvements support better feed intake and overall broiler performance under heat stress conditions (Teeter et al., 1985; Moghaddam et al., 2006).

While NH₄Cl supplementation offers considerable benefits, excessive dosages (e.g., concentrations exceeding 1%) can lead to blood acidosis, adversely affecting broiler health. This highlights the importance of precise dosing to optimize its benefits while minimizing potential physiological side effects (Teeter et al., 1985).

Ammonium chloride is an effective tool for mitigating heat stress in broilers by stabilizing blood pH, regulating electrolytes, and enhancing metabolic efficiency. However, its supplementation requires careful management to avoid adverse effects, ensuring the health and performance of broilers under heat stress conditions.

5. EFFECT OF SODIUM BICARBONATE IN POULTRY

Sodium bicarbonate (NaHCO₃) is a vital dietary supplement in poultry nutrition, particularly for birds exposed to heat stress. It provides sodium and bicarbonate ions, which are essential for maintaining acid-base balance, stabilizing blood pH, and preventing acidosis. These functions support metabolic processes that enhance growth, productivity, and overall bird health (Abbas et al., 2017). In commercial poultry production, heat stress remains one of the major environmental challenges affecting feed intake, nutrient utilization, immune response, and production efficiency. Under high ambient temperatures, birds increase respiratory activity through panting, resulting in excessive carbon dioxide loss and respiratory alkalosis. Supplementation with sodium bicarbonate helps restore electrolyte equilibrium and supports physiological adaptation to thermal stress conditions (Ahmad et al., 2009).

Sodium bicarbonate supplementation has also been recognized as an effective nutritional approach for maintaining dietary electrolyte balance (DEB), which plays a crucial role in regulating acid-base homeostasis in poultry exposed to elevated environmental temperatures. Heat stress increases respiratory rate, leading to excessive loss of carbon dioxide and bicarbonate ions, ultimately disturbing blood pH and electrolyte equilibrium. Supplementation with sodium bicarbonate restores bicarbonate reserves, improves blood buffering capacity, and supports normal physiological

functions during thermal stress. Furthermore, maintaining an optimum dietary electrolyte balance has been associated with improved feed intake, water consumption, nutrient utilization, and overall production performance in broilers (Mongin, 1981; Ahmad et al., 2009; Sayed and Downing, 2015; Olayiwola and Adedokun, 2025).

6. MECHANISM OF ACTION

Sodium bicarbonate plays a critical role in the bicarbonate buffer system, which is essential for regulating plasma pH. During oxidative metabolism, carbon dioxide is converted to carbonic acid by carbonic anhydrase, which dissociates into bicarbonate and hydrogen ions. The bicarbonate ions work in tandem with the respiratory and renal systems to maintain plasma pH within optimal ranges, ensuring metabolic homeostasis (Al-Ghoul, 2023).

Sodium bicarbonate also influences nutrient digestibility and intestinal health. Improved buffering capacity in the digestive tract enhances enzyme activity and nutrient utilization, leading to better feed efficiency and growth performance. Furthermore, bicarbonate ions facilitate proper transport of nutrients across intestinal membranes and support metabolic reactions associated with energy production (Ahmad et al., 2009). Research has further indicated that sodium bicarbonate supplementation may reduce oxidative stress by supporting antioxidant defense mechanisms and minimizing cellular damage caused by thermal stress (Sayed and Downing, 2015).

In addition to regulating systemic acid-base balance, sodium bicarbonate improves intestinal function by maintaining an optimal luminal pH that favors digestive enzyme activity and nutrient absorption. Improved digestive efficiency contributes to enhanced utilization of dietary protein and energy, thereby improving growth performance and feed conversion efficiency. Recent investigations have further suggested that adequate bicarbonate availability contributes to the maintenance of cellular homeostasis, reduces oxidative damage, and supports antioxidant defense mechanisms under heat stress conditions (Al-Ghoul, 2023; Olayiwola and Adedokun, 2025; Mangan and Siwek, 2024).

7. BENEFITS OF DIETARY SODIUM BICARBONATE SUPPLEMENTATION IN POULTRY

7.1. Growth and productivity

Abbas et al. (2017) reported that sodium bicarbonate supplementation enhanced feed intake, water consumption, weight gain, and feed efficiency in poultry. Similar findings were reported by Ahmad et al. (2009), who observed significant improvements in body weight gain and feed conversion ratio in broilers supplemented with sodium

bicarbonate under heat stress conditions. The positive effects are mainly attributed to improved acid-base balance, better nutrient digestibility, and enhanced physiological adaptation to thermal stress.

Several researchers have demonstrated that supplementation of sodium bicarbonate in broiler diets significantly improves body weight gain, average daily gain, feed conversion ratio, carcass yield, and survivability during hot climatic conditions. These beneficial responses are primarily attributed to improved electrolyte balance, enhanced water consumption, stabilization of blood pH, and better metabolic adaptation to heat stress. Moreover, maintaining an appropriate sodium to chloride ratio through dietary bicarbonate supplementation enhances nutrient digestibility and reduces physiological stress, thereby promoting efficient production performance (Ahmad et al., 2009; Abbas et al., 2017; Olayiwola and Adedokun, 2025).

7.2. Improvement in egg quality

Sodium bicarbonate also positively impacted egg production parameters, significantly improving egg weight, eggshell thickness, and specific gravity (Abbas et al., 2022).

7.3. Heat stress mitigation

Incorporating sodium bicarbonate into the diet of caged layers effectively mitigated the adverse effects of heat stress on blood chemistry during summer conditions, improving bird welfare and productivity (Abbas et al., 2017). Heat stress causes physiological disturbances such as electrolyte imbalance, oxidative stress, reduced feed intake, and impaired immune function. Sodium bicarbonate supplementation helps alleviate these negative effects by restoring electrolyte equilibrium and supporting thermoregulation. Supplementation has also been associated with reductions in stress indicators such as plasma corticosterone levels and heterophil-to-lymphocyte ratio, suggesting improved physiological resilience under stressful environmental conditions (Sayed and Downing, 2015). Additionally, birds receiving sodium bicarbonate exhibit better hydration status and reduced mortality during periods of severe heat exposure.

Heat stress induces oxidative stress by increasing the production of reactive oxygen species (ROS), which adversely affects cellular integrity, immune function, and productive performance. Sodium bicarbonate supplementation indirectly alleviates oxidative stress by maintaining acid-base equilibrium and improving electrolyte balance, thereby reducing physiological disturbances associated with prolonged exposure to high ambient temperatures. Birds receiving diets supplemented with sodium bicarbonate exhibit improved thermoregulatory capacity, enhanced hydration status, lower mortality rates, and better welfare under commercial production conditions (Shakeri et al.,

2020; Olayiwola and Adedokun, 2025).

Recent reviews have highlighted sodium bicarbonate as one of the most economical electrolyte supplements for poultry production because of its ability to improve dietary electrolyte balance without adversely affecting feed palatability. It is particularly beneficial when incorporated into comprehensive nutritional strategies alongside antioxidants, osmolytes, vitamins, and appropriate environmental management practices. Such integrated approaches provide greater protection against heat stress than any single intervention alone and contribute to sustainable poultry production under changing climatic conditions (Mangan and Siwek, 2024; Olayiwola and Adedokun, 2025).

Sodium bicarbonate is therefore considered an effective dietary intervention for maintaining acid-base balance and improving poultry performance under heat stress conditions. By supporting metabolic functions and alleviating the negative impacts of high temperatures, it serves as a valuable tool for enhancing growth, feed efficiency, and egg quality in poultry production systems.

8. EFFECT OF BETAIN IN POULTRY

Methyl groups are vital for the metabolism of all animals, as they cannot synthesize these groups and must obtain them through dietary sources. Betaine, a potent methyl group donor, plays a critical role in enhancing the availability of methionine, an essential amino acid required for protein synthesis. Traditionally derived from sugar beets, betaine is now also available as synthetic betaine anhydrous, which offers a cost-effective alternative for replacing methionine in animal diets (Nutautaitė et al., 2020). Betaine (trimethylglycine) is widely recognized as an important functional feed additive in poultry nutrition because of its dual role as an osmolyte and methyl donor. Betaine helps maintain cellular water balance by protecting intestinal and muscular cells against dehydration and osmotic stress, thereby improving thermotolerance and physiological stability in birds exposed to high environmental temperatures (Al-Tamimi et al., 2019).

9 . E F F E C T S O F B E T A I N E SUPPLEMENTATION

Numerous studies have highlighted the benefits of betaine supplementation in broiler diets, particularly under heat stress conditions:

9.1. Improvement in growth performance

Chand et al. (2017) evaluated the effect of betaine supplementation at different levels (0, 1, 1.5, and 2 g kg⁻¹ feed) on heat-stressed broilers. Their findings revealed that the group supplemented with 2 g kg⁻¹ betaine (Bet-2.0)

exhibited significantly enhanced feed intake, weight gain, feed conversion ratio (FCR), and dressing percentage.

Similarly, Amer et al. (2018) demonstrated that supplementing broiler diets with 2g kg⁻¹ betaine under standard-energy conditions significantly improved growth performance, economic efficiency, and overall welfare during the summer season. Additionally, Rokade et al. (2024) showed that even a lower supplementation level of 1 g kg⁻¹ effectively enhanced growth performance, gut structure, and overall welfare in heat-stressed broilers. In another study, Yeasmin et al. (2023) demonstrated that 0.06% betaine in drinking water significantly enhanced body weight (1758.3 g), reduced FCR (1.36), improved carcass traits, and reduced cholesterol levels without any mortality. These findings highlight betaine's potential as a growth promoter, stress reliever, and immune booster, with optimal results achieved at varying levels depending on conditions.

9.2. Enhancement of immune response and health status

Chand et al. (2017) reported that betaine supplementation boosted the immune response in broilers by lowering the heterophil count, increasing lymphocyte count, reducing the heterophil-to-lymphocyte ratio, and decreasing antibody titre in treated groups. Furthermore, Nutautaite et al. (2020) concluded that dietary betaine at 1 and 2 g kg⁻¹ reduced mortality rates and improved the overall health status of broilers.

9.3. Improved feed efficiency

Recent investigations have demonstrated that betaine supplementation improves intestinal morphology by increasing villus height, reducing crypt depth, and enhancing absorptive surface area of the small intestine. These structural improvements promote efficient nutrient digestion and absorption while maintaining intestinal barrier integrity under stressful environmental conditions. Improved gut health further contributes to enhanced feed conversion efficiency, growth performance, and resilience against heat-induced physiological disturbances (Ratriyanto and Mosenthin, 2018; Rokade et al., 2024; Olayiwola and Adedokun, 2025).

Nutautaite et al. (2020) found that betaine supplementation enhanced FCR, with greater benefits observed at higher inclusion levels. Additionally, Tahreem (2019) reported that dietary supplementation with betaine significantly ($p < 0.05$) improved FCR and body weight gain in heat-stressed broilers, further validating its role as an effective anti-stressor. Furthermore, Ratriyanto and Mosenthin (2018) concluded that betaine enhances thermotolerance by acting as an effective osmolyte, maintaining intracellular water balance, improving intestinal integrity, and reducing the metabolic energy required for cellular osmoregulation, thereby improving growth performance and feed efficiency

in heat-stressed poultry.

Collectively, these findings suggest that dietary betaine supplementation effectively improves feed efficiency, nutrient utilization, and productive performance in poultry subjected to heat stress conditions. Its role as a methyl group donor and a cost-effective alternative to methionine further enhances its value in poultry nutrition. Incorporating betaine at appropriate levels in broiler diets can mitigate the adverse effects of heat stress and promote better productivity and welfare.

10. EFFECT OF VITAMIN C IN POULTRY

Ahmadu et al. (2016) reviewed the crucial role of Vitamin C in mitigating stress and enhancing the health and productivity of broilers through its multifaceted mechanisms. As a potent antioxidant, it neutralizes reactive oxygen species (ROS) and regenerates other antioxidants, such as vitamin E and glutathione, to protect cellular components from oxidative damage. It regulates stress responses by lowering corticosterone levels, thereby reducing the adverse effects of heat and environmental stress on growth and immune function.

Vitamin C also acts as an essential cofactor in collagen synthesis, iron absorption, and carnitine production, supporting connective tissue development, haemoglobin synthesis, and energy metabolism. Additionally, it enhances immune function by stimulating phagocyte activity, lymphocyte proliferation, and cytokine production, improving disease resistance. During heat stress, Vitamin C supports thermoregulation by reducing body temperatures, minimizing panting rates, and restoring acid-base balance.

Studies show that supplementing broiler drinking water with 200 g/1,000 l of vitamin C improves growth, feed intake, and feed conversion ratio (FCR) while lowering stress hormone levels (Del Barrio et al., 2020). Another study by Hassan and Asim (2020) found that adding 360 mg l⁻¹ of vitamin C helped maintain healthy blood parameters under heat stress. It increased red blood cells, improved immune response by reducing harmful stress indicators, and lowered heat shock protein (HSP70) levels, which are markers of heat stress. Additionally, Desoky and Kamel (2018) reported that 250 mg kg⁻¹ of vitamin C in feed enhanced weight gain, FCR, and immune strength while reducing body heat and oxidative stress during hot conditions.

11. CONCLUSION

Heat stress was a major constraint in poultry production. Nutritional strategies using ammonium chloride, sodium bicarbonate, betaine, and vitamin C helped maintain acid-base balance, improve performance, and enhance immunity in broilers.

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